BML 888

May 1961

p4
p86

NATURE OF MATTER

Purposes of High Energy Physics

Edited by
LUKE C.L. YUAN

NATURE OF MATTER

Purposes of High Energy Physics

NATURE OF MATTER
Purposes of High Energy Physics

Edited by
LUKE C.L. YUAN

BROOKHAVEN NATIONAL LABORATORY

Associated Universities, Inc.

under contract with the

United States Atomic Energy Commission

Cover:

The photograph on the cover shows the bubble chamber tracks of the first production in hydrogen of an omega minus (Ω^-) hyperon in a negative kaon (K^-) beam, and its subsequent decay.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

PRINTED IN USA

PRICE \$1.75

Available from the
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards
U.S. Department of Commerce
Springfield, Virginia

January 1965

5000 copies

PREFACE

During the past three years, a group of scientists and engineers at several National Laboratories and universities has been intensively pursuing studies on the design and experimental programs for a super high energy accelerator in the energy region of multi-hundred BeV.

In the course of these studies, we have found enthusiastic support and encouragement from theorists and experimentalists alike. However, we also sensed the apparent existence of some misunderstanding of the objectives of high energy physics, not only among the general public but also among the scientific community as a whole. It seems, therefore, that some communication by way of explanations is urgently needed among high energy physicists, the scientific community as a whole, and the general public. For this purpose, we have asked some thirty leading theoretical physicists, both in this country and abroad, each to present his own view on this subject, and to discuss some of the problems and implications involved. In this way, a collection of diversified views embracing many different aspects of the subject would provide a comprehensive basis for a better understanding of the fundamental importance and great depth of high energy physics.

Professor J.R. Oppenheimer has written a Foreword to this volume, providing a general account of the views presented here. We have attempted to divide the articles into three groups. The first group, under the heading "Purposes of High Energy Physics," contains those articles dealing with the more general and philosophical viewpoints. The second group, under the heading "Some Problems of High Energy Physics," consists of articles which deal with more specific and technical aspects of the subject. The third group contains two articles of a somewhat different character with more technical and detailed considerations. In each group, the order of the contributions is alphabetical according to the authors' names.

At the end of this volume, a chapter on "Experimental Feasibility at Super High Energies" is included, so as to acquaint the reader with the general conclusions reached in the studies.

The general planning of this volume was done at Brookhaven National Laboratory, with advice from the Super High Energy Physics Committee, the members of which are J.P. Blewett, W.B. Fowler, S.J. Lindenbaum, R.P. Shutt, and L.C.L. Yuan (Chairman). We have been assisted by Brookhaven's Advanced Accelerator Development Division, which is responsible for the design study for a 600 to 1000-BeV accelerator.

We wish to express our deep appreciation and sincere thanks to all those who have graciously contributed to this volume, and particularly to Professor Oppenheimer for his Foreword and valuable counseling. We are grateful to Professors L.A. Radicati, R.P. Shutt, and S.B. Treiman, who have served as members of the Editorial Review Committee and have been extremely helpful. We wish to express our thanks to Dr. M. Goldhaber, Director of Brookhaven National Laboratory, for his interest and encouragement.

The Research Division of the U.S. Atomic Energy Commission has encouraged and supported this project. The cooperation of many universities and institutions is also acknowledged.

LUKE C.L. YUAN
Brookhaven National Laboratory
December, 1964

LIST OF CONTRIBUTORS

S.M. BERMAN
Stanford University	J.R. OPPENHEIMER
The Institute for Advanced Study
H.A. BETHE
Cornell University	A. PAIS
The Rockefeller Institute
G.F. CHEW
University of California	H. PRIMAKOFF
University of Pennsylvania
R.H. DALITZ
The Clarendon Laboratory, Oxford	L.A. RADICATI
Scuola Normale Superiore, Pisa, Italy
S.D. DRELL
Stanford University	R.G. SACHS
Argonne National Laboratory
G. FEINBERG
Columbia University	J. J. SAKURAI
University of Chicago
M. GOLDBERGER
Princeton University	L.I. SCHIFF
Stanford University
N.N. KHURI
The Rockefeller Institute	J. SCHWINGER
Harvard University
T. KINOSHITA
Cornell University	S.B. TREIMAN
Princeton University
T.D. LEE
Columbia University	K.M. WATSON
University of California
F.E. LOW
Massachusetts Institute of Technology	S. WEINBERG
University of California
R.E. MARSHAK
University of Rochester	V.F. WEISSKOPF
CERN
Y. NAMBU
University of Chicago	G.C. WICK
Brookhaven National Laboratory
K. NISHIJIMA
University of Illinois	C.N. YANG
The Institute for Advanced Study
S. OKUBO
University of Rochester	L.C.L. YUAN
Brookhaven National Laboratory

CONTENTS

Foreword.....	J.R. Oppenheimer	1
Views of Theoretical Physicists		
1. Purposes of High Energy Physics		
H.A. Bethe.....		9
G. Feinberg.....		12
A. Pais.....		16
H. Primakoff.....		18
R.G. Sachs.....		20
J. Schwinger.....		23
V.F. Weisskopf.....		24
G.C. Wick.....		28
2. Some Problems of High Energy Physics		
S.M. Berman and S.D. Drell.....		33
G.F. Chew.....		37
R.H. Dalitz.....		41
M. Goldberger.....		44
N.N. Khuri and T. Kinoshita.....		47
T.D. Lee.....		50
F.E. Low.....		53
Y. Nambu.....		55
L.A. Radicati.....		59
J. J. Sakurai.....		62
L.I. Schiff.....		64
S.B. Treiman.....		66
K.M. Watson.....		69
S. Weinberg.....		71
C.N. Yang.....		74
3. More Technical and Detailed Considerations		
R.E. Marshak and S. Okubo.....		79
K. Nishijima.....		102
Experimental Feasibility at Super High Energies.....	L.C.L. Yuan	125
Appendices		
1. Accelerators With Energy >1 BeV.....		148
2. Some Families of Particles.....		149

FOREWORD

When the first particle accelerators were designed and built, more than three decades ago, they had a clear purpose. Apart from the quanta of light and gravitation, the only particles known to physicists were electrons and protons, and atomic theory explained their interactions. The accelerators were built to study nuclear reactions, to enable protons and other nuclei to approach closely to nuclear targets, despite the fact that both projectile and target were positively charged, and thus repel one another. This program led to the rapid development of nuclear physics.

When, after the war, a new generation of accelerators was planned, the considerations that led to them were of another order. At that time we had only a very rough description of the interactions between nuclear particles, neutron and proton, and thought that these interactions must be related, according to Yukawa's suggestion, to the interchange of mesons between them. Mesons had indeed been discovered in the cosmic rays, and the accelerators were built and put into operation to produce them as it was found that the cosmic-ray mesons and Yukawa's were different objects, the latter formed by the decay of the former. The accelerators were thus intended to supplement and enrich cosmic-ray evidence about these new particles, and to throw light on the forces between nucleons. This they indeed did.

There were two other arguments for higher energy experiments, valid now, in a new stage, as then. The first is the argument that to explore structure on a small scale, and events that occur in short intervals of time, we in general need collisions in which momentum and energy transfer grow larger as the regions of space and time grow smaller. This is a very general consequence of the wave nature of all matter. It is supplemented by the fact that massive particles can be created only if the energy available in a collision exceeds their mass.

The second general argument was that in entering a new domain of experience, we would find unexpected things that were really new. In a vague way, the experience with cosmic rays then supported this expectation; it has of course been fulfilled.

Today, physicists have given serious thought and study to the very large enterprise of building an accelerator in the range of several hundred to 1000 billion volts to explore structure in the range below 10^{-15} cm, in times down to 10^{-25} sec. The general arguments still apply. The cosmic rays have this time hardly lit flares as to what we shall find in that region. Their last great revelation, more than 10 years ago, was the existence of unexpected new particles, and of a new quantum number, an almost conserved quantity, called strangeness. The cosmic rays have also taught us to expect roughly constant cross sections for nucleons at the highest energies, and to expect of such collisions jets of secondary particles with rather remarkable regularities, only partially understood. But the experience with the available great accelerators has been so rich, so puzzling, so obviously an unfinished story, that this small volume is concerned with reading from what we know and what we have learned, and above all from what we do not at all understand, what one may ask, what one may hope of the future.

This volume contains contributions from some 30 theoretical physicists, all active in the field of high energy physics, to whom collectively the theoretical progress of the last years is largely to be attributed. Each author suggests some questions to which he would like the answer, or for which he surmises one, which require accelerators not now available. There is necessarily a good deal of repetition in these questions. We are, in fact, trying to understand the same nature, with the same limited observations available, and with the inadequate but indispensable tools of the physics we have learned from the past. There is also great variety in the contributions, not only because there is variety in the personal interests of the authors, but because the current questions of this part of physics have a very high rate of turnover. Many of the questions here raised would not have been asked in the same terms six months ago; some surely will not be asked six months from now; and some few may become obsolete on the way to the printer. These contributions speak for themselves; and any attempt to synthesize them or adjudicate between them would seem to me an impudence, of no service to the reader, and likely only to add another personal view to the many here expressed.

There is also a longer chapter by Yuan, in which he reports on the many conscientious and responsible studies of the technical feasibility of machines to be built, and of the questions still open. Of this I do not think that it will be obsolete by the time it is published.

Let me then turn to a brief description of what we know today, that may be compared to our knowledge of the electron and proton, and of atomic theory, when accelerators were first envisaged. Apart from the quanta of electromagnetism and gravity, we have come to know two sets of particles: the leptons, which as far as we know have no strong interactions at known energies; and all others, which do have such very strong interactions. The leptons themselves are a puzzle. They are the two neutrinos – we do not know why there are two – the μ meson and the familiar electron, all with their antiparticles. The μ meson and the electron appear to have very similar electromagnetic interactions, and their “weak” interactions, those responsible for β decay, for the instability of the μ meson, for the emission of neutrinos, are in the present range of observation indistinguishable. We do not understand why the μ meson is some 200 times heavier than the electron, or the apparent redundancy of the two neutrinos. We do not understand why at low energies the weak interactions are as weak as they are. We do know that as energies promised by the new accelerator are reached, the description we give of these interactions at low energies will no longer be logically possible, and that either new particles whose existence has been conjectured and sought but not found, or new elements of structure, will be discovered, and that perhaps in that domain weak interactions will have turned strong. Puzzlement about these questions threads its way through most of the theoretical contributions.

The other particles which interact strongly with one another, even at low energy, number some 200, and any count would be guaranteed obsolete by the time of publication. The only stable object in this whole array is the proton (and, of course, in the absence of matter, its antiproton). Even the neutron is unstable, although in its 20-minute lifetime it plays an essential part in nucleogenesis, and thus in the possibility of organic matter, and of life, and even of course, in a most dramatic way, in altering the course of human history.

The strong interactions which these particles show when they collide with one another are in sharp contrast to their electromagnetic couplings. They are 100 to 1000 times stronger, thus reminding us again that we still do not understand the magnitude of the elementary electric charge, the famous fine structure constant, the small number $e^2/\hbar c$.

The subnuclear interactions are so strong that the approximation of regarding aggregates of these particles as a bonding of essentially unaltered particles is justified in application to nuclei and nuclear matter only in a rough way. Indeed, the interaction of the particles and their nature are not, as in atomic and even to some extent in nuclear physics, rather well separable questions; they are the same question. For dealing with this question we have no theory. For the dynamics of strongly interacting particles we have at this time interesting programs, apparently contradictory, but probably complementary, which have either a very uncertain logical consistency, or a very remote connection with the findings of the laboratory about nature. Once again, an awareness of this situation, and a nostalgia for an understanding and a theory comparable to that achieved in classical and quantum physics, recurs again and again in the contributions to this volume, as also do rather strongly phrased preferences for the nature of the description that we hope for, but do not have.

Two other main themes direct the questions and inform the hopes for the future of strongly interacting particles. One has to do with symmetries, and the other with our ideas of space and time and causality.

A symmetry, as we here meet the word, is an expression of the fact that some aspect of a physical system is irrelevant to what goes on. Thus in the special theory of relativity, uniform motion is a matter of irrelevance, and this leads to the symmetry described by the Poincaré group. Thus the interchange of electrons or protons makes no difference to observation, and leads to symmetries under the permutation group. As in atomic and in nuclear theory, such symmetries lead to constants of the motion for the systems which have them, and to quantum numbers that measure the constants characterizing stationary states.

There are some new quantum numbers in particle physics for the weakly interacting leptons: their total number minus the number of their antiparticles seems, for example, to be a perfect quantum number. Among the strongly interacting particles there is a class called baryons, with the proton as its lightest member, for which again the total number minus the total number of their antiparticles is a perfect quantum number. There is no such quantum number for the other strongly interacting particles, mesons, just as there is none for light quanta. Even these rigorous quantum numbers, though incorporated into formal expressions of symmetry, are less explained and less rooted than is even the conservation of electric charge.

Then there is another point: some change in a physical system may make, not no difference to its physics, but little difference, and in certain contexts negligible difference. The physics of the strongly interacting particles is fairly rich in these "almost" symmetries. The earliest to be found, about three decades ago, is that in nuclear problems the difference between neutron and proton is almost negligible. This is the symmetry of isotopic spin, formally identical to that of the spin itself. It also makes in most contexts very little difference in strong interaction physics whether

a meson has a positive or negative charge, or is neutral; though it makes all the difference in the world to the behavior of the free particle itself. Such isotopic multiplets characterize all the strongly interacting particles that we have seen. This symmetry obviously ignores and neglects the electromagnetic properties of these particles, which play so decisive a part in their experimental identification.

There is at least one other "almost" symmetry, reflected in one other "almost" quantum number: strangeness, or its equivalent, hypercharge. The last year has seen increasing evidence of a larger symmetry that includes both the isotopic symmetry and the approximate symmetry responsible for strangeness. There is today no understanding, and thus no consensus, on whether this larger symmetry is a part of a much larger one, with perhaps other quantum numbers. There is essentially no good understanding, and thus no consensus, about the reasons which make it possible to use this symmetry with great success in certain problems, and to restrict its use severely in many others. Discussion of the hope that new symmetries will be discovered, that approximate symmetries will become rigorous in the domain of higher energy, are to be found in many of the contributions. We wish we had insight into the origin and meaning of these symmetries, some strict, some so rough, some now perhaps only barely discernible. It is not unreasonable to suppose that the hope of a true dynamics, and that of an understanding of the symmetries, may be closely related; that when we have one we may have the other.

As for space and time and causality, what we do not know today, though we dispute it, is whether a description of happenings in space and time on an arbitrarily small scale of distances and intervals will follow from the possibilities of observation with existing physical objects, whether the traditional causal description of events affecting the future in a continuously traceable manner will make sense. In the domains so far studied, no evidence has been found that such views of space, time, and causality are wrong. This too is a question open for the future, and rather likely to find its answer either in the experience of the new domain which the planned accelerators will open, or in the achievement of that understanding which we lack today and for which we hope.

In this domain it is also clear that novelty will be uncovered in the behavior of the weakly interacting particles; if there is indeed a possibility of a unified comprehension of them and their more numerous strongly interacting objects, it may lie in the domain just ahead. Some references to these hopes will be found in the papers that follow.

These papers, for all their variety, clearly reveal one common belief. All authors recognize that we do not understand the nature of matter, the laws that govern it, the language in which it should be described. They are all aware of the innumerable times in the years just past when something unpredicted, unexpected, and rather understood has come out of the great experimental centers. But there is more; they all have the gravest doubt that within the energy range now available there are or will be enough clues to make possible for us a theory of the nature of matter. This is the constant theme in all the contributions, unifying them and giving them their thrust.

It may be asked why this state of affairs is important enough to warrant the effort, the expense, the public support needed to enter the domain of much higher en-

ergy physics. All of the theoretical contributors to this volume have other interests in physics. Many have contributed in an important way to nuclear physics, or to studies of the solid state, or of quantum liquids, or of plasma physics, or of gravitation. All know, with interest and reverence, of discoveries in other parts of science: in microbiology, in astronomy. All wish well for all of physics, and all of science. What is there then so special in their plea for a new accelerator?

It is not only, I think, that the techniques of ultra high energy physics, experimental, observational, computational, mathematical, will prove of the greatest value throughout the sciences, and indeed often in technology. This I regard as certain to happen. It is not only because of the possibility of an unanticipated discovery of profound importance to technology and to human welfare. This I think not impossible, though there are few serious speculations as to what such a discovery might be.

It is also this: the last centuries of science have been marked by an unabating struggle to describe and comprehend the nature of matter, its regularities, its laws, and the language that makes it intelligible. The successes in this struggle, from the Sixteenth Century until our own day, have inspired the whole scientific enterprise, and lighted the world of technology, and the whole of man's life. They have informed the education and the devotion of young people. They have played an ineluctable part in the growth, the health, the spirit, and the nature of science. We are now, despite tempting and brilliant topical successes, deep in the agony of this struggle. This volume attests the conviction of those who are in it that, without further penetration into the realm of the very small, the agony may this time not end in a triumph of human reason. That is what is at stake; that is why this book is written.

ROBERT OPPENHEIMER
Princeton, New Jersey
November, 1964

VIEWS OF THEORETICAL PHYSICISTS

1. Purposes of High Energy Physics

High Energy Physics

H.A. BETHE
Cornell University

High energy physics is undoubtedly today the frontier of physics. The discoveries in this field of study contribute most to the advance of our fundamental understanding of nature.

When I began my career as a physicist the frontier of the subject was in atomic physics. In 1926-30, most problems of atomic physics were solved by the application of quantum mechanics. It was astonishing how quickly the subject developed, and how every problem yielded to theoretical treatment. Physicists were spoiled by this period of amazing success of a single theoretical approach. The same approach gave us in addition the theory of the chemical bond, and an understanding of the solid state. Solid state theory is still a very fruitful field, giving many important advances and new insights into the working of the nonrelativistic Schrödinger equation for complicated systems. However, one could hardly claim that it advances our *fundamental* understanding of nature.

The 1930s and '40s were characterized by the advance of nuclear physics. There the task was to find the force between nucleons, and the quantum states of nuclei under the influence of this force. Neither of these tasks is completed, and much interesting work remains to be done.

Particle physics, or high energy physics, is different from atomic and nuclear physics in being far removed from our daily experience. It is easy to justify work in atomic physics: The subject has direct intellectual appeal because it explains so much of the world in which we live. Moreover, its applications in chemistry and solid state physics are of great technical importance, as are some direct applications of atomic physics such as lasers. Because of these many practical applications, much of the progress in the field is now being made by industry. In nuclear physics, the practical application of nuclear power and atomic weapons is too well known to need discussion.

No such practical application has appeared, or is likely to appear, for particle physics. Indeed the processes observed in particle physics may not occur in nature outside the laboratory to any important extent. (They do of course occur when cosmic rays interact with matter, and may conceivably take place in those distant astronomical objects which emit energy far beyond the usual amount for a galaxy.)

There are at least three reasons for the fascination of particle physics. One is the conviction that this is indeed the most basic field of knowledge in the physical world. We want to know and to understand, and no other field will give us such deep understanding. The second reason is that particle physics will give us the basis for the theoretical treatment of another field, nuclear physics, which *is* related to the world as we know it. To find the nuclear force we must know the interaction of sub-nuclear particles with nucleons.

The third reason is just the very difficulty of the theory. In contrast to atomic physics, which yielded to one single theoretical approach, the Schrödinger equation, it has been necessary to try many different approaches to particle physics which supplement each other. One of the difficulties is the great strength of the forces which makes approximation methods inapplicable – and approximation methods were the key to success of most of atomic theory. Secondly, we do not have any differential or integral equation in closed form, a fact closely related with the possibility of creating any number of additional particles in the interaction of two high energy particles. A third difficulty is the essential involvement of relativity theory together with the presence of many particles. Interesting theoretical methods have, however, been developed for dealing with some of these problems, such as dispersion theory, Regge pole theory, and many others. But because of the many difficulties of the theory, it is very hard to deduce the fundamental interactions from a given experimental result, such as the cross section of a certain process.

The difficulty of the theory puts greater demands on the experimenter. His experiments must allow a simple interpretation without involving complicated and therefore doubtful theoretical steps. A good example is the Brookhaven neutrino experiment which showed directly the existence of two different neutrinos, associated respectively with the electron and the μ meson. In the field of strong interactions, recent work has concentrated on finding resonances and their properties (charge, angular momentum, parity, etc.), rather than just on measuring cross sections. This demand to get easily interpretable results is combined with the difficulty of experimentation – extremely large apparatus, small number of events, often many particles in one event, some of which are neutral and therefore invisible, etc.

In spite of these difficulties, both theoretical and experimental, particle physics has already given results of great beauty. While at first sight there seems to be a confusing and overwhelming multitude of different particles, there appears to be a great amount of symmetry in their properties. Gell-Mann and others have shown that the particles can be grouped into families of 8 or 10 (perhaps in some cases more). The particles in each family have close resemblance, and the structure of the various families is either analogous or closely related.

This beautiful theory, known as $SU(3)$ symmetry, could be developed only after hundreds of painstaking experimental papers, and dozens of unsuccessful theoretical attempts at clarification. In addition to classifying the then-known particles, the theory predicted a new particle, the Ω^- , which was discovered at Brookhaven early in 1964. Both the theory and the experimental work have been written up in very good articles in the *Scientific American*.^{1,2} The $SU(3)$ theory is probably not the last word in particle physics. It leaves many problems unexplained; in particular, it gives a very incomplete account of particle masses and reaction cross sections.

Frequently the study of particle physics has given unexpected insights into the earlier branches of physics. For instance, the study of the decay of K mesons made it likely that in this process parity was not conserved. This led Lee and Yang to conjecture that the same might be true in other weak interactions, particularly in the β decay of nuclei. Although β decay had been studied for at least 25 years before, it was only after this suggestion that the violation of parity in this process was experimentally found. As a more recent example, in 1964 Fitch et al. discovered that in

at least one decay mode of a K meson, even the reversibility of time may not be satisfied. Thus particle physics touches the most fundamental concepts of space and time.

It is no surprise that particle physics has attracted the most ambitious, and the best brains among the young physicists. It would be wrong to support this branch to the exclusion of others. There are challenging problems in nuclear physics, solid state physics, and other branches. I myself have devoted the last ten years of my research to low energy nuclear physics. But I believe that particle physics deserves the greatest support among all the branches of our science because it gives the most fundamental insights.

REFERENCES

1. G.F. CHEW, M. GELL-MANN, AND A.H. ROSENFELD, *Scientific American*, February 1964, p. 74.
2. W.B. FOWLER AND N.P. SAMIOS, *Scientific American*, October 1964, p. 36.

The Future of High Energy Physics

G. FEINBERG
Columbia University

INTRODUCTION

There are two distinct facets to the question of whether the U.S. government should, at this time, finance the development of the next stage in high energy accelerators. These can be succinctly summarized in the form of two questions: (1) Why are physicists interested in doing experiments at energies some 10 to 50 times as high as those now available at accelerators? (2) Why should the U.S. government invest substantial sums of money in such an undertaking?

It is clear that rather different considerations are involved in answering these two questions, and I propose to treat them separately. The answer to the first question is mainly technical and concerns some of the unanswered questions and speculations of contemporary physics. It may therefore be expected that the different answers suggested either will overlap or will be cumulative in the sense that they represent distinct but equally valid areas of interest. On the other hand, it seems to me that the second question involves technical matters very little, but instead requires some thought about what activities are, or should be, valued by our society. The main contribution that scientists can make to it is therefore probably to clarify to the public just what we are trying to do. Nevertheless, in the second part of this article, I would like to suggest an answer to the question.

WHY GO TO HIGH ENERGY?

There are at least two reasons why physicists would like to carry out experiments at much higher energies than are now available.

The first reason is to study the effect on known phenomena of varying the energy in unexplored regions. In the fields of both weak and strong interactions specific predictions are available that may be tested by high energy experiments. This discussion will be restricted to the situation in weak interaction physics.

Weak interaction phenomena at low energies can be described by a matrix element essentially independent of energy. This is the case for decays such as nuclear β decay and muon decay. At the somewhat higher energies (~ 1 BeV) explored in neutrino scattering experiments, the matrix element can no longer be taken independent of energy, if the scattering involves a strongly interacting particle as a target. This is because the intrinsically weak interaction of such a particle is modified by its strong interacting so as to produce "form factors." Just as in the case of electromagnetic interactions, these may be thought of as an extension in space of the strongly interacting particle due to its associated cloud of mesons, etc. The question remains

whether the intrinsic weak interaction has any energy dependence before modification by strong interactions.

To answer this, it may be noted that the leptons do not share the strong interactions. Hence it may be expected that one can explore the energy dependence of the intrinsic weak interaction either by examining a purely leptonic process such as electron-neutrino scattering, or by measuring some quantity pertaining simply to the leptons in the scattering of neutrinos by nucleons. The latter is likely to be more feasible experimentally. Suppose that the intrinsic weak interaction matrix element is independent of energy. It can then be shown¹ that the cross section for a process such as

$$\nu + n \rightarrow \mu^- + p$$

can depend on the neutrino energy only through the very simple form

$$\frac{d\sigma}{dq^2} = A + \frac{B}{E_\nu} + \frac{C}{E_\nu^2}, \quad (1)$$

where E_ν is the neutrino energy in the laboratory, and A , B , and C are coefficients depending only on the momentum transfer q^2 and not on E_ν . A test of this behavior at high energy is quite important for the determination of whether our general picture of weak interactions is valid.

An even more searching test will come from a measurement of the reactions

$$\nu + e \rightarrow \nu + e \quad \text{and} \quad \nu + e \rightarrow \nu' + \mu.$$

Both these reactions proceed entirely via weak interactions (and electromagnetic corrections). The conventional theory, in which the weak interactions are evaluated to lowest order, predicts a cross section in the form such as Eq. (1), in which the coefficients A , B , C are given by the theory. However, this form cannot persist at very high energy because it contradicts the requirements of unitarity. Experiments on lepton-lepton scattering at high energy, particularly with colliding beams, are of crucial importance in determining how the theory is to be modified. It should also be noted that the total cross section for these reactions rises linearly with the energy, which means that it may become easier to measure at high energy. Indeed at laboratory energies of 10^3 BeV, the cross section for lepton-lepton scattering is expected to be comparable to that for the two-body scattering of neutrino on nucleon.

For these reasons, it seems clear that a great deal is to be learned from experiments with very high energy neutrinos, and that physicists working on weak interactions eagerly anticipate the availability of facilities for such experiments.

The second reason for going to much higher energies is to search for new phenomena. The work in particle physics for the past few years may be characterized as having led to the discovery of many new particles but few new conservation laws. It is of great interest to know whether exploration of a wider range of energies will continue to turn up only more unstable particles, or whether in addition, or perhaps instead, new stable particles will be found and, correspondingly, new quantum numbers to account for the stability. The occurrence of new stable particles of high mass could even have important technological applications, for example as a storable energy source.

Even the discovery of new particles and conservation laws is in my opinion not the main stimulus leading physicists to desire much higher energy accelerators. Rather, this comes from the uncomfortable feeling that work with the phenomena and concepts currently available will not result in an understanding of the physics of particles. By now the number of particles known is so large, and their properties are so diverse, that particles are beginning to be considered as perhaps not the ultimate constituents of nature after all but rather the manifestations of some deeper structure which has not yet been penetrated. It is not guaranteed that higher energy is the way to search for such a deeper structure, but such has generally been the case in the past when the atomic, nuclear, and particle levels were discovered by increasing the energy of the probes. The only probes now known for examining possible structure of particles are high energy scatterings, preferably of weakly interacting particles such as photons and neutrinos. Hence again the great excitement among particle physicists over the development of intense, high energy, neutrino beams.

In summary, I would say that the main scientific argument for building much higher energy accelerators than are currently available is that the problems of particle physics are not going to be solved with available tools, and that we should try to obtain the best possible tools if we are to have a chance of solving them at all.

WHY SHOULD THE GOVERNMENT SUPPORT HIGH ENERGY PHYSICS?

The question of the rationale for government support of high energy physics is a thorny one. It is well to recognize that high energy physics, as it is practiced today both in this country and abroad, is almost entirely a result of government support.² There is no question that if such support were lacking, the effort in experimental high energy physics would essentially disappear and with it the theoretical work as well. I believe that a similar result would occur, only more slowly, if government support were leveled off at roughly the present rate. The reason is that if high energy physicists are unable, for lack of funds, to carry out experiments which seem to be required by gaps in our knowledge, they are likely to migrate to other fields where for various reasons there are no such restrictions. Hence it appears to me that the real choice available is between supporting high energy physics at a scale which would enable it to develop according to internal requirements, or letting it wither away in the foreseeable future.

Granting that this is the choice, it may legitimately be asked why the government and the people of this country should be interested in having high energy physics flourish here. I think that the best answer to this is in terms of what our society is capable of doing. Each human society excels at a small number of the many activities that people carry out. Our own society is pre-eminent at large-scale technological and scientific projects, such as the building of high energy accelerators. It is therefore an expression of the highest spirit of our culture to carry on with the task we have begun, the exploration of nature to all its limits. Indeed, it may well be judged that this spirit is our greatest contribution to the human outlook. High energy physics is clearly one of the subjects on the frontiers of such exploration. If we cut back on it for reasons of budgetary limitation, or political squabbling, I think we will

have seriously damaged the best single element we have contributed to human culture. I would be grieved both as an American and as a scientist if we made that choice.

REFERENCES

1. T.D. LEE AND C.N. YANG, *Phys. Rev.* **126**, 2239 (1962).
2. A very clear analysis of the role of government support in scientific research is given by S. Klaw in *Fortune*, September 1964.

On the Need for Higher Energies

A. PAIS

The Rockefeller Institute

Since about 15 years ago a whole new world of then unanticipated phenomena has gradually been discovered in the high energy domain. We now know of the existence of modes of matter of which we had no inkling as late as, say, 1945. These recent discoveries have given an entirely novel turn to the age-old question of what should be meant by "the structure of matter." These new phenomena are collectively known by the name "particle physics." It would be more appropriate at this stage to speak of "particle chemistry," however. The present phase of the study of particles is in fact reminiscent of the situation in chemistry during the later parts of the last century. At that time rules of periodicity, valence rules, etc., were discovered, and these were very useful in predicting new elements and some properties of chemical compounds. Likewise, there are now available a number of important rules to order particles and tell something of their interactions. In chemistry the next phase was to be the insight that the atom has a structure. With the understanding of the Bohr-Rutherford model of the atom a major step towards a simpler underlying picture was given which eventually gave rise to the new mechanics, quantum theory.

If it is at all possible to define the common aspirations of today's high energy physicists, it is to say that we hope for a "Bohr-Rutherford model" for particles, and that many of us suspect that there may again be a need for a new mechanics to cope with the situation.

While during recent years there has been steady progress in the uncovering of new regularities in the particle patterns, it cannot be asserted that in the energy domain now available there are striking phenomena which show the way from particle chemistry to particle physics. It is evident therefore that to succeed in decoding the present growing complexity of phenomena we must go to higher energies. It would in fact be disastrous if we were to stop this pursuit, even though no one can say with any certainty what may be revealed in higher regimes of energy. Nor is this situation without precedent. At the time the Cosmotron at Brookhaven was planned, no one knew of the new particles which were going to be produced by this machine and which drastically changed our thinking about the structure of matter, as mentioned above.

When a physicist tries to speculate about the new, he inevitably makes analogies with the old. Let me try to sketch in "analogy language" why interruption of the pursuit toward higher energy machines would be disastrous. (a) We may be stranded with a chemistry of particles without the underpinning of a physics of particles. We may stop short of the discovery of the new Bohr-Rutherford atom. (b) Many physicists reckon with the possibility that there may exist an entirely new

kind of heavy particle, the W meson, as fundamental for weak interactions as the photon is for electromagnetism. We may be stranded without the analogue of the Hertz experiment on electromagnetic waves if we do not go to higher energies. (c) There are forces in nature which at present are unrelated, such as the weak forces and the strong forces. We may be stranded without their synthesis at a stage which may be compared with the Coulomb/Biot-Savart stage, where electric and magnetic phenomena were unsynthesized. We may stop short of the Maxwell stage of integrating such apparently disjointed forces into a new unification.

A great society is ultimately known for the monuments it leaves for later generations. We cannot foretell what detailed results may come from a very high energy machine, which should in fact aim for energies 20 to 30 times as high as the present ones to bring a sufficient new range within reach in the reasonably near future. We can foretell, however, that such a machine, which is on the scale of a national effort, will without question be a source of inspiration for new science and a monument to our days.

Is Elementary Particle Physics Useless?

H. PRIMAKOFF
University of Pennsylvania

As a member of the “older” generation of physicists, i.e., as one who obtained his formal graduate training in physics before the war, I can still vividly remember when what are now called elementary particle physics and nuclear structure physics were one subject, at least from the point of view of those who participated in the work. That each fructified and stimulated the other, then as now, cannot, I think, be questioned – for example, one of the first problems in which I became interested involved an attempt to understand the particularly large binding energy per nucleon of the α -particle nuclei (C_6^{12} , O_8^{16} , –) and of the α -particle on the basis of (modern terminology!):

i.e., on the basis of a presumed connection between meson-meson scattering and many-body internucleon forces. This stimulation has, of course, been immensely strengthened and deepened with the intervening years, and whatever gulf may have developed, because of a variety of human limitations, between the elementary particle and the nuclear structure physicists, there is no doubt regarding the essential intellectual unity of their fields of study. In fact, the attitude of the practitioners of the various branches of physics toward each other should be similar to that of members of a happy family: friendly mutual competition and a consistent and even firm attitude toward the external (not always friendly) world.

There is little question that experimental research in elementary particle or high energy physics has been, is, and no doubt will be most helpful in enlarging mankind's intellectual horizons – after all, our “elementary particles” are in *some sense* the fundamental building blocks, or at least are intimately related to the fundamental building blocks, out of which the material universe is constructed. Thus, any increase in the understanding of the structure and function of these “particles” is likely to serve not only the parochial interest of the physicist working in the field or in contiguous fields such as nuclear structure, but also to have a broad impact on other branches of physics, of science generally, and even on the whole human cultural outlook. In addition, past experience with what in their day were frontier investiga-

tions in physics, e.g., electromagnetism, indicates a reasonable expectation of very considerable and often entirely unforeseen benefits for technology from further intensive research in high energy physics. What then is the difficulty? The difficulty is that experimental high energy physics is "expensive," i.e., it requires, or, at the present rate of increase, will soon require, a yearly expenditure of some 0.02% of the gross national income and this is "too much," particularly since only about 0.0005% of the population are intimately involved in the venture.

What is the validity of the above reasoning? Without making invidious comparisons with other types of national activity, either of a scientific or of a non-scientific character, it is fair to emphasize that, wholly apart from the inherent worth – intellectual, methodological, and practical – of the effort, the circa \$100,000,000 spent or to be spent every year by the 1000 or so physicists engaged in high energy experimental work is ultimately as widely diffused among the population as a whole as the money spent in any other government supported activity. Thus, wholly apart from any of the above mentioned advantages, research in experimental high energy physics, precisely because of its financial magnitude and its eventual broad distribution of expended funds, can play a modest but not entirely negligible role in maintaining economic stability.

Objectives of High Energy Physics

ROBERT G. SACHS
Argonne National Laboratory

High energy physics is the principal operational arm of particle physics, which, in turn, is the essence of today's science of physics. The field of physics has many aspects, most of them being essential to its progress, but its scientific essence is the discovery of the fundamental (mathematical) laws governing the phenomena of the physical world, and it is in the domain of particle physics that the fundamental laws of nature are now being uncovered. This is the natural outcome of the fact that the fundamental laws, which are basically very simple, reveal themselves in their simplicity only in truly simple physical systems. A simple physical system is one requiring few variables to describe it; one containing as few parts as possible. For this reason, physicists are constantly trying to reduce physical systems to their simplest level – their constituent parts, usually referred to as “particles.” Molecules are parts of macroscopic matter, atoms are parts of molecules, nuclei and electrons parts of atoms, neutrons and protons parts of nuclei, and so on to those subnuclear particles which are now the subject of study in the field of high energy physics.

In striving to discover the laws of matter, the physicist has found it necessary to break matter down into these constituent parts. The deeper the penetration, the greater the energy required. For example, the study of atomic structure required electromagnetic radiation in the energy range of about one electron volt (optical region) to a few hundred thousand electron volts (x-rays). The investigation of nuclear structure became possible only when there were available energy sources capable of producing energies of the order of millions of electron volts, and the attack on subnuclear structure requires tens of billions of electron volts. Hence, even when the study of atomic structure was the frontier field of physics, the highest available controlled sources of particle energies were required. In that sense, “high energy physics” has been the focal point for work on the fundamental laws since early in this century.

As the frontier has moved, the effort required to attain the energies necessary to explore it and to push it on has increased rapidly, and we are now at the point where an extreme effort, measured in terms of both manpower and cost, is required to push it further. The magnitude of this effort tends to slow the pace, but we must be careful not to allow the pace to be greatly slowed, since there is a critical time, related to the interval of maximum productivity during a single man's life, over which new ideas must be generated and tested in order that the sense of direction of the work not be lost. If the sense of direction is lost, the work may well be brought to a halt.

The enormous effort required of each physicist to carry on this work can only be generated by internal motivations, and these motivations stem largely from the

anticipation of intellectual satisfaction. This motivation is good, since it serves to identify the human race as a race of beings of higher intellect. But there is also a great practical advantage to the community at large: Since no specific technological objective is involved, the scientific exploration is unconstrained, and it often leads to completely unexpected technological gains. For example, the discovery of the laws of quantum physics was pursued largely for its intellectual worth, yet the fruits of these very esoteric labors have great technological importance today, and in ways that could not possibly have been foreseen by the physicists who did the work at the time. Fortunately, enormously expensive apparatus was not required in order to pursue this work, and it was not necessary to justify the work on the unforeseen technological grounds in order to gain support for it.

From a knowledge of the fundamental laws of nature it is possible to predict phenomena of nature, and many of the phenomena so predicted are outside of ordinary experience, and quite unexpected. Of these unexpected phenomena, many bear fruit in the form of remarkable technological achievements. There is no way to know that the fundamental laws next uncovered will bear such fruit, but it would be remarkably shortsighted to assume that they will not. The pursuit and discovery of these laws is what keeps the deep wells of our technical knowledge flowing, and this work, currently identified with high energy physics, had best be pursued vigorously lest these wells dry up.

At the present time, our knowledge of the behavior of particles at the very highest energies attained in the laboratory is exceedingly confusing, and the problem seems to be exceedingly complex. Yet some underlying rhythm and meaning appear to be emerging, and many physicists feel that we are on the verge of uncovering the basic laws of subnuclear structure, but so it has seemed, on and off, for the last two decades. The reason for going to even higher energy is the conviction that, for energies greater than the masses of known particles, an ultimate simplicity will set in, and the truly simple underlying laws may be revealed. This simplicity may result if the particle kinetic energies are far greater than the energies of interaction between particles. Thus a determination of the asymptotic (high energy) behavior of scattering amplitudes, along with other well-known general properties of the amplitudes, may suffice to establish the mathematical behavior of the amplitude at all energies. On the other hand, at very high energies, an entirely new type of very massive particle (unitary triplets, for example) may be found to be the parts out of which the known particles are composed, and the study of these even simpler parts will be required to understand the basic laws.

