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LAMPF: The Meson Factory

A LASL Monograph

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LAMPF: THE MESON FACTORY

INTRODUCTION

As early as 1954, there was interest at Los Alamos Scientific Laboratory in the construction of a high-energy accelerator and in the advances in physics that an appropriate machine could engender.* The first record of LAMPF as such occurs in 1962 in a memorandum from Louis Rosen to J.M.B. Kellogg, then Physics Division Leader. Many people, some of whose names appear in this report, joined in the effort to produce a preliminary proposal in 1962 for a proton-linear accelerator (LINAC). Interest in a "meson factory" continued to grow at Los Alamos and at other locations within the country, including Yale, UCLA, and Oak Ridge National Laboratory.

LAMPF was officially proposed to the USAEC in August 1963. In December 1963, an Advisory Panel on Meson Factories, chaired by Hans A. Bethe, met for the first time. The panel report, issued in March 1964, recommended the construction of a meson factory, and in its further recommendations, leaned toward the LASL design. Construction, planning, and design funds were made available to LASL in April of 1964; in October 1964, a final cost estimate of $55 million was presented to the Atomic Energy Commission (AEC).

The initial construction cost of LAMPF was $57 million. Its annual operating budget exceeds $18 million (FY 1976). More than 300 people work at the accelerator in LASL's MP-Division. Probably 300 more people within LASL and outside it — as crafts and contractors — work in support of LAMPF. Additionally, some 1100 people from all over the world have declared their intention to do experiments at LAMPF — these are the members of the LAMPF Users Group. A large fraction of the users show serious intent to participate in LAMPF experiments, many of them bringing separate and additional funds for the purpose.

LAMPF is a complex enterprise, requiring many disciplines for its success. Among them are science, medicine, engineering, construction, and management, the latter including all the skills required to make sure that the needs of the other talents are met adequately and on time. Few people have either the time or the opportunity to see the entire operation of LAMPF, and those who do are mostly too busy to write about it.

This document is intended as a general and simplified introduction to the entire concept of LAMPF in terms of its experimental capabilities. Parts of the current experimental program are used as illustrative examples.

The origin of LAMPF lay in nuclear physics. Physics is the most quantitative of all the sciences, hence the most mathematical. But physics has its qualitative side as well, because it is a practical science which must relate to the world. Here the qualitative side is emphasized, so that the scientist, engineer, physician, craftsman — and the interested and intelligent outsider — may see just a little better what LAMPF is doing, and how its pieces fit together.

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*For a complete and detailed history, see M. Stanley Livingston, ***Origins and History of the Los Alamos Meson Physics Facility***, LA-5000, June 1972.

SOME THOUGHTS ABOUT PHYSICS

Philosophers ponder the question of the existence of the natural world and come to different answers depending upon their particular ontological persuasion. Physicists, on the other hand, who used to be called Natural Philosophers, assume the existence of the natural world but ponder questions regarding regularities in its structure. The most fundamental of these regularities are called "Physical Laws"; it is the business of the physicist to find these laws.

As knowledge of the physical world has grown, the number of physical laws has diminished. As of 1976, only four kinds of forces were required to describe every possible interaction in the physical world: nuclear, or strong forces; electromagnetic forces; "weak" forces; and gravitational forces. These forces are in the approximate ratios $1:10^{-2}:10^{-10}:10^{-38}$. Even so, it is beginning to appear that some of these forces may have a common origin.

In addition to the four forces, 12 conservation laws are presently known. A conservation law is simply a statement that the total amount of some designated quantity does not change, or is invariant. Corresponding to each of the conservation laws, there is thought to be an invariance principle, not all of which have been firmly correlated with a corresponding conservation law.

It is possible to say that within the framework of quantum mechanics all known physical principles can be understood in terms of the forces and the 12 conservation laws. We shall be more specific in some of these matters further along. By applying these various principles, physicists predict the behavior of the natural world with remarkable success.

CONSERVED QUANTITIES

Mass - Energy
Linear Momentum
Angular Momentum
Electric Charge
Baryon Number
Lepton Number – Electron Number
    Muon Number
Parity
Strangeness
Charge Conjugation Invariance
Time-Reversal Invariance
PCT (the combination of parity, charge-conjugation, and time-reversal invariance)

To give a concrete example, one of the conserved quantities is electric charge. The statement that charge is conserved means, in one interpretation, that the total amount of electric charge in the universe is an invariant constant. Put another way, we can neither destroy nor create charge. But since charge occurs with two signs, positive and negative, reactions are possible in which equal numbers of particles are produced having positive and negative charges, so that the total amount of net charge production is zero. The simplest example of such an event is the production of a pair of electrons, one positive, the other negative.