The phenomena just mentioned belong to the domain of strong interaction physics. The other domain, that of weak interactions, has developed as an aspect of particle physics into a remarkably rich field for the investigation of basic questions concerning the natural laws. The discovery of the failure of the symmetry between right-handedness and left-handedness was urged upon us by paradoxes in the behavior of the strange K particles of high energy physics. Now we may be on the verge of the discovery, through properties of these same particles, of the failure of the assumed symmetry between the forward and backward directions of the flow of time.

The laws involved here concern our basic concepts concerning the structure of space and time. Much more thorough study of weak interaction effects will be re-

quired to arrive at the full implications of what has now been observed. Many rare phenomena will need to be studied, and this will require an enormous consumption of time on existing high energy accelerators. Neutrino experiments provide one avenue, probably the most versatile, for investigation of the weak interactions. They make it possible to study the energy dependence of the interactions, and with increasing energy, the weak interaction effects become less weak. It is possible that these interactions are, in some sense, not local – that they are manifestations of some fundamental laws that lie outside the domain of what are now considered to be acceptable forms for the laws of physics. The nonlocality would presumably be limited in extent to enormously small distances, and the smaller the distance the higher the energy required to explore it. Therefore, we are again led to consider neutrino experiments at very high energies, or to look for particles (intermediate bosons) of very high mass, or to try to study the weak decay properties of very massive and very strange particles.

In sum, extensive research at considerably higher energies than are now available will probably be required before the next layer in simplicity of the laws of physics is uncovered, and this will not only be an enormous contribution to our culture, to the extent that our culture is concerned with our concept of the Universe, but it will undoubtedly open the way to completely unforeseen technical achievements.

The Future of Fundamental Physics

JULIAN SCHWINGER
Harvard University

The scientific level of any period is epitomized by the current attitude toward the fundamental properties of matter. The world view of the physicist sets the style of the technology and the culture of the society, and gives direction to future progress. Would mankind now stand on the threshold of the pathway to the stars without the astronomical and mechanical insights that marked the beginning of the scientific age? The quest for understanding has led outwardly to the galaxies and inwardly to the atom and then to the nucleus. Now it is the subnuclear world that is being actively explored. The goal here is not merely an organizing principle for subnuclear particles, a new periodic table of the elements, interesting and important as that may be. Rather we are groping toward a new concept of matter, one which will unify and transcend what are now understood only as separate and unrelated aspects of natural phenomena. In past triumphs, physics has unified light with electromagnetism, mass with energy, and comprehended chemistry and the mechanical-thermal properties of bulk matter in the atomic laws of quantum mechanics. But the fundamental problems remain. What is the role of gravitation in coupling the remote stars to the atom? Can one understand the magnitude of the unit of electrical charge? These are traditional queries. Recent research has provoked a whole battery of additional questions. What is the relation between the newly revealed internal degrees of freedom and space-time? How can one connect the diverse interactions, of different strengths and characteristics, that are required to account for the birth and death of the subnucleonic particles?

But perhaps the most important question concerns whether these particles must be accepted as basic and unanalyzable, to be described only in their own framework, or whether there exists a simpler and more fundamental substructure, a deeper level of description and understanding. These alternatives have been presented before in the history of physics. At the close of the Nineteenth Century it was strongly argued that the properties of bulk matter should not be accounted for by the characteristics of unobservable and hypothetical microscopic entities. Owing to the continued development of experimental techniques, this limited viewpoint had to be discarded and the atomic theory triumphed. A similar decision can be given again only if the tools will be at hand to continue the penetration into the totally new, totally unpredictable world of the microcosmos. And one should not overlook how fateful a decision to curtail the continued development of an essential element of the society can be. By the Fifteenth Century, the Chinese had developed a mastery of ocean voyaging far beyond anything existing in Europe. Then, in an abrupt change of intellectual climate, the insular party at court took control. The great ships were burnt and the crews disbanded. It was in those years that small Portuguese ships rounded the Cape of Good Hope.

In Defense of High Energy Physics

VICTOR F. WEISSKOPF
CERN

Today the development of science has arrived at a critical stage. The cost of science in terms of money and manpower has reached a point where society is beginning to question its further uninhibited growth. So far the cost of science has been negligibly small. All basic scientific activity ever undertaken from the times of Archimedes until today amounts, in terms of money expenditure, to less than 10 days' output of the industrial world, an amount below the yearly increase of world production. This represents an impressive rate of return on a capital investment if one considers that almost all industrial production today is a consequence of basic scientific research. Still, it is true that the requirements of modern basic research are beginning to be substantial, and a discussion becomes unavoidable of the importance of basic science and of the relative importance of its different branches. Clearly, the main targets of attack are the most expensive branches which, in addition, have a certain flavor of "uselessness," that is, high energy physics and astronomy. Modern astronomy, however, has the advantage of being connected with "space"; it therefore profits from the present emphasis on everything related to space science. Clearly, this emphasis is not exclusively based on arguments of scientific merit. High energy physics, or – as it should better be named – subnuclear physics, no longer enjoys such extraneous support, after having ridden on the coattails of nuclear energy for a number of years.

Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

One can easily distinguish four important steps of intensive research during this century: electrodynamics and relativity, quantum theory of the atom, nuclear physics, and recently subnuclear physics. The extensive dimensions of electro-

dynamics, relativity, and quantum theory reach very far today and are constantly expanding. Nuclear physics has already a large extensive part in the detailed studies of nuclear structure and in its astrophysical applications. Subnuclear physics is still mostly intensive in its character. Each part of this scientific frontier is of importance. It would be most dangerous to neglect some parts relative to others. It is often argued that subnuclear physics should be given less support because this field leads to very little extensive research, because it attracts too large a proportion of clever scientists, and because the cost per scientist is much higher than in many other parts of the scientific frontier. These reasons, however, are inherent in the fact that subnuclear research is at the frontier of intensive research.

Obviously, the most advanced part of intensive research has yet very little bearing upon the understanding of other phenomena, and therefore its extensive component is small. After all, one is at the very beginning of understanding what is going on at the subnuclear frontier itself. Clearly, the same situation existed at earlier periods when other fundamental discoveries were at the frontier of science. Faraday did not know that electricity is the basis of the structure of matter; when the first steps were made towards an understanding of atomic spectra, nobody knew that this would lead to a complete understanding of chemical reactions. Thus the extensive effect of subnuclear physics is not yet visible, but even today it seems already probable that subnuclear phenomena are important for the understanding of the recently discovered galactic explosions.

The frontier of intensive research has always attracted a certain group of very clever scientists. To work in an uncharted field, to discover new laws of nature and completely new types of phenomena, is a great lure for a scientist. One is placed at the spearhead of a great and successful tradition ranging from Galilei, Newton, and Maxwell to Einstein, Bohr, Dirac, and Heisenberg. It is improbable, however, that this field should in fact ever deprive other fields of science of skilled manpower. It is by its very nature a limited field. Competition is heavy; success is rare and depends more often than not on luck and opportunity. Many of the best scientific brains avoid this field because of the narrow choice of activities.

The high cost of subnuclear physics comes from the fact that it deals with new phenomena which were not previously observed. Subnuclear physics requires the study of matter under new conditions. As science progresses, these conditions become increasingly different from normal conditions on earth. Nuclear physics deals with intrastellar conditions, and subnuclear physics submits matter to even more abnormal conditions. Obviously, it is increasingly expensive to create increasingly abnormal environments in a laboratory.

There is today a clear danger that the alleged narrowness and the high cost of subnuclear physics will, in fact, retard its development compared to other fields at the scientific frontier. Already *The Physical Review* shows a stronger increase in the number of solid state physics papers compared to nuclear physics papers. This occurs just at a time when subnuclear physics begins to reveal the existence of a new world of phenomena within the nucleons. We see today the birth of a third spectroscopy compiling the excited quantum states not of atomic systems or of atomic nuclei but of the nucleon itself. We find today the first indications of regularities in these level schemes, which will soon lead to an insight into the structure within the nucleon.

This insight is bound to bring us nearer to the understanding of some of the most fundamental unsolved questions. Let us list three groups of such questions:

Today we understand the behavior of matter on the basis of the interaction of atomic nuclei and electrons. But the basic question remains: why is it that the proton, the neutron, and the electron are the elementary particles which make up matter under terrestrial conditions? Why are these particles, together with the light quantum and the neutrino, the most stable forms in a long series of particles including the hyperons, the numerous bosons, and the heavy electrons? These questions concern the basis of everything scientific. As long as they are not answered, the structure of any form of matter remains essentially not understood. The great triumph of quantum theory was the explanation of the characteristic properties of the elements on the basis of the recognition that the field of a given electric charge admits only certain well defined quantum states of the electron. This idea is fundamental to all atomic physics, chemistry, and molecular biology. However, it is valid only because of the existence of identical electrons and protons with fixed and well defined charges and masses. In fact, quantum theory does not really explain the existence of characteristic intrinsic properties of each element; it deduces it from another unexplained set of facts: the existence of a small number of elementary particles with their own characteristic intrinsic properties. Hence, the basic problem which underlies all physical sciences, that of the structure of matter, is still unsolved. It is precisely that problem which is attacked by subnuclear physics.

Another fundamental set of questions is connected with the problem of the different types of interaction between material particles. Physics has solved the problem of unifying a large number of interactions, such as electric and magnetic forces, chemical forces, cohesive forces, capillary forces, etc., all of which are reducible to the quantum effects of electric attraction between nuclei and electrons. But there is still no connection seen between nuclear, electromagnetic, gravitational, and weak interactions. Hence, the task of a consistent understanding of nature has only begun and is in need of further development. It is again mainly subnuclear physics which attacks these problems; theoretical research in relativity theory and astronomical research into the structure of the universe will contribute to the solution.

Finally, the same three fields of research are about to tackle the problems of the history of the universe. The question of the origin of matter can already be discussed on scientific grounds. So far, rational ideas are developed only concerning element formation from a gas of protons and electrons. But the problem of the origin of this gas begins to acquire some scientific aspects with the discovery of matter under extreme conditions of high energy at the centers of galaxies. These phenomena are obviously connected with the interaction of particles at very high energy, as studied in subnuclear physics.

We are facing today a situation in which it is threatened that all this promising research will be slowed down by constraining financial support to high energy physics. And this constraint is based, partially at least, on a claim that the aim of this field is narrow and restricted. The three above-mentioned groups of unsolved questions should be sufficient to invalidate this claim. It is granted that further progress, say, in biology or in solid state physics is possible without any further re-

search into the subnuclear field. But let there be no doubt that the style of the scientific community would change its character if the frontier of intensive research were hampered. It would subtly change towards over-emphasis on extensive research, and this would harm all fields of science. A spirit would be fostered, different from the one which created modern science, if basic questions that can be answered are left unanswered or are neglected by lack of attention. The questions remain, they cannot be overlooked.

This different spirit will do most harm in the education of young scientists. The study of science is based upon a burning interest in fundamental problems. The attitude of students would be perverted if they were not constantly aware of a lively quest for the solution of the basic problems of science. Even the scientist who will devote his life to purely extensive research must be aware of the existence and the spirit of intensive research. The reason is that, even in the most extensive research, at every step there is always an intensive component: at each unsolved problem one must go back to some fundamental idea, one must try to see more of the essence of the problem. This is an attitude which can be fostered and maintained only if intensive and extensive research have equal standing in the scientific community. There is one broad front in science and each part of it must be pushed forward with full vigor.

We find strong support today for space technology, which may allow us to explore the unknown parts of the solar system. Exploration of the unknown was always a strong component of human endeavor in our modern civilization. But it must go together, as it always did, with an equally strong component: the explanation of the unknown in whatever form it faces us. In the beginning of the Sixteenth Century, when the scientific era began, Magellan performed the first trip around the earth. But also in the same period Copernicus published his work on the motion of the planets.

The Relevance of High Energy Physics

G.C. WICK

Brookhaven National Laboratory

Other contributors to this book have already made the point that high energy physics is the “frontier of physics” or that part of research in physics that explores the least known realm of Nature, the realm where one expects to make the most fundamental findings. They have emphasized that to regard this kind of search as less important because of its alleged “remoteness from the rest of physical science” is in direct contradiction with the whole spirit of scientific inquiry; to adopt such an attitude would be, indeed, disastrous for the style of the whole scientific community.

I wish, therefore, to concentrate on just one point. I think high energy physicists are much too tolerant if they accept the statement that high energy physics is “remote” from the rest of physics, from chemistry, from biological science, and so on, i.e., that discoveries in the field of elementary particles, intrinsically interesting as they are, will have little effect on the other branches of science.

I wish to question this statement. I want to point out that, when such statements are made, people usually hasten to concede that judgments of this sort can be destroyed by new findings. My contention is that the possibility of new findings is the crux of the whole matter. The point of all truly fundamental research is, and always must be, that one doesn't know what one is going to find and what new ideas will come out in the process, hence one doesn't know what the possible consequences will be. True enough, one does not enter into a line of research blindly, one has certain ideas about questions one wants to have answered, and it so happens that none of the questions high energy physicists are asking themselves now seem much related to other branches of physics; but, as we all know, it usually turns out that the questions one had in mind were not quite the right ones, and as one proceeds further, new questions come up which are more pertinent and more interesting. Often these new questions are quite unexpected. One went in to find gold, and instead one finds oil or something which turns out to be just as valuable. It is the essence of true pioneering research that its results are wholly *unpredictable*. Therefore, it just does not make sense to ask: what will you do with your findings? One just goes ahead because the questions seem deep and interesting, and one wants to know the answers. The question – What will you do with them? – is something one was used to hearing from engineers, industrialists, etc., i.e., from so-called “practical” people. But it just is not a practical question at all because it cannot be answered. People should have learned by now that this is not because pure research has little practical consequence; in fact, just the opposite is true. But all pure research is just a big marvelous gamble, in fact the only gamble so far invented that really makes sense.

Now that old worn-out question is asked again, not by “practical” people but by fellow scientists from other branches of science, who want to know what is in it

for them. My answer is: you should have a little patience. I believe that even now one can predict with confidence that discoveries in this field will have a major influence on other branches of science. The fact is that no major advance in physics, in the past, has failed to affect the other sciences profoundly. Who would have thought 60 years ago that 100-kilovolt cathode rays could be of any interest to biology? Yet the electron microscope is now one of the major tools in that field. Who would have thought that 8-MeV α particles could produce effects of more than marginal interest to the chemist, such as causing a crystal to become yellowish, or something of that sort? After all, the chemist's world is a "very low energy world," just a few dozen electron volts will destroy any molecule. What could be done for chemistry with millions of electron volts? Yet Rutherford's insistence on playing with α particles has changed the whole face of chemistry. Of course, Rutherford's experiments did not cost much money. But what has money got to do with it? An irrelevant question does not become meaningful just because money is involved. Quite the contrary, I feel that, just because a lot of money is involved, one should be very careful to ask intelligent, meaningful questions.

I would like to contradict, as an example, an opinion which is often accepted much too easily, namely, that high energy physics is not relevant to ordinary nuclear physics, which, as everybody agrees, is not only interesting in itself, but also important for many other reasons. First let me note that it is perfectly useless to try to draw a line and say: well, perhaps "meson factories" will be useful, but that is not *really* high energy physics. This is nonsense; it is bad enough to deny the essential unity of science, but to try to split an already specialized field into two, and to really believe that the two parts can go on independently without deeply affecting each other, seems to me the height of improbability. As a matter of fact, it seems to me very likely that if one ever arrives at a really deep understanding of the structure of the so-called elementary particles, our whole way of looking at the structure of plain ordinary nuclei and their lowest levels cannot fail to be affected very deeply. After all, nuclei do consist of protons and neutrons, which are elementary particles, and are kept together by interactions of the type that high energy physics is concerned with.

In conclusion, I would like to say: the interrelation of high and low energy nuclear physics is much deeper, much more varied, and may be more full of surprises than is generally conceded. Let us explore it.

*2. Some Problems
of High Energy
Physics*

Aims of High Energy Physics

S.M. BERMAN AND S.D. DRELL
*Stanford Linear Accelerator Center**

This essay will begin with some general observations and then continue with more specific ideas of particular relevance for electromagnetic processes. In essence, high energy physics seeks to uncover the basic symmetries and basic laws of structure of the material universe. Since it is constantly probing into new and unknown territory with its vast and expensive new tools, the most fundamental progress in this field often results from major new surprises which cannot be extrapolated or planned from present experience. Moreover, the rich discoveries of the past four years have given us great confidence that there *are* fundamental new discoveries and insights to be achieved by studies that can be carried out in the 200 to 1000-BeV energy region. However, since new surprises cannot be predicted, this discussion must be confined to parts of a possible program that can already be foreseen for an accelerator extending the energy range.

Consider first the studies of new short-lived particle states (or resonances) which have been discovered, mainly in bubble chambers, since 1960. These have stimulated successful theoretical developments aimed at classifying these states into multiplets based on symmetry schemes [such as the $SU(3)$ group]. With higher energies, entirely new symmetries may appear. For example, the currently conceived multiplets (such as the 8 baryons: p , n , Λ^0 , Σ^+ , Σ^0 , Σ^- , Ξ^0 , Ξ^- ; or mesons: η , π^+ , π^0 , π^- , K^+ , K^0 , $\bar{K}^0$, K^-) contain members whose masses differ by several hundreds of MeV, and yet predictions of their mass splittings based on an assumption of weak symmetry-breaking forces hold to remarkable accuracy (better than $\frac{1}{2}\%$ for the baryon octet). Does this mean that more massive building blocks of mass $M \gg 1$ BeV, yet to be discovered, are the “basic” building blocks of the present schemes? If M were in the range 10 to 50 BeV, the splittings observed up to now would appear to be small on such a large energy scale, and some of the remarkably accurate mass relation predictions of $SU(3)$ would be more understandable. We would certainly like to be able to probe for such possible massive building blocks.

At very high energies it also becomes possible to study in detail the interaction cross sections of various members of the same multiplets under conditions for which both the energy and momentum transfers in the collisions appreciably exceed the mass parameters. It thus becomes possible to investigate the accuracy of the proposed symmetry classifications and to search for any “hidden” symmetries no longer obscured by mass effects. Moreover, individual pion and nucleon processes can be studied at impact parameters of $< 10^{-15}$ cm, or 1% of the “size” of a proton.

Another field of study now being pursued which could be probed further by the extension of parameters proposed for very high energy accelerators is that of the

*Supported by the U.S. Atomic Energy Commission.

asymptotic behaviors of cross sections. The Pomeranchuk theorem is an example of a very general prediction based on formal theoretical ideas; it states that particle and antiparticle cross sections on the same target eventually become equal at high energies. The simplest assumptions also suggest that the total cross sections approach constants independent of energy. Quantitative confirmation of this (or some other) behavior and of the way in which the cross sections actually approach their limiting behaviors is a promising field for study. These questions also apply to inelastic processes. Multiple particle jets (discovered and studied first in cosmic rays) are produced, and detailed studies of the secondary particle multiplicities and momentum distributions may lead at least to confirmation of models and concepts evolved during the current studies, if not to basic keys for further progress.

Next to be considered are the weak interactions, which are responsible for ordinary nuclear β decay and for the relatively long-lived decays of the free neutron ($\tau \sim 20$ min), π -meson ($\tau \sim 2 \times 10^{-8}$ sec), and μ -meson ($\tau \sim 2 \times 10^{-6}$ sec), for example. In all weak interactions either neutrinos appear (for example, $n \rightarrow p + e^- + \bar{\nu}$ or $\pi \rightarrow \mu + \bar{\nu}$) or there is a violation of one of the conservation laws, such as space parity or time reversal, obeyed by the strong interactions. However, little else is known and many basic principles remain to be clarified.

Mesons are identified as the intermediaries "carrying" the strong forces that bind nuclei and form the resonant particle states, and photons are the "agents" of electromagnetic forces, but are there quanta associated with weak interactions? Nuclear β decay, polarizations of the products in weak decays, and reactions induced by low energy neutrinos from reactors have made it possible to probe the weak force in the low energy region, and it has been shown to be of very short range. This means that if an intermediary existed in weak interactions its mass should be quite large. The answer to the question of whether the weak interactions exhibit structure which is similar or dissimilar to strong and electromagnetic interactions will require work in regions other than the very low energy region. Is there a heavy vector meson W (W for weak) mediating the weak interactions, as heavy photons? If the W exists, its mass exceeds that of the proton, and its discovery may well hinge upon the future development of high energy accelerators.

If the existence of the W is confirmed, higher energy studies will be absolutely necessary before its detailed role in the weak interactions can be established. These studies are also necessary to probe the basic parameters, such as the dependence on energy and momentum transfers and selection rules for the weak interactions at high energies, without which a theory is meaningless if not impossible.

To study a large class of weak interactions it is necessary to initiate the inverse of the decay process with neutrino beams. Because of the smallness of the cross sections involved ($\sim 10^{-38}$ cm²) as well as the desire to study their energy dependence, these beams must be very intense and should extend well into the BeV energy region. The crucial importance to this entire field of study of an extension of existing machine parameters, with regard to both energy and intensity, cannot be over-emphasized.

Finally, in the field of electromagnetic interactions, two specific research directions would be of great interest in extending our understanding to higher accuracy at higher energies.

Since charged pions and kaons decay primarily into muons, a machine producing large fluxes of high energy pions and kaons will also yield as a by-product large fluxes of high energy muons. Among the many experiments which can be readily envisioned with a high energy muon beam, the possibility of measuring the muon magnetic moment with greatly extended accuracy may be mentioned.

At present the muon magnetic moment has been measured¹ with an accuracy of 2 parts per million, which permits comparison with theory almost at the α^2 level, i.e., to second order in the fine-structure constant $\alpha \approx 1/137$. Thus far the assumption that the muon is a pure electrodynamic particle predicts results for the muon magnetic moment which are in excellent agreement with experiment. In order to confirm the existence of the α^2 term, however, at least a factor of 10 improvement in accuracy is required. A proposal² has been made at the CERN proton synchrotron for an experiment which it is hoped will be more accurate by a factor of 25. Since the precession rate of the muon's anomalous magnetic moment in a magnetic field is proportional to its energy (in the relativistic region), increased accuracy can be achieved by using higher energy muons. This is the feature that makes possible the increased accuracy of the proposed CERN experiment compared with the earlier experiment¹ done with muons of about 100-MeV energy. With muons an order of magnitude greater in energy than those now produced at Brookhaven and CERN, the muon magnetic moment might be measured to a precision possibly 250 times as great as in the last experiment, and this could lead to the measurement of α^3 terms.

Comparison between experiment and pure electromagnetic theory at this level of accuracy would be extremely interesting for the following reason. If one is looking for breakdowns in quantum electrodynamics, then there is an order of α^n for some n at which the photon, electron, and muon can no longer be treated as a closed system independent of the strongly interacting particles. It is expected that this level is α^3 in the muon magnetic moment because of the presence of pion pairs in the photon vacuum polarization. Should it turn out that experiments continue to give agreement with pure quantum electrodynamic theory down to the level of smallness at which strongly interacting particles begin to contribute, then quantum electrodynamics could be accepted as a correct theory. This would indeed be a great triumph for existing concepts, and it can be investigated only with the aid of very high energy muons from a very high energy accelerator.

In the realm of high energy neutral particles (e.g., π^0 , ω^0 , etc.), a large flux of high energy photons will result from their decays. Assuming the lack of availability of electron synchrotrons and linear accelerators in the energy region greater than several tens of BeV, these photons may be a unique source for studying the electromagnetic reactions induced by very high energy electromagnetic radiation. Investigations of these phenomena are of great interest, since they could shed light on such questions as whether the photon, through its coupling to strongly interacting particles, exhibits properties analogous to the properties of these particles, e.g., diffraction scattering. In other words, does the photon in its interaction with strong particles act like a neutral strong particle with simply a smaller coupling constant, or does the photon exhibit some new and different type of behavior at these high energies?

Common to many of the suggestions and thoughts presented in this volume is the feeling that investigations at very high energies genuinely represent research at

the very edge of man's experience and understanding. In this respect the study of the microscopic world stands not only as a worthwhile endeavor increasing our scientific knowledge but also as a very powerful demonstration of how our culture has been able to enter into a region of concepts and phenomena almost unimaginably different from the immediate world we live in.

REFERENCES

1. G. CHARPAK, F. J.M. FARLEY, R.L. GARWIN, T. MULLER, J.C. SENS, AND A. ZICHICHI, *Phys. Letters* **1**, 16 (1962).
2. F. J.M. FARLEY, Private communication.

Nuclear Physics: Democracy or Aristocracy?

GEOFFREY F. CHEW

University of California, Berkeley

A major achievement of high energy nuclear physics has been its raising of serious doubts about the elementary particle concept. These doubts have crystallized in the conjecture that with strongly interacting particles we may be dealing with a “nuclear democracy,” a regime where all strongly interacting nuclear particles from the least massive, the pion, up to excited states of transuranic nuclei stand on a dynamically equivalent basis. Each may be regarded as a stable or metastable bound state of those channels with which it communicates, the mass, spin, and partial widths (coupling constants) of each particle being calculable in terms of the Yukawa forces that act in the communicating channels.

What is a “Yukawa force”? It is a force arising through the crossing principle from states that communicate with crossed channels. The Yukawa force may be said to originate in the “exchange” of such states, the most important of which appear to be single particles. The characteristics of a Yukawa force are uniquely determined by the properties of the particle exchanged; the range and form by the mass, spin, and parity; and the strength by the partial reduced widths coupling to the channels in question. The force may be either attractive or repulsive, depending on the internal quantum numbers of the particle exchanged and the channels in which the force acts.

The best known example of a Yukawa force is that between two nucleons, where the long-range parts have been successfully explained in terms of single-particle exchanges of the known zero-strangeness mesons having mass < 1 GeV. The long-range parts of the force between a pion and a nucleon have similarly been explained, single baryon exchange here playing the dominant role. It is, in fact, now generally accepted that *all* long-range forces between *any* pair of particles are controlled by the Yukawa mechanism. Doubt remains only about what I shall here call “short-range” forces, a euphemism for interactions in states having angular momentum 0, $\frac{1}{2}$, and 1 but no higher. In conventional electrodynamics and weak interaction theory there *appear* to be non-Yukawa forces acting in certain of these low- J states, forces that correspond to an aristocratic rather than a democratic particle society. The assumption of nuclear democracy excludes non-Yukawa forces from strong interactions. Experimental evidence for strong non-Yukawa forces has never been seen, but the search for such forces continues to be a key motivation in high energy physics.

To avoid misunderstanding on this point let me give as a typical example of a non-Yukawa interaction the contribution to positron-electron scattering that arises from “direct” transitions to the intermediate photon. (See Figure 1.) This interaction, affecting $J=1$ only, cannot be described as a force due to particle exchange, but in

Figure 1.

Figure 2.

a conventional calculation one nevertheless inserts such a term at the beginning, employing the mass and coupling constant of the photon as given parameters. The photon, in other words, is not expected to “emerge” as a bound state of the electron-positron system, with properties determined by the dynamics. By contrast, in a calculation of n - p scattering it is felt unnecessary to insert directly the transition to the intermediate deuteron. (See Figure 2.) The existence and properties of the deuteron are supposed to be consequences of the Yukawa forces due to meson exchange.

In conventional electrodynamics and weak interaction theory, the photon with spin 1 and the leptons with spin $\frac{1}{2}$ are aristocrats in the sense that their properties are assumed not to be dynamically calculable, while other particles such as positronium *can* be predicted as bound states. In a nuclear democracy *all* strongly interacting particles would be predictable, including the spin- $\frac{1}{2}$ nucleon and the spin-1 mesons.

Dynamical calculations of nuclear particles as bound states are based on two related assumptions: (a) that communicating channels with thresholds sufficiently far above the mass of the particle in question may be neglected, and (b) that exchanged systems of sufficiently high mass make negligible contributions to the overall Yukawa force. It is not completely understood why such assumptions should be valid, although plausibility arguments have been given both in the special framework of the Schrödinger equation and, more generally, in terms of the unitarity and analyticity of the S -matrix. Experience strongly suggests, in any event, that the two assumptions actually work. The question is a quantitative one: To how high an energy in the communicating channels and in the exchanged systems must one go in order to achieve reasonable accuracy? The answer varies from one case to another, and theoretical efforts naturally tend to concentrate on predicting those particles for which a small number of communicating channels and exchanged systems promise to constitute an adequate approximation.

In this connection the relative positions of “classical nuclear physics” and “high energy nuclear physics” deserve some appreciation. Any particle with $A \geq 2$, whether in its ground state or an excited state, is supposed to be a citizen of the democracy with status equivalent to that of any meson ($A=0$) or baryon ($A=1$). We happen, however, to achieve a good dynamical approximation to particles with $A \geq 2$, $S=0$, by ignoring channels that contain any $A=0$ particles or $A=1$ particles other than nucleons. The channels considered have thresholds separated only by energies of the order of MeV from the mass of the nucleus being studied. The neglected channels

do not begin until several hundred MeV higher. The existence of the higher-threshold channels affects the properties of the nucleus, but the effect is small, and nuclear physics has in consequence been broken by its students into two separate subjects, one dealing with $A=0, 1$ and one dealing with $A \geq 2$. If one tries to understand *why* there is such a large gap between the two sets of thresholds, the explanation appears to involve the “unusual” smallness of the pion mass. Almost no current theories, whether democratic or not, give the pion a special status these days, but the fact remains that it *is* the least massive nuclear particle by a substantial margin and correspondingly it generates “unusually” long-range forces for those channels where it can be exchanged. The pion *is* exchanged between two nucleons, and the short-range force here happens to be repulsive. As a consequence we have acting between nucleons an average force of long range that corresponds to a potential energy of only $\sim m_\pi^2/2M$ or 10 to 20 MeV. This turns out to be barely strong enough to make bound states at all, so that nuclear masses for $A \geq 2$ occur close to the lowest communicating channel threshold.

In contrast, because of conservation laws, a pion generally cannot be exchanged between two particles if at least one of the two has $A=0$, and the shorter-range forces (e.g., ρ meson exchange) that do act here turn out to be sometimes attractive. The average potential energy in such channels is higher than for two baryons by a factor $\sim m_\rho^2/m_\pi^2 \gtrsim 30$ so that the characteristic energy of the dynamics turns out to be hundreds of MeV or even BeV. It is by such arguments that one tries to explain how, even in a democracy with equal treatment under the law, the population could become divided into two groups, possessing what seem to be qualitatively different characteristics.

It has been evident for some time, thanks to the circumstances just described, that all particles with $A \geq 2$ can be understood as dynamical bound states, once one knows the properties of particles with $A=0$ and $A=1$. Recent interest has revolved about the status of the latter, and it is here that the bootstrap idea becomes essential. In other words, the same particles that one is attempting to predict become involved in generating the important Yukawa forces. I emphasize “important” because particles with $A \geq 2$ also generate forces through their exchange, but they are so massive that the effect is small. The least massive particles are the most important force-producers and these all have $A=0$ or 1.

Dynamical bootstrap calculations of bound states with $A=0$ and $A=1$ have proved difficult because several different channels usually must be considered. In a few favorable cases, however, including that of the nucleon, the results have been qualitatively successful, and the prevailing belief now among high energy physicists is that none of the particles so far observed is an aristocrat. All seem to be bound states.

Even supposing that this belief will be substantiated by future work, a question still remains as to whether some *undiscovered* particles (or particles) has a favored “elementary” status. Is there a basic unit of strongly interacting matter, after all, out of which neutrons, protons, and the other observed nuclear particles are built? In that case our democracy would be only apparent. The aristocrats would be lying hidden. What tools does high energy physics have to attack such a puzzle?

The most obvious approach is to attempt the production and identification of new particles whose properties clearly identify them as aristocrats. This program is

a natural extension of the particle studies that are constantly going on. If it fails, what then? It can still be argued that even aristocrats have such a tiny proportion of blue blood that their disguise is difficult to penetrate.

We do not possess at present any clear criteria for smoking out nuclear aristocrats, but the effort to formulate and test such criteria must be rated as one of the most important and fundamental activities of present day science. It is hard to think of a concept that has had more impact than that of the elementary particle. If this concept has reached the end of its usefulness in the nuclear domain, the foundations of all science are affected.

Patterns in Elementary Particle Phenomena

R.H. DALITZ

The Clarendon Laboratory, Oxford

The deepest questions investigated by physicists today are those concerned with the properties of matter in the most primitive form available to us at present, the so-called “elementary particles.” These studies are mostly carried out with the highest energy particle accelerators available, in order to facilitate the production of the most massive of these “elementary particles” or of those whose production processes are the most complicated. In this sense, the term “high energy physics” corresponds to a misleading emphasis on the means, rather than on the ends, appropriate to this area of physics.

The established elementary particles have grown rapidly in number over the past few years, to such a degree that these objects can no longer be regarded as elementary in any sense of this term. However, with their growth in number, their study has made it clear that their properties and their interactions follow rather clear patterns. These interactions may be classified into at least 5 categories: the strong interactions (S), the moderately strong nuclear interactions (MS), the electromagnetic interactions (EM), the weak decay interactions (Wk), and the gravitational interactions (G), in descending order of intrinsic strength. With respect to their established quantum numbers, the particle states themselves form characteristic singlet, octet, and decuplet patterns which reflect properties of the S interactions. The properties of these particle states, of their interactions, and of the transitions which occur between them in consequence of the MS , EM , and Wk interactions also appear to follow patterns characteristic of each of these interactions. Most of these patterns are only partially explored to date, but enough is known to be sure that each pattern exists.

These patterns necessarily reflect symmetry properties characteristic of each class of interactions. These symmetries are such as to relate the properties of different particle states, and so are not simply a reflection of the symmetries of our space-time continuum. Their exploration and elucidation will not depend just on a few spectacular “Nobel Prize” experiments, but will require many painstaking measurements from a range of lesser (but difficult) experiments, whose results will have to be taken together and compared, in order to test and establish the precise nature of these patterns.

Thus, the existence of symmetries which relate the properties of different particle states implies the need for exploration of these properties over the widest possible range of these “elementary particles.” For example, the S interactions have recently been shown to have a characteristic symmetry form [known as $SU(3)$ symmetry], a property dramatically illustrated by the prediction and discovery of the Ω^- particle. Yet, until the strange particles, previously known only rarely in cosmic rays, could be produced copiously in selective experiments at high energy proton

accelerators, only one limited aspect of this deep symmetry property had been known, as the property of charge-independence [$SU(2)$ symmetry] for the neutron and proton (and later for the pion) first observed in the patterns of levels established for atomic nuclei. From low energy nuclear information alone, the existence of $SU(3)$ symmetry could scarcely have been suspected as a larger symmetry comprising this established $SU(2)$ symmetry. In turn, it appears quite possible that the $SU(3)$ symmetry may represent only a part of some more extensive symmetry property, which may hold valid only for some class of still stronger interactions.

The “elementary particles” known are of at least two types, the leptonic particles which participate in EM , Wk , and G interactions, and the hadronic particles which feel all of the interactions listed above, especially the S interactions. Little is known about the nature of the leptonic particles. From the weakness of their known interactions, one would suspect them to be simpler in nature than the hadrons, were it not for the large mass ratio between the muon and the electron ($m_\mu/m_e \simeq 210$) despite their close similarity in all other respects. As for the hadrons, their profusion already suggests that they must be composite, in some sense. Also, the quantitative success of the comparison between $SU(3)$ symmetry and the properties of the hadron states is not easy to understand unless the hadrons are composite, and the primary objects exceedingly massive. Most probably, these primary objects follow triplet patterns, in some manner. This situation was almost unsuspected a year ago, and has emerged only as the pattern of the hadronic states has begun to fill in and to allow quantitative study. The nature of these primary objects is not yet at all known, and their massive character implies the need for higher energy accelerators for their production and study, perhaps accelerators of a kind different from those in operation today.

The Wk interactions have already shown a clear pattern for some time, a pattern which has suggested that these interactions are carried by a massive intermediate vector boson field, in a manner analogous with the way the Coulomb EM interaction is carried by the photon field. Certain data on Wk interaction processes suggest that these Wk bosons may also follow the triplet pattern appropriate to $SU(3)$ symmetry. Not enough detail is yet known about weak decay processes to decide this important possibility. Neutrino interaction experiments have already shown that such Wk bosons must be very massive, greater than 2 BeV. Further such neutrino experiments (for which higher intensities are really desirable) can provide an additional range of information about the pattern of Wk interactions. Especially, the search for the Wk bosons must be continued at higher energies, in neutrino or photon processes. The outstanding property known for the Wk interactions is that they are not symmetric with respect to space reflection or to charge reflection (and possibly not for time reversal, either), although the S , MS , and EM interactions do possess these symmetries. No reason is yet known why the pattern of the Wk interactions should differ in such a remarkable way.

Our first need in elementary particle physics is the ability to extend our knowledge of the patterns appropriate to all these classes of interaction. These patterns must bear some kind of interrelationship. Naturally, it is impossible to anticipate which studies will prove the most fruitful in providing the needed clues. It is certainly essential to continue the search for “elementary particle” states, not as an end

in itself, but to provide a more complete picture of the patterns of these states and of their interactions. The recent discovery of unsuspected patterns in elementary particle phenomena has emphasized the shallowness of our present appreciation of the nature of matter. The situation leaves man little choice but to go on and to explore these patterns to the end, to discover what really is the underlying structure of the world about him. Without the development of high energy accelerators, these patterns would not yet be known; certainly, further patterns still remain to be discovered, perhaps with present accelerators or with accelerators not yet constructed. This exploration will necessarily involve much patient experimentation, with a development of our knowledge of the patterns of elementary particle phenomena proceeding step by step, on a broad front.

Although the necessity for experimental programs ranging over a broad front is a commonplace observation, its importance is not always acknowledged, since such developments are often overshadowed by the excitement associated with the "Nobel Prize" type of experiment. The reassuring way in which knowledge based on phenomena apparently rather unrelated can come together to make new progress may be conveniently illustrated here by recounting briefly the story of the Λ hypernucleus (a nuclear system consisting of Λ particles bound to an ordinary nucleus). Although such systems appear exotic and esoteric, even to elementary particle physicists, the fact that accurate and extensive data exist on their properties has meant that their study has been able to throw light on a wide range of questions concerning elementary particle physics and nuclear physics. The analysis of data on their production and decay has led to spin values for certain Λ hypernuclei. This has led in turn to the determination of the K -meson parity, important for our knowledge of the S and MS interactions, and to a knowledge of the strength and spin-dependence of the nuclear interaction between Λ particle and nucleon. The accurate knowledge of their binding energies has led to a test of the $SU(3)$ symmetry for the EM interactions. Analysis of their decay processes led to the first determination of the spin of the Λ hyperon and to information on the isospin properties of the Wk interactions. At the same time, their analysis has also tested the properties believed for certain nuclear systems, for example with regard to information on the α - α and p - α interactions, to evidence for new nuclear states, and even to information on new nuclear species. Knowledge of the formation processes for Λ hypernuclei has added greatly to understanding of the emission processes for ordinary nuclear fragments from nuclear collisions, a problem of interest to radiochemists and cosmic-ray physicists. Here, the moral is that accurate and systematic data on new phenomena ultimately provide their own justification, their implications going far beyond the phenomena themselves in the end. The analysis of the patterns of Λ -hypernuclear phenomena has led to advances in an unexpectedly wide range of physical questions.

Deeper and more fundamental studies than those which are stimulated by the questions posed by our developing knowledge of the patterns of "elementary particle" phenomena can scarcely be imagined. If man has curiosity, these questions must be answered. It is true that these patterns appear remote from everyday experience, yet it is just as clear that we can have no deep understanding of the nature of the world around us until all these patterns are known and their relationship with everyday phenomena is established.