To give another example, one of the conservation laws most frequently invoked in physics is that of the conservation of mass-energy. Matter and energy are what physics is really all about, so at this point we are simply using the terms without definition. The equivalence of matter and energy was shown by Albert Einstein in his famous paper on "Special Theory of Relativity" published in 1905. This conservation law tells us that although matter may become energy or energy become matter, when the two are added properly, the sum does not change during an interconversion.

The basic point made here is that physics is based on principles and laws for which no explanation can be offered at a more fundamental level. Their justification lies only in the fact that they work. They are heuristic and empirical, and fortunately there are not very many of them. In what follows we shall from time to time invoke one or more of these principles and not attempt to offer a deeper explanation, since none is available.

THE MESON FACTORY: HOW DID IT EVOLVE?

Man is the only animal who builds and uses tools. Tools permit Man to extend his influence more widely over his world than would otherwise be possible. They permit him to extend his senses beyond their innate limits. They allow him to create new things. They permit him to extend his knowledge. They may also provide pleasure, as, for example, do the tools for playing games. Particle accelerators, one of Man's most useful and elaborate tools, do all of these things and perhaps more.

Some examples may help clarify the proposition. The first particle accelerator was the x-ray generator invented by Wilhelm Röntgen in 1895. X radiation is closely akin to visible light, differing only in that it has a much shorter wavelength. It is produced when fast-moving electrons impinge on a target, which is usually metallic, but need not necessarily be so. In the first x-ray tubes, electrons ejected from a cold metallic surface due to the electric field existing upon it gained energy in passing to a positively charged target electrode, or anode. Upon striking the target, such as copper, zinc, or tungsten, the accelerated electrons disturb the electrons of the target atoms. In rearranging themselves to their initial configurations, these disturbed electrons also undergo accelerations and decelerations. Now it is a theoretical prediction and an experimental fact that when electrical charges are accelerated (by increase or decrease of their velocity) they emit radiation. The radiation so produced was named x radiation by Röntgen because neither he nor anyone else knew at the time what it was.

Today we understand that x rays are composed of entities that we call photons, whose properties are fairly well understood. The usefulness of x rays need hardly be more than recited here: diagnostic and therapeutic use in medicine; nondestructive testing of industrial machine parts and welds; determination of the crystal structure of materials by x-ray diffraction, including the elucidation of the structure of the double helix, DNA. These are only a few of the important applications of x radiation to date.

The energy given to the electrons accelerated in an x-ray tube is derived from a high-voltage transformer. There are, however, limitations on the voltage that can be produced by a transformer. One is that if the voltage gets too high between the output electrodes, an arc will be drawn between them. For this reason, transformers often are submerged in oil, whose insulating property is better than that of air. Nonetheless, there is an eventual limit on the voltage that can be produced by an ordinary x-ray machine — typically 200,000 or 300,000 volts. An electron passing between the emitting and target electrodes in an x-ray tube excited at a voltage, say, of 200,000 volts, will gain a certain speed and hence a certain energy in its passage. In this example, we would say the energy of the electron is 200,000 electron volts. An electron passing across a potential difference of one volt, approximately the voltage of a flashlight dry cell, would gain energy of one electron volt.

It is an experimental fact, quite well explained by theory, that the higher the voltage of an x-ray tube, the more penetrating is its radiation. Ignoring for the moment why this is so, it is evident that the more penetrating a radiation, the more useful it would be in investigating things, especially if they are either very large or very dense. For this reason, there was early and continuing interest in producing higher and higher voltages for x-ray machines. It was also realized that other particles could be accelerated in much the same way. Lord Ernest Rutherford pointed up the need for protons of high energy when he found the energy of alpha particles from naturally radioactive materials less than adequate in his first experiments on disintegration of nuclei.

An answer to Rutherford's challenge was invented by Sir John Cockcroft and E.T.S. Walton and has become known as the Cockcroft-Walton accelerator. It works in the following way. A high-voltage transformer is connected in series with a rectifier, a device that allows the flow of electric current in but a single direction. If the rectifier in series with our transformer is connected to a capacitor, a device which can store electric charge, the capacitor will charge to the peak voltage of the transformer. If we have two capacitors and charge both of them, say with a 100,000-volt transformer, we can then produce 200,000 volts by stacking one capacitor upon the other, or putting the two in series. Such a configuration is called a "voltage doubler." It can be developed from a series of rectifiers and capacitors, using the rectifiers as automatic switches. The invention is not limited to merely doubling the voltage, but can multiply it by several factors, in the present example up to about a factor of 10. Thus, beginning with a 100,000-volt transformer, one can produce a 1,000,000-volt, direct-current source. A modern version of this system is used as an injector at LAMPF, whose output voltage terminal operates at 750,000 volts, or 0.75 MV. A particle passing from the high-potential head of the Cockcroft-Walton generator at LAMPF to ground potential will thus gain 750,000 electron volts of energy, assuming its charge is that of the electron. Since this is the case for either protons or negatively charged hydrogen, that is exactly what happens at the LAMPF injector.

The first transmutation of elements was observed by Lord Rutherford about 1915. Using alpha particles from a natural source, he observed the reaction $^{14}N(\alpha,p)^{17}O$, the conversion of nitrogen to oxygen. This was the beginning of the realization of the alchemist's dream. Rutherford also discovered the law that describes the scattering of charged particles by atomic nuclei and which bears his name. The electrical repulsion of nuclei of like charge was understood to require that projectile nuclei would need high energies to overcome this "Coulomb" barrier. Deviations from the Rutherford scattering law, which began to be observed in the measurements shortly to be described, gave rise to the knowledge that a new force, which we know today as the nuclear force, was in effect in addition to electromagnetic forces.

As early as 1920, the voltage multiplier circuit was invented. Cockcroft and Walton adapted the votage multiplier to an accelerating tube and produced the first successful disintegration of nuclei by artificial means in 1932. Almost coincidentally in time, Lawrence and Livingston, at Berkeley, were engaged in the construction of the first cyclotron, conceived by Lawrence in 1930. The first practical cyclotron, a 10-inch model producing protons of about 1-MeV energy, was completed and described in a publication by Lawrence and Livingston in 1932. They were able to confirm the results of Cockcroft and Walton of the disintegration of lithium by energetic protons.

Before this time, the development of accelerators had branched into several directions. Robert J. Van de Graaff invented the machine which bears his name and which is today produced by High Voltage Engineering, Corp. of Cambridge, Mass., among others. This machine charges its high-voltage electrode by conveying electric charge on a moving insulating belt to a high-voltage electrode. That brief statement hardly does justice to the elegant and stable systems that the Van de Graaff principle produces. The experiments done with these machines, using various particles as projectiles, have taught us much about the structure of atomic nuclei. Many of these electrostatic generators are still in operation in laboratories around the world. They are, however, limited to high voltages of the order of several million volts by various factors. A principal limitation is that if the Van de Graaff machine is to be used as a particle accelerator, an accelerating tube, evacuated inside, is required to guide and focus the beam. Various effects cause arcs and discharges to form along this tube. In spite of many ingenious attempts at a solution to this problem, it appears to be a basic one for the Van de Graaff accelerator. The best of such machines have not gone beyond an accelerating potential of 15,000,000 volts in a single accelerating tube.

The discovery of "phase stability" independently by McMillan and Veksler lead to the proposal of frequency modulation of the cyclotron by McMillan for obtaining high energies and overcoming the effects of relativistic increase in mass of accelerated particles. In a subsequent *tour de force*, McMillan used the principle of phase stability to invent the synchrotron, which was in its turn improved by the addition of alternating gradient focusing (see below). While these machines differ in important ways, they all share the common feature that the accelerated particles move in circular or spiral paths and that they are accelerated more than one time — in fact, many millions of times, as they traverse accelerating gaps whose voltages are adjusted and kept "in step" with the increasing energies of particles. This principle is used in the basic design of the meson factory TRIUMF in Vancouver, British Columbia, and the SIN facility, Villigen, Switzerland. However, this circular design did not lend itself well to the extremely high intensity desired at LAMPF, and for this reason was not used in the LAMPF accelerator.

The forerunner of LAMPF, the linear accelerator, had its beginnings as early as 1925. In contrast to the circular machines, the linear accelerator uses repeated acceleration across electrical field gaps in a straight line, hence its name. The first design was proposed by Ising. Other names from the early days, *circa* 1930, include Wideroe, Sloan, Lawrence, Coates, and Kinsey.

Modern linear accelerators owe their origin to two groups, that of the late W. W. Hansen at Stanford University, and that of L. W. Alvarez and W.K.H. Panofsky, both of whom were at the time at the University of California at Berkeley.

Following its Cockcroft-Walton injector, at an energy of 0.75 MeV, the proton beam of LAMPF enters an accelerator section, usually called the Alvarez section, which works on the principle developed at Berkeley and accelerates the beam to 100 MeV. Subsequent acceleration of the beam is accomplished in a wave-guide section which owes its basic concept to the ideas of Hansen, although it differs in important ways from Hansen's principal design, as LAMPF's Alvarez section differs from early Berkeley designs.

The linear accelerator principle has been used for many other facilities, notably including the Stanford Linear Accelerator (SLAC) which produces an electron beam having an energy of 22 billion electron volts (GeV). The accelerator with highest beam energy so far built is at Fermilab in Batavia, Illinois, where a proton beam is produced having energy up to 500 GeV by the synchrotron principle.

The foregoing brief survey of accelerator development describes the expenditure of several hundreds of millions of dollars. Indeed, the market for all kinds of particle accelerators is numbered in the hundreds of thousands of units. The value and utility of particle accelerators lies in the fact that their use permits us to develop useful information in ways which are otherwise impossible. As we shall see later, the higher the energy of the accelerator, the greater the detail it is capable of probing. For similar reasons, the higher the energy of the accelerator, the more penetrating is its radiation. These two factors have given continued impetus to the development of new particle accelerators and to the extension both of their energy and of their intensity. The LAMPF accelerator is one of the newest in this long chain of accelerator development.