Remarks on High Energy Processes

M.L. GOLDBERGER
Princeton University

In order to explore the fine structure of matter, one needs fine instruments. The fact that a proton has “size” cannot be ascertained by scattering light quanta from it until these quanta (photons) have energies of the order of the first excited state of the proton (i.e., until the photon energy approaches that for the production of particles which interact strongly with protons, namely π -mesons). Roughly speaking, one cannot study structures of dimensions Δr until one transfers momentum to the system, Δp , which is so large that $\hbar/\Delta p \lesssim \Delta r$. High energy physics is in large part the study of the exceedingly intimate fine structure of particles which under rough scrutiny appear elementary in the elementary sense of the word. The more carefully these objects are examined, the more it becomes apparent that they are far from elementary in any sense.

STUDY OF RESONANCES

The complexity of particle physics has increased directly in proportion to the energy available in the accelerators used to produce beams of energetic projectiles, notably electrons and protons, the truly stable readily accessible “elementary” particles. For the past 5 years a substantial fraction of the total activity in the field has been directed toward the detection and study of resonances or, as they are frequently called, particles. This research has paid off handsomely, especially in connection with uncovering unsuspected symmetries which have helped to guide the theoreticians attempting to provide a group theoretical basis for particle classification.

DETAILED INVESTIGATION OF INELASTIC PROCESSES

The search for resonances, which is carried out primarily by studying the mass distributions of groups of particles produced in highly inelastic collisions, surely does not exhaust all the information available from the analysis of such collisions. Very little work, either experimental or theoretical, has been done to elucidate the dynamics of these processes. Although there is a strong intuitive feeling that reactions at high energies and large momentum transfers enable one to study interactions at small distances, no one has put this idea into very quantitative form. In a reaction initiated by a pion and a nucleon the total cross section (for all processes) per momentum transfer (to an arbitrarily designated final baryon) surely has a bearing on the space-time correlations between current operators. The latter can be given a meaning irrespective of any religious differences between field theoreticians and S -matrix devotees. Whether or not the conventional space-time structure will play a

fundamental role in the ultimate theory, one must learn to make statements about space and time in order to present current field theory with some challenges. This point will be further discussed below.

ELASTIC SCATTERING EXPERIMENTS

The study of elastic scattering at high energies and large momentum transfers, in part because of the very simplicity of the reactions, has been vigorously pursued. Another reason for the popularity of this research is that there have been theoretical conjectures (based on the Regge-pole hypothesis) which predicted some very striking behavior at high energies and *small* momentum transfers. The theory is quite silent about the large momentum transfer regime. It was found that the most naive Regge theory predictions were not borne out by experiment. The theory has become more intricate recently and has not yet yielded further quantitative predictions. One way of exploring the predictions of a theory which has not yet been fully exploited involves the measurement of the differential cross sections for processes like $\pi^- + p \rightarrow \pi^0 + n$, $\pi^- + p \rightarrow \eta + n$, $\pi^- + p \rightarrow \Lambda + K^0$, etc., as functions of momentum transfer for various energies. These two-body reactions may well be more illuminating than the truly elastic processes.

One difficulty that appears in the confrontation between theory and experiment is the decision as to whether one is or is not in what can be termed the asymptotic region. From the Regge standpoint, one relevant parameter is the projectile laboratory energy measured in units of its rest mass. If the approach to the limit should depend on the logarithm of this quantity (E/m for present accelerators ranges between about 30 and 200), the need is clearly seen for pushing this research to much higher energies. Another possibly relevant parameter is the total center-of-mass energy (of the order of 8 BeV for the present proton-proton experiments). This unfortunately increases only as the square root of the projectile energy (except for colliding beam experiments), and again the need for higher energies is obvious. There are no clear-cut theoretical guidelines on when this number is large enough.

Another possible theoretical use of elastic scattering data is in the use of the scattering amplitude to define the quantum mechanical analogue of the classical distance of closest approach. This in turn has relevance for the study of space-time structure of the dynamics. Finally, it is worth noting that one must study the nature of inelastic processes which can lead to the experimentally observed, largely imaginary, elastic scattering amplitudes, which fall spectacularly at large momentum transfers.

POSSIBLE TESTS OF THEORETICAL IDEAS

The theory of reactions between strongly interacting particles ought not really to be dignified with the name theory. This applies with equal vigor to the axiomatic field theories and to the sophisticated phenomenology known as S -matrix theory. There are a few places where these two approaches meet and can be exposed to experiment simultaneously. The most accessible one is the forward-scattering dispersion relations for the pion-nucleon system. They can be derived rigorously from the revered axioms; they are postulated (essentially) in S -matrix theory. It is of crucial

importance that they be tested experimentally at higher energies than are now available. If they continue to hold, we will have learned something, but not a great deal, about the validity of our theoretical views. If they fail, something dreadful is going on with the axioms, and the professional dispersion theorists will have to get out their crystal balls and guess anew for a theoretical foundation.

Another aspect of this type of experiment has to do with the behavior of cross sections at high energies. On the basis of rather mild assumptions one is led to the equality of particle and antiparticle cross sections (Pomeranchuk theorems) at very high energies, provided the latter are bounded. (There are some interesting generalizations to more complex processes yielding relations between cross sections other than those involving particle-antiparticle, but these will not be gone into here.) The total cross sections for $\pi^- + p$ and $\pi^+ + p$ seem to be constant at high energies (~ 25 millibarns), but there is an annoying 2-millibarn difference which continues to appear even out to 20 BeV. If this persists, it implies that there are unsuspected singularities in scattering amplitudes regarded as functions of the complex energy. The asymptotic equality of cross sections can be deduced without requiring the analyticity necessary for the dispersion relations; this type of test together with others recently devised by Khuri and Kinoshita which do not require infinite energy may well uncover some serious deficiencies in the theory.

SUMMARY

A number of categories of research in high energy physics have been quite briefly discussed. The persistent theme of this discussion has been that deeper understanding and a sharp differentiation between various theoretical ideas can be achieved only by studying scattering processes at energies considerably in excess of those currently available. Topics discussed in other contributions to this document have been deliberately avoided, and surely many others of great importance have been omitted. There is little question that the ultra high energy regime will be a rich one.

The Real Part of the Forward Scattering Amplitude and Local Field Theory

N.N. KHURI
The Rockefeller Institute
and
T. KINOSHITA
Cornell University

One of the central problems of high energy particle physics is to ascertain whether some kind of relativistic local field theory could adequately describe the particles and their interactions. Unfortunately, as is well known, local field theories have serious and frustrating mathematical disadvantages. Except in the case of quantum electrodynamics, very few quantities of physical interest can be directly computed from quantum field theory.

These frustrations led some theoretical physicists in the middle of the last decade to look in two related directions. The first was to turn to an S -matrix type of theory, concentrate on the physically measurable quantities, and look for those properties of these quantities which follow just from general principles. For example, those mathematical properties of scattering amplitudes were sought which were expected to hold in a future theory, regardless of its detailed nature, as long as the theory satisfied certain general principles. Such general principles as relativistic invariance, causality, an asymptotic condition which allows a particle interpretation, and some reasonable requirements on the Hilbert space of physical states and the energy-momentum spectrum, were and are still believed to be reasonable features of a future theory. A scattering formalism starting with these principles was first developed by Lehmann, Symanzik, and Zimmermann.¹ Among other things, this formalism gave expressions for scattering amplitudes from which it was possible to give a proof of the forward dispersion relations first derived by Goldberger.²

A second approach was that initiated by Wightman.³ It consisted of first formulating a set of rigorous mathematical axioms for local field theories satisfying the general principles mentioned above and, second, investigating mathematically the consequences of these axioms. This has led to several interesting results of which only one is of concern here. Namely, K. Hepp has recently shown that the formalism of Lehmann et al.¹ can be rigorously derived from the Wightman axioms, and also that the forward dispersion relations follow from these axioms.⁴

For concreteness and simplicity, consider the scattering of pions on nucleons. Let $f_{\pm}(E)$ be the forward amplitudes for π^+p scattering, respectively, where E is the laboratory energy of the incident pion. The symmetric amplitude $f(E)$ is defined as

$$f(E) = \frac{1}{2}[f_+(E) + f_-(E)] - [\text{nucleon pole terms}] . \quad (1)$$

As a consequence of local field theory it follows that $f(E)$ satisfies the forward dispersion relation,

$$f(E) - f(0) = \frac{2E^2}{\pi} \int_{\mu}^{\infty} dE' \frac{\text{Im} f(E')}{E'(E'^2 - E^2)}; \quad \text{Im} E \neq 0. \quad (2)$$

This relation, or more exactly the analytic properties it implies, can, at least in principle, be tested experimentally. If such an experimental test should disagree with (2), then the careful mathematical work of several physicists in the last decade would be handsomely rewarded. One would be able to conclude, beyond any reasonable doubt, that pions and nucleons cannot be described by local fields. This would certainly be a major revolution in physics.

At low energies it is well known that (2) is reasonably in agreement with experiment. However, recent experiments⁵ at high energies (>6 BeV) show that $f(E)$ has a substantial negative real part. While the data obtained so far are not yet in contradiction with (2), the real part measured is larger than what was expected, and with the little data available it does not seem that $\text{Re} f/E$ decreases with energy as it should if local field theory is valid.⁶

In a practical test the relation (2) has two disadvantages. The first is the fact that it involves integrations up to infinite energies. The second is that as $\text{Im} E \rightarrow 0$ principal value integrals have to be used in (2). However, sum rules can be written for $\text{Re} f$, which, although they follow directly from (2), do give for practical purposes a better tool for testing the consequences of local field theory.⁷ These sum rules also show explicitly the fact that a large and repulsive real part at high energies, if maintained for a certain large energy range, will lead to a contradiction with (2).

The first such sum rule holds for all real E , and gives

$$\int_0^E \frac{\text{Re} f(E') - f(0)}{E'^2} dE' = \frac{1}{\pi} \int_{\mu}^{\infty} dE' \frac{\text{Im} f(E')}{E'^2} \ln \left| \frac{E' + E}{E' - E} \right|. \quad (3)$$

The integrand on the right-hand side in (3) is always positive. If the integration is cut off at the maximum energy, E_m , for which data are available on the total cross section, then an inequality is obtained which should be satisfied regardless of the actual value of the total cross section for $E' > E_m$,

$$\int_0^E \frac{\text{Re} f(E') - f(0)}{E'^2} dE' > \frac{1}{\pi} \int_{\mu}^{E_m} dE' \frac{\text{Im} f(E')}{E'^2} \ln \left| \frac{E' + E}{E' - E} \right|. \quad (4)$$

It is already evident from (4) why a large and negative $\text{Re} f$ is dangerous to analyticity. The present data give roughly $\text{Re} f \sim -cE$ for energies between 7 and 12 BeV. Clearly, such a behavior if maintained to higher energies will not only make the left-hand side of (4) smaller but might even make it negative for large enough E .

In an actual comparison of (4) with the data, $\text{Re} f$ must be known in the unphysical region $0 \leq E' < \mu$. This can be obtained from the dispersion relation. As mentioned earlier, the dispersion relation is reliable for low energies. However, since it is already known that the dispersion relation is reliable for energies below a few BeV, the low energy data can be subtracted from (3). For $E_1 \approx 1$ to 4 BeV one obtains the sum rule

$$\int_{E_1}^E \frac{\text{Re} f(E') - f(0)}{E'^2} dE' > \frac{1}{\pi} \int_{\mu}^{E_m} dE' \frac{\text{Im} f(E')}{E'^2} \ln \left| \frac{(E' + E)(E' - E_1)}{(E' - E)(E' + E_1)} \right| \quad (5)$$

where $E_m \geq E > E_1$. The only quantity in (5) which cannot be directly measured is $f(0)$. But for estimating it one can always use the dispersion relation.

The present data are still sketchy for $\text{Re}f$. But just to see how serious the situation is, take $E_1 = 4$ BeV, $E_m = 30$ BeV, and $E = 30$ BeV. Furthermore, assume that for $4 \text{ BeV} \leq E' \leq 30 \text{ BeV}$,

$$\frac{\text{Re}f}{\text{Im}f} \approx \alpha \quad \text{and} \quad \text{Im}f \approx cE'. \quad (6)$$

For $\text{Im}f$ this is not a bad approximation, and for $\text{Re}f/\text{Im}f$ the data seem to give $\alpha \approx -0.2$ between 6 and 12 BeV. If the expression (6) is substituted in (5), it is seen that a value $\alpha \leq -\frac{1}{3}$ will already violate the inequality (5). On the other hand, if a 100-BeV machine were available and $\text{Re}f/\text{Im}f \approx \alpha$ for $4 \text{ BeV} \leq E' \leq 160 \text{ BeV}$, then, setting $E_m = E = 160 \text{ BeV}$, one would obtain a contradiction in (5) with $\alpha \approx -0.2$. Even if α should decrease with energy beyond 30 BeV, one could still get a contradiction with (5) if that decrease were slow and if the total cross section did not start to decrease at a faster rate than at present available energies. But in that case one would need energies beyond the 160 BeV mentioned above.

Clearly, measurements of both $\text{Re}f$ and the total cross sections beyond the 30 BeV now available would be of great importance. For, if the present trend in the data continues up to say 200 or 300 BeV, (5) would be violated and hence the forward dispersion relation would be in disagreement with experiment. Such a situation would lead to a revolution in theoretical physics much more far-reaching than that caused by the discovery of parity violation in weak interactions.

REFERENCES

1. H. LEHMANN, K. SYMANZIK, AND W. ZIMMERMANN, *Nuovo Cimento* **1**, 1425 (1955); **6**, 319 (1957).
2. M.L. GOLDBERGER, *Phys. Rev.* **97**, 508 (1955).
3. A.S. WIGHTMAN, *Phys. Rev.* **101**, 860 (1956).
4. K. HEPP, *Helv. Phys. Acta*, in press.
5. K.J. FOLEY ET AL., paper presented to the 1964 Conference on High Energy Physics, Dubna, U.S.S.R.; G. BELLETTINI ET AL., *Ibid.*
6. See for example N.N. KHURI AND T. KINOSHITA, *Phys. Rev.*, in press.
7. N.N. KHURI AND T. KINOSHITA, *Phys. Rev. Letters*, to be published.

Comments on Elementary Particle Physics

T.D. LEE

Columbia University

The urge and the interest to find those ultimate elements in terms of which everything else is made are almost as old as human civilization. However, as our knowledge increases, what were thought to be elementary often turn out to be composites. Consequently, the class of these supposedly fundamental elements changes with time, and the continuous search for these elementary units is the purpose of elementary particle physics.

Because of the inherently basic nature of the field, the principles discovered in elementary particle physics are applicable not only to these elementary units, but are automatically valid for their composites and therefore for all matter. Thus, for example, the discoveries of the electron and the atomic nuclei by J. J. Thomson, E. Rutherford, and others made possible a complete understanding of atomic structure, which affects not only atomic physics itself but also fields such as solid state physics, molecular physics, chemistry and, indeed, almost all branches of natural sciences. The subsequent search for what the various nuclei are made of led to the discoveries of the neutron, the π meson, the neutrino, and finally to the present set of the large varieties of different "elementary particles." Through these discoveries, the properties of nuclear structure became largely understood. These understandings, on the one hand, changed our basic concept of stellar evolution and stellar structure, and on the other hand made possible the vast range of technological developments that are related to nuclear energy.

The present principal unanswered problems in particle physics lie in the region of high energy physics, the study of particles in the subnuclear domain. Most of these "elementary particles" can only be created by bombarding the nucleus with other particles having energies of billions of electron volts. Only through these high energy collisions can the existence of many of these particles be established and their properties be studied. Remarkable progress has been made in the field of elementary particle physics during the past decade, mainly through the extensive use of high energy accelerators. Multitudes of new particles have been discovered. They are found to exist in hundreds of different physical states, and many of these states are extremely short-lived. While most of the properties of these particles, such as charge, mass, spin, lifetime, etc., have been measured, it is clear that these particles cannot be all "elementary," and the central problem is to find the apparent order in their properties and to search for the underlying basis of their interactions.

Recently, there are many evidences supporting the idea, first suggested by Gell-Mann and Ne'eman, that all these particle states (except the leptons) can be grouped into multiplets, each of which is identified with the various irreducible representations of the mathematical $SU(3)$ group. The main parts of the strong interactions

between these particles are assumed to be symmetrical with respect to this $SU(3)$ group of transformations, under which the different particles within the same multiplet can be changed into each other, and this results in similar properties for these particles. Among these recent evidences, the most impressive ones are the successful predictions of several new particles such as η^0 , Ω^- , etc., and the remarkable accuracy of the various mass formulas for the different particle multiplets. The derivation and the form of these mass formulas are similar to that of, say, Zeeman splittings of the atomic levels in a weak magnetic field; they are obtained by using the first-order perturbation formula in which the effects of the symmetry breaking interactions are regarded as small. The accuracy of these mass formulas varies from about $3\frac{1}{2}\%$ for the pseudoscalar meson octet to less than $\frac{1}{2}\%$ for the baryon octet. Yet, the mass differences between the particles within each multiplet are all of the order of a few hundred MeV. In order to regard energy differences of such a magnitude as small, it seems necessary to assume the basic $SU(3)$ symmetry maintaining interaction as characterized by an energy scale M which is much bigger than a few hundred MeV. A reasonable estimation based on the accuracy of the mass formula itself leads to a value of M roughly of the order of 10 BeV. At present, almost nothing about the detailed dynamics of this strong $SU(3)$ symmetrical interaction is known. A high energy machine in the range of 200 to 1000 BeV will certainly be crucial in this respect.

Speculations have been made concerning the basic nature of this strong symmetry maintaining interaction by correlating the $SU(3)$ symmetry with the existence of some basic triplets. All the so far observed strongly interacting particles are assumed to be composites of these fundamental triplets. It seems natural to identify the basic energy scale M with the masses of these triplets. The threshold energy for the production of such triplets in the center-of-mass system is $2M$, which is estimated to be about 20 BeV. Thus, in order to produce these triplets and to study their properties, the construction of a super high energy machine is essential.

Besides these strongly interacting particles, there is another group of particles called leptons, which do not have any strong interactions. At present, the leptons consist of only four members: the muon, the electron, and the two different kinds of neutrinos. These leptons have only electromagnetic interactions and weak interactions. It has been speculated that all the observed weak interactions are transmitted by a carrier, called the intermediate boson, which plays the same role for the weak interaction as that of the photon for the electromagnetic interaction. Intensive efforts have just been made at Brookhaven National Laboratory and at the European Organization for Nuclear Research in Geneva to search for the intermediate boson by using the high energy neutrinos produced in their machines. From these experiments it is concluded that in order to investigate this important question of the intermediate boson hypothesis of weak interactions, much higher neutrino energy than what is at present available is required. The lowest mass limit of the intermediate boson is currently set to be about 2 BeV, which means that only neutrinos of an energy about 8 BeV or higher can give any sizable contribution to the production of the intermediate boson. Thus, a high energy proton machine in the several hundred BeV range appears to be, again, necessary in order to make any extensive investigation of weak interactions.

The study of particle physics is intimately connected with the problem of symmetry properties of space and time. For example, the study of the strange behavior of the charged K meson led in 1946 to the discovery of the basic right-left asymmetry of our physical laws. More recently, another unexpected property was discovered in the decay of the neutral K meson by Christenson, Cronin, Fitch, and Turley. While the full impact of this new discovery is far from being understood, it has already stimulated theoretical suggestions that either the physical laws are not symmetrical with respect to the time-reversal transformation, or there might exist new long-range interactions between the macroscopic world at large and the microscopic regions of elementary particles. Whatever may be the final form of the correct theory, it is expected that this experiment is but the beginning of a series of new discoveries which should lead not only to the understanding of K mesons but also to new foundations for all physical laws as well.

The purpose of science is to seek for that simple set of fundamental principles through which all known facts are understood and new results predicted. Since all matter is composed of the same fundamental units, the ultimate foundation of all natural sciences must be based on the laws governing the behavior of these elementary particles. High energy machines are not just expensive tools for particle physicists; they are, at present, the most effective tools to study these elementary particles in order to uncover the basic principles which underlie the multitudes of all natural phenomena.

Elementarity of Particles at High Energy

F.E. Low

Massachusetts Institute of Technology

The study of the interactions of particles at high energy exposes their underlying structure. This has been understood for a long time in a general way, since the uncertainty principle tells us that to examine spatial properties with a resolution of Δx we need a momentum $p \sim \hbar/\Delta x$, where $\hbar \sim 10^{-27}$ erg-sec. Thus, the present 25 to 30 BeV accelerators provide us with proton momenta (in the center-of-mass system) of about 1.5×10^{-13} g-cm/sec and therefore a probe for distances of the order of 10^{-14} cm. However, the above relation between p and Δx does not contain a scale of length (or momentum), and therefore gives no hint as to how far we have to go before we are “inside” a particle. On the other hand, an empirical scale does exist. This is furnished in first instance by the masses of the observed particles. Second, we expect, on the basis of incomplete information from very high energy cosmic-ray events, that in the asymptotic region total cross sections will become independent of energy. We also expect, on the basis of plausible theoretical arguments, that particle and antiparticle cross sections (for example, σ_{p-p} and $\sigma_{\bar{p}-p}$) will become equal. At the maximum energy of the present accelerators neither condition is yet satisfied, although the trend appears to be towards constancy and equality as expected. We therefore appear to be approaching an asymptotic region, indicating an end to the spectrum of particles. This is in direct contradiction to the recently advanced idea that the “elementary” objects are yet to be discovered with masses above 5 BeV. It will be very interesting to see how this turns out.

In recent years it has become clear that the asymptotic behavior of scattering amplitudes at finite momentum transfer yields direct information about the angular momentum that is exchanged in the crossed channels, that is, about the angular momentum of the particles whose exchange provides the “potential” for the process. Exchange of angular momentum J gives a contribution to the scattering amplitude with an energy dependence $f \sim W^{2J-1}$, where W is the total energy in the center-of-mass system. In general, therefore, a given amplitude will be a sum (or integral) of all such contributions:

$$f \sim \sum_i \beta_i W^{2J_i-1}.$$

It turns out that this sum does not range over all integral $J(0, 1, 2, \dots)$ as might at first be supposed. Rather, as shown by Regge, it may include (i) a finite sum over integral $J=0$ and 1 (corresponding to the exchange of elementary particles of spin 0, $\frac{1}{2}$, and 1), (ii) a finite sum over non-integral J 's which are themselves functions of t , the momentum transfer (corresponding to the exchange of non-elementary particles or poles in the complex J plane), and (iii) an integral over a continuum of J values, corresponding to cuts in the complex J plane. The functions $J_i(t)$ which

occur in (ii) above are called trajectories. Each trajectory may be associated with a small number of particles. These occur as solutions of the equation $J_l(M^2) = l$ where l (or $l + \frac{1}{2}$) is the spin of the particle, and M its mass. Thus the measurement of angular distributions at high energy can in principle distinguish between the contribution of elementary particles and compound ones to the potential. Evidently the cut contributions of type (iii) complicate this analysis considerably, but by no means hopelessly. We may actually be able to distinguish between compound and elementary particles in this way.

Although the number of interesting subjects that can be explored with an accelerator in the several hundred BeV range is very large, I would like to mention only one more, associated with the weak interactions. The present theory of the weak interactions is so singular that it cannot be correct at very high energies without violating the principle of conservation of probability (usually called unitarity). Therefore, the weak interactions must eventually be expected to show some structure, although possibly not at the energies we are now considering. This structure is most likely to be associated with one or more new particles. The most popular candidate has already been named (W) and is expected to have spin 1 and to carry charge. If the W particle is discovered, it will explain the vector nature of the weak interaction and will remove the previously discussed contradiction with the conservation of probability to unattainable energies. Nevertheless, even the W does not provide enough structure to give a consistent theory. An interesting question is: How has nature arranged the weak interactions to be at the same time consistent and transmitted through approximately conserved vector currents?

Outlook of Elementary Particle Physics

YOICHIRO NAMBU
University of Chicago

I believe no physicists today are satisfied with the present status of elementary particle physics. It is not that we do not yet know all the particles and their properties, but that something seems to be lacking in our understanding of subnuclear phenomena. This lack of understanding does not show up in glaring contradictions between theory and experiments, but rather only in some scattered surprises which we quickly learn to swallow as we get used to them. Since we do not have a logically closed way of describing elementary particles, all we can do is to stretch the proven formalisms of quantum mechanics and relativity a little bit and add some *ad hoc* assumptions each time we find a new surprise. The trouble is that we have so far been able to get away in this fashion without coming to a final confrontation. Such a confrontation, which would be necessary before we can make a new quantum jump, must come from further experiments if it comes at all. Maybe the theoretical games we are playing in high energy physics are all wrong. Or maybe there is nothing fundamentally wrong, we only lack some vital new elements. What our basic premises and expectations seem to be in our pursuit of elementary particle physics will be rather briefly analyzed below.

FUNDAMENTAL PARTICLES

In our well-known physical world, a physical phenomenon consists of certain definite physical objects and the laws that govern their behavior. It is impossible to discuss a physical system without knowing both. In the old days we thought an electron was an electron and an atom was an atom, consisting of certain definite components. The physical laws have changed in passing from classical to quantum mechanics, but this has been only a matter of translation from one language to another of the same equations of motion. In present elementary particle physics, on the other hand, we are seriously confronted with our ignorance of both physical objects and the dynamical laws. In fact, we do not know whether there are such things as elementary particles, much less about their equations of motion. These questions are age-old ultimate problems of physics, and neither relativity nor quantum mechanics have touched them in any basic sense.

The success of $SU(3)$ symmetry has sharpened our interest in this direction. Will there be more fundamental objects than what we know in everyday life and laboratories, the latter being actually mere shadows of the former? Or are they all more or less co-equal, being shadows of each other? I myself do not subscribe to the second fairy tale, but if there are fundamental objects, we will have to seek them at still higher energies.

To be specific, we can list, for example, the following possibilities regarding the fundamental objects: (a) There is a fundamental triplet with fractional charges (“quarks” or “aces”). (b) There is a fundamental quartet of objects, or a triplet plus another object, with integral charges. (c) There are two different triplets of objects.

Ordinary particles (baryons and mesons) are all made up of certain numbers of these fundamental objects. We do not know the dynamics of binding fundamental objects, but, extrapolating from our daily physics, presumably we can “ionize” the ordinary matter into more basic parts by giving it sufficient energy. The ordinary matter must correspond to stable “closed-shell” structure with particularly low masses. The currently available energy (~ 30 BeV) in accelerators is equivalent only to a center-of-mass energy of 8 BeV in nucleon-nucleon collision, which is clearly not sufficient to explore the “high-lying” levels involving excitations of fundamental objects.

What are the expected properties of fundamental objects? It is not very likely that they have fractional charges, since at least one of them must be absolutely stable, and they could have been detected in cosmic rays (unless the masses are unreasonably high, in which case they would not be accessible to accelerator physics either). For other versions of fundamental objects, however, the masses and lifetimes could be almost anything. If the masses are not very high and the lifetimes short ($< 10^{-12}$ sec, say), it will be difficult to distinguish them from other more ordinary particles or resonances except by establishing their multiplet structure (triplet, sextet, etc.). On the other hand, if the masses are large compared to baryon masses (e.g., 20 BeV), they are clearly something different from ordinary resonances, and may show peculiar properties.

A rather different aspect in the search for new particles is the so-called intermediate boson (W), which has to do with weak interactions. The present experimental evidence for it is very weak, and the question probably can be solved only by higher energy machines. Theoretically too, the *raison d'être* for W is not quite so compelling as for the triplet. In fact if such a particle should be found to exist, we might not make much progress in understanding elementary particles, but rather get more puzzled: why should they exist? But we must be prepared for W at any rate, since we already have another mysterious particle, the muon.

DYNAMICS

To determine whether or not there exist new dynamical laws which we are missing so far is a more difficult task than finding new particles. However, two aspects of dynamics can be listed here which are more or less of a qualitative nature:

Symmetries

Various symmetries are reflections of the nature of fundamental objects and their dynamical properties. They manifest themselves in the form of conservation laws and selection rules, which have the advantage of being independent of the details of dynamics. The fact that these symmetries do not appear to be perfect should not puzzle us. First, many of the symmetries may be only of phenomenological nature with a limited range of applicability (e.g., low-lying levels only). Like the sep-

arate conservation of orbital and spin angular momentum and the “accidental” degeneracy of hydrogenic levels in nonrelativistic theory, they may not be of a fundamental nature. Second, as far as the so-called internal symmetries are concerned, there is no reason to expect that even the fundamental objects should have perfect symmetry among themselves. Nature would prefer variety to duplication. Third, there is a possibility that a small inherent asymmetry, fundamental or otherwise, will get amplified by a mechanism of feedback. The ideas of spontaneous breakdown and bootstrap belong to this category, and there are several indications of this thing actually happening. If this is the case, we might be able to “control” the symmetry dynamically, e.g., by giving relatively small energy to a system, just as we control a radio amplifier.

Causality and Space-Time Structure

People have long anticipated some kind of breakdown in our notion of space-time structure and causality at extremely small distances. So far nothing concrete has turned up. However, our knowledge is limited to only $\sim 10^{-14}$ cm, and something might happen at much shorter distances (or energies much higher than 1 BeV). An indirect but potentially powerful means for exploring this would be the analytical and related properties of reaction amplitudes. For example we can raise the following questions: (a) Is unitarity good? Check of the optical theorem in high energy scattering and the shape of a resonance cross section may reveal whether there is indefinite metric (negative energy or negative probability) in nature. (b) Is crossing symmetry good? This will involve comparison of crossed reactions. (c) Checks of other properties or hypotheses, such as the Regge behavior, Froissart bound, etc., of high energy cross sections.

SUPER-STRONG, WEAK, AND SUPER-WEAK INTERACTIONS

If there are, for example, fundamental triplets of large masses, they probably have very strong interactions among themselves, stronger than what we call strong interactions at present. This is because ordinary particles must be tightly bound systems (of dimensions $\lesssim 10^{-14}$ cm) of the fundamental objects. The ordinary strong interactions would then be of secondary nature, somewhat like the van der Waals force. Namely, the mesons that mediate nuclear interactions merely correspond to polarizations of the medium (or low-lying collective excitations).

On the other hand, there is also ample room for speculation regarding weak interactions. Weak interactions are even more elusive than strong interactions because of their weakness and because we do not quite know their own logic yet. There are two directions which we are following: (a) High energy weak interactions (neutrino reactions, intermediate bosons, etc.) which might even become strong (say, in the 100-BeV energy ranges). (b) Search for weak, semi-weak, or less-than-weak interactions associated perhaps with new violations of space-time symmetries. The latter would presumably reveal themselves in very minute effects which require high precision measurements rather than high energies. For example, the CP violation in K_0 decays, and possibly the hyperfine structure of hydrogen, are indications that there may be some new types of weak interactions.

SUMMARY

We have discussed here the main problems left unsolved in present high energy physics, and made speculations about what to look for and where. We emphasize especially the following points: (1) The success (or partial success) of $SU(3)$ symmetry makes us believe more strongly than before that there must be a subnuclear structure involving fundamental objects, which may be fully revealed only at very high energies. (2) The subnuclear structure is conceivably combined with new dynamical laws and the breakdown of conventional causal space-time structure. (3) Technically it seems feasible to realize experiments in the 100 to 1000-BeV range. It is at the same time not unreasonable to expect that we shall be able to answer many of the questions posed above within this energy range. (4) Search for new weak or super-weak phenomena is another direction to follow besides the direction toward higher energies.

Remarks on Strong Interactions

L.A. RADICATI*
*Scuola Normale Superiore,
Pisa, Italy*

In the last few years a new chapter of physics has begun; it is often referred to as elementary particle spectroscopy, the adjective “elementary” being used here mostly for historical reasons. The chapter began 13 years ago when the first pion-nucleon resonance was discovered, but the main developments are only 4 or 5 years old. In this short time a large number of excited states have been produced, and their masses, widths, sums, and parities have in many cases been measured.

The theoretical understanding of these phenomena is, however, rather limited. Perhaps the only progress in the theory of strong interactions has been the realization of a number of regularities in the spectra of elementary particles which have their origin in the approximate $SU(3)$ symmetry discussed by Gell-Mann and by Ne’eman.¹ However, these are at most approximate laws whose meaning and validity are not yet fully understood. Indeed when the mass of the newly discovered Ω particle turned out to be so close to the one predicted on the basis of $SU(3)$, the main effort of the theorists was to try to understand why a first-order perturbation calculation should be valid and could give such good agreement with experiment.

One may take the optimistic view that, with the accumulation of new data from the present generation of accelerators, in a few years we will be able to formulate a complete theory of strong interactions. This need not, however, be so, and I think it is perfectly conceivable that as long as we do not go to a much higher energy domain we will not learn the fundamental laws which govern strong interactions. To cite an example from past history, if the study of matter had been confined to chemical phenomena, it would certainly have been hard to guess the elementary laws of quantum electrodynamics which are ultimately responsible for chemical binding. It was the study of atomic physics, in particular the study of the simplest atom, the hydrogen atom, and of the simplest particle, the electron, which made possible the discovery of quantum mechanics and later of quantum electrodynamics. In terms of the energy involved, the step from molecular spectra to the hydrogen spectrum corresponds to an increase by a factor of the order of 10^4 . It is, of course, difficult to prove that nuclear and particle physics are a kind of “high energy chemistry” – neither can anybody be sure that we will ever find the high energy equivalent of the simple hydrogen atom.

Most physicists would, however, agree that what we call elementary particles hardly deserve this name. They are complicated structures which at the moment we can describe only by means of certain form factors, usually rather poorly known,

*Visiting Brookhaven National Laboratory, June 1964 – January 1965.

and a number of internal degrees of freedom: the isotopic spin, the strangeness, etc., whose origin and meaning are still mysterious. Moreover, the approximate conservation laws of the isotopic spin, the strangeness, and the $SU(3)$ symmetry are very different from the exact conservation laws which obtain in a simple and closed theory like quantum electrodynamics. Perhaps they are, in some sense, similar to the approximate conservation laws which are valid for composite systems like the conservation of the total intrinsic spin for atoms.

In the last few years the possibility has often been suggested² that all particles are composite structures built from a few massive fundamental particles. At the moment, there is no experimental evidence for the existence of these particles. However, the validity of the $SU(3)$ scheme suggests that particles with entirely new properties may indeed exist. They would belong to the fundamental representations of $SU(3)$ which at present do not seem to occur in nature, a fact not easy to explain. Indeed, up to now, we have been used to seeing the lowest representations of a symmetry group realized in nature: this is true for the Lorentz group, for the $SU(2)$ group corresponding to charge independence, for the group $SU(4)$ of Wigner's supermultiplet theory, etc. Gursley, Lee, and Nauenberg² have also pointed out that the existence of massive fundamental triplets could explain the validity of the Okubo-Gell-Mann mass formula and perhaps also of other approximate conservation laws.

Assuming these fundamental particles to exist, it is not at all impossible that the laws they satisfy could turn out to be simple, though possibly radically different from those we have learned in quantum electrodynamics. It would thus be understandable why our present-day composite particles cannot be described in simple terms and do not obey simple laws, as they would be regarded as complicated structures with which simple laws are not usually associated. The discovery and the study of this subelementary world would certainly have far-reaching consequences. The proof of its nonexistence would equally be of the greatest theoretical interest by giving us the assurance that we have reached the core of matter and know all its elementary constituents. Neither of these conclusions can probably be obtained with energy available from the CERN or Brookhaven accelerators, and, even if the new particles could be observed in cosmic rays, their detailed study would require production in the laboratory.

It is clear that what I have discussed here is only one of the possible results that could conceivably be produced by a super high energy accelerator. A machine capable of accelerating protons to an energy of a few hundred GeV will certainly allow investigation of weak interactions in a far more complete way than is possible today, and will probably also shed new light on the validity of quantum electrodynamics by providing energetic γ -ray beams obtained from π^0 decay. Prediction is, however, a risky business: when the plans were made 12 years ago for the present Brookhaven and CERN machines, few people would have predicted that one of the most important results would be the finding of a second neutrino and the beginning of the understanding of the weak interactions.

The main justification for building a super high energy machine is, therefore, the importance of continuing the search for the unknown which is, by definition, unpredictable. This search, and not the practical advantages which arise from it,

remains the ultimate motivation of science: it would be very sad if the lack of the necessary experimental tools should put an end to this search in an area which has produced so many fundamental results and where so much has still to be learned.

REFERENCES

1. M. GELL-MANN, *Phys. Rev.* **125**, 1067 (1962); Y. NE'EMAN, *Nucl. Phys.* **26**, 22 (1961).
2. M. GELL-MANN, *Phys. Letters* **8**, 214 (1964); G. ZWEIG, CERN preprint (1964); F. GURSEY, T.D. LEE, AND M. NAUENBERG, *Phys. Rev.* **135**, B467 (1964); T.D. LEE, *Nuovo Cimento*, to be published; H. BACRY, J. NUYTS, AND L. VAN HOVE, CERN preprint (1964).

Some “Less Spectacular” Experiments in High Energy Physics

J. J. SAKURAI
University of Chicago

This note will be concerned with high energy physics experiments that are not likely to be mentioned by other theoreticians. I am, of course, in favor of experiments designed to look for metastable (or even stable) “fundamental triplets” and the W boson at high energies, *precise* high energy neutrino experiments (elastic, inelastic, strange particle production) which, I believe, are possible only in a huge hydrogen (or deuterium) bubble chamber, colliding e^+e^- beam experiments to study $e^+e^- \rightarrow J=1^-$ states, experiments to test CP invariance in high energy neutrino experiments and in $K_{\mu 3}$ decay, etc. But since the importance and urgency of these “spectacular” experiments are universally recognized by most high energy physicists, this discussion will be limited to somewhat less glamorous experiments.

Recent bubble chamber experiments have provided very rich spectra of strongly interacting states called hadrons (following Okun). With the advent of the eightfold way some progress has been made in the classification of the old and new hadrons. However, there are still a number of “orphans” with no unitary partners in sight. For instance, where are the unitary partners of A_1 (1090), A_2 (1310), B (1215), $K\pi\pi$ (1215), etc.? Where are the Ξ^* 's that correspond to the series of N^* 's recently discovered in total cross section measurements? Moreover, some higher symmetries predict more particles; for instance, $SU(3) \times SU(3)$ requires a scalar octet and an axial vector octet for which there is no evidence. In the future there will undoubtedly be still more “bump hunting” physics.

To the extent that these newly discovered hadrons have strong couplings with older and more familiar hadrons, it is equally important to study their production mechanisms once their quantum numbers are firmly established. One very striking feature of production processes is that they are very peripheral. As is well known, various decay angular correlations can be used to deduce the type of meson exchange (e.g., 0^- vs. 1^- exchange) in a given reaction. Because this simple-minded meson exchange picture seems to work in a surprising number of cases, we are in a very fortunate position to study the structure of various strong interaction vertices. For instance, it is now known from the study of

$$K^+ + p \rightarrow N_{3/2}^{*++} (1240) + K^0 \quad (\text{via } \rho \text{ exchange})$$

that, although the most general $\bar{N}N_{3/2}^*\rho$ vertex involves 4 arbitrary amplitudes, this vertex is dominated by the unique combination of amplitudes expected on the basis of ρ -photon analogy. In spite of the partial success of meson exchange, for the study of strong interaction vertices in a *quantitative* way, much better data are needed than are currently available.

Recently it has been recognized by a number of theoreticians that simple meson exchange amplitudes must be corrected to take account of absorption in competing channels, especially at high energies. To verify theoretical predictions based on single-particle exchange with such unitarity corrections, again much better data are needed than are available at present.