HOW TO BUILD AN ACCELERATOR*

Unlike charges attract. Like charges repel. In a changing magnetic field, electric charges experience forces very much like those due to other charges. These simple rules are the beginning principles for accelerator design — though, of course, their application requires quantitative and sophisticated understanding.

Electromagnetic forces are the only ones which have so far been used to accelerate charged particles. It is first of all necessary that the particles to be accelerated have an electric charge. In its normal state, an atom has as many orbiting electrons as it has positive charges (protons) on its nucleus. Atoms can, therefore, be charged positively if one or more of their electrons is removed. In a similar way, they can be charged negatively because one or more electrons can be bound along with the usual number of electrons. Charged particles are produced by an "ion source" — the term "ion" denoting an atom with a deficit or excess of electric charge.

To accelerate the atoms of a gas, hydrogen, for example, it is first necessary to strip an electron or to add an extra electron to the atom. Free electrons can be produced by boiling them off an incandescent filament, such as one made of tungsten. It is also possible to use high-frequency electromagnetic waves to energize atomic electrons, which in turn strip electrons from atoms in a gaseous discharge. All particle accelerators require an ion source. In the LAMPF accelerator, the ion source is located in the high-voltage head of the Cockcroft-Walton accelerator. In fact, LAMPF has three ion sources and three Cockcroft-Walton accelerators. One produces positive hydrogen ions (H^+), the second produces negative hydrogen ions (H^-), and the third (yet to be built) will produce "polarized" H^-, ions similar to the second but differing in that they are oriented alike, their magnetic axes pointing in the same direction.

Thus, by either adding or subtracting electrons from elementary atoms, one forms ions. We are now able to consider how ions may be accelerated by attraction and repulsion of charges of unlike and like signs, respectively.

The simplest accelerator imaginable is shown in Fig. 1. It consists of two very large, flat plates, parallel to each other. Connected to each of the plates is the terminal of a battery which causes electrons to leave the positively charged plate and to go to the negatively charged plate.

If now we place an ion, say positively charged, between the plates, it is clear that the ion will experience a force causing it to move and gain energy. The positive ion will be repelled by the positively charged plate and attracted to the negatively charged plate. If the plates are quite large, the effect on the positive ion should not depend on the lateral position of the ion between the plates. Hence, this arrangement would not be a very useful particle accelerator, because the particles that are accelerated would merely strike the negative electrode, and it would be difficult to make any use of them. The object is to get the particles out from between the plates.

One way to proceed with the present example would be to drill a small hole in the negative electrode. If then the ions were properly placed initially, a few of them would get out through the hole in the negative plate; however, if the hole is small, it would be hard to hit. And, if it were large, there would be no negative charge there to attract the positive ion, and the ion would tend to be deflected. Clearly, a useful design requires a refined idea.

Let us look then at the design of the accelerating column of the Cockcroft-Walton injector at LAMPF. This sophisticated design uses a series of porcelain cylinders to form the accelerating tube (see Fig. 2). Between each pair of cylinders there is a metal disk with a central hole. The electric potential, or voltage, is controlled in such a way that opposite sides of the metal disks are positively and negatively charged. Thus, a positive ion proceeding down the accelerating column sees a sucession of gaps that tend to force it from the positively charged high potential head to

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*Livingston and Blewett, in their book *Particle Accelerators* (McGraw Hill, 1962), give a detailed and expert description of the operation of the many kinds of particle accelerators which have developed since about 1870. The present brief account is much indebted to this work, as well as to Dr. Livingston personally.

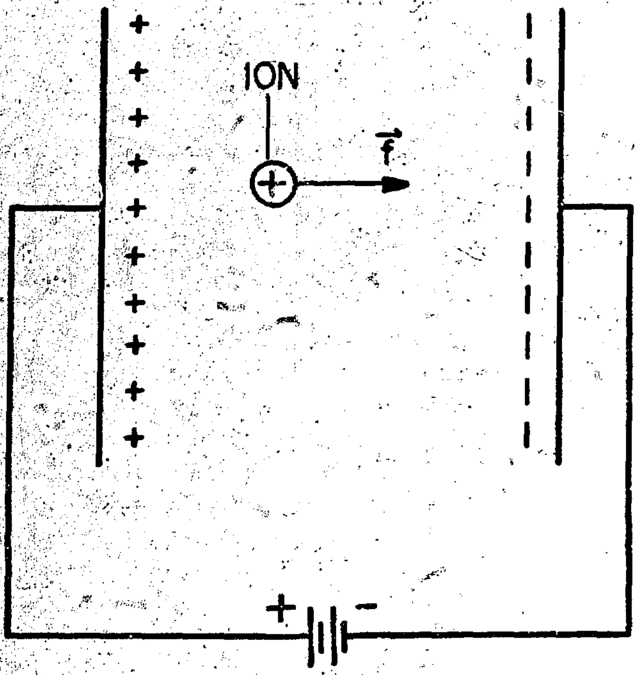


Fig. 1.

The force on the ion, $\vec{f}$, is due to repulsion from the positive plate and attraction to the negative plate.

the opposite end of the column. Furthermore, the lines of electric force tend to compress the beam toward the central axis of the accelerating column. This is an important and desirable feature of the machine, because it is important that the beam be as nearly parallel as possible.

This general configuration for an accelerating column is used in ion accelerators up to several millions of volts. As the voltage increases, it becomes progressively more difficult to avoid arcing and sparking, both inside and outside the accelerating column. The trouble is that some particles are accelerated that shouldn't be, and that some of the particles that should be accelerated strike parts of the electrode system, giving rise to free electrons that, in turn, give rise to more electrons, resulting in breakdown of the accelerating tube. This is one reason that accelerators of the Cockcroft-Walton and Van de Graaff variety are limited to about 15 million volts. Going beyond this accelerating voltage requires an entirely different design, one in which the ions receive successive increases of energy rather than a more or less continuous acceleration. Cyclotrons, synchrotrons, and linear accelerators accomplish this end, each in a different way.

A photograph of the Alvarez section of the LAMPF accelerator is shown as Fig. 3, and a schematic drawing illustrating the principle of this accelerator is shown as Fig. 4. In this design, advantage is taken of the fact that electric fields do not penetrate the surface of a conductor. Thus, an ion inside one of the accelerating cylinders is not subject to accelerating fields. For this reason, the cylinders are called "drift" tubes. High-frequency electromagnetic energy is supplied to the cavity in such a way that the polarity of the accelerating gaps reverses periodically. In LAMPF the frequency of this reversal is 201.25 MHz. Ions moving down the center of the Alvarez accelerator are subject to electric fields only during that portion of time when the fields can accelerate them in the desired direction. During intermediate times, the ions are inside the drift tubes, simply coasting. The Alvarez section increases the proton energy from its injected value of