Concerning the decay modes of the newly discovered mesons, first, consider $\eta \rightarrow \pi\pi\pi$. It is not clear at this moment whether the matrix element for this decay mode is enhanced by the existence of a $T = 0$, $J = 0^+$ meson (σ). If the σ meson exists, σ enhancement may be expected not only in η decay but also in X^0 (960) decay, τ decay, and especially K_{e4} decay. It appears that much better data are needed on η decay and K_{e4} decay really to prove the existence of the σ meson.

The radiative decays of ρ , ω , and ϕ (e.g., $\rho \rightarrow \pi + \gamma$, $\omega \rightarrow \pi + \pi + \gamma$, etc.) are also of considerable importance. Take the $\rho\pi\gamma$ vertex, for instance. It is amusing to note that this vertex appears in several places in particle physics, low energy photopion production (via ρ exchange), high energy photo- ρ production (via π exchange), π^0 decay, etc. The strength of this vertex is highly controversial; there have been estimates on the strength of this vertex determined from $\gamma + p \rightarrow p + \rho^0$ (via π^0 exchange) which differ by two orders of magnitude from the strength deduced from π^0 decay using the ρ dominance model:

$$\begin{array}{c} \pi^0 \rightarrow \rho^0 + \gamma \\ \quad \downarrow \\ \quad \gamma \end{array}$$

Obviously the best way to settle this difference is to determine *directly* the branching ratio

$$\frac{\rho \rightarrow \pi + \gamma}{\rho \rightarrow \pi + \pi}.$$

The leptonic (e^+e^- and $\mu^+\mu^-$) mode of the vector meson is of considerable interest. Qualitatively the very existence of the leptonic mode proves that the vector meson plays a substantial role in the electromagnetic form factor of hadrons. Quantitatively the ratio

$$\frac{\Gamma(\omega \rightarrow e^+e^-)}{\Gamma(\phi \rightarrow e^+e^-)}$$

directly measures the $\omega\phi$ mixing angle, provided that the electric charge operator does not have a unitary singlet component.

So far no experimental data on the leptonic decays of strongly interacting particles contradict the Cabibbo theory based on $SU(3)$. However, the agreement obtained so far does not exclude the possibility that the success achieved is accidental. It is important to see whether the V/A ratio in $\Sigma^- \rightarrow n e^- \bar{\nu}$ and both the decay rate and the V/A ratio in $\Xi^- \rightarrow \Lambda e^- \bar{\nu}$ fit into the predictions of the Cabibbo theory.

As for the hadronic (nonleptonic) decays of hyperons, the old question of whether $\Sigma^- \rightarrow n \pi^-$ is predominantly S or P is of great interest since most theories based on $SU(3)$ predict that this must be an S -wave decay.

The Future Role of High Energy Physics in Interaction With Other Parts of Physics

L.I. SCHIFF
Stanford University

The best evidence for the great scientific importance of high energy physics is the large number of first-class physicists who are devoting their research efforts to this field. There is general agreement among working physicists, both high energy specialists and others, that this is a frontier area in which knowledge is incomplete at best and often fragmentary, and that continued progress can be expected for many years to come.

High energy physics research has also become extremely expensive, both in money and in manpower. It appears to be one of the two areas of research (the other being oceanography) that are by large margins the most expensive in any scientific discipline. This, too, is likely to continue, with future projects dwarfing existing ones that are already unprecedentedly large. No doubt this is the reason that comments on interactions with other parts of physics are being solicited from me and others.

In my opinion, there are two important kinds of interactions: those that stem from the scientific prospects of high energy physics, and those that stem from its size *per se*. The former are of course the more interesting, but the latter unfortunately cannot be ignored. In this second category, certain cautions must be observed if all of physics, including high energy physics, is to continue to progress. For one, as was pointed out by V. Fitch and M. Goldhaber in a round-table discussion last April (*Physics Today*, November 1964), provision must be made for university faculty and graduate students to participate in research at distant high energy physics laboratories with a minimum disruption of their own academic affairs and those of their colleagues and students. At the same time, it must be remembered that high energy physics is only one of several equally interesting parts of physics, in spite of its overwhelming size. The unity of research and teaching in all parts of physics, firmly based in the university physics department, must not be irreversibly damaged by hastily considered solutions to the very real problems that exist.

Returning to the first category of scientific interactions, I will mention only three examples among the many that could be cited. A link between high energy physics and cosmology may be provided by attempts to account for the two-pion decay mode of the K_2^0 meson in terms of a long-range field of cosmological origin. Similar considerations will certainly play a role in the discussion of related high energy phenomena which may be discovered in the future, for it is probably only through a modification of the weak interaction that any local effects of cosmological origin could be established. The other two examples link high energy and low temperature physics. On the technological side, there is now an excellent prospect for construction of a superconducting linear electron accelerator. Such an accelerator

would have a greatly improved duty cycle and might even be operated continuously, which would eliminate the principal disadvantage of this type of machine. On the scientific side, it seems likely that independent evidence on CP violation and the intermediate boson will come from a measurement of the electric dipole moment of the He^3 nucleus. Such a measurement now seems feasible within the next year or so, thanks to the recent discovery of the quantization of the magnetic flux that links a multiply connected superconductor.

Comments on Very High Energy Elastic Scattering

S.B. TREIMAN
Princeton University

Every step upward in accelerator energies has revealed, so far, significantly new aspects of the structure of matter, a structure which appears increasingly to be very rich and complex. The patterns that have already emerged go some way in suggesting new directions of research. But the very steepness of the slope of discovery with energy suggests that further increases in energy will prove to be rewarding in ways which cannot now be foreseen.

Higher energies can serve to reveal structures (stable particles, resonances, etc.) of higher mass. In this direction, it is clear from recent experience that we are surely still far from an end. Indeed, there may not be "an end." But then the issue is whether the multitude of particles and resonances already known are sufficiently representative to outline the essential features of the structure of matter. The answer is, almost surely not. Indeed, according to certain current ideas, we have so far been observing what is in effect only the low-mass fine structure of a spectrum which has a much larger scale of mass.

If distinctive structures ("particles") are one aspect in the search for understanding of matter, another is the nature of their mutual interactions, as revealed in collision processes. High energy collisions lead to final states of varying sorts, characterized by particle types, multiplicities, energy and angular distributions, etc. Not surprisingly, attention so far has centered mainly on the simplest (few-body) channels, where measurement and theoretical speculation can still hope to encompass something like the full range of detail. For the many-particle channels, however, the range of detail becomes overwhelming, and the problem is one of discovering significant over-all patterns against a background of less significant detail. Here it can be argued, in analogy with other branches of physics, that understanding is more likely to emerge from the study of truly high multiplicity phenomena rather than from those of intermediate multiplicity. But this view of course entails very high energies.

The main purpose of this note, however, is to emphasize the importance of very high energies for the study of the simplest reactions, elastic scattering. There are several reasons why high energy elastic scattering is interesting, even though the elastic channel is only one of many channels which are opened up at high energies. In the first place, elastic scattering (together with other two-body final-state processes) is kinematically the simplest kind of reaction possible; and it will therefore continue to figure as a pre-eminent testing ground for new theoretical ideas on fundamental particle dynamics. A number of these ideas hinge critically on the properties of elastic scattering in the limit of very high energies.

In recent years physicists have come to attach special importance to the study of the analytic structure of S -matrix elements. This structure is bound to be simplest,

therefore most directly testable, for the two-particle $\rightarrow$ two-particle amplitudes. Two other far-reaching principles, unitarity and crossing symmetry, also take on their simplest forms here. The consequences of these principles are most dramatically apparent in the so-called dispersion relations for forward elastic scattering, say for pion-nucleon reactions. These relations, which connect quantities which are in principle physically measurable, rest on very general and deep principles, notably, on the principle of causality. It is of major importance that the experimental test of the dispersion relations be extended to the very highest attainable energies. In fact, strictly speaking, *any* test requires knowledge of the total cross section at *all* energies.

There is another respect in which the elastic scattering channel stands out in significance even at high energies where it is but one of many open channels. This has to do with unitarity (the optical theorem), according to which the imaginary part of the forward elastic amplitude reflects in a simple way the influence of *all* the other open channels. Even for non-forward scattering, in the diffraction region, the elastic amplitude carries more or less directly useful information bearing on all other channels. Indeed the whole phenomenon of diffraction makes elastic scattering uniquely informative, and especially at high energies. What is the size of the diffraction peak? How does it vary with energy? Etc.

An important over-all question is whether elastic amplitudes display simple limiting behavior as the collision energy grows very large. There are indications in this direction from present evidence, and a great deal of theoretical superstructure is concerned with such asymptotic properties. The point is, of course, that the discovery of simple asymptotics would provide theoretical tie-points of major significance. Let us recall some of the issues.

Consider the elastic reaction $a + b \rightarrow a + b$ and, along with it, the "crossed" reaction $\bar{a} + b \rightarrow \bar{a} + b$, where $\bar{a}$ is the antiparticle of a . For all processes so far studied in sufficient experimental detail, it appears on present evidence that *total* cross sections are trending with energy to finite, non-vanishing limits. This is perhaps intuitively reasonable, but the discovery, if true, is no less important for that. One could imagine that the cross section, even though bounded, has no definite limit; or that it vanishes in the limit of infinite energy. On the theoretical side, certain fairly weak assumptions about the analytic properties of scattering amplitudes lead to the result that the total cross section cannot grow more rapidly than $(\ln E)^2$, where E is the energy. More specific assumptions, of the Regge pole sort, lead to an asymptotic behavior of the form $\sigma \sim E^{\alpha-1}$, with $\alpha \leq 1$. These ideas have lately run into difficulty. But the question remains, do cross sections really approach constants? As Pomeranchuk has shown, on the basis of the dispersion relations taken together with other reasonable assumptions, if the total cross sections for a given reaction and its crossed reaction approach constant limits, then these limits must be identical. Again, present evidence is trending in this direction, especially for $\pi^\pm$ - p and $K^\pm$ - p collisions, less obviously for p - p and $\bar{p}$ - p collisions.

It also follows from Pomeranchuk's arguments that the ratio of the real to the imaginary part of the forward elastic amplitude must vanish asymptotically if the total cross section approaches a limit. However, recent evidence indicates that, even at the highest energies currently available, the real amplitudes may not be so negligible. In general, it seems that we are now only at the threshold for the study of

asymptotics. Do the simplifying properties now only hinted at really hold up? And, if so, in what manner are the asymptotes approached? A big step forward in energy seems essential.

Other questions concern the ratio of elastic to total cross section as a function of energy. Present evidence suggests that this ratio is at most a very slowly varying function of energy, at high energies. On some theoretical views, the ratio must vanish logarithmically with increasing energy. A related matter concerns the asymptotic energy dependence of the width of the diffraction peak. Insofar as the scattering is purely absorptive, one can set, by unitarity considerations alone, an upper bound on the width, for given total and elastic cross sections. Interestingly enough, this bound is very nearly saturated at the highest present energies for the various reactions studied in sufficient detail. Will this persist at higher energies?

Perhaps the most striking, and unheralded, development of all concerns the behavior of the elastic scattering cross sections at large angles and high energies. The rate of fall-off with angle is initially sharp, but, for p - p scattering at any rate, the variation with angle eases off near 90° . However, the variation with energy for fixed large angle is very sharp, something like a decreasing exponential function of energy. Is this describable by a statistical model? It is interesting that, from simple analyticity assumptions taken together with unitarity, one can show that the large-angle cross section *cannot* fall off faster than $e^{-C(E \ln E)}$ where C is a constant, which, apart from the logarithm, is the form actually seen. That is, a theoretical bound is once again not far from the observed situation.

Finally, it is important to consider how the various characteristic features of scattering compare as between one process and another – total cross section, width of diffraction peak, etc. There are indications that the relationships become simple at high energies. Thus the ratio of elastic to total cross sections seems roughly similar for the various reactions studied at the highest available energies. Also the momentum transfer dependence seems to scale roughly in the same way for various processes when momentum transfer is measured in units of the inverse of the forward differential cross section. Much can be explored at energies now available, but the real test of ideas will have to depend on measurements carried out over a much wider range of energies.

A Comment on the Motivation For Studying Elementary Particle Physics

KENNETH M. WATSON
University of California, Berkeley

The diversification and expense of doing research seems to keep well apace of the continuous increase of human collective knowledge and consequently threatens to challenge the capacity of even the richest of national treasuries. As scientists we are thus finding ourselves in a position of competing ever more vigorously with our colleagues in other fields to obtain support for our research. We may hope, but not necessarily anticipate, that allocation of research funds can be decided more rationally than through lobbies, mink coats, and deep freezes. (There is a current saying among government supporters of research that scientific research is the only pork barrel for which the pigs determine who gets the pork.)

To comment on a proper division of emphasis among the branches of science is not a task to be undertaken lightly – and, indeed, I shall avoid this to argue only that elementary particle physics deserves its spot in the market place.

The principal appeal of the so-called nonapplied branches of science must, I think, remain to our curiosity. In this context elementary particle physics and cosmology have a somewhat unique feature: We do not know the basic laws governing the phenomena being studied. This contrasts with such fields as geology, oceanography, atomic physics, and presumably biology, where known physical laws are applicable, but the wealth of detail leaves the phenomena only partially understood. The laws of physics, as at present understood, do not tell us if they are uniquely self-determined or how the universe was formed. They do not tell us what are the smallest intervals of space and time that have significance. They do not tell us what particles remain to be discovered, or even if this question has meaning (the term “particle” may be too unprecise).

It is currently felt by theoretical physicists that the answers to such fundamental questions (except perhaps the cosmological ones) may be found in the study of “elementary particle physics.” Among the most optimistic it is hoped that the basic laws of physics will be uniquely implied by a few symmetry principles, such as that of relativistic invariance (the isotropy and homogeneity of space and the notion that all inertial systems are equivalent). According to this point of view the particles that can exist and the interactions among them would then also be uniquely implied. From this, in turn, the properties of macroscopic physical systems – i.e., our everyday world – could be deduced and the universe might be “understood.”

Evidently our present understanding falls far short of this happy goal. To study these fundamental phenomena experimentally we seem to need ever larger and more expensive particle accelerators – and these have shown an ever increasingly complex and strange array of structure on a microscopic scale that recedes farther and farther from the scale of macroscopic experience. Our notion of “what a parti-

cle is” remains vague and unprecise, as does our notion of microscopic space and time intervals.

The large and elaborate particle accelerators represent the only tool known for practical study* of these remote, and presumably very fundamental, phenomena. That such large and cumbersome devices are needed to investigate such microscopic phenomena is a little disturbing. Indeed, the experiments performed with such machines to study fundamental laws seem a little like building freeways to study the chemical properties of concrete. To a certain extent, the phenomena observed may reflect the artistic ability of the experimenter rather than just basic laws. To develop this point further, let us recall that the “particles” fall into two classes. The first are the *stable particles* (such as the electron and proton), which will last indefinitely when isolated from other particles. The second class are the unstable particles (such as neutrons and π mesons), which when left alone will spontaneously break up into other particles (which in turn may or may not be stable). The difference between the two kinds of particles may be illustrated by an analogy from communications engineering: The stable particles may be represented by pure sine waves, whereas the unstable particles are represented as transient signals, which may be constructed from a superposition of sine waves. (In the language of quantum mechanics the unstable particle can be described by a wave packet.)

An important distinction between the stable and unstable particles becomes plausible from this analogy. So far as we know all particles of a given stable species are identical – while this is not the case for unstable particles. An unstable particle must be assembled by explosively concentrating energy in a small volume of space over a short time interval. In fact, this concentration of energy within a definite, small volume of space is the property to which we give the name “particle.” Since it is not feasible exactly to duplicate the process of formation, we conclude that never can we make two identical unstable “particles.” (Thus, for example, no two neutrons are quite identical; however, in this case the differences would be hard to detect experimentally.)

The practical usage of the term “particle” is usually arbitrarily restricted to concentrations of energy** which hold together for a “sufficiently long time.” This is admittedly not at all precise, and it may turn out that at higher and higher energies there is no useful distinction between long and short times for energy to hold together. (We are reminded of our freeway builder, who will find that some designs will give longer lasting freeways than others. This reflects physical properties of concrete, but not necessarily in the most direct manner.)

I emphasize the unstable particles, since it is largely to study these that accelerators are built. It is not very surprising that a machine designed to build freeways will build freeways. It would be surprising if it made anything other than freeways. It is perhaps unfortunate that to give up now the study of particle physics with accelerators, in the absence of a substitute tool, would mean that we, as human beings, were stopping the quest for an understanding of the most fundamental properties of our environment.

*High energy cosmic-ray particles, accelerated in the far reaches of space by natural processes, are too rare to provide adequate tools for these studies.

**Ordinarily associated with this are momentum and angular momentum, sometimes electrical charge, etc.

Why Build Accelerators?

STEVEN WEINBERG

University of California, Berkeley

Scientists generally show a wise reluctance to debate the importance of their own specialities in public. However, the increasing cost of experiments in high energy nuclear physics has led to some questioning of the necessity of building further accelerators. It may therefore be appropriate at this time for physicists to share their thoughts on the importance of new accelerators to elementary particle physics, and on the importance of elementary particle physics to the whole of science.

The first point is clearly one which the lay and scientific public must ultimately accept on the authority of the particle physicists. However, it may be useful to point out one instance of the value of large accelerators; this example is certainly not the most important that could be found, but it illustrates nicely how the progress of particle physics is shaped by the ordnance available in the arsenal of the experimentalist.

A recent Brookhaven experiment¹ on the weak interactions of neutral K mesons seems to have provided evidence that nature does not in fact possess symmetry under what had been thought to be one of her most cherished transformations, the simultaneous interchange of particles and antiparticles (C) and of right and left (P). Both field theory and S -matrix theory agree that nature must be invariant under CPT , the simultaneous transformation by C , P , and time reversal (T). Hence if CP goes out the window, T must follow it. But then we may wonder why T -violation effects have not shown up in the fairly accurate low energy experiments² on neutron β decay.

In order to make sense of this situation, it has been suggested³ that CP and T violation in β decay takes place in a very specific way. We may presume that we know how the weak interaction currents behave under the operation of charge symmetry (R), which interchanges protons and neutrons. But then the part of the weak interaction that conserves CP will behave normally under RCP , and the part that changes sign under CP will undergo an extra sign change under RCP . Some years ago it was pointed out⁴ that the ordinary coupling constants of low energy β decay receive contributions only from the "first-class" currents, which behave normally under RCP ,* while any RCP -abnormal "second-class" currents can contribute only to certain exotic first-forbidden matrix elements proportional to the momentum transferred to the electron and neutrino. Hence we do not see the effects of CP or T violation in neutron decay simply because the momentum transfer is too low.

How can this suggestion be tested? The momentum transfer in β decay is never greater than about 15 MeV, probably too low for second-class effects to be seen. (Coulomb forces in heavy nuclei tend to turn off charge symmetry, but the imaginary parts thereby developed by the coupling constants are probably still quite small.)

*Recall that RC is the symmetry usually called G .

Muon capture has a momentum transfer of 100 MeV, but it does not seem to afford any practical test of CP or T invariance. We are naturally led to the unique weak interaction process for which the momentum transfer can be made as large as we like: inverse β decay produced by energetic neutrinos. A violation of T invariance would show up as a non-zero expectation value of the triple scalar product of the muon and neutrino momenta and the muon polarization. This expectation value would be proportional to the interference between the first- and second-class currents, and hence to the momentum transfer. What we want, then, is to be able to pile up sufficient statistics on the decay of muons after their production by neutrinos at high energy and wide angle. This is a formidable task, requiring a neutrino beam of an energy and intensity which may be outside the capabilities of the existing large accelerators at CERN and Brookhaven. If larger machines existed now, we would already have definite information on the CP and T invariance of elementary particle physics. It also may be worth stressing that without the Brookhaven AGS we would not have suspected that CP and T might not be conserved.*

Who cares? Macroscopic phenomena will continue to be governed by an irreversible increase of entropy whether or not the weak interactions are time-reversal invariant. Are the symmetries of elementary particle physics just one more interesting area for scientific study, neither more nor less important than any other?

I believe that such questions must be answered on the assumption that nature has absolute laws** of great simplicity, from which all the sciences flow in an ordered hierarchy. Thus, working backward, the nervous system has evolved as it has because of certain facts of chemistry and classical physics, which themselves follow from the ordinary quantum mechanics of nuclei, electrons, and photons, which itself follows from – what? *All* scientists accept this ordering as a tool in their work – for instance, the biologist discovers laws governing life which are stated in purely biological terms, but (ever since the synthesis of urea) he is quick to reject any hypothesis which could not possibly have a basis in the physical sciences further up the hierarchy.

It is generally recognized that the sciences furthest up this hierarchy at present are elementary particle physics and cosmology.† The discovery that next moves us closer to the ultimate laws of nature will almost certainly be made in one (or hopefully both) of these two fields. For this reason particle physics and cosmology have an intrinsic interest not shared with any other science; we are interested in the structure of DNA because we are alive ourselves; we are interested in phase transitions because they are a challenge to calculate and have practical importance; but we are

*If it is confirmed that CP is violated in K decay, and if all experiments fail in finding any T violation in weak interactions, we may find ourselves forced to save T by abandoning CPT . The consequences would be stupendous.

**I do not necessarily wish to imply that we can expect to find a finite set of ultimate physical truths within the next few centuries (though I happen to believe we shall). It may be that we shall discover an infinite regress of more and more fundamental sciences, or even that we shall pass outside the bounds of science itself to some new mode of thought which we can now no more imagine than Plato could conceive of the modern scientific method. In any case, not only scientists will be interested to see what happens.

†For brevity I use the term “particle physics” to mean all of high energy nuclear physics, including field theory and S -matrix theory. Similarly, under “cosmology” I include general relativity and much of modern astrophysics.

interested in the question of time-reversal invariance because it brings us as close as now possible to the absolute logical structure of the universe. It is a pity that new accelerators and telescopes happen to be expensive, but not to build them would mean that science must renounce the highest of its objectives, the discovery of the laws of nature.*

Instead of feuding with one another for public favor, it would be fitting for scientists to think of themselves as members of an expedition sent to explore an unfamiliar but civilized commonwealth whose laws and customs are dimly understood. However exciting and profitable it may be to establish themselves in the rich coastal cities of biochemistry and solid state physics, it would be tragic to cut off support to the parties already working their way up river, past the portages of particle physics and cosmology, toward the mysterious inland capital where the laws are made.

REFERENCES

1. J.N. CHRISTENSON, J.W. CRONIN, V.L. FITCH, AND R. TURLAY, *Phys. Rev. Letters* **13**, 138 (1964).
2. M. J. BURGY, V.E. KROHN, J.B. NOVEY, G.R. RINGO, AND V.L. TELEGDI, *Phys. Rev. Letters* **1**, 324 (1958).
3. N. CABIBBO, *Physics Letters* **12**, 137 (1964).
4. S. WEINBERG, *Phys. Rev.* **112**, 1375 (1958).

*One sometimes encounters the puritanical opinion that a failure to build the next generation of accelerators will be compensated by an increased cleverness in the use of theory, string, and sealing wax. But the decades of stagnation in the study of gravity show what must happen to even the most exciting subject without the pressure of new data.

Some Considerations Concerning Very High Energy Experiments

C.N. YANG

The Institute for Advanced Study

I. Why is high energy physics worthy of large public support? To answer this question one would be missing the point if one merely stated, in no matter how many words, that high energy physics is an exciting science. In fact the public does not seem to challenge the validity of this statement at all, only its relevance. Some congressmen, for example, have been reported by the newspapers to say that “scientists’ curiosity is insatiable,” implying (I believe quite correctly) that intellectual curiosity is fine, but by itself is not enough to justify large public support.

To answer the question why high energy physics is worthy of large public support, one will have to demonstrate why high energy physics is not just an intellectual exercise. This demonstration is not difficult to make and rests, I believe, on three very solid grounds.

First, high energy physics studies the fundamental structure of matter, out of which the physical and biological world around us is built. It represents the natural continuation of the brilliantly successful tradition in physics to study the structure of macroscopic matter, of molecules, of atoms, and of nuclei. While one may raise the question whether knowledge gained in such studies has invariably benefited mankind, one cannot possibly deny that high energy physics seeks knowledge that is of supreme importance in the eternal interaction between man and his surroundings, an interaction that is a major part of human history.

Second, the search for an understanding of the fundamental structure of matter has in the past served as a fountainhead of new concepts, and new principles, upon which the whole of physics and various branches of physical sciences were built. The development of the special theory of relativity and of quantum mechanics has in fact even left deep impacts on man’s philosophical thinking. In their present struggle with phenomena of very high energies and very small distances, physicists investigate the basic structure not only of matter but also of space-time, of energy, and of the electric charge. True progress in this search would produce a profound reorientation in the very foundation of the field of physics, and with it, the whole of the physical sciences.

Third, it is always difficult to foretell what are the prospective technological consequences of scientific inquiry. However, generally speaking, we have the examples before us of the solid state physics industry which is a direct offspring of the physical inquiry into the electronic structure of atoms, molecules, and solids. We have the example of the nuclear energy program which is a direct offspring of the physical inquiry into the structure of nuclei. We are clearly at the beginning of a new era of sophisticated technology where man begins to manipulate smaller and smaller units down to atomic and subatomic sizes. Such technology is still in its

infancy. Its further development will require increasingly more sensitive and more subtle *control*. High energy physics, in studying the most minute distances and the shortest time intervals, should be expected to serve as a source of new ideas and new stimulation that will be essential in such technological developments.

II. We shall now discuss a few problems that can already be more or less precisely defined today that would require a very high energy accelerator for their resolution, fully aware of the fact that most of the problems that such an accelerator will investigate, say, ten years from now, are not formulable today.

1. One very important problem is the meaning of the symmetry of the strong interactions. On the one hand, there exist a striking number of confirmations of the idea that strong interactions observe approximately $SU(3)$ symmetry (included in this category are multiplet structure, Cabbibo's discussion of the weak interactions, mass formula, electromagnetic mass splits, and magnetic moments). On the other hand, there is obviously very large symmetry breaking, and there is every evidence that peripheral collisions predominate at high energies and these collisions do not obey $SU(3)$ symmetry. One is thus faced with the question of the meaning of $SU(3)$ symmetry, when it is applicable and when it is not applicable. In particular, the strong peripheral collisions clearly contribute in an important way to the mass of the particles. Now, peripheral collisions due to π exchange and K exchange do not observe $SU(3)$ symmetry. It is thus very difficult to understand how arguments based on symmetry, such as the derivation of the mass formula by perturbation calculation, could be as good as they empirically seem to be.

To solve these difficulties, experiments concerning high energy, large momentum transfer reactions must be performed. In other words, very small distance interactions will have to be examined. (The problem of extracting information about very small distances from high energy, large momentum transfer experiments is not yet solved. But such information is necessary for an understanding of the meaning of symmetries.)

2. Recent CERN experiments have shown that the intermediate boson W , if it exists, has a mass greater than 2 BeV. It is very difficult with the present accelerating machines to investigate the possible existence of W with a mass greater than 2 BeV. Since the existence of W remains an attractive idea concerning the weak interactions, especially concerning the conserved vector current, it is desirable to construct accelerators reaching higher energies to explore the possibility of heavier W masses.

3. It has recently been reported^{1,2} that CP invariance is not observed in the weak interactions. This extremely important result indicates that the weak interaction is once again a source of surprise to the physicists, as Niels Bohr once described it to be. CP noninvariance introduces new complexities into our understanding of the weak interactions, and we must explore it in greater detail. A number of experiments have been suggested in this connection. They can be performed with existing machines. However, increasing complexity of our description of the weak interactions indicates that we are still far from a simple synthesis of the origin of the weak interactions. It seems imperative that phenomena at higher energy be investigated in the hope that such a synthesis might be achieved through studies in the higher energy domain.

REFERENCES

1. J.H. CHRISTENSEN, J.W. CRONIN, V.L. FITCH, AND R. TURLAY, *Phys. Rev. Letters* **13**, 138 (1964).
2. A. ABASHIAN, R.J. ABRAMS, D.W. CARPENTER, G.P. FISHER, B.M.K. NEFKENS, AND J.H. SMITH, *Phys. Rev. Letters* **13**, 243 (1964).

*3. More Technical
and Detailed
Considerations*

Towards a Unified Field Theory of Elementary Particles*

R.E. MARSHAK AND S. OKUBO
University of Rochester

1. LIST OF PARTICLES

The usefulness of the concept of elementary particles depends very much on the state of knowledge at the time, the hierarchy of interactions with which one is dealing, and the order which is introduced into the description of the empirical facts. From one point of view, that of representations of the Lorentz group, any particle with a well-defined mass and spin is an elementary particle, and in this context even a molecule could be regarded as elementary. However, when the electromagnetic law of force was established between the atoms in a molecule and also between the electrons and the positively charged nucleus of the atom, it was more convenient at that stage to think of the electron and the various types of atomic nuclei as the elementary particles. When quantum mechanics was developed and the wave-particle dualism became an essential ingredient of our understanding of all atomic phenomena, it was proper to add the photon to the list of elementary particles out of which atomic nuclei are built up. Within this framework, for example, the completely stable deuteron with a well-defined mass and spin is considered a composite structure, whereas the unstable neutron is treated as an elementary particle. The reason for this anachronistic point of view is that within the hierarchy of medium strong (nuclear), electromagnetic, and weak interactions, the neutron lives for a very long time (10^3 sec) on a nuclear time scale of 10^{-23} sec.

The situation is even more curious. If the field is restricted to atomic physics and stable atomic nuclei (at least within our galaxy), the only elementary particles which enter the picture are the electron, proton, neutron, and photon. Even if the horizon is enlarged to include the unstable atomic nuclei, only the neutrino, anti-neutrino, and positron need be added. It is only when some of the above particles acquire sufficient kinetic energy (either as components of the cosmic radiation or in high energy accelerators) that many new varieties of particles are created which, at this stage of our understanding, are added to the list of elementary particles. Some of these particles, which result from the conversion of kinetic energy into mass, in turn create new particles through decay or through secondary production.

As a result of a great deal of experimental work during the past 25 years, much of it done during the last 5 years, a large number of particles and antiparticles have

*This article contains a considerable amount of background material (particularly the tables) which can be used in reading some of the other contributions to this volume. In order to avoid misunderstanding, it should also be pointed out that while attention has been focused here on the symmetry principles underlying a unified theory of the strongly interacting particles (hadrons), the success of the complete theory will be judged by its ability to make correct dynamical predictions and to explain the properties and interactions of the nonhadronic particles as well (see section 3).

Table 1

List of Particles

Particle	Anti-particle	J^P	Mass (MeV)	Charge No., Q	Baryon No., B	Hyper- charge, Y	Stability (S=stable) (U=unstable)
GAUGE PARTICLES							
γ	(γ)	1^-	0	0	0	0	S
LEPTONS							
ν_e	$\bar{\nu}_e$	$\frac{1}{2}$	0	0			S
ν_μ	$\bar{\nu}_\mu$	$\frac{1}{2}$	0	0			S
e^-	e^+	$\frac{1}{2}$	0.511006 ± 0.000002	-1			S
μ^-	μ^+	$\frac{1}{2}$	105.659 ± 0.002	-1			U
HADRONS (MESONS)							
π^0	(π^0)	0^-	135.01 ± 0.05	0	0	0	U (EM)
π^+	π^-	0^-	139.60 ± 0.05	1	0	0	U (W)
K^+	K^-	0^-	493.8 ± 0.2	1	0	1	U (W)
K^0	$\bar{K}^0$	0^-	498.0 ± 0.5	0	0	1	U (W)
η	(η)	0^-	548.7 ± 0.5	0	0	0	U (EM)
ρ^+	ρ^-	1^-	763 ± 4	1	0	0	U (MS)
ρ^0	(ρ^0)	1^-	763 ± 4	0	0	0	U (MS)
ω	(ω)	1^-	782.8 ± 0.5	0	0	0	U (MS)
$K^{*+}, 0$	$\bar{K}^{*+}, 0$	1^-	891 ± 1	1, 0	0	1	U (MS)
ϕ	(ϕ)	1^-	1019.5 ± 0.3	0	0	0	U (MS)
B^+	B^-	$1^+, 2^-$	1215 ± 18	1	0	0	U (MS)
B^0	(B^0)	$1^+, 2^-$	1215 ± 18	0	0	0	U (MS)
K_c^+	$\bar{K}_c^+, 0$	1^+	1215 ± 15	1, 0	0	1	U (MS)
f	(f)	2^+	1253 ± 20	0	0	0	U (MS)
A_2^+	A_2^-	2^+	1310 ± 15	1	0	0	U (MS)
A_2^0	(A_2^0)	2^+	1310 ± 15	0	0	0	U (MS)
(BARYONS)							
p	$\bar{p}$	$\frac{1}{2}^+$	938.256 ± 0.005	1	1	1	S
n	$\bar{n}$	$\frac{1}{2}^+$	939.550 ± 0.005	0	1	1	U (W)
Λ	$\bar{\Lambda}$	$\frac{1}{2}^+$	1115.40 ± 0.11	0	1	0	U (W)
Σ^+	$\bar{\Sigma}^+$	$\frac{1}{2}^+$	1189.41 ± 0.14	1	1	0	U (W)
Σ^0	$\bar{\Sigma}^0$	$\frac{1}{2}^+$	1192.4 ± 0.3	0	1	0	U (EM)
Σ^-	$\bar{\Sigma}^-$	$\frac{1}{2}^+$	1197.08 ± 0.19	-1	1	0	U (W)
$N_{3/2}^{*+, +, 0, -}$	$\bar{N}_{3/2}^{*+, +, 0, -}$	$\frac{3}{2}^+$	1236 ± 2	2, 1, 0, -1	1	1	U (MS)
Ξ^0	$\bar{\Xi}^0$	$\frac{1}{2}^+$	1314.3 ± 1.0	0	1	-1	U (W)
Ξ^-	$\bar{\Xi}^-$	$\frac{1}{2}^+$	1320.8 ± 0.2	-1	1	-1	U (W)
$\Upsilon_1^{*+, 0, -}$	$\bar{\Upsilon}_1^{*+, 0, -}$	$\frac{3}{2}^+$	1382.1 ± 0.9	1, 0, -1	1	0	U (MS)
Υ_0^*	$\bar{\Upsilon}_0^*$	?	1405	0	1	0	U (MS)
Υ_0^{**}	$\bar{\Upsilon}_0^{**}$	$\frac{3}{2}^-$	1518.9 ± 1.5	0	1	0	U (MS)
$N_{1/2}^{*+, 0}$	$\bar{N}_{1/2}^{*+, 0}$	$\frac{3}{2}^-$	1518 ± 10	1, 0	1	1	U (MS)
$\Xi^{*0, -}$	$\bar{\Xi}^{*0, -}$	$\frac{3}{2}^+$	1529.1 ± 1.0	0, -1	1	-1	U (MS)
$\Upsilon_1^{**+, 0, -}$	$\bar{\Upsilon}_1^{**+, 0, -}$	$\frac{3}{2}^-$ (?)	1660 ± 10	1, 0, -1	1	0	U (MS)
Ω^-	$\bar{\Omega}^-$	$\frac{3}{2}^+$	1675 ± 3	-1	1	-2	U (W)
$N_{1/2}^{***, 0}$	$\bar{N}_{1/2}^{***, 0}$	$\frac{5}{2}^+$	1688	1, 0	1	1	U (MS)
Υ_0^{***}	$\bar{\Upsilon}_0^{***}$	$\frac{5}{2}^+$ (?)	1815	0	1	0	U (MS)
$N_{3/2}^{***+, +, 0, -}$	$\bar{N}_{3/2}^{***+, +, 0, -}$	$\frac{7}{2}^+$ (?)	1924	2, 1, 0, -1	1	1	U (MS)
$N_{1/2}^{****, 0}$	$\bar{N}_{1/2}^{****, 0}$	?	2190	1, 0	1	1	U (MS)
$N_{3/2}^{****+, +, 0, -}$	$\bar{N}_{3/2}^{****+, +, 0, -}$	?	2360	2, 1, 0, -1	1	1	U (MS)

been added to those mentioned above. Table 1 gives the latest count,^a including only those particles that are quite well established (the list can be substantially augmented by particles for whose existence there is only preliminary evidence). In Table 1 the elementary particles are listed under three categories (gauge particles, leptons, and hadrons) in order of increasing mass. The only firmly established gauge particle which is associated with a gauge transformation of the "second kind" is the photon, which is responsible for the electromagnetic interactions; other gauge particles (of both zero and nonzero mass) have been hypothesized (cf. Sakurai²), but no experimental evidence has been adduced for their existence. The photon is a massless, chargeless, $J=1^-$ particle which is completely stable. The particles in the lepton class undergo weak interactions with each other and, if they are charged, interactions with the photon as well. The two neutral leptons (neutrinos) possess zero mass while the two charged leptons (e and μ) have widely different finite masses. All four leptons are spin $\frac{1}{2}$ particles, and the lightest three are stable; the muon is unstable and decays by virtue of its weak interaction with the other leptons. The leptons certainly possess another internal quantum number (in addition to the charge number Q), which has been called lepton number (L), but it is not yet clear whether there are two distinct lepton numbers (L_e and L_μ) or even whether L is a multiplicative or an additive quantum number.

The members of the hadron class comprise two groups of particles, mesons and baryons. All members of the hadron class interact strongly with each other (in addition to interacting with the photon and weakly with the leptons and with each other). The distinction between mesons and baryons lies in the empirical fact^b that mesons possess integral spin whereas baryons are particles with half-integral spin. Examination of Table 1 shows that as of now hadrons have been observed with masses in excess of two nucleon masses, spins as high as $J=\frac{5}{2}$, and charges as large as $Q=2$. The only completely stable hadron is the proton, and all others are unstable by virtue either of their medium strong (MS), electromagnetic (EM), or weak (W) interactions with the other particles. In the column labeled "Stability," MS , EM , or W indicates the type of instability for each of the hadrons. Thus there are at least 100 particles and antiparticles, of which one (the photon) belongs to the class of gauge particles, eight to the lepton class, and the remainder to the hadron class.

2. SYMMETRY PRINCIPLES

We cannot believe, of course, that all the particles listed in Table 1 are equally "elementary." Somehow it must be possible to find regularities in the apparent

^aThe experimental numbers for the particles are taken from a combination of Rosenfeld et al.¹ and the tables distributed at the Twelfth International Conference on High Energy Physics held at Dubna in August 1964.

^bOur terminology is lagging behind the new experimental results; there are now mesons heavier than some baryons so that the term "meson" (intermediate in mass between lepton and baryon) is no longer appropriate. Moreover, there are particles with nonzero baryon number (e.g., the deuteron with $B=2$) which possess integral spin. In the future, we shall no doubt start speaking of hadronic bosons (in contradistinction to the photon) and hadronic fermions (in contradistinction to the leptonic fermions), but in this article we shall stick with the current terminology (cf. Marshak and Sudarshan³).

chaos of Table 1 and to discover the ordering principles which govern the sub-nuclear world. In pursuing this objective, we take a leaf from the book of atomic and nuclear theory where we have learned that the discovery of symmetry principles or invariances under certain types of transformations leads to conservation laws which greatly reduce the multiplicity of processes and states which might otherwise be possible. Indeed, we already know in classical physics that invariance under space and time translations leads to conservation of momentum and energy, respectively, and that rotation invariance leads to angular momentum (J) conservation. In the atomic and nuclear domain, we have learned that when Lorentz invariance is combined with quantum theory, J must have half-integral or integral values, that particles with half-integral spin must be fermions (obey Fermi-Dirac statistics) and particles with integral spin must be bosons (obey Bose-Einstein statistics), and that particles with zero mass can have only two polarizations (no matter what spin they have) whereas particles of finite mass will have $(2J+1)$ polarizations for a spin J . We have had experience with the discrete Lorentz transformations (space reflection P and time reflection T) and the multiplicative constants of motion to which these lead. We have also become familiar in atomic and nuclear theory with certain internal symmetry principles: the discrete charge conjugation operation C and its associated multiplicative quantum number, the charge gauge transformation of the "first kind" and its associated additive quantum number (Q), and the isospin rotation operation (in analogy to ordinary spin rotation) and its associated vector quantum number (I). Finally, atomic and nuclear theory have brought us into contact with another type of invariance principle, invariance under a gauge transformation of the "second kind," which enables the electric charge to play the role not only of an additive quantum number but also as a coupling constant whose magnitude can be directly measured in the presence of an external electromagnetic field. It is invariance of the electromagnetic field under a gauge transformation of the "second kind" which guarantees zero rest mass for the quantum of the electromagnetic field, i.e., the photon.