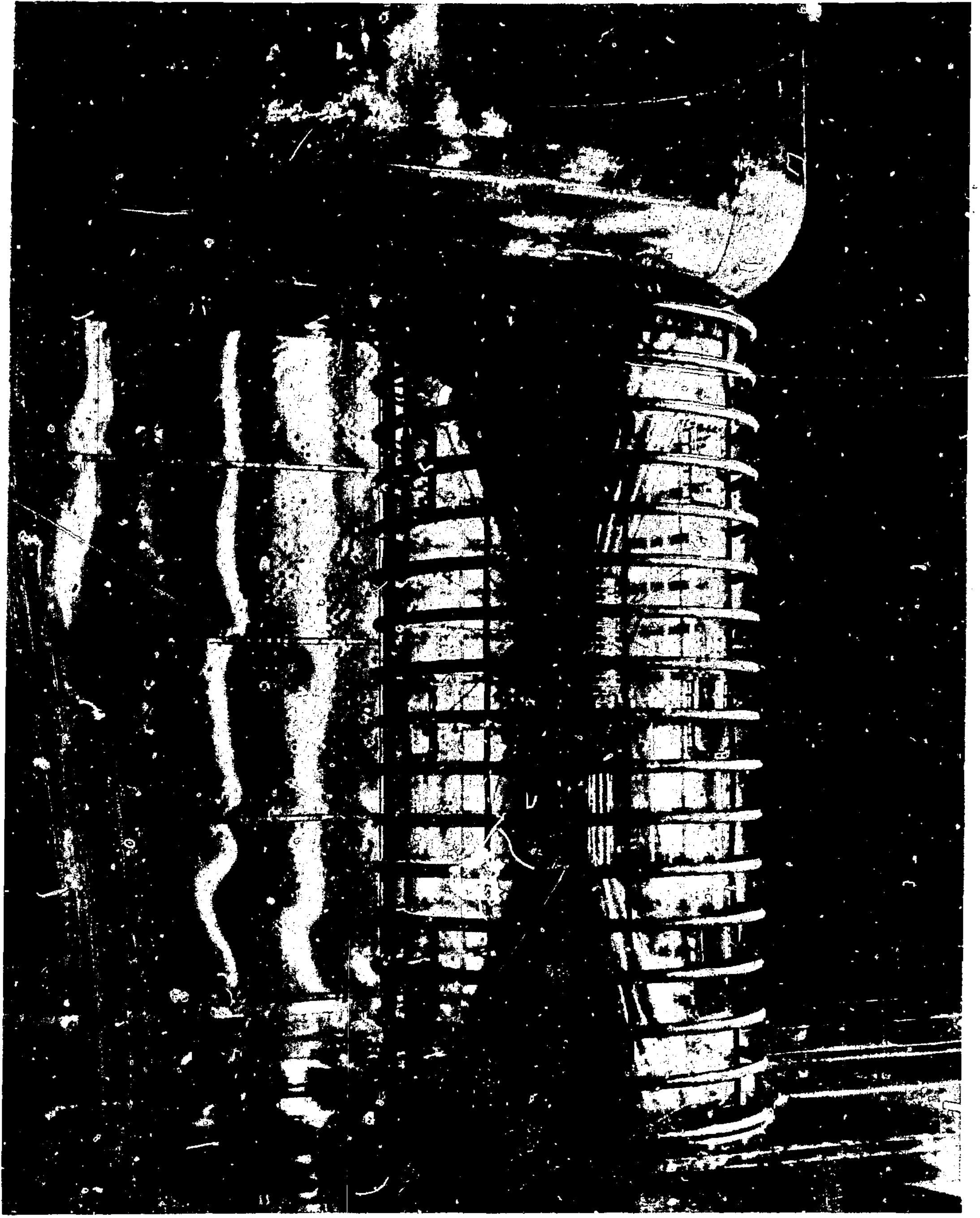


Fig. 2.
Accelerating Column of Cockcroft-Walton Accelerator.

0.75 MeV to 100 MeV. At the lower energy, a proton is moving at only 4% the speed of light; at 100 MeV, the speed has increased to 43% of the speed of light. To accommodate increasing speed, it is necessary to adjust the length of the drift tubes in such a way that the protons arrive

Fig. 3.
Alvarez Section of LAMPF.

at the accelerating gaps at the proper time; this, of course, means that the drift tubes must get longer and longer.

By the time a proton has reached the end of the Alvarez section at LAMPF, it can travel 0.64 meters during one cycle of the electromagnetic oscillation. While it is possible in principle to use the Alvarez design to achieve the full energy of 800 MeV, a more economical design principle becomes feasible once the protons have achieved a fairly high velocity — of the order of 50% the speed of light. This is the waveguide accelerator. The LAMPF design is based upon, but differs importantly from, Hansen's earlier designs. At LAMPF the accelerator frequency is quadrupled to 805 MHz to drive the waveguide section. A most ingenious design feature is the use of "side-coupled cavities" to adjust the phasing of electromagnetic energy to coincide with passage of accelerated protons across successive gaps. The selection of this design, due to Nagle and Knapp,

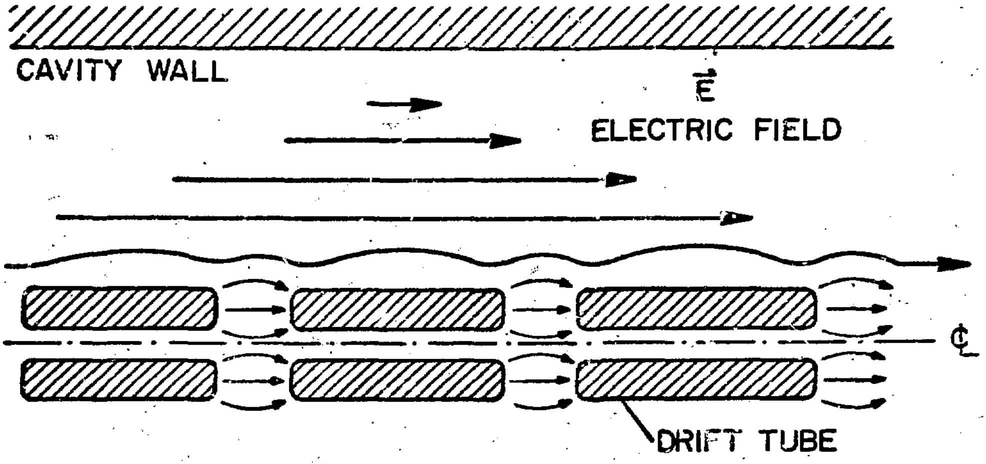


Fig. 4.
Alvarez Section — Schematic.

cut the length of the "wave-guide section" in half and saved some tens of millions of dollars in the construction of the LAMPF accelerator. This design principle was first used for an electron prototype accelerator (EPA) and was so successful that numerous electron accelerators for use in cancer radiotherapy have been built based upon it. As in the Alvarez section, it is, of course, necessary to allow for the increasing velocity of the protons as they proceed down the wave-guide section. Cross sections and schematics of the wave-guide accelerator are shown as Figs. 5 and 6, respectively.

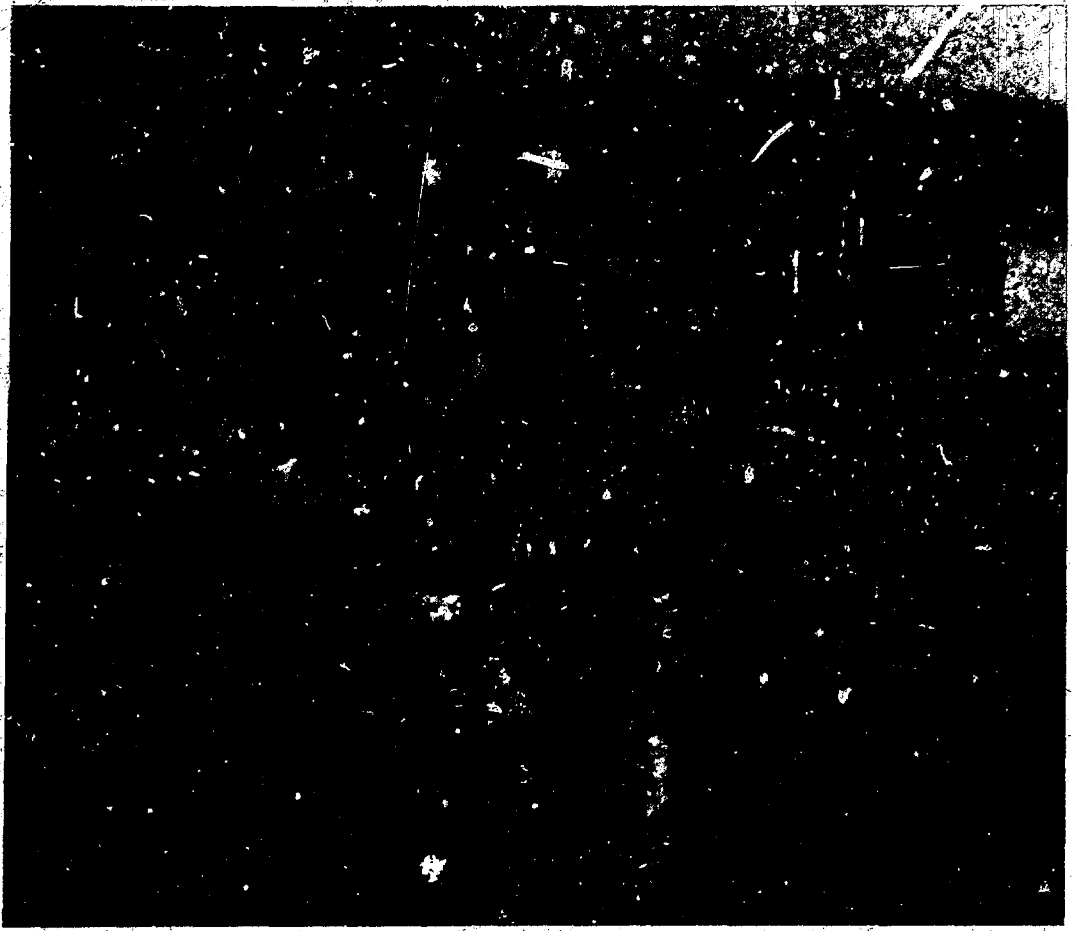


Fig. 5.
Cross-Section of Side-Coupled Cavity, Wave-Guide Section of LAMPF.