When we turn to elementary particle physics, it is natural to inquire whether the symmetry principles and invariance laws which obtain in the domain of atomic and nuclear phenomena are applicable and can even be extended, and also whether there are new symmetry principles and invariance laws which manifest themselves on the subnuclear level. This indeed turns out to be the case, except for some qualifications with regard to P , C , and T . To the best of our knowledge, Lorentz invariance as well as invariance under an electromagnetic gauge transformation of the "second kind" still hold in the domain of particle physics. In the atomic and nuclear domain, where we are concerned primarily with the medium strong and electromagnetic interactions, separate invariance under P , C , and T seems to hold. In the particle physics domain, where the weak interactions play an equally prominent role, it was found several years ago that separate P and C invariance did not hold and, very recently, some rather convincing evidence has been obtained that separate T invariance does not hold either.^c

^cThe recent work of Christenson et al.⁴ gives strong evidence for the breakdown of CP invariance; if we continue to accept the CPT theorem (which we shall proceed to do), noninvariance under CP implies noninvariance under T .

The internal symmetry principles have been the richest source of new conservation laws in the domain of elementary particle physics. The concept of isospin has been particularly useful in bringing some semblance of order into the long list of hadron particles. Examination of Table 1 reveals that there are important mass groupings within the hadron class which bear a relationship to the charge numbers. While the nucleon is the most favorable case, with the masses of the neutral and charged members (neutron and proton) separated by 1.3 MeV, there are many other subgroupings of particles which differ by only several MeV in mass and may be regarded as different charge states of the same particle. An isospin I is assigned to each subgrouping of $(2I+1)$ particles, and the slightly different masses of the members of the isomultiplet are then attributed to electromagnetic self-energy effects produced by virtual interactions with the electromagnetic field.^d The concept of isospin in particle physics has a wide use in that the medium strong interactions of all the hadrons are invariant under rotation in isospin space; this is not true of the electromagnetic and weak interactions among the hadrons.

The new internal symmetries which have helped to bring order into the physics of elementary particles include the baryon (B) and hypercharge (Y) gauge transformations (of the "first kind") and, most recently, unitary symmetry. The baryon gauge transformation leads to an absolute conservation law for the additive quantum number B (i.e., absolute in the sense that all known particle processes, whether they are governed by MS , EM , or W interactions, conserve B). Invariance under the hypercharge gauge transformation seems to hold only for the MS and EM interactions (but not for the W interactions) so that the additive quantum number Y is conserved only for the MS and EM but not for the W interactions. Table 2 lists the hadrons with their average masses (averaged within an isomultiplet) and their spins and parities and with their internal quantum numbers I , B , Y .

There are at least three well-established empirical relations among the quantum numbers of the hadrons listed in Table 2. One relation is the Gell-Mann–Nishijima equation which relates Q to I_3 and Y , namely,

$$Q = I_3 + \frac{1}{2}Y. \quad (1)$$

Eq. (1) must be supplemented by the condition

$$2I + Y = 0 \pmod{2}.$$

If condition (2) were not imposed,^e the Gell-Mann–Nishijima relation would permit half-integral values of Q (since I_3 and $Y/2$ could independently take on half-integral values), and these are not observed. Moreover, it seems that the quantum numbers J and B are related through an equation analogous to (2), namely,

$$2J + B = 0 \pmod{2}. \quad (3)$$

The facts that J and I both refer to rotations in some space (Lorentz and isospin respectively) and that B and Y both represent quantum numbers associated with

^dRecent calculations of the electromagnetic mass differences of the mesons and baryons have been fairly successful (cf. Wojtaszek, Marshak, and Riazuddin⁵ and Coleman and Schnitzer⁶).

^eL. Michel⁷ seems to have been the first to recognize the importance of this condition.

gauge transformations of the "first kind" are very suggestive and will be mentioned again.

The most recent internal symmetry principle which has been applied with considerable success to the elementary particles, that of unitary symmetry, must now be discussed. The discussion can best proceed by introducing the language of group theory, and this language can best be introduced by returning to isospin rotation. Recall^b that under a rotation in isospin space, an isospinor, such as that of the nucleon, transforms in accordance with the law

$$\psi \rightarrow e^{i\tau \cdot \epsilon} \psi \quad (4)$$

where the three components of the isospin operator τ are defined by

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad (5)$$

Table 2
Hadron Isomultiplets

Particle	J^P	Average Mass	B	I	Y
(MESONS)					
π	0^-	138.07	0	1	0
K	0^-	495.9	0	$\frac{1}{2}$	1
η	0^-	548.7	0	0	0
ρ	1^-	763	0	1	0
ω	1^-	782.8	0	0	0
K^*	1^-	891	0	$\frac{1}{2}$	1
ϕ	1^-	1019.5	0	0	0
B	$1^+, 2^-$	1215	0	1	0
K_c	1^+	1215	0	$\frac{1}{2}$	1
f	2^+	1253	0	0	0
A_2	2^+	1310	0	1	0
(BARYONS)					
N	$\frac{1}{2}^+$	938.903	1	$\frac{1}{2}$	1
Λ	$\frac{1}{2}^+$	1115.40	1	0	0
Σ	$\frac{1}{2}^+$	1193.2	1	1	0
$N_{3/2}^*$	$\frac{3}{2}^+$	1236	1	$\frac{3}{2}$	1
Ξ	$\frac{1}{2}^+$	1317.6	1	$\frac{1}{2}$	-1
Υ_1^*	$\frac{3}{2}^+$	1382.1	1	1	0
Υ_0^*	?	1405	1	0	0
Υ_0^{**}	$\frac{3}{2}^-$	1518.9	1	0	0
$N_{1/2}^*$	$\frac{3}{2}^-$	1518	1	$\frac{1}{2}$	1
Ξ^*	$\frac{3}{2}^+$	1529.1	1	$\frac{1}{2}$	-1
Υ_1^{**}	$\frac{3}{2}^- (?)$	1660	1	1	0
Ω^-	$\frac{3}{2}^+$	1675	1	0	-2
$N_{1/2}^{**}$	$\frac{5}{2}^+$	1688	1	$\frac{1}{2}$	1
Υ_0^{***}	$\frac{5}{2}^+ (?)$	1815	1	0	0
$N_{3/2}^{**}$	$\frac{7}{2}^+ (?)$	1924	1	$\frac{3}{2}$	1
$N_{1/2}^{***}$	?	2190	1	$\frac{1}{2}$	1
$N_{3/2}^{***}$	?	2360	1	$\frac{3}{2}$	1

and ϵ is a vector in isospin space. Eq. (4) can be rewritten in the form

$$\psi \rightarrow \begin{bmatrix} \cos\epsilon + i\epsilon_3 \frac{\sin\epsilon}{\epsilon}, (i\epsilon_1 + \epsilon_2) \frac{\sin\epsilon}{\epsilon} \\ (i\epsilon_1 - \epsilon_2) \frac{\sin\epsilon}{\epsilon}, \cos\epsilon - i\epsilon_3 \frac{\sin\epsilon}{\epsilon} \end{bmatrix} \psi = \begin{bmatrix} \alpha, \beta \\ -\beta^*, \alpha^* \end{bmatrix} \psi = U\psi \quad (6)$$

where α and β are complex numbers satisfying the condition $|\alpha|^2 + |\beta|^2 = 1$. The matrices U , which are unitary 2×2 matrices with unit determinant, evidently form a group, which is known as SU_2 , the unitary unimodular group in two dimensions. The three generators of the SU_2^I group representing isospin rotations (in two-dimensional realizations) are τ_1, τ_2, τ_3 (cf. refs. 5 and 6) just as $\sigma_1, \sigma_2, \sigma_3$ (three components of σ) are the two-dimensional representations of the three generators of the SU_2^J group representing ordinary spin rotations. Similarly, the representations of SU_2^I are 1, 2, 3, etc., corresponding to $I=0$ (isoscalar), $I=1/2$ (isospinor), $I=1$ (isovector), etc., respectively – in analogy to the representations of the SU_2^J group. The $I=1$ representation of SU_2^I is called the regular representation because the dimension of the matrix (3) is the same as the number of generators. Finally, products of representations of the SU_2^I group can be decomposed in an analogous fashion to those of SU_2^J , e.g., $2 \times 2 = 1 + 3$, $2 \times 3 = 2 + 4$, $3 \times 3 = 1 + 3 + 5$, etc.

It has already been remarked that the medium strong (MS) interactions among all the hadrons are invariant under isospin rotation (i.e., the SU_2^I group) so that, for example, the pion-nucleon interaction can be written in the form $(\bar{N}\tau\theta N \cdot \pi)$ where N is the isospinor nucleon and π is the isovector pion (θ is a space-time operator). The electromagnetic interaction of the hadrons $j\mu A^\mu$ ($j\mu$ is EM hadron current, A^μ is the EM potential), by virtue of the relation (1), singles out the third direction in isospin space and thereby breaks the symmetry of the SU_2^I group. As an illustration, one can write the isospin dependence of the magnetic moment of the Σ hyperons:

$$\mu(\Sigma) = aI_3 + b \quad (a, b \text{ are constants}). \quad (7)$$

Eq. (7) leads immediately^f to the well-known relation among the Σ magnetic moments:

$$\mu(\Sigma^0) = \frac{1}{2} [\mu(\Sigma^+) + \mu(\Sigma^-)]. \quad (8)$$

Similarly, since the electromagnetic self energy is proportional to the square of the electromagnetic current, the SU_2^I symmetry is broken to second order in I_3 and one may write the following mass equation for the components of an isomultiplet:

$$m = aI_3^2 + bI_3 + c \quad (a, b, c \text{ are constants}). \quad (9)$$

The generalization to the SU_3 group now seems very natural, but several years ago, when the suggestion was first made,^g it seemed quite revolutionary. The point is that examination of Table 2 reveals that the mass differences between particles of the same B , J , and P are generally small compared to the masses of the hadrons themselves; that is to say, the masses of the hadrons do not depend too sensitively on

^fThis result was first derived by Marshak, Okubo, and Sudarshan.⁸

^gThe earliest papers on SU_3 seem to be those of Klein,⁹ Yamaguchi,¹⁰ and Ikeda, Ogawa, and Ohnuki.¹¹

the internal quantum numbers I and Y . This suggests the possibility of a higher internal symmetry group than SU_2^I which, when broken in a well-defined way, gives rise to a mass equation correctly predicting the observed dependence of the masses on I and Y (for given B , J , and P). The success of the Gell-Mann–Okubo mass equation^b has given strong support to the idea that the hadrons possess an underlying SU_3 group structure for certain of the internal symmetries and that SU_3 symmetry is broken in a way very analogous to the manner in which the electromagnetic interaction breaks the SU_3^I symmetry group. The physical idea behind this statement is that the hadrons enjoy a much stronger interaction which is hidden by the medium strong (MS) interaction which is so familiar; this very strong (VS) interaction is presumed to be responsible for the part of the mass which is independent of I and Y (see below), whereas the MS interaction accounts for the I and Y dependence [in the same way as the EM interaction gives rise to the I_3 dependence in the mass equation for the members of an isomultiplet – cf. Eq. (9)].

Let us compare the SU_3 with the SU_2^I group. The SU_3 group is the unitary unimodular group in three dimensions rather than in two dimensions. The three generators τ_1, τ_2, τ_3 of the SU_2^I group are replaced by eight generators, namely:

$$\begin{aligned}
 \lambda_1 &= \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, & \lambda_2 &= \begin{bmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, & \lambda_3 &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
 \lambda_4 &= \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}, & \lambda_5 &= \begin{bmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{bmatrix}, & \lambda_6 &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \\
 \lambda_7 &= \begin{bmatrix} 0 & 0 & 0 \\ i & -0 & 0 \\ 0 & i & 0 \end{bmatrix}, & \lambda_8 &= \begin{bmatrix} 1/\sqrt{3} & 0 & 0 \\ 0 & 1/\sqrt{3} & 0 \\ 0 & 0 & -2/\sqrt{3} \end{bmatrix}.
 \end{aligned} \tag{10}$$

The ensemble of the three-dimensional representations of the eight generators $\lambda_1, \dots, \lambda_8$ comprise the “unitary spin” in the same way in which τ_1, τ_2, τ_3 constitute the isospin, and certain components of the unitary spin can be related to the generalized isospin and hypercharge operators, namely,

$$I^2 = \frac{1}{4}(\lambda_1^2 + \lambda_2^2 + \lambda_3^2), \tag{11a}$$

$$Y = \lambda_8 / \sqrt{3}. \tag{11b}$$

The definitions of I and Y in terms of the generators of the SU_3 group enable us to specify Q in such a way as to guarantee the Gell-Mann–Nishijima relation (1). The fundamental representation of the SU_3 group is the triplet representation 3 (and¹ 3*) just as the fundamental representation of the SU_2^I group is the doublet representation 2 whereas the regular representation is now 8 in contrast to the regular 3 repre-

^bGell-Mann¹² derived the octet formula; Okubo¹³ derived the general mass formula for any unitary multiplet.

¹3* is the conjugate representation to 3 for the SU_3 group; for the 2 (fundamental) representation of an SU_2 group, the conjugate representation is still 2.

sensation of the SU_2' group. Some of the low-dimensional representations of the SU_3 group in addition to the 3, 3^* , and 8, are 1, 6, 6^* , 8, 10, 10^* , 15, 15^* , 27, etc.; we say that the particles in a given representation comprise a unitary multiplet of the specified dimension. The decomposition of the product of two representations of the SU_3 group can be worked out in a manner analogous to that for the SU_2' group, and one finds for some of the combinations which we shall need:

$$3^* \times 3 = 1 + 8, \quad (12a)$$

$$3^* \times 3^* = 3 + 6, \quad (12b)$$

$$3 \times 3 = 3^* + 6^*, \quad (12c)$$

$$3 \times 3 \times 3 = 1 + 8 + 8 + 10, \quad (12d)$$

$$3^* \times 3 \times 3 = 3 + 6 + 15 + 3. \quad (12e)$$

These definitions and results should suffice for the purposes of our discussion.

The next step is to postulate that the underlying group structure of the hadrons (SU_3) is broken by the MS interaction in a well-defined way. Okubo¹³ assumed that

Table 3

Check of Gell-Mann-Okubo Mass Formulas

$J=0^-$ MESON OCTET			
	Mass	I	Y
π	138.07	1	0
K	495.9	$\frac{1}{2}$	1
$\bar{K}$	495.9	$\frac{1}{2}$	-1
η	548.7	0	0
m_η (theor.) = 567.0 or m_K (theor.) = 480.2			
$J=\frac{1}{2}^+$ BARYON OCTET			
	Mass	I	Y
N	938.903	$\frac{1}{2}$	1
Λ	1115.40	0	0
Σ	1193.2	1	0
Ξ	1317.6	$\frac{1}{2}$	-1
m_Ξ (theor.) = 1330.8			
$J=\frac{3}{2}^+$ BARYON DECUPLET			
	Mass	I	Y
$N_{3/2}^*$	1236	$\frac{3}{2}$	1
Σ_1^*	1382.1	1	0
Ξ^*	1529.1	$\frac{1}{2}$	-1
Ω^-	1675	0	-2
m_{Ξ^*} (theor.) = 1528.2; m_Ω (theor.) = 1674.3			

the masses of a unitary multiplet of hadrons are split by an SU_3 symmetry-breaking term proportional to λ_8 ; in this way, he derived the mass equations for mesons and baryons as follows:¹

$$m_M^2 = m_0^2 + b(I^2 - \frac{1}{4}Y^2) \quad (m_0, b \text{ are constants}), \quad (13)$$

$$m_B = m_0^1 + a^1 Y + b^1(I^2 - \frac{1}{4}Y^2) \quad (m_0^1, a^1, b^1 \text{ are constants}). \quad (14)$$

The first constant in each equation represents the common mass of the unitary multiplet in the absence of the MS interaction, and the other terms give the predicted dependence on I and Y . Table 3 shows a comparison between theory and experiment for the better known unitary multiplets, namely the $J=0^-$ meson octet, the $J=\frac{1}{2}^+$ octet, and the $J=\frac{3}{2}^+$ baryon decuplet. The agreement is good, and one is encouraged to search for other evidence of an underlying SU_3 group structure by studying other types of SU_3 symmetry-breaking processes. For example, the electromagnetic interaction clearly breaks SU_3 symmetry (since it already breaks SU_2^I symmetry); if it is assumed that the EM symmetry-breaking interaction is proportional to λ_3 [the generalization of the third component of the isospin – cf. Eq. (10)], relationships can be predicted between the electromagnetic mass differences of the hadrons within a unitary multiplet. A good example is the relation¹⁴ for the $J=\frac{1}{2}^+$ octet:

$$m_{\Xi^-} - m_{\Xi^0} = m_{\Sigma^-} - m_{\Sigma^+} + m_p - m_n. \quad (15)$$

With use of the values of the masses given in Table 1, Eq. (15) is very well satisfied.

The success of broken SU_3 symmetry as exemplified by the Gell-Mann–Okubo and electromagnetic mass formulas has encouraged a long-standing hope that all the symmetry principles (not only isospin rotation and hypercharge) will be encompassed within the framework of a single large symmetry group, and we shall then have a truly unified theory of hadrons on the group-theoretic level. While the success of broken SU_3 symmetry is very striking, one difficulty must be noted. The fundamental representation of the SU_3 group is the triplet representation, but there is no experimental evidence for particles which belong to the 3 representation [this is in contrast to the SU_2^I group, for which nature provides numerous instances of the fundamental (2) representation]. This would in itself perhaps not be so surprising except that, using the definition of the hypercharge operator [cf. Eq. (11 b)] which works so well for the 8 and 10 representations, we are forced to non-integral values of the hypercharge; *a fortiori*, the Gell-Mann–Nishijima relation (1) compels us to assign non-integral values of the electric charge to the members of the 3 representation. The internal quantum numbers Q, I, Y are listed in Table 4 for the triplet representation, and the members of this representation have been given the rather literary name “quarks.”^k

While it is still an open experimental question as to whether a triplet of quarks of sufficiently large mass actually exists, it should be remarked that one can obtain integral values of Q for the members of the 3 representation by a small modification

¹We shall follow the custom of writing m_M^2 for the mesons, m_B for the baryons.

^kThe term “quark” can be used for any member of a representation with nonzero triality (see next paragraph) but we shall be concerned chiefly with the quarks in the triplet representation (see Gell-Mann¹⁵ and Zweig¹⁶).

Table 4

Quantum Numbers of Quark Triplet

	B	Q	I	Y
ψ_1	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$
ψ_2	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$
ψ_3	$\frac{1}{3}$	$-\frac{1}{3}$	0	$-\frac{2}{3}$

Table 5

Triality[†] for Low-Dimensional Representations of SU_3

	Representation										
	1	3	3*	6	6*	8	10	10*	15	15*	27
Triality	0	1	-1	1	-1	0	0	0	1	-1	0

[†]Triality is defined by $t = (p - q) \pmod{3}$ where $D(p, q)$ is an irreducible representation of SU_3 ; we assign positive (negative) t to unstarred (starred) representations.

of the SU_3 group. If one enlarges the SU_3 group slightly by lifting the unimodular condition, one ends up with the U_3 group which has nine generators (rather than the eight generators of the SU_3 group). One can use the ninth generator in such a way as to define a new additive quantum number, t , which has been called "triality," which takes on the values $0, \pm 1$ depending on the representation of the SU_3 group; the values of t for the low-lying representation are given in Table 5. It can be shown that the generalized Gell-Mann–Nishijima relation (which would hold for particles in representations with nonzero triality as well as zero triality) becomes¹

$$Q = I_3 + \frac{1}{2}Y + \frac{1}{3}t. \quad (16)$$

This formula leads to integral values of Q for all representations but at the expense of enlarging the SU_3 group to U_3 . Thus far, there is no experimental evidence for the existence of unitary triplets of hadrons of integral or non-integral electric charge.^m The quark problem will come back to "haunt" us in connection with our discussion of a unified field theory of hadrons.

Neglecting the quark problem for the moment, this section can be concluded by listing in Table 6 the hierarchy of interactions which are reasonably well established and the symmetry groups which govern these interactions among hadrons. Invariance under space-time translations, rotational invariance, and Lorentz invariance are all included under the proper orthochronous Lorentz group L_p . The

¹Cf. Okubo, Ryan, and Marshak,¹⁷ although in this paper we redefined Y by $\frac{1}{2}Y' = \frac{1}{2}Y + \frac{1}{3}t$.

^mPepper, Ryan, Okubo, and Marshak¹⁸ have recently examined the interesting possibility that the intermediate vector boson, presumed to mediate the weak interactions, belongs to a triplet representation of the U_3 group.

Table 6

Underlying Group Structure of Various Interactions

Interaction	L_p	L_d	(U_1^Q)	U_1^B	U_1^Y	SU_2^I	SU_3
Very strong (VS)	yes	yes	(yes)	yes	yes	yes	yes
Medium strong (MS)	yes	yes	(yes)	yes	yes	yes	no
Electromagnetic (EM)	yes	yes	(yes)	yes	yes	no	no
Weak (W)	yes	no	(yes)	yes	no	no	no

totality of discrete transformations, P , T , and C , is denoted^a by L_d . The gauge groups are equivalent to one-dimensional unitary groups, and for example, the baryon gauge group is denoted by U_1^B . U_1^Q is in parentheses in Table 6 because this is not an independent gauge group [by virtue of Eq. (11)]. Furthermore, the empirical relation (2) implies that (even without SU_3 invariance) we can not treat $U_1^Y \times SU_2^I$ as a direct product but must replace it⁷ by $U_2^{I,Y}$. Table 6 shows in a striking way the well-known fact that the stronger the interaction, the higher the symmetry group which governs its behavior. From Table 6 we can say that weak interactions of hadrons are governed by the underlying group structure $L_p \times U_1^Q \times U_1^B$; electromagnetic by $L_p \times L_d \times U_1^Q \times U_1^B \times U_1^Y$; medium strong by $L_p \times L_d \times U_1^B \times U_2^{I,Y}$, and, finally, very strong interactions by $L_p \times L_d \times U_1^B \times SU_3$. With this summary of the situation, we are prepared to discuss in the next section the meaning and progress to date of a unified field theory of hadrons.

3. TOWARDS A UNIFIED FIELD THEORY OF HADRONS

In section 2 it was shown how symmetry principles and invariance laws serve to bring order into the physics of elementary particles. Table 6 is particularly helpful in exhibiting the number and character of the symmetry principles which characterize the various types of interactions among hadrons. Since the largest number of symmetry principles are involved in the MS and VS interactions, attention will be focused on these two types of interactions. Even in the case of the MS and VS interactions, the number of hadrons is vastly greater than the number of symmetry groups known to govern these two types of interactions. Throughout the discussion in section 2 it was implicitly assumed that distinct quantized *fields* could be set up in one-to-one correspondence with the diversity of *particles* and that these *fields* were the "carriers" of the symmetry properties. The question naturally arises whether a reduction can be made in the number of "carriers" of symmetry properties.

On the *group-theoretic* level, it is the goal of a unified field theory of hadrons to find the minimum number of fields which, through a specified form of interaction,

^aWe have included C in L_d even though, strictly speaking, C is not a discrete Lorentz transformation; C is related to the discrete Lorentz transformations P and T through the CPT theorem. It is worthy of note that C changes $Q \rightarrow -Q$, $B \rightarrow -B$, $Y \rightarrow -Y$, and hence $I_3 \rightarrow -I_3$ [by virtue of Eq. (1)] so that the space-time operators P and T are, through the "intervention" of C , somehow connected with the isospin group.

will correctly predict the largest underlying symmetry group governing the maximal interaction among all the hadrons and the precise ways in which the highest symmetry is successively broken to yield the successive subgroups which are applicable to the observed hierarchy of interactions. One can be more ambitious about a unified field theory of hadrons (as the Heisenberg school¹⁹ is) and hope to derive the relative strengths of the various types of interactions as well as the absolute values of the masses of all the hadrons. On this *dynamical* level, one might also hope to explain the masses of the leptons as well as the mass and properties of the photon itself. The objective of developing a unified field theory of all elementary particles on the dynamical level is certainly one of the major, if not the major, goal of modern physics and should be pursued with all sensible speed. However, this account will be confined to a discussion of the progress which has been made on the program of developing a unified field theory of the hadron particles on the group-theoretic level. This goal is more modest, may even be attainable in the not-too-distant future, and in any case should serve as a useful starting point for the full-fledged dynamical theory.

We have seen that at the level of the *MS* interactions (cf. Table 6) the underlying group structure for the hadrons is $L_p \times L_d \times U_1^B \times U_2^{I,Y}$, whereas at the next higher level, that of the *VS* interactions, the underlying group structure becomes $L_p \times L_d \times U_1^B \times SU_3$. To fix our ideas, let us put aside L_p and L_d for the moment and consider the number of fields required to represent the internal symmetries denoted by U_1^B , $U_2^{I,Y}$, and SU_3 . Suppose for the sake of argument that only one additive internal quantum number (say B) distinguished the various hadron particles. It is evident that the choice of a single boson field ϕ with $B=0$ could never lead to a baryon particle with $B=1$, say; on the other hand, a single fermion field ψ with $B=1$ could give rise to a meson particle with $B=0$ by allowing $\bar{\psi}\psi$ to operate on the vacuum (i.e., $\bar{\psi}\psi|0\rangle$). The next step, if we follow somewhat the historical sequence of events, is to inquire as to the minimum number of fields which would be necessary if only B and I distinguished the various hadron particles. It is clear that an isospinor field (i.e., the fundamental 2 representation of the SU_2^I group) with $B=1$ would do the job; indeed, back in 1949, Fermi and Yang²⁰ proposed to explain the $I=1$, $B=0$ pion in terms of the $I=1/2$, $B=1$ nucleon field.

The discovery of the strange particles required the introduction of a new additive quantum number, the hypercharge, but related to the isospin by Eq. (2). Condition (2) implies that half-integral values of I are associated with odd values of Y , whereas integral values of I are associated with even values of Y (this is, of course, the reason⁷ why we have chosen the group $U_2^{I,Y}$ rather than the direct product $U_1^Y \times SU_2^I$). The baryon number B seems, however, to be capable of varying independently of I and Y , and so we must ask what is the minimum number of fields which can explain the underlying group structure $U_1^B \times U_2^{I,Y}$ at the *MS* interaction level. The answer is three fields: an isospinor field with $B=0$ and an isoscalar field with $B=1$ or an isospinor field with $B=1$ and an isoscalar field with $B=1$. An example of the first possibility would be the choice K^+ , K^0 , Λ , and of the second possibility p , n , Λ . [We are using the particle symbols for the fields because the internal quantum numbers of the fields and the hadron particles are identical and not because, as we now know, any of the observed hadron particles can serve as the basic fields in a unified theory

of hadrons (see below).] The point is that the hadrons which we observe, with the physical masses which we measure, are conceived, within the present framework, as being the outcome of an extremely strong interaction among the small number of fields about which we are speaking.

The two triplets of hadron fields mentioned above exemplify a constantly recurring dichotomy in the approach to a unified theory of hadrons. The first choice involves both fermions and bosons, and it is natural to write Yukawa-type interactions between the fermion fields and the bosons (as well as nonlinear interactions among the bosons themselves) in order to generate the various hadron particles. This is the approach taken in quantum electrodynamics, where one works with the interaction between one boson field (photon) and the charged fermion fields (electrons), or the approach taken by Yukawa in developing his pion theory of nuclear forces (in analogy to the electromagnetic case). Since the discovery of strange particles, this was the approach taken by Lévy and Marshak,²¹ by Goldhaber,²² and, more recently,^o by Schwinger²³ and by Gursey et al.²⁴ In this type of approach, the success of the renormalization program in quantum electrodynamics is considered a powerful argument, and the hope is fondly entertained that a renormalized unified field theory of the strong interactions^p can similarly be worked out. Some authors² have pushed the analogy to the electromagnetic field pretty far and have attempted to develop a unified theory of hadrons with a small number of vector gauge fields (with or without mass) in addition to a small number of fermion fields. While many of these attempts to develop a unified theory of hadrons by starting with a small number of boson and fermion fields are of considerable interest, it seems to us that the second type of approach, in which only fermion fields are used, holds greater promise, and we shall develop this thesis in the remainder of this section.

First, some historical remarks are in order concerning the purely fermion approach to a unified theory of elementary particles. We have already remarked that the Fermi-Yang model of the pion was an example of this type of approach. Actually, at a much earlier date, de Broglie^q tried to construct (rather unsuccessfully) a neutrino theory of light, according to which the photon is supposed to be a composite system of a massless fermion and antifermion (neutrinos). However, the most serious program in the direction of a purely fermion unified theory of elementary particles has been that of Heisenberg and his coworkers.^r Heisenberg set himself the objective of constructing a theory of elementary particles based on *one* massless 4-component Dirac field (which he calls Urmaterie – not to be identified with any of the observed baryons) satisfying a nonlinear equation with the maximum number of invariance properties. By a judicious choice of the nonlinear four-fermion interaction (axial

^oSchwinger²³ uses three fermion and three boson fields (as do Gursey et al.²⁴).

^pThe intermediate vector boson was introduced into weak interactions with a similar hope that a renormalized theory could be worked out; neither has the intermediate vector boson been found nor has it been demonstrated that it would result in a renormalized theory of weak interactions.

^qde Broglie²⁵; the most recent attempt to develop a theory of the photon in terms of a bound fermion-antifermion pair (electron-positron pair) is that of I. Bialnycki-Birula.²⁶

^rIn addition to Heisenberg (cf. ref. 19), Nambu and his co-workers have pursued this program vigorously (cf. Nambu and Jona-Lasinio²⁷).

vector), Heisenberg could enlarge the underlying symmetry group to U_2 and take care of baryon conservation as well as isospin invariance; however, he was compelled to postulate a degenerate vacuum and spurions in order to account for hypercharge and to introduce rather unconventional definitions of P and C in order to recapture these discrete operations. This is not surprising since Thirring²⁸ has shown that if one wishes to work with massless fermion fields, at least three Weyl (2-component) fields are required to yield the underlying group structure for the internal symmetries, $U_1^B \times U_2^{I,Y}$, and that six Weyl fields (equivalent to three Dirac fields) are needed in order to obtain, in addition, the multiplicative quantum numbers which follow from P , C , T invariance. In other words, the minimum number of fields which will not disrupt the usual treatment of the discrete group L_d and account for the internal symmetries are three massless 4-component Dirac fields. This agrees with our earlier conclusion.

The next important step in the direction of a purely fermion field theory of hadron particles was taken by Sakata.²⁹ The Sakata model satisfied Thirring's conditions since three Dirac fields were associated with the observed particles p , n , Λ . (This is the example given earlier of a choice of a triplet of fields which could explain the internal group structure $U_1^B \times U_2^{I,Y}$.) On the MS level of interaction among the hadrons, the Sakata three-field model works fine and can account for all the internal quantum numbers of the hadrons. It would further appear that the Sakata triplet could serve as a model at the VS interaction level if we neglect the mass difference between Λ and N (thereby obtaining an underlying SU_3 group structure) and if we treat the mass differences between Λ and N as an effective interaction term^{12,13} which breaks the SU_3 symmetry. The trouble is that the observed triplet of particles (p , n , Λ) belongs to the octet representation of the SU_3 group and, indeed, we know of no baryons which belong to the triplet representation of the SU_3 group. Furthermore, as pointed out earlier (compare Table 4), the members of the 3 representation of the SU_3 group possess fractional values of the electric charge (we shall see below that they must be assigned fractional values of the baryon number as well).

While the success of broken SU_3 symmetry rules out the identification of the three Dirac fields in the Sakata model with the known particles (p , n , Λ), the fact remains that a model based on a triplet of Dirac fields with equal bare mass m_0 interacting via four-fermion terms is a good starting point for a unified theory of hadrons, at least on the group-theoretic level. This can readily be seen if one recalls the reduction formulas (12) of the products of representations of the SU_3 group. The triplet of basic Dirac fields is denoted by ψ_i ($i=1, 2, 3$); the ψ_i belong to the 3 representation and *a fortiori* the $\bar{\psi}_i$ belong to the 3^* representation. It should be reiterated that the three ψ fields possess fractional electric charge and hypercharge (cf. Table 4), i.e., they are quark fields. We shall see that the baryon number $B=1/3$ must be assigned to each ψ field, but in any case the baryon number associated with $\bar{\psi}$ is opposite to that of ψ . It follows that mesons (with $B=0$) can be built up from pairs of $\bar{\psi}_i$ and ψ_j operating on the vacuum, namely,

$$\bar{\psi}_i \theta \psi_j |0\rangle \quad (17)$$

where the spin and parity of the resulting meson particle will depend on the space-

time operator θ . Thus the well-known pseudoscalar ($J=0^-$) octet can be constructed by choosing $\theta=1$ (corresponding to the 1S_0 state of a quark-antiquark system since the intrinsic parity of a fermion-antifermion pair is odd). Similarly, the vector ($J=1^-$) mesons and mesons with higher spin values and both parities can be built up by choosing θ appropriately. Since $\bar{\psi}_i$ and ψ_j in (17) belong to the 3^* and 3 representations of the SU_3 group, we are evidently dealing with the product representation $3^* \times 3$ [cf. Eq. (12a)] so that (17) leads to a unitary meson octet and unitary meson singlet; this last statement is independent of the space-time operator θ .

The situation is more complicated for the baryons. Since we must end up with at least a $B=1$ octet (with $J=\frac{1}{2}^+$) and a $B=1$ decuplet (with $J=\frac{3}{2}^+$) (cf. Table 3), we cannot use the same product representation as for the mesons. It is readily seen from Eqs. (12a)-(12c) that bilinear combinations will not work and that we must go to trilinear combinations; the trilinear combination which contains both an octet and a decuplet in its reduction is

$$\psi_i \psi_j \psi_k |0\rangle \quad (18)$$

where a suitable space-time operator is implied. Moreover, since we want the particles defined by (18) to carry unit baryon number, it follows that each ψ must be assigned $B=\frac{1}{3}$. Once this assignment is made, there is no difficulty in building up unitary baryon multiplets with the spins and parities which have been observed.

Let us summarize the situation at this point. We have seen that a triplet of quark fields with common mass m_0 and baryon number $B=\frac{1}{3}$ will yield the desired underlying internal group structure for a system of hadrons, namely $U_1^B \times SU_3$. If we further ask that the four-fermion interactions^s among the triplet of quarks be invariant under L_p and L_d , then of course the total underlying group structure is $L_p \times L_d \times U_1^B \times SU_3$. To be more explicit, the Hamiltonian for our triplet of quarks can be written in the following form:^t

$$H = \sum_{i=1}^3 \sum_{\mu=1}^3 (\bar{\psi}_i \gamma_\mu \partial^\mu \psi_i) + m_0 \sum_{i=1}^3 \bar{\psi}_i \psi_i + \sum_{n=1}^5 g_n \sum_{i,j=1}^3 (\bar{\psi}_i \theta_n \psi_i) (\bar{\psi}_j \theta_n \psi_j) \quad (19)$$

where θ_n = scalar (S), pseudoscalar (P), vector (V), axial vector (A), or tensor (T) operator. Without specifying the relative strengths of the S, P, V, A, T four-fermion interactions, it is easy to show that H is invariant under the three-dimensional unitary unimodular transformation of the fields ψ_i , that is, under

$$\psi_i \rightarrow \sum_{j=1}^3 a_i^j \psi_j \quad (i=1, 2, 3)$$

where $\|a_i^j\|$ is a three-dimensional unitary unimodular matrix. With H obviously invariant under L_p, L_d , and U_1^B , we can say that we are operating at the VS interaction level for a triplet of quarks (cf. Table 6). Now we must consider the breaking of the SU_3 symmetry by the MS type of interaction; since the charge of the third quark (cf. Table 4) is different from that of the first two, it is natural to write for this

^sSix-fermion and higher-order interactions could be considered (cf. ref. 30) but there seems to be no significant gain in generality by doing so.

^tWe have written the kinematical part of H in abbreviated form; the proper symmetrization is understood.

symmetry-breaking term an interaction of the form

$$H_1 = m_1 \bar{\psi}_3 \psi_3. \quad (20)$$

H_1 reduces the SU_3 invariance to invariance under the subgroup $U_2^{I,Y}$ of isospin rotations and hypercharge gauge transformations and, indeed, can be shown to yield the Gell-Mann–Okubo mass formulas (13) and (14). Thus it would seem that we have reached the end of our journey and, in the combination of H and H_1 , we have an explicit total Hamiltonian which not only specifies the underlying group structure of a system of hadrons but also defines the behavior of the symmetry-breaking term. In a sense, it would appear that we have achieved our goal of a unified field theory of hadrons on the group-theoretic level.

Needless to say, this optimistic conclusion is premature, since there are many questions still left unanswered. Among them are: where are the particles which belong to representations of SU_3 with nonzero triality (cf. Table 5)? It is certainly surprising that, if the basic fields belong to such a (triplet) representation, the only particle realizations so far observed belong to representations with zero triality. Perhaps these quarks will be discovered with much higher physical masses than the non-quarks. A second question still unanswered is whether SU_3 is really the highest internal symmetry group or whether it would make sense to start with an underlying internal group structure higher than SU_3 and to reach SU_3 as an intermediate stage by breaking this higher symmetry in a well-defined way. Even if a higher internal symmetry group is found useful, the mass relations which would follow by breaking this higher symmetry could be applied only to hadrons with identical spin and parity; this follows from the fact that L_p and L_d would still be in the relation of a direct product to the higher internal symmetry group. Since hadrons with different spins and opposite parities exist, it would seem reasonable to expect that a truly unified field theory of hadrons would lead to a universal mass formula that would correctly predict, at least in a well-defined approximation, the masses of all the hadrons. However, it is clear that in order to relate the masses of hadron multiplets with different spins and opposite parities, it is necessary somehow to mix the groups L_p and L_d with the internal symmetry groups. In other words, we must pose the question as to whether there exists a larger mixed Lorentz–internal symmetry group which is broken in a well-defined way so that a substantial part of $L_p \times L_d \times U_1^B \times SU_3$ constitutes a subgroup.

The program sketched in the last paragraph is very ambitious and can be tackled in an arbitrary number of ways. We have recently shown^u one way in which the triplet quark model can, with slight modifications, define a mixed Lorentz–internal symmetry group as well as the precise manner in which this group is broken. Let us sketch briefly how this is done. In order to mix one of the discrete Lorentz transformations (parity) with the SU_3 group, we specialize the Hamiltonian (19) setting $m_0 = 0$ (common zero bare mass for the triplet of quarks) and consider only the vector four-fermion interaction ($g_V \neq 0$). We have then

$$\bar{H} = \sum_{i=1}^3 \sum_{\mu=1}^3 (\bar{\psi}_i \gamma_\mu \partial^\mu \psi_i) + g_V \sum_{i,j=1}^3 (\bar{\psi}_i \gamma_\mu \psi_i) (\bar{\psi}_j \gamma^\mu \psi_j). \quad (21)$$

^uMarshak, Mukunda, and Okubo³⁰; despite the different starting point, there is a close connection between this paper and that of Gell-Mann.³¹

We next decompose the three quark fields ψ_i into their positive and negative (2-component) chiral projections ξ_i and χ_i respectively, namely, we choose γ_5 diagonal and write

$$\xi_i = \frac{1}{2}(1 + \gamma_5)\psi_i, \quad \chi_i = \frac{1}{2}(1 - \gamma_5)\psi_i. \quad (22)$$

We can now rewrite (21) in terms of ξ_i and χ_i as follows:

$$\bar{H} = \sum_{i=1}^3 \sum_{\mu=1}^3 (\bar{\xi}_i \gamma_\mu \partial^\mu \xi_i + \bar{\chi}_i \gamma_\mu \partial^\mu \chi_i) + g_V \sum_{i,j=1}^3 (\bar{\xi}_i \gamma_\mu \xi_i + \bar{\chi}_i \gamma_\mu \chi_i) (\bar{\xi}_j \gamma^\mu \xi_j + \bar{\chi}_j \gamma^\mu \chi_j) \quad (23)$$

and readily show that (23) is invariant under *separate* three-dimensional unitary transformations of the ξ_i and χ_i , to wit:

$$\xi_i \rightarrow \sum_{j=1}^3 a_i{}^j \xi_j; \quad \chi_i \rightarrow \sum_{j=1}^3 b_i{}^j \chi_j \quad (i=1, 2, 3) \quad (24)$$

where $\|a_i{}^j\|$ and $\|b_i{}^j\|$ are independent 3×3 unitary matrices. If we denote the three-dimensional unitary group associated with ξ_i by $U^{(+)}$ and the one associated with χ_i by $U^{(-)}$, we can say that $\bar{H}$ is invariant under the product group $\bar{W}_3 = U_3^{(+)} \times U_3^{(-)}$. This $\bar{W}_3$ is not to be confused with the W_3 group studied by several other authors,^{23,24} since the parity operation interchanges the two U_3 groups comprising $\bar{W}_3$.^v This feature of the $\bar{W}_3$ group leads to a mixing of the parity (part of L_a) with the internal symmetry groups. Now, the invariance of $\bar{H}$ [Eq. (21)] under the higher symmetry group $\bar{W}_3$ implies that we are operating at a higher level, so to speak, than the VS interaction level; we shall call this the “cosmic” interaction level [that is to say, the vector four-fermion interactions of (21) among the three massless Dirac quark fields represent the “cosmic” interaction]. If we then use these quark fields to build up mesons in the manner sketched earlier, we soon find that there is no way whereby the “cosmic” interaction can separate the masses of mesons of opposite parity (with the same value of J). In other words, the fact that the parity operation interchanges the $U_3^{(+)}$ and $U_3^{(-)}$ groups leads to an intrinsic parity degeneracy for the mesons.^w In order to remove the parity degeneracy for the mesons, we must add a common mass term H' , presumed to be due to the VS interactions, namely,

$$H' = m' \sum_{i=1}^3 \bar{\psi}_i \psi_i \equiv m' \sum_{i=1}^3 (\bar{\xi}_i \chi_i + \bar{\chi}_i \xi_i). \quad (25)$$

Eq. (25) immediately reduces the invariance group of $\bar{H}$ from $\bar{W}_3$ to U_3 , since H' is invariant only under common unitary transformations of the two chiral projections of the ψ_i 's [i.e., when $a_i{}^j = b_i{}^j$ in Eq. (24)]; this follows from the fact that H' [cf. Eq. (25)] evidently mixes the ξ_i and χ_i fields, in contrast to $\bar{H}$ [cf. Eq. (23)], which does not. Thus H' has brought us from the “cosmic” to the VS interaction level. If we further add a term H'' (due to the MS interaction) of the form

^vSince the parity operation converts ξ into χ and conversely (because it involves the γ_4 operator which anticommutes with γ_5), it interchanges the associated groups $U_3^{(+)}$ and $U_3^{(-)}$.

^wThe problem is more subtle for the baryons, and we shall only remark here that there is no parity degeneracy for the baryons because we must use *both* 2-component chiral projections to build up the 4-component baryon spinors.

$$H'' = m'' \bar{\psi}_3 \psi_3 = m'' (\bar{\xi}_3 \chi_3 + \bar{\chi}_3 \xi_3), \quad (26)$$

we break the U_3 invariance in the standard fashion. Since we expect the MS to be smaller than the VS symmetry-breaking interaction, m'' should be smaller than m' . Moreover, the three-field vector model prescribes, through (25) and (26), a definite behavior, in terms of the generators of the $\bar{W}_3$ group, for the symmetry-breaking terms H' and H'' that successively destroy first the $\bar{W}_3$ and then the U_3 symmetry. The consequences of this model are fully discussed in ref. 30.

It should be emphasized that implicit in the above chiral decomposition [i.e., according to the operators $(1 \pm \gamma_5)$] of the triplet of quark fields is the separate invariance of the theory under L_p so that one can not expect a mixing of L_p with the internal symmetry groups. In other words, the underlying group structure of the quark triplet will still have L_p as a factor in the direct product with $\bar{W}_3$. If we make another type of decomposition of the three quark fields [e.g., according to $(1 + \gamma_4)$ – we shall call this a “Casimir” decomposition^x], we can hope to mix L_p with the internal symmetry groups. Such an undertaking has acquired particular interest in view of the phenomenological correlations found by Sakita³² and Gurse et al.³³ by treating unitary spin and ordinary spin as a subgroup^y $SU_3 \times SU_2^s$ of the larger mixed group SU_6 . These authors were led to this particular SU_6 group by a straightforward generalization of the Wigner supermultiplet theory in nuclear physics where the product of the two SU_2 groups, namely $SU_2' \times SU_2^s$ is treated as a subgroup of SU_4 .

We shall not go into detail³⁴ but merely point out that the “Casimir” decomposition of the triplet of quark fields, when used in conjunction with the scalar four-fermion interaction, leads to the very large group $W_6 = U_6 \times U_6$ (much larger than the $\bar{W}_3$ group of the three-field vector model when we made a chiral decomposition of the three quark fields). This large group is maintained even when we allow a common mass^z for the triplet of fields [cf. Eq. (19)],

$$H(m_0) = m_0 \sum_{i=1}^3 \bar{\psi}_i \psi_i, \quad (27)$$

since $H(m_0)$ is a scalar; that is to say, invariance under the higher symmetry group W_6 is not affected by assigning an arbitrarily large (rather than zero) bare mass to the fundamental triplet. On the other hand, it can easily be shown that the kinematical part of the Hamiltonian, H_0 [compare Eq. (19)] is not invariant under the W_6 group.

^xThis term is used because $(1 \pm \gamma_4)$ are the well-known Casimir operators found so convenient in evaluating spurs with Dirac spinors, in the zero momentum limit.

^yWe use the notation SU_2^s rather than SU_2' to emphasize the point that these authors are not working with the full rotation group in the relativistic sense but only with the nonrelativistic spin part of it.

^zWe could have referred to Eq. (25) for the structure of the common mass term, but we wish to call attention to the difference between introducing such a term as a symmetry-breaking interaction [Eq. (25)] and considering it as part of the unperturbed Hamiltonian with its maximal symmetry [Eq. (27)].

The three-field scalar model with “Casimir” decomposition is thus a most interesting probe of higher group symmetries. We can start with a triplet of very massive quark fields which enjoy a “cosmic” interaction through the scalar four-fermion term. The underlying group structure of the common mass term and the scalar four-fermion interaction is the very large group W_6 . It is now the kinematical term, H_0 , which breaks the W_6 symmetry and brings one down to the subgroup $SU_3 \times SU_2^8$. It even turns out that H_0 has a tensorial behavior in U_6 of a type similar to the one considered by Sakita³² and Gursev et al.³³ and is capable of splitting the masses of the $J=0^-$, 1^- unitary octets and the $J=1^-$ unitary singlet within a “35” meson representation and the masses of the $J=\frac{1}{2}^+$ unitary octet and the $J=\frac{3}{2}^+$ unitary decuplet within a “56” baryon representation. And if one adds the usual MS symmetry-breaking term [i.e., Eq. (26)], one can obtain unitary spin-spin mass relations of the kind derived on a phenomenological basis by the aforementioned authors.

But here we arrive at a crucial point; the three-field scalar model with “Casimir” decomposition is rich enough to supply a mechanism for mixing unitary spin and spin along the lines of the recently proposed generalization of the Wigner supermultiplet theory. Unfortunately, it is precise enough to expose a fundamental difficulty in the method of mixing the proper orthochronous Lorentz group L_p with the internal symmetry groups which is implicit in the program of Sakita and Gursev et al. This difficulty consists in the fact that Lorentz covariance can be achieved only at the expense of enlarging the underlying group to an infinite number of dimensions. This raises a whole complex of new problems with which theoretical particle physicists will no doubt have to cope.

To summarize this section, we have tried to define the meaning of a unified field theory of hadrons on the group-theoretic level and to indicate the extent to which three-field models (both with chiral and with “Casimir” decomposition) can contribute to the attainment of this goal. If we adopt the more modest goal of mixing the discrete transformations of the Lorentz group with the internal symmetry groups, the three-field vector model with chiral decomposition is a promising candidate and can be subjected to definitive experimental tests. If we set ourselves the more ambitious goal of mixing the proper orthochronous Lorentz group with the internal symmetry groups, then we are led to a larger mixed group of an infinite number of dimensions. New mathematical and physical ideas will be required to make progress on this more ambitious program. In any case, it is suggestive that the three-field four-fermion interaction model (with chiral decomposition or “Casimir” decomposition or possibly some other mode of decomposition) can yield underlying group structures which are large enough^{aa} to provide a foundation for a truly unified theory of hadrons on the group-theoretic (and possibly even the dynamical) level.

4. EXPERIMENTAL TESTS AT SUPER HIGH ENERGIES

The increasing effort which is now going into the development of a unified field theory of hadrons (and of the leptons and photon as well) can profit greatly from the

^{aa}The maximal unitary group which is contained in the three-field four-fermion interaction model is U_{12} .³⁵

clues which only super high experiments can provide. In this final section, we wish to touch briefly on some of the crucial experiments which may provide the much needed guidance for the difficult theoretical investigations which lie ahead.

Before commenting on the role which super high energy experiments might play in clarifying and revealing the symmetry properties of nature, let us recall some historical highlights in this constant search for higher symmetries. Up to the first quarter of this century, the only known (or at least well understood) interactions were the electromagnetic and gravitational interactions, and the only known elementary particles were the electron, photon, and proton. Hence, the only known symmetries were those of space-rotation and translation, which had been enlarged into the proper orthochronous Lorentz group by Einstein. During the next decade, the discrete transformations were placed on a firm footing by means of experiments in atomic and low energy nuclear physics. It was not until the early 1950's that the isospin group SU_2^I was well established by pion-nucleon scattering experiments performed on synchrocyclotrons in the several-hundred-MeV region. Subsequently, the ideas of hypercharge (or strangeness) conservation and baryon number conservation were fully understood when the high energy machines in the several-BeV region produced the strange particles (e.g., K , Λ , Σ , Ξ). Finally, experiments on the highest energy machines (up to 30 BeV) during the past few years have helped to establish the importance of unitary symmetry through the discovery of many new resonant particles and Ω^- .

Thus, the enlargement of our knowledge of the symmetries of nature has been in direct proportion to the availability of higher energies. This fact is not accidental if the symmetries become increasingly broader in scope as we penetrate to smaller distances. Up to now, refined investigations have been carried down to distances of the order of 10^{-14} cm, and we have no convincing evidence that the Lorentz group breaks down nor that it mixes with the internal symmetry groups. It is possible that a lack of commutativity of the Lorentz and internal symmetry groups will show up at distances substantially smaller than 10^{-14} cm and manifest itself as apparent violations of hypercharge and/or isospin invariance at sufficiently high energies.

One might inquire whether particle physics gives any cause to think that ultimately deeper connections will be discovered between space-time and internal symmetries. We have already cited one possible example of such a connection, namely, that P and T seem to be connected with isospinⁿ (via the CPT theorem). Another example of a similar nature^{bb} is that of the "crossing" symmetry relation in S -matrix theory where, again, not only Q , B , Y , I_3 but also the energy-momentum four-vector of a particle changes sign under "crossing." As a final example, we mention the experimental relation $2J+B=0 \pmod{2}$ [cf. Eq. (3)]. We believe that these may be small hints of more deep going relations between space-time and internal symmetries which require super high energies to be fully uncovered.

Up to this point we have spoken in rather general terms of the role which super high energy experiments might play in subjecting our present symmetry principles to more crucial tests and in revealing new and more comprehensive invariance laws. We now wish to comment more specifically on what we might hope to learn con-

^{bb}This has been emphasized recently by Wigner.³⁶

cerning the proper direction for a unified field theory of hadrons and particularly on the relevance of a three (fermion) field model to probe these higher symmetries. We recall that the three-field model with chiral decomposition assumes that the bare masses of all three quark fields are zero. It is then clear that the most reliable evidence for a higher symmetry group will be obtained at energies which are large compared to the masses of any hadrons involved in the experiment. The now known mass spectrum of the hadrons extends to about 2.5 BeV, and there is no reason to think that there may not be higher mass states (as well as larger spins, isospins, etc.). In an energy region where the masses of all hadrons may be neglected, one should be able to study the properties of the highest symmetry groups which exist in nature. In the particular case of the higher symmetry group $\bar{W}_3$, it is quite possible that some of the predictions³⁰ of broken $\bar{W}_3$ symmetry (e.g., the mass relations between the unitary meson multiplets of opposite parity) will hold reasonably well only at quite high energies. For example, the mass relations between unitary meson multiplets of opposite parity may not hold too well for small J (because of the large relative importance of the centrifugal barrier) and may hold rather well for the large values of J . The experimental evidence suggests that the larger J values go with the higher particle resonance energies and hence experiments at higher energies will be needed.

Equally, if the three-field model with "Casimir" decomposition is a more valid description of nature's underlying symmetries, super high energy experiments will be necessary to provide conclusive proof of a mixing of the Lorentz group with the internal symmetries (in some such fashion as suggested above). Furthermore, since, with "Casimir" decomposition, the large underlying group will be sustained for large bare masses of the triplet of basic quark fields, one ought to find massive quark particles at sufficiently high energies. The discovery of quarks would not only drastically change our current group-theoretic views but would strongly encourage dynamical calculations with the three-field model.

Whether or not some form of three-field fermion model turns out to be the proper framework for a unified theory of elementary particles,^{cc} we believe that it would be very surprising if the underlying group structure already known (and higher symmetries yet to be established) should turn out to be an accident. We agree that it is highly unlikely that any of the particles thus far observed will turn out to be more elementary than any other – to this extent we go along with the concept of "nuclear democracy."³⁸ However, it is our conviction that a small number of basic fields (three is the most likely at present) – sufficient to fix the underlying group structure but no more – will provide a much more satisfactory framework for an un-

^{cc}We believe that a three-field model will provide a guide for a theory of leptons side by side with a theory of hadrons (this is why we have lapsed into a statement about a unified theory of "elementary particles" rather than merely "hadrons"). Our old baryon-lepton symmetry principle (cf. Gamba, Marshak, and Okubo³⁷) would now postulate a correspondence between the triplet of 4-component lepton fields $[(\nu_e, \nu_\mu), e, \mu]$ and the triplet of quark fields whose "cosmic" interactions give rise to the observed hadrons. While this new "quark-lepton" symmetry principle raises difficulties of its own (see ref. 30), we share Schwinger's conviction²² that the number of lepton *particles* is not unconnected to the number of *fields* required to develop a unified theory of hadron particles.

derstanding of the hierarchy of interactions and the multiplicity of particles; in other words, we believe in an “oligarchy of fields”^{dd} structuring the “democracy of particles.” Super high energy experiments will be indispensable in deciding which “political” framework is operative in the subnuclear world.

REFERENCES

1. A.H. ROSENFELD ET AL., *Rev. Mod. Phys.* **36**, 977 (1964).
2. J. J. SAKURAI, *Ann. Phys. N.Y.* **11**, 1 (1960).
3. R.E. MARSHAK AND E.C.G. SUDARSHAN, *Introduction to Elementary Particle Physics*, Wiley, New York, 1961.
4. J.H. CHRISTENSON, J.W. CRONIN, V.L. FITCH, AND R. TURLAY, *Phys. Rev. Letters* **13**, 138 (1964).
5. J.H. WOJTASZEK, R.E. MARSHAK, AND RIAZUDDIN, *Phys. Rev.* **136**, B1053 (1964).
6. S. COLEMAN AND H. J. SCHNITZER, *Phys. Rev.* **136**, B223 (1964).
7. L. MICHEL, Lectures at Institut des Hautes Études Scientifiques, 1962.
8. R.E. MARSHAK, S. OKUBO, AND G. SUDARSHAN, *Phys. Rev.* **106**, 599 (1957).
9. O. KLEIN, *Arkiv Fysik* **16**, 191 (1959).
10. Y. YAMAGUCHI, *Progr. Theoret. Phys. Kyoto Suppl.* **11**, 1, 37 (1959).
11. M. IKEDA, S. OGAWA, AND Y. OHNUKI, *Progr. Theoret. Phys. Kyoto* **22**, 715 (1959).
12. M. GELL-MANN, *Phys. Rev.* **125**, 1067 (1962).
13. S. OKUBO, *Progr. Theoret. Phys. Kyoto* **27**, 949 (1962).
14. N. CABIBBO AND R. GATTO, *Nuovo Cimento* **21**, 872 (1961); S. COLEMAN AND S.L. GLASHOW, *Phys. Rev. Letters* **6**, 423 (1961).
15. M. GELL-MANN, *Phys. Letters* **8**, 214 (1964).
16. G. ZWEIG, CERN preprint.
17. S. OKUBO, C. RYAN, AND R. MARSHAK, *Nuovo Cimento*, in press.
18. S.V. PEPPER, C. RYAN, S. OKUBO, AND R. MARSHAK, preprint UR-875-60; *Phys. Rev.*, in press.
19. H.P. DÜRR, W. HEISENBERG, H. MITTER, S. SCHLIEDER, AND K. YAMAZAKI, *Z. Naturforsch.* **14a**, 441 (1959) and subsequent papers; the latest account is in lectures by H.P. Dürr at the Institute of Mathematical Sciences, Madras (issued as a report).
20. E. FERMI AND C.N. YANG, *Phys. Rev.* **76**, 1739 (1949).
21. M. LÉVY AND R.E. MARSHAK, *Nuovo Cimento* **12**, Suppl. No. 2, 253 (1955).
22. M. GOLDBERGER, *Phys. Rev.* **101**, 433 (1956).
23. J. SCHWINGER, *Phys. Rev.* **135**, B816 (1964).
24. F. GURSEY, T. LEE, AND M. NAUENBERG, *Phys. Rev.* **135**, B467 (1964).
25. L. DE BROGLIE, *La Lumière*, Hermann, Paris, 1940.
26. I. BIALNYCKI-BIRULA, *Phys. Rev.* **130**, 465 (1963).
27. Y. NAMBU AND G. JONA-LASINIO, *Phys. Rev.* **122**, 345 (1960) and subsequent papers.
28. W.E. THIRRING, *Nucl. Phys.* **10**, 97 (1959).
29. S. SAKATA, *Progr. Theoret. Phys. Kyoto* **16**, 686 (1956).
30. R. MARSHAK, N. MUKUNDA, AND S. OKUBO, *Phys. Rev.*, in press.
31. M. GELL-MANN, *Physics* **1**, 63 (1964).
32. B. SAKITA, *Phys. Rev.*, in press.
33. F. GURSEY AND L.A. RADICATI, *Phys. Rev. Letters* **13**, 175 (1964) and subsequent papers.
34. S. OKUBO AND R.E. MARSHAK, *Phys. Rev. Letters*, in press.
35. S. OKUBO AND R.E. MARSHAK, to be published.
36. E.P. WIGNER, *Science* **145**, 995 (1964).
37. A. GAMBA, R.E. MARSHAK, AND S. OKUBO, *Proc. Natl. Acad. Sci. U.S.* **45**, 881 (1959).
38. G.F. CHEW, M. GELL-MANN, AND A.H. ROSENFELD, *Scientific American*, February 1964, p. 74.

^{dd}We would prefer to use philosophical (rather than political) analogies: the observed particles would represent Aristotle's “substance” and the basic fields would correspond to Plato's “forms.”

Weak Interactions at High Energies

K. NISHIJIMA
University of Illinois

In this article the role played by weak interactions at high energies is discussed, as well as its significance in elementary particle physics. Also, a possible connection between strong and weak interactions is suggested.

1. DESCRIPTION OF ELEMENTARY PARTICLES

First the appropriate language for describing elementary particles is indicated. Since elementary particles are the smallest units of which our universe is composed, quantum mechanics must be used in their description. Also, the elementary particles observed travel usually at velocities high compared to that of light so that it is imperative to employ relativity as one of the basic postulates. Next two distinctive ways of describing the motion of a dynamical system are presented, followed by a discussion of which description suits our purpose better.

Particle Description

Consider a dynamical system consisting of a certain number of particles. The most naive way of describing the motion of a system is to watch all the particles in the system and then express all the particle coordinates as functions of time. This is the classical description and is probably the most useful way of describing the behavior of a macroscopic system. When applied to a microscopic system this method suffers from various difficulties, e.g., when two identical particles collide it is not possible to identify particles before and after the collision. However, since a quantum mechanical description is used, this objection is not a serious one. In quantum mechanics a wave function is introduced which is a function of all the particle coordinates of the system under consideration as well as of time. In this case the system of identical particles can be properly described unambiguously. This is useful as long as the total number of particles involved in the system is conserved; when the number of particles can change, this description ceases to be useful.

Field Description

The situation described above may be compared to the police activity of finding a criminal. The most natural way is to let detectives follow and watch all the suspects until they discover some evidence. However, if a suspect suddenly escapes from the observation of the detective following him, the investigation becomes incomplete and the police might fail to find a clue. Instead, one can think of a better, more complete way of finding the offender. Namely, send as many detectives as possible to all the important spots and let every detective report what happened at every spot. In this way every spot can be covered and one can expect complete ob-

servation of the suspects. In the world of elementary particles similar things happen, and the second method of observation is needed.

It has long been known that certain nuclei are radioactive and emit β rays, and the β radioactivity is due to the following fundamental interaction first introduced by Fermi:

$$n \rightarrow p + e^- + \bar{\nu} \quad (1.1)$$

where n , p , e^- , and $\bar{\nu}$ denote the neutron, proton, electron, and antineutrino, respectively. Had a detective followed the neutron and observed it decaying into three particles, he would certainly be confused in deciding which particle to follow. In order to describe such phenomena it is necessary to watch every small domain of space and observe what happens there. Incidentally, there are also two distinctive descriptions in hydrodynamics. The particle description corresponds to Lagrange's and the field description corresponds to Euler's. In elementary particle physics it is an especially convenient way of description to give the numbers of various particles in every small domain of space. Then it is possible to describe phenomena in which creation and annihilation of particles take place, and this is essentially the field theoretical description. Field theory is a branch of quantum mechanics which deals with elementary processes accompanied by creation and annihilation of particles. Also, it is first in field theory that one can correctly understand the dual nature of matter as particles on one hand and as waves on the other hand. Suppose that a particle is created at a point A and destroyed at another point B ; then it exhibits the particle nature at A and B , since the number of particles changes at these points, but between A and B it exhibits the wave nature propagating like a wave, i.e., showing interference and diffraction phenomena. The photoelectric effect is an example of the former.

2. INTERACTIONS

When two or more particles collide they are scattered by the force they exert on each other, or something more complicated happens. As an example consider the chemical reaction

In this reaction all the particles before and after the collision consist of "indivisible" atoms, and in general a chemical reaction represents a rearrangement of the indivisible constituents. In chemical reactions and also in low energy nuclear reactions the number of each basic constituent does not change, but this is the case only at certain low energy regions. Even in classical physics, however, there are examples of processes in which the number of particles changes. Take, for instance, a broadcasting station which sends radio waves generated by oscillating electric current. Clearly this process represents creation of a large number of photons, but in classical physics radio waves are regarded as waves and the number of emitted photons is never counted.

Correspondingly in quantum mechanics various processes are known involving creation and/or annihilation of photons, e.g.,

$$\gamma + d \rightarrow p + n , \quad (2.2)$$

where γ and d denote the photon and deuteron, respectively. In the photodisintegration of the deuteron quoted above only the number of photons changes, but the number of protons or of neutrons remains unchanged provided the deuteron consists of a proton and a neutron.,

Another more drastic example is the β decay of the neutron (1.1) in which none of the four kinds of particles are conserved. This example leads to the conclusion that there are no "indivisible" particles in the world of elementary particles. The "indivisible" atoms in chemical reactions are really indivisible only when the kinetic energies involved are low enough and of the order of electron volts. At high energies the atoms lose the appearance of "indivisible" particles. The atomic nuclei seem to be more rigid than the atoms, but even they can be disintegrated when the kinetic energies involved are of the order of MeV or higher. This leaves the so-called elementary particles, but they, too, cannot be regarded as the basic constituents of matter, since none of them are really conserved in reactions involving energies of the order of BeV or higher. Consequently one may ask, what are the most basic constituents? This question is clearly related to another question: What are the elementary particles? No one knows the answers to these questions, but some people think that the most fundamental constituents of matter are not particles but something more abstract, such as charge, baryon number, and isospin. No attempt will be made to define these attributes here, but it should be mentioned that these attributes are conserved or approximately conserved in elementary particle reactions so that they are "indivisible." They do not represent particles, but certain combinations of them can be represented by particles. In other words, particles render to attributes certain frames in which these attributes can manifest themselves to be the basic constituents.

Next to be discussed are interactions. Roughly speaking, the term interaction in elementary particle physics is used as the quantum mechanical extension of the concept of force in classical mechanics. When there are two charged particles the force acting between them is the Coulomb force, and this is also true in the microscopic world, so that the mechanism of this force will be analyzed microscopically. In classical field theory, e.g., in general relativity or in classical electrodynamics, it is known that a force is transmitted by a field. Namely, a charged particle generates the electromagnetic field and a massive particle generates the gravitational field, and the field generally carries energy and momentum received from the source. When another particle feels the field it can receive energy and momentum from the field. Consequently two particles can exchange energy and momentum between them, and this exchange is said to be generated by the force acting between them. Classically the exchange of energy and of momentum is supposed to take place continuously in time, and the motion of these particles is described by differential equations. Quantum mechanically, however, the exchange of energy and of momentum occurs discontinuously in time, as is clear from the example of the photoelectric effect. In other words, the field exhibits its particle nature when the source particles release or receive energy and momentum. The particle associated with a field is called the quantum of that field. As is well known, Yukawa deduced the presence of π mesons as the quanta of the fields responsible for the strong nuclear forces holding nucleons tightly together to form nuclei. This leads naturally to the conclusion

that the interaction between two particles is generated by the exchange of quanta between them, e.g., photons are exchanged between two charged particles and π mesons are exchanged between nuclear particles to generate the Coulomb force and nuclear force, respectively. The nuclear particle, either the proton or the neutron, is called the nucleon. Therefore, the most fundamental interactions are emission and absorption of a quantum, e.g.,

$$e^- \rightleftharpoons e^- + \gamma, \quad (2.3a)$$

$$n \rightleftharpoons p + \pi^- \quad (2.3b)$$

where e^- and π^- denote the electron and the negatively charged π meson, respectively.

By piling up these fundamental interactions elementary processes can be generated. Upon carefully examining the elementary interactions one might wonder how these processes could take place, since they inevitably violate conservation of energy-momentum. For instance, if the neutron on the left side of Eq. (2.3b) is at rest, the $p + \pi^-$ system on the right side always has more energy. This is, however, not a contradiction, since neither energy nor momentum of such states is well defined if such an elementary reaction takes place in a very short time. For instance, assume that the state $p + \pi^-$ goes back to the original state after a short time Δt ; then the uncertainty of energy or the energy difference between the initial and intermediate states, ΔE , should satisfy the uncertainty relation

$$\Delta E \cdot \Delta t \sim \hbar. \quad (2.4)$$

If the rest energy of the π meson is taken as ΔE , the time for Δt will be extremely short:

$$\Delta t \sim 10^{-23} \text{ sec.} \quad (2.5)$$

As long as the intermediate state disappears in such a short time, there is no conflict with the conservation laws.

To discuss elementary particle reactions the language of field theory or of the second quantization will be used. Consider, as an illustration, the Compton scattering. Combining the fundamental interaction (2.3a) twice results in

$$\gamma + e^- \rightarrow e^- \rightarrow \gamma + e^-, \quad (2.6a)$$

or

$$\gamma + e^- \rightarrow \gamma + \gamma + e^- \rightarrow \gamma + e^-. \quad (2.6b)$$

In the first case, emission of a photon follows absorption of the photon initially present, and in the second case emission precedes absorption. The intermediate states in both cases are short-lived because of the uncertainty principle, but the final state can live long enough to be subjected to observation since it does not offer any conflict with conservation laws even when it lives a long time.

Quantum mechanics is concerned with the probability of a certain process occurring, and a mathematical formalism may be used to describe this. In order to describe transitions between states, consider a complete set of states with each state living long enough to be subjected to experimental measurements. Assume that the starting state is α and some experiments are done. According to quantum mechanics

one cannot say what the final state will be, nevertheless one can say that such and such processes will occur with such and such probabilities. With the probability for the process $\alpha \rightarrow \beta$ denoted by $p_{\beta\alpha}$, it is clear that one obtains

$$\sum_{\beta} p_{\beta\alpha} = 1, \quad (2.7)$$

provided one sums over the complete set of states, since “something” should be in the final state. This equation expresses the conservation of probability. According to quantum mechanics the transition probability is given by the absolute square of the transition amplitude, denoted by $S_{\beta\alpha}$, i.e.,

$$p_{\beta\alpha} = |S_{\beta\alpha}|^2. \quad (2.8)$$

In terms of S the conservation of probability is expressed by

$$\sum_{\beta} S_{\beta\alpha}^* S_{\beta\alpha} = 1. \quad (2.9)$$

When S is regarded as a matrix, this relation can further be simplified:

$$\sum_{\beta} (S^+)_{\alpha\beta} S_{\beta\alpha} = (S^+ S)_{\alpha\alpha} = 1, \quad (2.10)$$

where S^+ denotes the Hermitian conjugate of the matrix S .

By making use of the fact that α is an arbitrary state one can prove that S is a unitary matrix. Take two orthogonal states α and β , and define the third state α' by

$$|\alpha'\rangle = c_1 |\alpha\rangle + c_2 |\beta\rangle, \quad (2.11)$$

where

$$|c_1|^2 + |c_2|^2 = 1. \quad (2.12)$$

From (2.10) one gets

$$(S^+ S)_{\alpha\alpha} = (S^+ S)_{\beta\beta} = (S^+ S)_{\alpha'\alpha'} = 1. \quad (2.13)$$

With the help of (2.11) the last equation can be written as

$$(S^+ S)_{\alpha'\alpha'} = |c_1|^2 (S^+ S)_{\alpha\alpha} + |c_2|^2 (S^+ S)_{\beta\beta} + 2 \operatorname{Re}[c_2^* c_1 (S^+ S)_{\beta\alpha}] = 1.$$

Then by using (2.12) and (2.13) one finds

$$\operatorname{Re}[c_2^* c_1 (S^+ S)_{\beta\alpha}] = 0. \quad (2.14)$$

Since c_1 and c_2 are arbitrary except for the normalization condition (2.12), one arrives at

$$(S^+ S)_{\beta\alpha} = 0. \quad (2.15)$$

This shows that

$$(S^+ S)_{\beta\alpha} = \delta_{\beta\alpha} \quad (2.16)$$

and similarly

$$(S S^+)_{\beta\alpha} = \delta_{\beta\alpha}. \quad (2.17)$$

This concludes the proof of the unitarity of the S -matrix. S is called the scattering

matrix or simply the S -matrix following Heisenberg.¹ One of the main problems in field theory is to compute the S -matrix by piling up fundamental interactions. The transition amplitude corresponding to a fundamental interaction is called the coupling constant. The magnitude of the coupling constant gives a measure of whether the corresponding fundamental process takes place fast or slowly. The electric charge is also the coupling constant for the process (2.3a).

3. CLASSIFICATION OF INTERACTIONS

The concept of fundamental interactions was introduced in the preceding section. All the known interactions may be classified into four classes in the order of decreasing strength: (1) the strong interactions, (2) the electromagnetic interactions, (3) the weak interactions, (4) the gravitational interactions. The strong interactions are represented by the interaction between the π meson (or pion) and the nucleon. They represent the strongest interactions of all the four classes. The second and fourth classes are already familiar in classical physics since they give long-range forces. The third class is represented by the β -decay interaction.

First of all it should be pointed out that there are remarkable differences in the order of magnitude of the coupling constants among these four classes. The electromagnetic interactions are weaker than the strong interactions by a factor of about 100, but the weak interactions are much weaker by an enormous factor of about 10^{12} . This is really a fantastic difference, so that there is no ambiguity in classifying interactions between the strong and weak interactions.

It is also known that the strong interactions are very rich in symmetry properties, but for weaker interactions there are fewer symmetries. As a matter of fact it was only seven years ago that the violation of parity was discovered in weak interactions. In general, weaker interactions are less symmetric.

In the family of strongly interacting particles it is known that there exists a multiplet structure of particles, i.e., some elementary particles behave in a very similar manner just as twin or triplet brothers do. Thus they can be grouped into many families. The characteristic feature of each family is that each member carries a different unit of charge just as twin brothers carry their name tags. This family of elementary particles is called the charge multiplet, and, since all the members behave very similarly independent of charge, this symmetry law is called the principle of charge independence. Examples of the charge multiplets are (1) the nucleon doublet consisting of the proton and neutron, and (2) the pion triplet consisting of π^+ , π^0 , and π^- . It is also clear, however, that the members of a charge multiplet behave quite differently for the electromagnetic interactions, which are then utilized to distinguish among the members of a multiplet. Thus the electromagnetic interactions violate the principle of charge independence, though only slightly, because of the weakness of the electromagnetic interactions as compared with the strong interactions.

A few years ago the possibility was studied by Gell-Mann and also by Ne'eman² of whether members from different families might be related, and they concluded that some of them could be cousins. Thus, based on the kinship among some families, they grouped the elementary particles into larger families. This symmetry is called

the unitary symmetry. An example of a large family is given by the eight baryons, (p, n) , $(\Sigma^+, \Sigma^0, \Sigma^-)$, (Λ) , and (Ξ^0, Ξ^-) . As is clear from its realization, the unitary symmetry is violated strongly already within the framework of the strong interactions. Besides, the strong interactions are invariant under various reflections such as charge conjugation, space reflection, and time reversal. In weak interactions almost all such symmetries are violated.

4. QUANTUM ELECTRODYNAMICS AND RENORMALIZATION

Two clear-cut differences between the strong and weak interactions have been discussed. For many purposes it is convenient to include the electromagnetic interactions with the strong interactions. There is, however, one more important difference between them which was left out in the preceding section. The discussion of the third difference constitutes the theme of this article, but for that purpose some preparation is needed.

As an example of strong interactions consider the electromagnetic interactions, since they are familiar in classical and atomic physics. The main subject in quantum electrodynamics is the evaluation of the S -matrix by iterating the fundamental interaction (2.3a), and the Compton scattering (2.6) is a typical example of the objects of the calculation. In Eq. (2.6) two alternative possibilities, (2.6a) and (2.6b), were given, but they are not the only possibilities. One can reach the same final state by iterating the fundamental interaction four times or generally an even number of times. These represent the higher-order corrections, and the corresponding amplitudes are proportional to higher powers of the coupling constant. In quantum electrodynamics the S -matrix elements are computed in powers of the fine structure constant α defined by

$$\alpha = \frac{e^2}{4\pi\hbar c} \approx \frac{1}{137}, \quad (4.1)$$

where the electronic charge e is given in Heaviside units. Since the expansion parameter is rather small as compared with unity, higher-order corrections are numerically small; and, as long as lowest-order results are satisfactory, there are no serious difficulties. The progress of the experimental technique, however, forced the theoreticians to compute the higher-order corrections.

The most serious difficulty in calculating higher-order corrections is that they diverge and thus prevent one from obtaining any sensible results from the calculations. This difficulty was recognized immediately after the formulation of quantum field theory. In the 1940's, however, a prescription called the renormalization prescription was developed to extract meaningful results from divergent expressions and was successfully applied to quantum electrodynamics. In order to present this idea, two types of basic divergences encountered in quantum electrodynamics are introduced here.

Self Energy

Consider an electron which generates a static Coulomb field around itself. This field is called the self-field of the electron. The energy of this system or of this physi-

cal electron is given by the sum of the rest energy of the electron and the energy carried by the self-field. Since this effectively increases the mass of the electron, one should distinguish between the effective mass m and the original mechanical mass m_0 of the bare electron. Then one can write a relation

$$m = m_0 + \delta m, \quad (4.2)$$

where δm is the change of mass due to the energy carried by the self-field. Even the classical Lorentz theory of the electron suffered from the divergent character of the self energy δm for the point electron. This difficulty has been inherited by quantum electrodynamics. It should be emphasized here that the experimentally observed mass is not m_0 but m .

Vacuum Polarization

In a dielectric medium the Coulomb potential between two charged particles of charges e' and e'' is given by

$$V(r) = \frac{1}{4\pi} \left(\frac{e' e''}{\epsilon r} \right), \quad (4.3)$$

where ϵ denotes the dielectric constant and the unfamiliar factor 4π enters into the denominator in the Heaviside units.

In classical physics it is assumed that the vacuum cannot be polarized since it is empty, so that

$$\epsilon_{\text{vac}} = 1. \quad (4.4)$$

In quantum field theory, however, this is not the case. Relativity requires that the elementary process (2.3a) be generalized so as to include

$$\gamma \rightleftharpoons e^+ + e^-. \quad (4.5)$$

This means that the electromagnetic field can produce the electron-positron pair out of the vacuum so that the vacuum is a polarizable dielectric medium. Therefore, the Coulomb potential between two charges e'_0 and e''_0 in the vacuum is given by

$$V(r) = \frac{1}{4\pi} \left(\frac{e'_0 e''_0}{\epsilon_0 r} \right), \quad (4.6)$$

where ϵ_0 is the dielectric constant of the vacuum. If e' and e'' are defined by

$$e' = e'_0 / \sqrt{\epsilon_0}, \quad e'' = e''_0 / \sqrt{\epsilon_0}, \quad (4.7)$$

the classical Coulomb potential can be reproduced in the vacuum:

$$V(r) = \frac{1}{4\pi} \left(\frac{e' e''}{r} \right). \quad (4.8)$$

In quantum electrodynamics the dielectric constant of the vacuum is denoted by Z_3^{-1} , i.e.,

$$\epsilon_0 = Z_3^{-1} \quad (4.9)$$

which is supposed to be larger than unity. The actual evaluation shows that it is

divergent. It should be mentioned that the experimentally observed charge is not e_0 but it is e that enters into (4.8).

Renormalization³

Two types of divergences have been discussed, the self energy δm and the dielectric constant ϵ_0 . In the higher-order calculations of the S -matrix elements, divergences are again encountered. When a certain S -matrix element is regarded as a function of m_0 and e_0 and of some external momenta, i.e., the momenta of particles in the initial and final states, this expression involves divergences. In order to overcome this difficulty one can reason in the following way: When m_0 is assumed to be finite, m becomes infinite since δm is infinite; but when, instead, m is assumed to be finite, m_0 becomes infinite. The latter choice seems to be more reasonable than the former since one can observe only m and never m_0 . Similarly it seems more reasonable to assume e to be finite and e_0 to be infinite. Therefore, the same idea can be applied to the S -matrix elements. If a typical matrix element is written as

$$F(m_0, e_0, \mathbf{p}_1, \mathbf{p}_2, \dots) = F(m - \delta m, \sqrt{\epsilon_0}e, \mathbf{p}_1, \mathbf{p}_2, \dots), \quad (4.10)$$

then it so happens that in the second form, δm and ϵ_0 cancel all the divergences in the rest of the matrix element. In other words, every S -matrix element becomes a finite function of $m_0 + \delta m$ and $e_0/\sqrt{\epsilon_0}$, i.e.,

$$S(m_0 + \delta m, e_0/\sqrt{\epsilon_0}, \mathbf{p}_1, \mathbf{p}_2, \dots). \quad (4.11)$$

When m_0 and e_0 are regarded as finite quantities, this matrix element becomes divergent because of the divergent character of δm and ϵ_0 , but when $m_0 + \delta m$ and $e_0/\sqrt{\epsilon_0}$ are identified with the experimentally observed finite mass and charge, the result is a completely finite expression:

$$S(m, e, \mathbf{p}_1, \mathbf{p}_2, \dots). \quad (4.12)$$

Namely, in quantum electrodynamics δm and ϵ_0 are the only sources of divergences, and all the other divergences can be attributed to them. These reinterpretations of mass and of charge are called the mass and charge renormalization, respectively.

As can be seen in (4.12), the unobservable unphysical divergent quantities m_0 and e_0 disappear completely from the S -matrix. The proof that all the divergences in the S -matrix can be traced back to those of δm and of ϵ_0 as in (4.11) is by no means trivial, and it will not be given here. With the help of the renormalization technique higher-order corrections can be computed without suffering from divergences. The theoretical calculations of the Lamb shift and of the anomalous magnetic moment of the electron based on the renormalization prescription showed excellent agreement with experiment, and quantum electrodynamics became a highly successful theory.

The renormalization prescription, however, has a limited applicability, and it is useful in eliminating divergences only for a limited class of interactions. In quantum electrodynamics all the divergences can be eliminated by means of the mass and charge renormalization, but for some other types of interactions there remain divergences that cannot be attributed to the self energy or to the vacuum polarization. When all the divergences can be attributed to the masses or self energies and

the charge or coupling constants, the interaction is called renormalizable, otherwise it is called unrenormalizable. It is important to classify all the known interactions into these two categories in order to know the limitations imposed on the applicability of the renormalization prescription. There has been an extensive study of this problem, and at present there seems to be no reason to believe that unrenormalizable interactions are needed to describe strong interactions including the electromagnetic interactions, nor do we know for sure that they are really renormalizable. On the other hand, however, it is rather certain that renormalizable interactions cannot properly describe the properties of weak interactions. For instance, the Fermi interaction (1.1) is known to be unrenormalizable. The renormalizability of interactions is the third difference between the strong and weak interactions.

Anyway, it must be admitted that the renormalization prescription is not almighty – that the real unsolved divergence problem is still present, although the renormalization technique has proved to be surprisingly successful in quantum electrodynamics. This problem has never been studied seriously, however, since the weak interactions are so weak that the troublesome higher orders are rarely of interest.

5. DISPERSION THEORY

Following the success of laboratory production of pions and subsequently of many other particles, the uselessness of perturbation theory in strong interaction physics became widely recognized, and more powerful methods were sought. Two main outcomes of these efforts are (1) dispersion theory, and (2) group theory or invariance principles. The discussion here will be mainly about the former, in connection with weak interactions.

One of the reasons why the renormalization prescription was not useful in strong interaction physics, in particular in pion physics, was that the prescription has been formulated only in perturbation theory, i.e., in series expansions in powers of the coupling constant. It was not clear how to remove divergences from the theory in approximations other than perturbation theory. For this reason relationships which hold among finite observable quantities alone were looked for, and the one outstanding relationship of this kind happened to be the dispersion relations connecting the real and imaginary parts of scattering or reaction amplitudes. The best known example, first formulated by Goldberger, is the forward-scattering dispersion relations in pion-nucleon scattering.⁴ One of the characteristic features of dispersion relations is that they are supposed to be valid independently of the details of interactions, so that they could provide a consistency check of the fundamental principles underlying relativistic quantum mechanics. The forward-scattering dispersion relations were so successful that efforts have been made to generalize the dispersion theory to a dynamical theory. In other words, dispersion relations, instead of being used as a means of checking the consistency of field theory, were and still are considered to provide an adequate basis for evaluating scattering and reaction amplitudes.⁵ The dispersion relations have been formulated not only for those amplitudes that are essentially the S -matrix elements but also for vertex functions or reaction amplitudes for virtual particles. The concept of virtual particles and the

definition of vertex functions will be discussed below. The best known vertex functions of this kind are the electromagnetic form factors of the nucleons whose analyses led to the prediction regarding the presence of the vector mesons ρ^6 and ω .⁷

Vertex Functions

As discussed above, the fundamental process (2.3) cannot be observed, since the uncertainty principle (2.4) requires either the initial or final state or both to be short-lived, otherwise they violate conservation of energy. Particles appearing in such unobservable intermediate states are called virtual particles. Since virtual particles live only for short periods of time, their energies cannot be sharply defined, so that the masses of such particles are not necessarily equal to the experimentally observed masses.

Consider the electron-proton scattering due to a photon exchange:

$$e^- + p \rightarrow e^- + \gamma + p \rightarrow e^- + \bar{p} . \quad (5.1)$$

This process consists of the following two fundamental processes:

$$e^- \rightleftharpoons e^- + \gamma , \quad p \rightleftharpoons p + \gamma . \quad (5.2)$$

An important observation is that both the electron and the proton are real particles in (5.1) so that their masses are well defined, while the photon is a virtual particle in this process so that its mass is not well defined. The fundamental interactions (5.2) were represented by point interactions in section 2, but higher-order corrections can be incorporated in evaluating the amplitude for

$$p \rightleftharpoons p + \text{"}\gamma\text{"}, \quad \text{or} \quad p + \bar{p} \rightleftharpoons \text{"}\gamma\text{"}, \quad (5.3)$$

where the quotation marks refer to virtual particles and $\bar{p}$ denotes the antiproton. The corresponding amplitude is a function of the variable mass of the virtual photon and is called the vertex function or the form factor. Although it is physically impossible, one can mathematically continue the vertex function into an unphysical configuration in which all the particles are real, then the vertex function reduces to the so-called renormalized coupling constant. In the case of the electromagnetic interactions the renormalized coupling constant coincides with the observed charge. If the square of the variable mass of the virtual particle is denoted by s and the vertex function by $F(s)$, then, in the case of the electromagnetic vertex function,

$$F(0) = e . \quad (5.4)$$

In general more than one vertex function is needed to express the spin dependence of the interactions, but such complications will not be introduced here. The function $F(s)$ is called the electromagnetic form factor, since it is a generalization of the atomic form factors used in the description of the scattering of x rays from atoms.

It is amusing to speculate on how the function $F(s)$ would behave for large values of s , or for large values of the momentum transfer to the proton. The virtual photon gives a sudden impulse to the proton, and the proton suddenly changes its course leaving its self-field behind it, and the interaction would reduce to the one between the photon and the bare proton that is equal to bare charge e_0 , i.e.,

$$F(\infty) = e_0 . \quad (5.5)$$

Of course, the above argument, as well as the result, is an oversimplification, but it gives some insight into the relationship between the high energy behavior and renormalization.

Unitarity

An S -matrix element may be thought of as a box, with lines originating from this box corresponding to incoming and outgoing particles. This box is supposed to be composed of combinations of fundamental interactions, and the problem is to study its structure. The most direct way is to cut the box into two parts to see what is happening inside, and in this way various intermediate states can be found. Since the box is cut into two, however, the two parts are no longer identical with the original box. The two parts represent the so-called absorptive part of the S -matrix element under consideration. In other words, the absorptive part of an S -matrix element can be decomposed into the product of two other S -matrix elements or their sum. It will be shown that this observation can be realized by the unitarity condition for the S -matrix.

The S -matrix may be written in the following form:

$$S_{\beta\alpha} = \delta_{\beta\alpha} + i(2\pi)^4 \delta^4(P_\beta - P_\alpha) T_{\beta\alpha}, \quad (5.6)$$

where P_α and P_β stand for the total energy-momentum vectors of the initial and final states, α and β , respectively. The four-dimensional δ -function, then, expresses the conservation of energy and momentum. When there are no interactions at all, T is equal to zero. Substitution of (5.6) into the unitarity condition for S gives

$$\text{Im} T_{\beta\alpha} = \frac{(2\pi)^4}{2} \sum_n T_{\beta n} \delta^4(P_\beta - P_n) T_{n\alpha}. \quad (5.7)$$

The left side is the absorptive part of T and the right side corresponds to the two pieces of the cut box. In order to study the structure of the box it was cut into two pieces and the absorptive part was obtained, but in order to recover the original box a tool is needed to sew them together. The sewing machine for this purpose is the dispersion relations.

Dispersion Relations

The S -matrix elements are the scattering or reaction amplitudes for real particles, and the vertex functions are the corresponding amplitudes for virtual particles. For both objects dispersion relations can be introduced.

The dispersion relations are considered to follow from the causality condition, but their connection is not very clear, since the causality condition alone does not suffice for the proof of dispersion relations. The dispersion relation in field theory is a statement about the analyticity property of a certain amplitude as a function of a certain Lorentz invariant dynamical variable. As an example, the dispersion relation for a form factor $F(s)$ will be considered. Assume that this function is analytic in the upper half complex s -plane, then, from Cauchy's theorem,

$$\text{Re} F(s) = \frac{P}{\pi} \int_{-\infty}^{\infty} ds' \frac{\text{Im} F(s')}{s' - s}, \quad (5.8)$$

where P stands for the principal value. A number of amplitudes and vertex functions satisfy dispersion relations of this type. $\text{Re}F(s)$ and $\text{Im}F(s)$ are called the dispersive and absorptive parts, respectively. The dispersion relation (5.8) can be cast into an alternative form,

$$F(s) = \frac{1}{\pi} \lim_{\varepsilon \rightarrow +0} \int_{-\infty}^{\infty} \frac{\text{Im}F(s')}{s' - s' - i\varepsilon} ds'. \quad (5.9)$$

This dispersion relation indicates that the amplitude $F(s)$ can be determined if its absorptive part $\text{Im}F(s)$ is given, and this is exactly what was needed in the preceding subsection.

Apparently no new parameters are introduced through dispersion relations of this type, called the unsubtracted dispersion relations. They fail to hold, however, in many cases, e.g., when the integral on the right side of (5.8), called the dispersion integral, fails to converge. The box representing a certain amplitude cannot always be cut into two pieces, e.g., when the box represents a point-interaction. In such a case the amplitude is equal to the (bare) coupling constant, and its absorptive part is equal to zero, so that the dispersion relation (5.8) clearly fails to hold. When the unsubtracted dispersion relation fails, it can be modified into the following form as the first step:

$$\text{Re}F(s) = \lambda_0 + \frac{1}{\pi} P \int_a^{\infty} ds' \frac{\text{Im}F(s')}{s' - s}, \quad (a > 0) \quad (5.10)$$

where an appropriate lower limit $a > 0$ is introduced in order to cope with the real physical situation. The constant λ_0 cancels the divergence in the dispersion integral when it diverges, or it represents the bare coupling constant that cannot be represented by the dispersion integral. In general, however, these two causes of failure of (5.8) are not independent but are intimately related. When the dispersion integral diverges, λ_0 must be divergent in order to make $F(s)$ finite. This subtraction of a divergent constant has a strong formal resemblance to the renormalization procedure, and in fact the equivalence can be established by a direct comparison of the higher-order contributions. Thus it is known that the above subtraction corresponds to the charge renormalization. The form (5.10) is not convenient for practical purposes, however, since it involves a divergent constant λ_0 as well as a divergent integral; therefore, it will be rewritten in a more convenient form. If the physical mass of the virtual particle in the form factor $F(s)$ is called $\sqrt{s_0}$, then the equation

$$\text{Re}F(s_0) = \lambda \quad (5.11)$$

defines the renormalized coupling constant. Then putting $s = s_0$ in (5.10) results in

$$\lambda = \lambda_0 + \frac{1}{\pi} P \int_a^{\infty} ds' \frac{\text{Im}F(s')}{s' - s_0}.$$

Subtraction of this equation from (5.10) gives

$$\text{Re}F(s) = \lambda + \frac{s - s_0}{\pi} P \int_a^{\infty} ds' \frac{\text{Im}F(s')}{(s' - s_0)(s' - s)}. \quad (5.12)$$

When $s_0 < a$, $F(s_0)$ is real and equal to λ . In this form the integrand acquires an extra factor $s' - s_0$ in the denominator, and the convergence of the dispersion integral

is improved as compared with the original one. Furthermore, (5.12) guarantees (5.11). The dispersion relations of this type are called the once-subtracted dispersion relations. The subtraction obviously introduces a new parameter in the theory which cannot be calculated within the framework of the theory. Thus these parameters play exactly the same role as do the renormalized coupling constants in field theory. In the case of the proton charge form factor

$$F(0) = e, \quad (5.13)$$

where e is the protonic charge, which is nothing but a renormalized coupling constant.

Once external parameters are introduced, the situation is very similar to that of field theory. The subtraction constants give the Born approximation expressions to the vertex functions or the S -matrix elements, and the higher-order corrections are given by the dispersion integrals provided the absorptive or imaginary parts are known. The absorptive parts can be expressed in terms of the vertex functions and the S -matrix elements with the help of the unitary condition. In this way one can formulate a theory based on dispersion relations and unitarity. This program was pushed further forward by Mandelstam's discovery of the double dispersion relations bearing his name.⁸

At this stage it is instructive to study the merits of the dispersion theory as compared with the renormalized field theory. The simplest and most direct comparison can be made by computing the S -matrix elements in powers of the renormalized coupling constant or of the subtraction constant. In the lowest few orders one can verify their equivalence and learn a lot of interesting lessons. First of all, subtraction of divergences or renormalization in field theory can be carried out only in perturbation theory, but an important observation about the divergences is that they appear in every order only in the *dispersive or real part of the amplitude*. The separation between absorptive and dispersive parts can be clearly introduced only in dispersion theory, and furthermore the divergences can be removed in dispersion theory in such a way that they do not appear explicitly by using the subtracted form of dispersion relations, whereas this separation cannot be introduced into field theory since only the combined amplitudes can be computed in this method. This enables dispersion theory to eliminate divergences without recourse to perturbation theory. This is one of the most important features of dispersion theory and deserves emphasis in connection with its applications to strong interaction physics.

6. RENORMALIZATION OF WEAK INTERACTIONS

When dispersion relations are applied to weak interactions, the three main differences between strong and weak interactions should be kept in mind: (1) There is an enormous difference in the order of magnitude of the coupling constant. (2) There are big differences in the transformation properties, i.e., many of the invariance principles in strong interactions are violated in weak interactions. (3) The last, but not the least, difference consists in the renormalizability.

In this article the last point is of particular interest, and the condition of renormalizability will be formulated in dispersion theory based on the correspondence

between dispersion and field theories mentioned above. The condition of renormalizability has been formulated in perturbation theory, therefore it will be reformulated in dispersion theory based on the power series expansion. If a perturbation calculation of the S -matrix elements or the vertex functions is carried out in dispersion theory in the manner described in the preceding section, the Born terms are given by the subtraction constants, and the higher-order corrections are given by dispersion integrals. For the sake of definiteness, once-subtracted or unsubtracted dispersion relations are assumed for the amplitudes of interest. The integrand of the dispersion integral in the lowest order is given by the product of the two Born terms as is clear from unitarity. Suppose that the once-subtracted or unsubtracted dispersion integral is convergent as originally assumed, then the iteration procedure can be continued to higher orders. When all the once-subtracted and unsubtracted dispersion integrals in higher orders are convergent, the subtractions originally assumed are sufficient to make the theory convergent in power series expansion, and the theory is called renormalizable. On the other hand, it happens sometimes that one subtraction is not sufficient to make some dispersion integrals convergent. In such a case more subtractions, say two, are needed to make the integrals convergent, but this does not help the situation since it makes the Born terms more divergent. The more subtractions are introduced, the worse become the divergences in the dispersion integrals leading to an avalanche of divergent integrals. This leads to the conclusion that the theory cannot be made convergent by means of subtractions, and when this is the case the theory is called unrenormalizable. The Fermi interactions are unrenormalizable in this sense.

A device is needed to remove unmanageable divergences from weak interactions. It is clear from the above arguments that no solution to this problem can be found with use of the power series expansion. One particularly interesting problem is the determination of the number of subtractions in each dispersion relation. It should be mentioned beforehand that the use of perturbation theory for strong interactions has to be avoided since its convergence is very unlikely. As a matter of fact, the coupling constant for the pion-nucleon interaction corresponding to the fine structure constant in electrodynamics is as large as 15. Strong interactions are renormalizable in perturbation theory and do not give rise to any unmanageable divergences, but it is not known what would happen if a nonperturbative method were used. It is hoped, however, that the divergence difficulty in the exact theory is less serious than in perturbation theory, since unitarity imposes strong limitations on all the amplitudes.⁹ In perturbation theory the limitations imposed by unitarity are satisfied only term-wise in each power of the expansion but not necessarily by the sum. Hence it may be reasonable to assume the absence of divergence difficulties in the pure strong interactions.

Since the unrenormalizability of the weak interactions arises when they are treated in perturbation theory, perturbation theory should be avoided; but the interpretation of this requirement is not unique. There are two kinds of interaction in interplay, renormalizable strong interactions and unrenormalizable weak interactions. The criterion for the renormalizability refers to perturbation theory. Therefore, in order to find a convergent theory, perturbation theory should be avoided in at least one of these two types of interactions. It will be assumed here that perturba-

tion theory for weak interactions is reasonable, since the way in which some selection rules manifest themselves in weak interactions seems to provide evidence for the higher-order corrections in weak interactions being unimportant. Exact conservation laws valid in the lowest-order weak interactions are likely to survive also in higher orders, but selection rules governing the change of a certain quantum number, such as the $|\Delta I| = \frac{1}{2}$ in strange particle decays, are likely to be subjected to modifications if higher-order corrections should be essential in making the theory convergent. The selection rule $|\Delta I| = \frac{1}{2}$ will be further discussed in the next section. For this reason it is assumed that it is the nonperturbative treatment of strong interactions that makes weak interactions free from unmanageable divergences. In other words, it is assumed that the high energy behavior of weak interactions can be improved by strong final-state interactions before they are iterated to give higher-order weak interactions. This viewpoint is contrasted with another viewpoint that the high energy behavior of weak interactions can be improved only by taking higher weak interactions into account.

Taking the above assumption for granted, what can be said about the properties of weak interactions? Since there is as yet no satisfactory theory of weak interactions based on that assumption, the following arguments are merely conjectures based on analogies. It seems instructive to look for other objects for which weak perturbation theory does not work in order to get some useful suggestions as to how the theory of weak interactions should be formulated without reference to perturbation theory; and a good example can immediately be found within the framework of the pure strong interactions, i.e., the bound states or composite particles, provided the distinction between elementary and composite particles makes sense. It is clear that bound states can never be generated in perturbation theory and therefore they bear a strong resemblance to weak interactions. What really should be compared with weak interactions are the interactions of composite particles with other particles.

By assumption neither interaction can be treated in perturbation theory, or, more strongly stated, neither interaction exists in the perturbation expansion. As an example, consider the deuteron and the interaction describing the virtual process

$$d \rightleftharpoons n + p. \quad (6.1)$$

This interaction, if regarded as a fundamental interaction, turns out to be unrenormalizable according to the known criterion for the renormalizability of interactions since the deuteron has unit spin. In order to avoid the divergence difficulty it must be assumed that the interaction (6.1) is not fundamental but induced. In other words, the box representing (6.1) has no point structure, and consequently it is reasonable to assume an unsubtracted dispersion relation for the vertex function corresponding to (6.1), or, in general, for all the vertex functions involving the deuteron.¹⁰ Then in perturbation theory all the vertex functions involving the deuteron are equal to zero, which is consistent with an earlier statement that bound states cannot be generated in perturbation theory. The use of unsubtracted dispersion relations is also justified on the grounds that there should be no arbitrary parameters associated with the deuteron or generally with composite particles. All such parameters should be expressible in terms of more fundamental parameters, at least in principle. This requirement excludes the possibility of introducing subtraction constants which are

not known before the solution of the theory is given, except possibly for the deuteron charge form factor, for which the subtraction constant must be the universal charge.

The formulation of the theory of bound states in strong interactions is certainly of help in formulating a theory of weak interactions, and based on the similarity between them it may be assumed that all the weak vertex functions satisfy unsubtracted dispersion relations. Then these two types of interactions are expected to share various common features. One of the possible candidates for the common features is the eigenvalue restriction. For the sake of argument, reference is made to the eigenvalue problem for the bound states in an elementary one-dimensional Schrödinger equation,

$$u''(r) + k^2 u(r) = V(r)u(r), \quad (6.2)$$

where $V(r)$ is assumed to be an attractive short-range potential. It is known for positive values of k^2 that the wave function $u(r)$ oscillates for large values of r , but for negative values of k^2 the wave function generally increases exponentially. The energy levels of bound states are determined by looking for those values of k^2 for which the coefficient of the exponentially increasing term vanishes. Next consider a form factor in weak interactions: its energy dependence is determined by strong final-state interactions. This time the precise energy dependence of the form factor is not known, but by putting the coefficient of the most rapidly increasing term equal to zero an eigenvalue restriction will be obtained. The actual eigenvalue problem is much more complicated, and the characteristic features of each process should be fully utilized to derive eigenvalue equations. Putting aside these complicated problems, one may simply assume the existence of eigenvalue restrictions. Since the energy dependence of the weak form factors is determined solely by the strong final-state interactions, the eigenvalue restriction should be imposed on the choice of the parameters in strong interactions. In this sense strong interactions are controlled by weak interactions, however small the latter interactions are. A possible formulation of weak interactions based on these ideas is described below.

7. TRANSFORMATION PROPERTIES OF WEAK INTERACTIONS

The dynamical origin of weak interactions described in the preceding section leads to some predictions regarding the transformation properties of weak interactions. As already assumed, inclusion of weak interactions does not introduce any new parameters into the theory. Thus, when the theory is formulated based on unitarity and dispersion relations, the fundamental set of equations for the pure strong interactions and those for the combination of both strong and weak interactions are the same. This would mean that the solution of the fundamental set of equations is not unique. This, however, is a rather embarrassing situation. To find the conditions under which the solution becomes unique, invariance principles will be considered. Strong interactions are known to be invariant under certain groups of transformations, either exactly or approximately, so that the corresponding symmetries should be incorporated into the subtraction constants or the renormalized coupling constants. Then the fundamental set of equations is invariant under those groups. In order to guarantee the uniqueness of the pure strong interactions the

uniqueness of the solution will be assumed when the S -matrix is required to be invariant. This requirement is formulated as follows: *Let L_i be the infinitesimal generating operators of the groups under which the pure strong interactions are invariant, the S -matrix representing the pure strong interactions should commute with them, i.e.,*

$$[L_i, S] = 0, \quad (7.1)$$

and when all these conditions are satisfied the solution of the fundamental set of equations is unique.

In order to admit weak interactions, the boundary conditions should be relaxed, namely, violation of at least one of the invariance principles (7.1) has to be assumed. This way of introducing weak interactions seems to be reasonable in view of present experimental knowledge about weak interactions. When the invariance requirements on the solution are lifted, it may be assumed that the fundamental set of equations in dispersion theory allows a one-parameter group of solutions (or a several-parameter group of solutions – this difference is irrelevant in the following discussions). If this parameter is called λ , then the matrix T in (5.6) can be expanded in powers of λ as

$$T = T_0 + \lambda T_1 + \lambda^2 T_2 + \dots, \quad (7.2)$$

where λ essentially denotes the weak coupling constant and T_0 expresses the pure strong interactions. The parameter λ is considered to be arbitrary except that it should be very small. In this connection one should recognize the basic difference between bound states and weak interactions. In the case of bound states no arbitrary parameters are allowed, whereas in weak interactions an arbitrary parameter λ has been introduced. This difference can be explained as follows: In both cases a new set of interactions are generated in a nonperturbative manner, but in the case of bound states not only interactions but also new particles are generated, and the normalization condition for them determines their coupling constants. This seems to be reasonable since λ is extremely small and there is no hope of getting such small values by solving eigenvalue equations involving only strong interaction parameters.

So far only the dynamical aspects of this proposed formulation of weak interactions have been discussed, but it is amusing to speculate on the group theoretical aspects of this approach. At the end of section 3 reference was made to the multiplet structure of elementary particles. In atomic physics the multiplet structure is a consequence of the rotational invariance of the theory, and it can be inferred from that experience that there must be a certain rotational invariance in elementary particle physics. The rotations in the latter case are not those in ordinary space but are those in an abstract charge space. In the case of atoms the degeneracy of the multiplets can be lifted by applying an external magnetic field, since it destroys the spherical symmetry of the system. This phenomenon is the so-called Zeeman effect. In the case of elementary particles the electromagnetic interactions destroy this symmetry by bringing in a preferred direction in the charge space.

Corresponding to the angular momentum in ordinary space, the isospin is introduced in elementary particle physics. Then the three components of the isospin denoted by I_1 , I_2 , and I_3 satisfy commutation relations analogous to those for the three components of the angular momentum, i.e.,

$$[I_1, I_2] = iI_3, \quad [I_2, I_3] = iI_1, \quad [I_3, I_1] = iI_2, \quad (7.3)$$

and therefore the isospin should have the same eigenvalues as does the angular momentum.

In strong interactions excluding the relatively weak electromagnetic interactions the S or T matrix commutes with the isospin, i.e.,

$$[I_i, T] = 0, \quad (i=1,2,3) \quad (7.4)$$

but when the electromagnetic interactions are introduced only I_3 can commute with T . In weak interactions even I_3 is no longer conserved and, in particular, when I_3 changes by $\frac{1}{2}$ the isospin I itself changes by $\frac{1}{2}$. This selection rule is called the $|\Delta I| = \frac{1}{2}$ rule. It seems possible to understand this feature along the lines of the theory proposed in this article.

From now on T_0 and T_1 in (7.2) will be denoted simply by T and W , respectively. Suppose that L commutes with the T matrix for strong interactions, i.e.,

$$[L, T] = 0. \quad (7.5)$$

Dispersion relations for T_1 or W can be written in the unsubtracted form:

$$W(s) = \frac{1}{\pi} \int ds' \frac{\text{Im} W(s')}{s' - s - i\epsilon}, \quad (7.6)$$

where $W(s)$ expresses a matrix. The unitarity condition for W is obtained from (5.7) by keeping terms linear in λ :

$$\text{Im} W(s) = \pi [T^\dagger(s) \rho(s) W(s) + W^\dagger(s) \rho(s) T(s)], \quad (7.7)$$

where the summation in (5.7) has already been carried out. Both $T(s)$ and $W(s)$ are matrices connecting different channels, and $\rho(s)$ is the diagonal matrix representing the phase-space factors in the intermediate states. When (7.5) is valid, $\rho(s)$ also commutes with L .

W may be expanded according to the transformation properties under the group generated by L and some others by

$$W(s) = \sum_l W_l(s), \quad (7.8)$$

where

$$[L, W_l(s)] = l W_l(s). \quad (7.9)$$

The eigenvalue l is equal to zero for T and ρ . In the case of the isospin two equations are introduced to carry out the decomposition, i.e.,

$$W(s) = \sum_{I', I'_3} W_{I', I'_3}(s), \quad (7.10)$$

where

$$[I_3, W_{I', I'_3}(s)] = I'_3 W_{I', I'_3}(s),$$

$$\sum_{i=1}^3 \{I_i [I_i, W_{I', I'_3}(s)]\} = I'(I'+1) W_{I', I'_3}(s), \quad (7.11)$$

where I' and I'_3 express eigenvalues. Returning to the general case, it can be shown that the dispersion relations (7.6) and the unitarity condition (7.7) hold for each term in the expansion (7.8) separately, i.e.,

$$W_l(s) = \frac{1}{\pi} \int ds' \frac{\text{Im} W_l(s')}{s' - s - i\epsilon}, \quad (7.12)$$

and

$$\text{Im} W_l(s) = \pi [T^\dagger(s) \rho(s) W_l(s) + W_l^\dagger(s) \rho(s) T(s)]. \quad (7.13)$$

In other words, equations for W_l for different values of l are completely decoupled from each other. Each set of equations is supposed to lead to a solution with some definite energy dependence. It is the principle here to pick up the solution that falls off most rapidly at high energies. In this way one can pick up one particular value of l , and also get eigenvalue restrictions corresponding to that particular value of l . In terms of group theory this means that weak interactions should transform according to an *irreducible representation* of the group that leaves the strong interactions invariant. Take the isospin group, for example: the weak interactions should transform irreducibly under this group and, in particular, if $I' = 1/2$ is chosen in (7.11), the selection rule $|\Delta I| = 1/2$ results,¹¹ which is known to hold with very good accuracy in the nonleptonic decays of strange particles. Take the $SU(3)$ group, which is a generalization of the isospin group to incorporate “cousins” discussed at the end of section 3, and assume that the weak leptonic decays of strongly interacting particles transform like components of the irreducible 8-representation or of an octet: the phenomenological Cabibbo theory results.¹² Furthermore, in some cases a set of equations is found to lead to more-than-one eigenvalue restrictions that are most easily satisfied by assuming an appropriate symmetry in strong interactions. This is not surprising, since renormalizability in some critical cases depends on the presence or absence of conservation laws, e.g., a neutral vector field coupled to a conserved current leads to a renormalizable theory whereas it leads to an unrenormalizable theory when the current is not conserved. One such example in weak interactions is the $\pi \rightarrow \mu + \nu$ or $K \rightarrow \mu + \nu$ decay that was first studied by Goldberger and Treiman.¹³ Restrictions in these cases are most easily satisfied by assuming the $SU(3)$ group.¹⁴

8. CONCLUSION

In this article we have presented a new dynamical interpretation of weak interactions. In this scheme, when the strong interactions are given, the weak interactions are almost determined, as discussed in the preceding section, while the equations for weak interactions lead to the eigenvalue restrictions to be imposed on the choice of the parameters in strong interactions. In this sense the strong and weak interactions are not independent but are intimately related and control each other.

The present viewpoint on weak interactions was motivated by divergence difficulties inherent in weak interactions. As discussed in section 6, the renormalizability of interactions manifests itself in high energy behavior. Historically this difference has long been known. Soon after Fermi's proposal on β decay Heisenberg recognized

that Fermi's interaction leads to a picture of high energy interactions completely different from that expected from then familiar electromagnetic interactions.¹⁵ Based on the difference in energy dependence between electromagnetic and Fermi interactions, Heisenberg concluded that the effects of weak interactions should start to dominate over those of strong interactions above a certain critical energy, of the order of 300 GeV, if Fermi's original picture of β decay should continue to be valid up to energies of this order without modifications. In the present article we have proposed a scheme in which such a catastrophic feature of weak interactions is avoided. If such a mechanism should turn out to be correct, it should manifest itself in the energy dependence of high energy reactions like

$$\bar{\nu}_l + p \rightarrow n + l^+, \quad \nu_l + n \rightarrow p + l^-, \quad (8.1)$$

where l stands for either the electron or the μ meson. These interactions are described by form factors corresponding to the original spin-non-flip Fermi interactions and the spin-flip Gamow-Teller interactions, $F_V(s)$ and $F_A(s)$. If our assumptions should be correct, these form factors are expected to fall off as fast as s^{-1} or even faster. The high energy neutrino experiments will clarify these points in the near future.

REFERENCES

1. W. HEISENBERG, *Z. Physik* **120**, 513, 673 (1943); *Z. Naturforsch.* **1**, 608 (1946).
2. M. GELL-MANN, *Phys. Rev.* **125**, 1067 (1962); Y. NE'EMAN, *Nucl. Phys.* **26**, 222 (1961).
3. See, for instance, *Quantum Electrodynamics*, J. Schwinger, Editor, Dover, New York, 1958.
4. M.L. GOLDBERGER, *Phys. Rev.* **99**, 979 (1955); M.L. GOLDBERGER, H. MIYAZAWA, AND R. OEHME, *Ibid.* 986.
5. See, for instance G.F. CHEW, M.L. GOLDBERGER, F.E. LOW, AND Y. NAMBU, *Phys. Rev.* **106**, 1337, 1345 (1957).
6. W.R. FRAZER AND J.R. FULCO, *Phys. Rev.* **117**, 1603, 1609 (1960).
7. Y. NAMBU, *Phys. Rev.* **106**, 1366 (1957); G.F. CHEW, *Phys. Rev. Letters* **4**, 142 (1960).
8. S. MANDELSTAM, *Phys. Rev.* **112**, 1344 (1958).
9. See, for instance, H. LEHMANN, K. SYMANZIK, AND W. ZIMMERMANN, *Nuovo Cimento* **2**, 425 (1955).
10. R. BLANKENBECLER AND L.F. COOK JR., *Phys. Rev.* **119**, 1745 (1960).
11. E.R. MCCLIMENT AND K. NISHIJIMA, *Phys. Rev.* **128**, 1970 (1962).
12. N. CABIBBO, *Phys. Rev. Letters* **10**, 531 (1963).
13. M.L. GOLDBERGER AND S.B. TREIMAN, *Phys. Rev.* **110**, 1178 (1958).
14. K. NISHIJIMA, *Phys. Rev.* **113**, B1092 (1964), and another article to be published soon.
15. W. HEISENBERG, *Z. Physik* **101**, 533 (1936); **110**, 251 (1938); **113**, 61 (1939).

EXPERIMENTAL FEASIBILITY

Experimental Feasibility at Super High Energies

LUKE C.L. YUAN
Brookhaven National Laboratory

CONTENTS

I. Introduction.....	125
II. Experimental Contributions of Present High Energy Accelerators.....	126
III. Feasibility of a Super High Energy Accelerator in the Energy Range 200 to 1000 BeV.....	129
IV. Feasibility of Experimentation Using a Super High Energy Accelerator.....	133
1. Possible Beams and Beam Separation.....	134
2. Particle Detection and Identification.....	135
3. Effective Utilization of Accelerator: Multiple Targeting, Automatic Data Handling, and On-Line Computer Analysis.....	144
V. Concluding Remarks.....	145

I. INTRODUCTION

In the main body of this volume, eloquent and urgent pleas have been presented by some 30 leading theoretical physicists focusing on the desirability and importance of extending our knowledge to the super high energy region of multi-hundred BeV. As Professor Oppenheimer stated in the Foreword, all these theoretical contributors not only are active in the field of high energy physics but also have a deep interest in physics and science in general. In quest of the fundamental understanding of the nature of matter, they clearly recognize the inadequacy of the present existing energy range of the particle accelerators. They strongly believe that by extending the frontier of high energy physics we will enter into a new realm of enlightenment. It is also generally recognized that any progress in the techniques of super high energy research will be of the most profound value to science in general.

The progress of science has always been made through the interplay between theoretical investigations and experimental observations. Our observations are meaningful only through theoretical understanding, and fundamental concepts of nature and theoretical conjectures are usually developed from what we observe. In fact, any theory without experimental proof will always remain a speculation.

This point may be illustrated by two prominent examples: (1) the existence of antiprotons had been predicted by theory for a long time, but it was finally verified in the experiment of Segrè, Chamberlain, et al.¹ only upon the completion of the 6-BeV Bevatron at the Lawrence Radiation Laboratory, when the energy became sufficiently high to create a proton-antiproton pair, and (2) the famous θ - τ puzzle led Lee and Yang² to make the bold suggestion that the long-held parity conservation law may not be valid in weak interactions. It was from this challenge that Wu and her colleagues performed the now well-known Co⁶⁰ experiment³ which verified the nonconservation of parity in weak interactions.

The Co^{60} experiment is particularly significant in that it demonstrates remarkably well that there is really no demarkation between so-called high and low energy physics, since the theoretical prediction of parity nonconservation in weak interactions was originally conceived from the θ - τ puzzle observed in high energy experiments and it was verified in the low energy β -decay experiment. This fact opened up a new realm of understanding in the field of weak interactions which consequently led to many exciting speculations and experimental investigations of important implications at high as well as low energies.

Now the questions are: (1) How feasible is it to reach the super high energy region? (2) How readily can such high energy particle beams be separated and collimated? (3) Are there suitable and adequate detection and measuring devices for these high energy particles? (4) What improved data handling and analyzing systems are available so that maximum use can be made of a super high energy accelerator?

All these questions have been studied very extensively⁴ during the past 4 years, both in this country and abroad: at Brookhaven National Laboratory, Lawrence Radiation Laboratory, University of California, and California Institute of Technology in the United States, and at CERN (European Organization for Nuclear Research) in Geneva.

These studies have shown that with regard to question (1) it is entirely feasible to design an alternating gradient type of synchrotron in the multi-hundred BeV region.⁴ This can be accomplished simply by extension of the principles involved in the design of the Brookhaven AGS (Alternating Gradient Synchrotron) or the CERN PS (Proton Synchrotron), incorporating a number of new ideas which are of great technical importance. The detailed parameters of this design will be given in section III.

With regard to questions (2), (3), and (4), these studies showed that various beams of adequate intensity can be obtained in such a super high energy accelerator; that various detection methods including beam separation, particle identification, momentum measurement, etc., are feasible; and that the great advancement in data reduction and analyzing techniques in the past few years will be of immense value toward full utilization of such an accelerator when it is built. Some specific details will be discussed in section IV.

II. EXPERIMENTAL CONTRIBUTIONS OF PRESENT HIGH ENERGY ACCELERATORS

To study high energy physics an essential requirement is a source of particles which possess energy sufficiently high to produce other particles of interest and to study the particle interactions especially at very small distances.

About two decades ago, the study of high energy physics was mainly accomplished through the study of cosmic rays. Until then, cosmic rays were the only source of high energy particles, and this was the only way to engage in high energy studies. Although some of the elementary particles such as pions, muons, and a few of the "strange" particle family were first observed in cosmic rays, it was only after the completion of high energy accelerating machines supplying an adequate flux of high energy particles whose energy, intensity, and direction could be directly con-

trolled that the properties (mass, lifetime, decay schemes, and quantum numbers) and interactions of these particles were fully studied and classified. Since the intensity from cosmic rays becomes increasingly lower for particles having shorter lifetimes and higher “strangeness,”* it became more and more difficult to do experiments using cosmic rays. Consequently, the accelerating machines took over the task in the past two decades and made possible the tremendous progress achieved in the field of particle physics during this comparatively short period of time.

Now, as we probe more deeply into the nature of matter, we find that the energy range covered by our present accelerators is clearly still inadequate, and an extension to much higher energies is urgently needed.

In this section a few specific examples will be mentioned from the vast list of important contributions made with the aid of high energy accelerating machines:

1. First observation of neutral pions.
2. Establishment of the existence of pion-nucleon resonances and of the validity of isotopic spin for pion-nucleon scattering.
3. Establishment of the associated production of “strange” particles.
4. Establishment of the existence of a family of antiparticles such as antiproton, antineutron, antilambda, etc.
5. Determination of nucleon structures, such as the nucleon size and charge distribution.
6. Measurements of the production of secondary particles in proton-proton collisions up to incident energies of 30 BeV showed that particles such as pions, kaons, and antiprotons are strongly collimated in the forward direction, much more so than was predicted by Fermi’s statistical theory; and, in fact, they are compatible with a universal transverse momentum distribution.
7. Establishment of the existence of two types of neutrinos, one associated with the muon and one with the electron.
8. Extensive neutrino experiments performed at the highest energy accelerators existing today (the Brookhaven 33-BeV AGS and the CERN 28-BeV PS) gave the conclusion that in order to investigate the important question of the predicted existence of an intermediate boson which mediates the weak interactions, much higher energy than is now available is required. The lowest mass limit of the intermediate boson is now set to be about 2 BeV.
9. Determination of the mass, lifetime, decay schemes, spin, isotopic spin, parity, etc., of elementary particles such as pions, kaons, and baryons. A large number of excited states of these particles has been produced and their properties have been analyzed. The recent discovery of the omega-minus particle at the Brookhaven 33-BeV AGS machine is especially significant because it supplies, very probably, the missing particle corresponding to the one predicted by the “eightfold way” [SU(3) symmetry] to complete the $J^P = \frac{3}{2}^+$ multiplet and gives crucial support to the correctness of this scheme and to the important part it plays in strong interactions (see Appendix 2).
10. The total cross section measurements of particles and antiparticles on protons showed that the proton-proton, antiproton-proton, kaon-proton, and pion-

*Strangeness is a quantum number which characterizes a class of particles (strange particles) that have relatively long lifetimes on a nuclear time scale.

Figure 1. The number of strongly interacting particles actually discovered per year up to now plotted as a function of time. The times of operation of some high energy accelerating machines which are mainly responsible for most of these discoveries are indicated.

proton total cross sections up to 22 BeV are all approaching, in various degrees, an approximately constant value, thus giving some indication of asymptotic behavior.

11. Accurate measurements of elastic scattering cross sections of various elementary particles showed a shrinkage of the diffraction scattering peak with increasing energy for protons and positive kaons but, in disagreement with the Regge pole theory predictions, showed no shrinkage for pions and negative kaons. In addition, the measurement of the elastic scattering of antiprotons by protons showed an antishrinkage effect. Although no convincing theoretical explanation of these basic results of elastic scattering has been found, we now have a rather complete basic survey of the field.

12. The elastic proton-proton scattering with large momentum transfers demonstrated a much slower decrease in elastic cross section as a function of the momentum transfers.

13. Recent experiments on the decay of neutral kaons showed an unexpected property, namely, an apparent violation of invariance under time reversal transformation. The interpretation of this experimental result is not yet complete.

A plot of the number of strongly interacting particles discovered per year as a function of time is shown in Figure 1. It can be seen that there is a sharp rise in the

number of new particles discovered per year since the advent of high energy accelerating machines.

The above list of high energy experimental results is but a small fraction of the total number of contributions accomplished with the aid of accelerators thus far. The last few experimental results mentioned above have been obtained only very recently and their implications are not fully understood. This list, as well as Figure 1, clearly demonstrates not only the important role high energy accelerating machines have played in the past, but also that it is essential to extend the energy range of the present accelerators to the multi-hundred BeV region in order to obtain answers to the many fundamental questions left unanswered in the understanding of the nature of matter.

III. FEASIBILITY OF A SUPER HIGH ENERGY ACCELERATOR IN THE ENERGY RANGE 200 TO 1000 BEV

The design for a 200 to 1000-BeV accelerator described below is the result of an extensive and careful study by leading accelerator physicists and engineers during the past several years. It is based on the successful design and operating experience with the existing high energy accelerators such as the Brookhaven AGS and the CERN PS, and it is a conservative, intelligent, and reassuring design. It also includes several design improvements which are important contributions to the accelerator art. Further innovations in accelerator design that may occur during the next few years will, of course, be included if they seem appropriate.

Figure 2. An aerial view of the Brookhaven AGS.

Figure 3. A close view of some segments of the AGS.

Figure 4. A sketch diagram of a 1000-BeV alternating gradient synchrotron, showing its scale, beam side-track, and general layout.

Figure 5. An artist's drawing of a section of the main tunnel, beam side-track, and experimental area of a 1000-BeV accelerator.

Figure 6. A conceptual layout of the 200-BeV proton synchrotron.

Table 1
Possible Parameters for Super High Energy Accelerators

	200 BeV	600 BeV	1000 BeV
Peak magnetic field, kG (kilogauss)	15	15	15
Radius of curvature, m (meters)	444	1,340	2,220
Average radius (including straight sections), m	702	2,000	3,200
Circumference, m	4,410	12,600	20,100
ORBIT AND BEAM CHARACTERISTICS			
Injection energy, BeV	6	6	6
ν (Betatron oscillation per revolution)	16.75	30	40
Beam intensity, protons per pulse	3×10^{13}	2×10^{13}	2×10^{13}
MAGNET PARAMETERS			
Magnet length, m	5.8	8	10
Number of magnets	480	1,050	1,400
Weight of magnet steel, metric tons	8,400	25,000	42,000
Number of magnets per lens element	4	6	6
Length of lens element, m	30	46	58
Gradient parameter, $\frac{1}{B} \frac{dB}{dr}$, m^{-1}	3.17	4.5	4.5
Aperture, cm	5×12	5×10	5×10
Number of long straight sections	12	12	12
Clear length in L.S.S., m	40-60	40	50
Pulse rate, per min	30	30	30
Average magnet power, MW (megawatts)	8	24	39
RF SYSTEM PARAMETERS			
Final frequency, Mc/sec	50	200	200
Harmonic number	740	8,000	13,000
Final period of revolution, μsec	14.7	42	67
Final revolution frequency, kc	68	24	15
Energy gain per revolution, MeV	3.7	25	67

On the basis of cost, maximum experimental utilization, and other practical considerations, the alternating gradient proton synchrotron is considered to be the most suitable machine in the energy range 200 to 1000 BeV. Linear accelerators for protons or electrons appear to be more expensive by a factor of at least 10.

An aerial view of the Brookhaven AGS is shown in Figure 2, and a close view of some segments of the accelerator inside the shielding is shown in Figure 3. A diagram (from the 1961 Brookhaven design study) of a 1000-BeV alternating gradient proton synchrotron is shown in Figure 4, and an artist's drawing showing an experimental area for this accelerator is shown in Figure 5. Figure 6 is a conceptual layout of the 200-BeV proton synchrotron under study at the Lawrence Radiation Laboratory.

The basic parameters for such an accelerator at three different energies are given in Table 1.* The parameters for the 200-BeV machine are a possible set de-

*The information on the basic parameters has been supplied by Dr. J.P. Blewett, who is in charge of the accelerator design study at Brookhaven.

veloped at the Lawrence Radiation Laboratory. The 600 and 1000-BeV figures were evolved at Brookhaven.

Recent developments in the design of magnets with superconducting coils have led to serious consideration of the possibility of using such magnets in a super high energy accelerator design. Magnetic fields of >100 kilogauss have been reached using superconducting coils, and still higher fields are within practical possibility in the near future. By incorporating such magnets in a super high energy accelerator design, it would be possible to reduce appreciably the physical size of the accelerator ring.

One of the novel features incorporated in the present design is of great importance to the experimental utilization of the machine, and it merits mention here. A very important requirement of a super high energy accelerator for experimental utilization is that secondary beams be allowed to emerge freely at very small angles to the forward direction. This requirement is based on the experimental findings mentioned in section II, 6. The way to accomplish this is to have extremely long straight sections (field-free regions) so as to allow secondary beams produced in the forward direction in a target placed at the upper end of a straight section to emerge at the lower end of the straight section without traversing any magnetic field. Usually, straight sections of the order of $\frac{1}{30}$ of the betatron wavelength (betatron oscillation is a characteristic oscillation in the synchrotron type of accelerators) or shorter can easily be included where desired without undue increase in the required aperture.* It has been shown,^{4a} however, that it is possible to include straight sections much longer than this by putting quadrupole magnets in these straight sections to match the focusing properties of the regular alternating gradient magnets.

The injector for a super high energy accelerator can be either a linear accelerator or another synchrotron of a few BeV energy. If a "booster" synchrotron is used, it will be cycled at a rapid rate, and several cycles of its output will be deposited in the large ring at the beginning of each of its acceleration cycles. Present indications are that the linear accelerator is somewhat more satisfactory as an injector but is more expensive than the synchrotron injector. Either injector is quite feasible with no extension of known techniques.

IV. FEASIBILITY OF EXPERIMENTATION USING A SUPER HIGH ENERGY ACCELERATOR

Experiments in particle physics essentially involve the measurement of quantities that describe the initial and final states of the physical processes being studied, such as collision processes, decay processes, etc. Generally the measurements include the location of the trajectory of the particle under investigation, its velocity (including the angle giving the direction of motion), momentum, and range. From such measurements on each individual particle, an interpretation of the phenomenon as a whole is deduced, and conclusions may be drawn from comparison with pertinent theoretical predictions.

Here, the following questions will be examined: (1) What particle beams are obtainable from a super high energy accelerator, and to what extent can they be

*For example, the longest straight sections in the 33-BeV AGS are only 10 ft long.

collimated? (2) What kind of detection and measuring devices, if any, are suitable for performing experiments with these very high energy particles? (3) Are there suitable data reduction and analyzing systems for full utilization of a super high energy accelerator?

1. Possible Beams and Beam Separation

a. Possible Beams. In principle, it is possible to make beams of all stable particles or of those particles which have a sufficiently long lifetime so that they can be studied before they decay [see (iv) below]. Calculations have been made by extrapolating our present knowledge of particle production obtained at the Brookhaven and CERN accelerators, and these results show that practically all the desirable particle beams can be obtained from a multi-hundred BeV accelerator.

The recent success in the design of superconducting magnets giving magnetic fields of well over 100 kilogauss makes it possible to produce a much larger beam deflection and may provide a much more compact and practical beam transport system. With the appropriate beam transport system and collimations taken into consideration, the possible secondary beams may be listed as follows:

- (i) Separated secondary beams (separated by radiofrequency and electrostatically), with use of superconducting magnets:
 - (a) Positive and negative pion beams,
 - (b) Proton and antiproton beams,
 - (c) Positive and negative kaon beams.
- (ii) Unseparated secondary beams, with use of superconducting magnets:
 - (a) Positive and negative pion beams,
 - (b) Proton and antiproton beams,
 - (c) Neutron and antineutron beams,
 - (d) Positive, negative, and neutral kaon beams,
 - (e) Positive and negative muon beams,
 - (f) Neutrino beams.
- (iii) Extracted proton beams; fast beams for bubble chamber experiments, and slow beams for counter and spark chamber experiments.
- (iv) Hyperon beams.

With regard to (iii), the extracted proton beams in the present accelerators show an extraction efficiency of better than 80%. The flexibility of an extracted beam makes it more attractive to use than the beam siding idea mentioned in ref. 4a (also see Figure 4).

Referring to (iv), note that, because of their extremely short lifetime ($\sim 10^{-10}$ sec), at present machine energies hyperons decay as soon as they leave the target where they are produced, and hence it is very hard to study them. In a super high energy machine, however, hyperons produced can acquire energies as high as a few hundred BeV; thus they can have large enough velocities to enable them to travel sufficiently far without decay to make hyperon beams practical for study.

b. Beam Separation. One of the primary purposes of a multi-hundred BeV accelerator will be to provide a source of antiprotons, kaons, and other rare particles of high energy for (1) the study of the interaction of these particles with protons and neutrons and (2) the search for possible new particles produced at the much higher energy interactions. For experiments with electronic detectors, physical

purification of the beams to obtain desired particles only is generally not required. However, physically purified beams are essential in at least the following two instances: (i) experiments with liquid hydrogen or deuterium bubble chambers, spark chambers, etc., because of the complexity of the interactions as well as their unexplored character, and (ii) experiments with electronic detectors, in which extremely high discrimination is needed for the selective detection of rare particles against the overwhelming presence of unwanted particles (such as pions and protons) in the beam – this is especially important in the search for new particles or rare processes.

At present there are two successful methods for beam separation. One, the technique of electrostatic velocity selection, has been commonly in use. The other is the radiofrequency method. In the case of the electrostatic separator, a momentum range of between 15 and 150 BeV/ c has been considered. A criterion of 15 particle tracks of the desired type per picture is arbitrarily set. Relatively straightforward extrapolations of present techniques of electrostatic separation can be used at the multi-hundred BeV accelerator to produce separated K beams up to about 30 BeV/ c momentum and antiproton beams above 50 BeV/ c but probably below 100 BeV/ c . It is considered very difficult with this method to extend the peak energies of the separated beams beyond 60 BeV/ c for kaon beams and 100 BeV/ c for antiproton beams.

In the case of the radiofrequency particle separators, the present designs⁵ can provide beams of the following particles and peak momenta: 25-BeV/ c antiprotons, 18-BeV/ c kaons, and 15.4-BeV/ c pions. This particular design employs three rf deflecting cavities operating at 3000 Mc/sec, the cavities being separated by 250 ft with a total beam length of 800 ft. In principle, complete separation of 50-BeV pions and antiprotons can be achieved with a single deflecting cavity 500 ft from the target, followed by an appropriate drift distance. Radiofrequency separators can now be designed for momenta up to about 100 BeV/ c . Future developments in beam separation techniques may well raise the usable region during the next few years to much higher energies. In any case, a higher primary energy beam would yield high intensity beams of the now so-called “rare particles” at comparatively lower energies and thus make it possible to study them in detail.

2. Particle Detection and Identification

The experience gained from current and past experiments performed at the existing high energy machines, and the various problems encountered in such experiments, have served as a guide in studies of future experiments at super high energies. The general conclusions from these studies are that various detection methods, including particle identification and momentum measurements, are found to be feasible either with the extension or improvement of present detection techniques or possibly with new techniques. A brief summary of some of the detection methods is given below.

a. Cloud and Bubble Chambers. Charged particles give rise to visual tracks when they traverse the medium of the chamber (gases are used in cloud chambers, and liquids in bubble chambers). One excellent feature of these chambers is their good space resolution. With existing chambers one can count on obtaining tracks of 1-m length or more. Sagittas of curved tracks can be measured with accuracies approaching $25\ \mu$ in the chamber space. Magnetic fields are of the order of 20 kG,

Figure 7. An artist's drawing of the 14-ft liquid hydrogen bubble chamber proposed by Brookhaven National Laboratory. For comparison, at the lower left, the 80-in. chamber, which is now in operation, is also shown. Bubble chambers of approximately the size of the 14-ft chamber are expected to be very useful detection devices at super high energies, especially when provided with superconducting coils to obtain magnetic fields of the order of 100 kilogauss. (The picture shows the 14-ft chamber located in a conventional 20-kilogauss magnet.)

which is sufficient to measure the momentum of a 100-BeV track with 3% accuracy but becomes unsatisfactory for still higher energies. The recent success in obtaining fields of 100 kG or more with superconducting coils may make it possible to measure a 500-BeV track with an accuracy about equal to the limit given by multiple Coulomb scattering, but the angle measurements will not be correspondingly good. A design for a 14-ft-diameter liquid hydrogen bubble chamber has recently been proposed at Brookhaven for use at the AGS.⁶ Here the momentum accuracy will be improved considerably because of greater length of the tracks and very much improved for the particles that stop in the chamber. An artist's sketch of this chamber is shown in Figure 7 with a sketch of the present 80-in. bubble chamber on the same scale for comparison. A photograph of the 80-in. chamber is shown in Figure 8. The value of such a large chamber (14-ft-diameter) lies not only in the increase in accuracy but also in the completeness of information about the events observed. A chamber of this size would be very useful at a super high energy accelerator, especially if provided with a 100-kG magnetic field.

Figure 8. Photograph of the 80-in. liquid hydrogen bubble chamber which is now operating at the 33-BeV Brookhaven Alternating Gradient Synchrotron. The chamber, 80 in. long $\times$ 27 in. wide $\times$ 26 in. deep, is located in the center of the magnet structure seen in the photograph. Pictures of tracks are taken from the left side, where the cameras are visible.

Particle identification can be accomplished by gap counting in bubble chambers and drop counting in cloud chambers. At very high energies, determinations of γ (≈ 100) to an accuracy of about $\pm 10\%$ for tracks about 1 m long are possible in heavy liquids but to only about $\pm 30\%$ in liquid hydrogen, where $\gamma = (\sqrt{1 - v^2/c^2})^{-1}$ and v is the velocity of the particle. In cloud chambers, notably when filled with xenon, an ionization increase of 40% over the minimum rate has been observed at $\gamma = 100$, and 70% at $\gamma = 300$.

Complete analysis of events of the type that can be carried out at lower energies will be very difficult at very high energies, mostly because one must expect production of many neutral particles in addition to the charged ones. Even in hydrogen, events will have to be treated more statistically rather than individually. Occasionally, individual particles will be recognizable. High energy neutral particles decaying into charged particles with very short decay times would be observable. For a decay path of 2 mm, a particle of hyperon mass with 1000-BeV energy has lived about 10^{-14} sec. Thus, while complete analysis of production events will not be possible, production characteristics and properties of individual particles will still be determinable in a number of cases. Possible new particles should then be detectable with some probability.

An important application of higher energy accelerators is the production of copious beams of only medium energies of now still somewhat rare particles such as K particles or even Ξ particles, and events produced by such beams should be more easily analyzable. Cross sections, scattering characteristics, lifetimes, parities, spins

and isotopic spins, and polarization properties should in many cases be observable in chambers with not much more difficulty than encountered at present high energy accelerators.

Thus, a liquid hydrogen bubble chamber of the size mentioned can be extremely useful at a multi-hundred BeV machine, particularly since the factor of merit of the chamber for many experiments varies faster than linearly with the linear dimensions of the chamber. (The volume of the 14-ft chamber is about 25 times as great as that of the Brookhaven 80-in. chamber, and for some experiments the factor of merit may be in at least that high a ratio.) Examples of these experiments are low energy neutrino experiments, in which the relevant quantity is the volume of the chamber; or experiments in which several successive interactions are involved; or experiments in which a threshold in size is involved, as in the experiments utilizing the magnetic trapping of charged particles.

Another important aspect is the identification of the products of weak interaction events, either decays or neutrino interactions. For example, in a reaction such as (refer to Appendix 2)

$$\bar{\nu} + p \rightarrow n + \pi^+ + \pi^- + \mu^+,$$

it is essential to know which particle is the muon. It is also important to be able to tell whether there are electrons produced in some types of neutrino interactions.

Examples (refer to Appendix 2) of weak decays are

$$K^0 \rightarrow \pi^+ + e^-(\mu^-) + \nu,$$

$$\Lambda \rightarrow p + e^-(\mu^-) + \nu,$$

$$\Sigma^\pm \rightarrow n + e^\pm(\mu^\pm) + \nu, \quad \text{etc.}$$

The decay rates for most of these reactions are quite small, and it would be very useful to have an efficient means of recognizing the leptonic decays, to distinguish them from the more common decays involving pions. This is provided by three particle identification capabilities of the 14-ft chamber: the trapping of charged particles, the identification of electrons by means of heavy metal plates, and the observation of neutral decays over a wide momentum interval. The particle identification abilities of the chamber are particularly useful for the K^0 decays, where it is difficult to provide kinematic constraints.

Two typical examples of bubble chamber photographs of interesting events are shown in Figures 9 and 10. Figure 9 shows the production of an anti-cascade-hyperon, the $\bar{\Xi}^-$, by an antiproton of 3.7-BeV/ c momentum, and Figure 10 shows interactions of 5-BeV/ c K^- mesons.

b. Spark Chamber. A spark chamber generally consists of thin parallel conducting plates separated by small gaps. The chamber is usually filled with neon or argon gas, and the adjacent plates are charged with a high electric field pulse which causes an electric discharge or spark to occur at the location where a high energy charged particle traverses.

A spark chamber has much better time resolution than a bubble chamber but perhaps not as good space resolution. It has better space resolution than electronic counters but not as good time resolution. The resolving time is $\sim 0.5 \mu\text{sec}$ for a plate spacing of 1 cm. The position of a spark can be measured to $\frac{1}{4}$ mm in two dimen-

Figure 9. (Left). Production of an antiscascade hyperon, the Ξ^- , by an antiproton of 3.7-Bev/c momentum, observed in a 20-in. liquid hydrogen bubble chamber. The sketch at the left of the picture points out the details of the reaction $p + p \rightarrow \Xi^- + \bar{\Xi}^-$ with subsequent decays of the hyperons. (The π^- from the decay of Ξ^- undergoes a scattering which is of no significance to the process.)

Figure 10 (Right). Photograph of interactions of 5-BeV/c K^- mesons in the Brookhaven National Laboratory 80-in. liquid hydrogen bubble chamber. There are two interactions and one decay of an incident K^- meson observed in this particular picture. One interaction (to the left) involves four emerging prongs, one (π^+) which interacts and another (Σ^+) which decays. The second interaction (to the right) has two emerging prongs and many unseen neutrals.

sions and is determined by the plate spacing in the third dimension. For a chamber comprised of six 1-cm gaps, a typical measurement will give angles to an accuracy of $\frac{1}{2}^\circ$ for tracks at 20° to the plates. A spark chamber as large as a room with many tons of material could be built without undue difficulty.

Because of the good time resolution, a spark chamber is valuable for relatively rare events when data collection by use of a bubble chamber would be difficult. The space resolution makes it preferable to counters in cases in which a large solid angle with good angular resolution is desired.

Recent developments in the sonic spark chamber technique, which uses acoustic detectors for defining the position of the spark, have led to the feasibility of digitization of the location of the spark into a computing machine and thus of rapid analysis of spark chamber data.

The most recent development is the wire spark chamber, in which parallel conductive wires are closely spaced to form a wire plane, which replaces the conventional solid sheet plane. The wire chamber promises even more useful applications of this type of detector to high energy experimentation. Unlike the regular spark chamber or the sonic spark chamber, in which strong energetic sparks are needed to provide for their visual or acoustic detection, the wire chamber requires only a very feeble spark with just enough energy to set a magnetic core attached to the wire on which the spark took place, resulting in much faster recovery time. The information thus obtained is already digitized and can be easily fed into a digital computer, and a system of wire chambers will be able to define the space location of the particles under investigation to an accuracy of a fraction of 1 mm, which is the practical limit of the wire spacing.

Combined use of spark chambers, Cerenkov and scintillation counters and/or a bubble chamber would be extremely useful in many high energy applications.

A photograph of a spark chamber assembly showing the tracks of traversing high energy particles produced in a neutrino interaction is shown in Figure 11, and a photograph of the assembly is shown in Figure 12. This assembly was actually used in the recent neutrino experiment performed at the Brookhaven AGS.

c. Time-of-Flight. The time-of-flight method for particle identification has been commonly used because of its simplicity and its wide velocity range. The main limitations are the difficulties involved in measuring accurately very short time intervals. These involve (1) the time resolution of the coincidence or chronotron circuit, (2) rise time and time dispersion of signal output pulses from the detectors and photomultiplier tubes, (3) transit time dispersion in photomultiplier tubes, and (4) rise time of amplifier or discriminator circuits.

Assuming the best time resolution measurable for individual particles to be 10^{-10} sec, it can be shown that for a flight path of ~ 10 m, kaons and pions of 5-

Figure 11. Photograph of spark chamber tracks of traversing high energy particles caused by a neutrino interaction.

Figure 12. Photograph of a spark chamber assembly used in the recent Columbia-BNL neutrino experiment.

BeV/ c momentum can be separately detectable. For particles of higher momenta, the time-of-flight path required for accurate velocity measurements would be extremely long and therefore rather impractical in many instances. In these cases Cerenkov counters are much more suitable and convenient to use.

However, the wide velocity range of the time-of-flight method makes it possible to detect particles within an extremely wide momentum range. When this method is used in conjunction with an appropriate beam separator for the rejection of undesired particles, the combined system proves to be extremely valuable in the search for possible new heavy mass particles.⁷

d. Cerenkov Counter and Cerenkov Chamber. Up to the present, the most accurate and widely used method in the detection and identification of charged particles in the high energy region is still the Cerenkov counter method. A Cerenkov

counter measures, basically, the velocity of a charged particle traversing the counter. This is accomplished by measuring the Cerenkov radiation which is emitted by a charged particle traversing a medium of refractive index n when the particle velocity exceeds the velocity of light in the medium, c/n . The angle θ of emission (Cerenkov angle) of the radiation is given by the relation $\cos \theta = 1/\beta n$ where $\beta = v/c$. By use of a focusing-type gas Cerenkov counter with a built-in anticoincidence channel for undesired particles, antiprotons of 20-BeV/ c momentum were easily identified and separated from pions and kaons in a negative beam at the 33-BeV Brookhaven Alternating Gradient Synchrotron. The velocity resolution of this counter is $\Delta\beta = 8 \times 10^{-4}$ with a Cerenkov angle $\theta = 5^\circ$, where β is the ratio of the particle velocity to the velocity of light. With the same Cerenkov light output, by decreasing θ to 1° , the velocity resolution can be increased to $\Delta\beta = 5.8 \times 10^{-6}$, which is comparable in magnitude to the limit in resolution imposed by the dispersion effect. It would appear possible to separate antiprotons from pions of 200-BeV/ c momentum with such a counter having a length of ≈ 90 ft.

By introducing appropriate lenses in the Cerenkov counter to correct for the dispersion effect, the resolution $\Delta\beta$ can be increased by a factor of about 20.^{4a}

In a Cerenkov chamber where the light emitted by a single particle traversing a radiator is imaged by means of a lens or mirror focused at infinity on the cathode of an image intensifier tube, the image is a ring whose diameter measures accurately the Cerenkov cone angle and thus the particle velocity. In addition, the coordinates of the center of the circular image accurately indicate the orientation of the particle trajectory (though not its position). Limitations on the intensity obtainable and the usable angular field of view would probably restrict its application to particles of momentum less than ~ 50 BeV/ c .

The extremely fast resolution times inherent in both the Cerenkov and scintillation counters make it possible to use a combined Cerenkov counter-scintillation hodoscope system⁸ incorporating an on-line computer and to provide an experimental device (see section IV, 3) with extremely high precision, high resolution (low background), and high counting rate. Furthermore, instantaneous analysis of results obtained permits much flexibility in experimental planning and improvement leading to a much better experiment. Such systems or similar ones employing Cerenkov counter and sonic or wire spark chamber combinations with on-line computers can be used to great advantage in high energy experiments at multi-hundred BeV accelerators. A photograph of a counter hodoscope (multiple counter array) is shown in Figure 13.

e. Photographic Emulsion. There are a few problems for which emulsions could profitably be employed: (1) a search for new very short-lived particles originating in nuclear stars, (2) a search for the monopole (single magnetic pole predicted by Dirac), and (3) investigation of high energy jets, etc. Of course, it is expected that nuclear emulsions will be used routinely to study background radiations and similar technical problems around the high energy machine.

f. Solid State Detectors. The main advantage of semiconductor radiation detectors lies in the small energy required to create a hole-electron pair by the passage of a charged particle, e.g., 3.5 eV in silicon, instead of ~ 35 eV required for conventional ionization. This results in the creation of a large number of hole-electron pairs for the expenditure of quite small energies, and consequently good statistics.

Figure 13. A counter hodoscope assembly used in the recent BNL small-angle elastic scattering experiment. This assembly consists of 120 vertical scintillator elements (0.486 in. wide, 13 in. long) and 24 horizontal elements (0.486 in. wide, 61 in. long).

Minimum ionizing particles produce $\approx 1.8 \times 10^{-14}$ Coulombs/mm in silicon. With the present obtainable sensitive thickness of a few millimeters in silicon p - n junction detectors, the output signals are of the order of millivolts. This necessitates the use of special low noise amplifiers. Results obtainable in a 750-MeV mixed proton and positive pion beam show that the pion peak (minimum ionizing) is clearly separable from the proton peak (twice minimum ionizing). Recently lithium-drift silicon detectors a few centimeters in length have become more available and show promising characteristics for high energy particle detection.

In terms of size, speed of response, and amplifier requirements, existing silicon detectors clearly compare unfavorably with scintillator-plus-photomultiplier combinations for use with minimum ionizing particles. In one respect they do offer an immediate advantage, that is, the ability to operate in high magnetic fields. It is also possible that use may be made of their inherently good statistics when working on the relatively steep portion on the low energy side of the Landau distribution.

g. Relativistic Rise. According to theory, the ionization produced by a charged particle traversing low density media such as gases rises logarithmically with energy. This is known as the relativistic rise. The rise is reduced in denser materials such as solids, because of the screening of the Coulomb field by the close packing of the atoms. This is known as the density effect. The identification of particles of

such high energies that their velocities reach the relativistic region is extremely difficult with existing methods. It may be possible to use the relativistic rise characteristics in the ionization loss of a relativistic particle traversing a certain medium to identify the desired particle.

A xenon gas scintillation counter, 1 m long and with a pressure of 1.5 atm, has been tested in a momentum-analyzed secondary beam at the Brookhaven 33-BeV AGS in coincidence with a counter telescope consisting of scintillation detectors and a focusing-type Cerenkov counter. The pressure of the xenon counter is low enough that the density effect should be negligible within the momentum range tested. Preliminary results obtained on the pulse-height distribution of the signal output from the xenon counter as selected by the Cerenkov counter (either pions or protons) show the characteristic Landau distribution. The peak of the spectrum for 12-BeV/ c negative pions shows a large increase in the ionization loss compared to that for 7-BeV/ c negative pions, and a clear separation of the two peaks is evident. Similar results with a clear separation of the spectrum peaks were also obtained for 4-BeV/ c ($\gamma \cong 30$) positive pions and 7 BeV/ c ($\gamma \cong 7$) protons.

Results were also obtained with the xenon counter alone in a negative beam at two momenta, 3 and 10 BeV/ c . The shifts in the peak positions of the two spectra agree well with the predicted relativistic increase.

If the density effect is not present, the separation of the peaks due to two relativistic particles of different mass but of the same momentum is independent, at least in theory, of the momentum region they are in. It is expected that this would apply to high energy particles in the multi-hundred BeV region.

With an array of such gas counters, say a 10-section scintillation train of overall length 30 m, with xenon at 1 atm, pion-proton separation can be expected at 100 and perhaps at 200 BeV/ c .

There is some evidence that a "secondary emission" exhibits a relativistic rise when electrons impinge on thin metal foils. Results showed that the secondary emission current caused by an electron beam increases logarithmically with the electron energy between 40 MeV ($\gamma=80$) and 600 MeV ($\gamma=1200$). No density effect was in evidence, possibly because a surface phenomenon is involved. Similar relativistic rise effects have also been observed in very thin scintillators.⁹ An estimated 2000 to 3000 foils will be needed to separate a single pion at $\gamma=50$ from a muon of the same momentum. It would be extremely difficult to put this into practice with conventional techniques.

However, if it is true that the density effect can be ignored for thin films, it may be possible to utilize very thin solid state detector slabs. Here one would collect all the released secondaries and gain several factors over the secondary emission foils mentioned above. Furthermore, the advantage of much smaller energy required to produce an electron-hole pair in a solid state detector would add considerably more gain, especially if the effective thickness of no density effect is of finite thickness and not merely a surface phenomenon.

3. Effective Utilization of Accelerator: Multiple Targeting, Automatic Data Handling, and On-Line Computer Analysis

The intense interest shown by physicists in high energy research has resulted in innumerable proposals for experiments at the highest energy accelerators in existence

today. Unfortunately, the available machine time in these accelerators falls far short of adequately satisfying these demands. It has become essential to seek ways to improve the efficiency of utilizing these machines. Significant success has already been achieved in the direction of scheduling several experiments simultaneously. As many as 5 separate experiments have been carried out successfully at the AGS by proper programming of multiple targets and by appropriate sharing of beams from these targets. Significant success has also been achieved in another direction – that is, by the maximum utilization of high intensity beams available through proper design of the experiment so that the detection system is capable of making use of all the desired particles contained in the beam; it must also cover as much of a useful solid angle as feasible so as to detect the maximum number of interesting interactions involved. An example of this is the high energy elastic scattering experiments (see section II, 11) where a system of counter hodoscopes⁸ (multi-counter arrays) was successfully used with automatic data handling and on-line computer analysis with immediate feedback of analyzed results to the experimenters. The present system is capable of handling one million events per hour; this can be further expanded if necessity demands it. Due to these new techniques, up to two orders of magnitude increase in data accumulation rate, accompanied by a higher systematic accuracy than previously attained, was possible, and for the first time a wide survey of the field was practical in one experimental run. The automatic data handling and on-line computer analysis system is equally applicable to sonic or wire spark chambers.

Similarly, for bubble chamber photograph analysis, successful development of measuring devices on-line to computers is expected to reach a capacity of about 10,000 events per week. An eventual rate of 100,000 events per week may be within possibility, especially when problems concerning automatic “pattern recognition” can be solved.

It is apparent from the above that when a super high energy accelerator is built, one can be well assured that it will be fully utilized. It would provide not only more beams (see section IV, 1) than the existing accelerators, but would also have more room and flexibility to accommodate many more experiments than can be done with the present machines. Since this machine would undoubtedly be a unique, central facility of a national nature, increased participation by university faculties and students could certainly be realized with great advantage to the high energy physics program in the whole nation and to science in general.

V. CONCLUDING REMARKS

From the experimental feasibility studies summarized in sections II, III, and IV the following conclusions may be drawn:

1. It is feasible to design and construct an alternating gradient synchrotron in the multi-hundred BeV region up to 1000 BeV with a beam intensity of $>10^{13}$ protons per second.
2. All the known particle beams including hyperon beams can be obtained from such an accelerator, and various detection methods will be available. The latter include very large bubble chambers possibly with high magnetic fields (~ 100 kG), counter hodoscopes incorporating an on-line computer for immediate data re-

duction, the combined time-of-flight method and beam separator system, and other promising methods. With these techniques most, if not all, of the experiments envisaged in the theoretical considerations presented in this volume can be performed.

The results thus obtained from these experiments would not only enable us to gain a much deeper insight into the nature of matter, but may also greatly benefit the other branches of science and engineering such as astronomy, chemistry, biology, medical sciences, electronic engineering, etc., either through demands made on technology or by the direct application of results.

One might raise the question – if we built a 1000-BeV machine, would we consider designing an even bigger machine than this? There is no logical answer to this question at the present time. The discoveries made in high energy physics and the improvements made in the art of accelerator design during the next 10 years probably will indicate clearly what should be the future direction of high energy physics.

REFERENCES

1. O. CHAMBERLAIN, E. SEGRÈ, C. WIEGAND, AND T. YPSILANTIS, *Phys. Rev.* **100**, 947 (1955).
2. T.D. LEE AND C.N. YANG, *Phys. Rev.* **104**, 254 (1956).
3. C.S. WU, E. AMBLER, R.W. HAYWARD, D.D. HOPPE, AND R.P. HUDSON, *Phys. Rev.* **105**, 1413 (1957).
- 4a. *Experimental Program Requirements for a 300 to 1000-BeV Accelerator and Design Study for a 300 to 1000-BeV Accelerator*, L.C.L. Yuan and J.P. Blewett, Editors, Brookhaven National Laboratory, BNL 772 (T-290), revised 1962.
- 4b. *The Berkeley High-Energy Physics Study, Summer 1961*, L. Smith, Editor, University of California, UCRL-10022.
- 4c. *Proceedings of the 1963 Summer Study on Storage Rings, Accelerators and Experimentation at Super-High Energies*, J.W. Bittner, Editor, BNL 7534.
- 4d. *Possible Beams and Experiments for a High Intensity AGS*, L.C.L. Yuan, Editor, BNL 7956, May 1964.
- 4e. *Report of the Working Party on the European High Energy Accelerator Programme*, CERN Report FA/WP/23/Rev. 3, June 12, 1963.
- 4f. *Report of the Panel on High Energy Accelerator Physics of the GAC and PSAC*, US AEC, TID-18636, April 26, 1963.
5. H. FOELSCH, J. LACH, J. SANDWEISS, AND M. GUNDZIK, BNL Accelerator Department Internal Reports HF/JL/JS/MG-1, HF/JS-1.
6. *Proposal for Construction of a 14-Foot Diameter Liquid Hydrogen Bubble Chamber*, BNL 8266, June 1, 1964.
7. P. FRANZINI AND M. SCHWARTZ, Private communication.
- 8a. S. J. LINDENBAUM, in *Proceedings of the 1962 Conference on Instrumentation for High Energy Physics*, CERN, July 1962, p. 297, North-Holland Publishing Company.
- 8b. K. J. FOLEY, S. J. LINDENBAUM, W.A. LOVE, S. OZAKI, J. J. RUSSELL, AND L.C.L. YUAN, *Phys. Rev. Letters* **10**, 376 (1963); *Nucl. Inst. Methods* **27**, 82 (1964).
- 8c. K. J. FOLEY, W. HIGINBOTHAM, S. J. LINDENBAUM, W.A. LOVE, S. OZAKI, D. POTTER, AND L.C.L. YUAN, *A High Capacity Digital Data Handling System for Use With Counter Hodoscopes and Digitized Spark Chambers in On-Line Computer AGS Experiments*, BNL 852 (T-338), March 1, 1964.
9. A.I. ALIKHANYAN ET AL., *Soviet Phys. JETP (English Transl.)* **17**, 756 (1963).

A P P E N D I C E S

Appendix 1

ACCELERATORS WITH ENERGY >1 BeV

Proton Accelerators			Electron Accelerators		
OPERATING					
Delft	1	BeV	Frascati (Italy)	1.1	BeV
Birmingham	1	"	Lund (Sweden)	1.2	"
Saclay (France)	3	"	Stanford (Linac)	1.3	"
BNL (Cosmotron)	3	"	Orsay (Linac) (France)	1.3	"
Princeton	3	"	Tokyo (Japan)	1.3	"
LRL (Bevatron)	6.2	"	CalTech	1.5	"
Moscow (USSR)	7	"	Cornell	1.5	"
NIRNS (UK)	7	"	Kharkov (Linac) (USSR)	2	"
Dubna (USSR)	10	"	Cambridge (USA)	6	"
ANL (ZGS)	12.5	"	Hamburg (Germany)	7	"
CERN (Switzerland)	28	"			
BNL (AGS)	33	"			
UNDER CONSTRUCTION					
Serphukhov (USSR)	70	BeV	Liverpool (UK)	4	BeV
			Yerevan (USSR)	6	"
			Stanford (Linac)	20	"

Appendix 2

SOME FAMILIES OF PARTICLES

For the convenience of the reader, some families of particles are listed here, grouped according to the $SU(3)$ symmetry scheme. The symbols used here are for the most part without meaning. In the table below, J represents the spin, P the parity, Y the hypercharge, and T the isotopic spin of the particle. The numbers on each level represent the mass of the particle in MeV.

I. LEPTONS ($J = 1/2$)

Particle	Mass, MeV	Mean Life, sec
ν_e	0	stable
ν_μ	0	stable
$e^\pm$	0.51	stable
$\mu^\pm$	105.66	2.2×10^{-6}

II. MULTIPLETS OF STRONGLY INTERACTING PARTICLES

1. The $J^P = 1/2^+$ baryon octet

2. The $J^P = 3/2^+$ baryon decuplet

3. The pseudoscalar meson octet

4. The vector meson octet

All these strongly interacting particles are unstable except for the proton. Similar multiplets exist for the antiparticles.