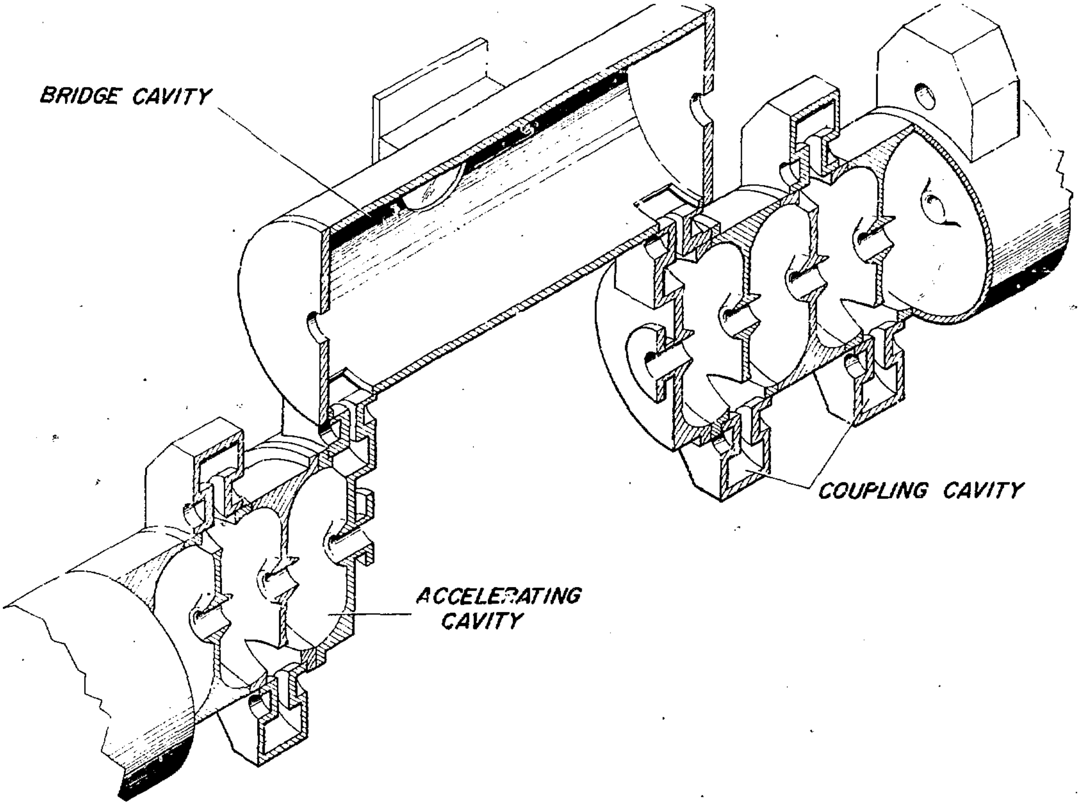


Fig. 6.
Schematic of Side-Coupled Cavity, Wave-Guide Section of LAMPF.

STRONG FOCUSING

LAMPF was designed to produce pion beams of intensity 10,000 times greater than any previous accelerator had produced. For this reason, the beam current is quite large — one milliampere average — a value never before approached in an accelerator of such high energy. This very high beam current, and the risk of beam spill, dictated the selection of a linear accelerator design, rather than a cyclotron. As the beam leaves the accelerator, its power level is 800 kilowatts. Such a beam cuts its way through steel like a warm knife hitting so much butter. It is extremely important that the minimum amount of beam strike the accelerating structures and electrodes. To this end, use is made of a principle invented by Courant, Livingston, and Snyder called magnetic strong focusing.

The principle is as follows: Consider a magnet (see Figs. 7 and 8) with four magnetic poles, called a q[illegible] magnet, alternating north and south, as shown in the drawing. Suppose a pair of identical quadrupole magnets is placed in succession, with one of the quadrupoles rotated 90°, such that north and south poles alternate along the beam direction as well as circularly around the beam. If an ion proceeding down the accelerator encounters the two oppositely directed magnetic fields, one after another, its trajectory will be bent outward at first and then inward, or *vice versa*. It turns out that the inward bending is always greater in effect than the outward bending, and on this account the quadrupole pair causes a convergence of the ion beam called "strong focusing."

From the time that ions leave the Cockcroft-Walton injector until they exit the wave-guide section of the beam, they pass through many hundreds of such quadrupole magnets, each pair acting to focus and contain the ion beam.

Thus, the LAMPF accelerator combines the inventions of Cockcroft, Walton, Livingston, Alvarez, Hansen, Nagle, Knapp, and many others, each of whom has made a major contribution to its operation.

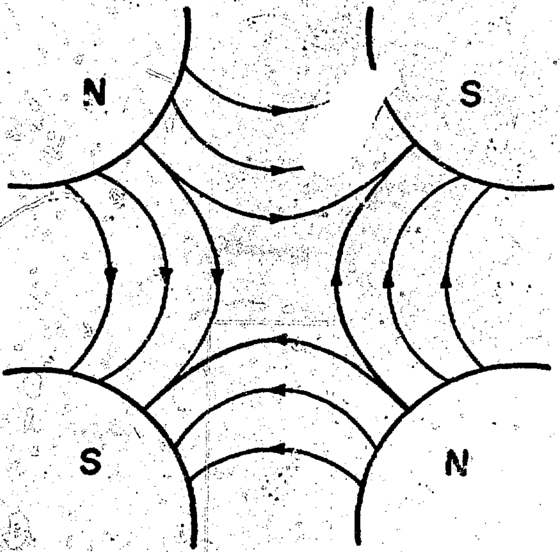


Fig. 7.
Magnetic Quadrupole. Arrows indicate the direction of the magnetic-induction field.

Fig. 8.
Magnetic Quadrupole, a Strong-Focusing Lens.

ACCELERATOR INNOVATIONS AT LAMPF

A project of the magnitude of LAMPF, drawing upon the skills of physicists, many branches of engineering, and state-of-the-art high technologists, is almost certain to produce major advances in accelerator technology. Many of these advances are the result of the joint efforts of several people. Thus adequate credit is not easy to assign. Here we list some of the major achievements in design which have contributed importantly to the success of the LAMPF accelerator, some developed at Los Alamos, others adapted from other machine designs.

1. high-current, low-emittance ion sources.
2. "post couplers" in the Alvarez accelerator.
3. side-coupled cavity design for the wave-guide section of the accelerator.
4. "feed-forward" control of r.f. power, to anticipate beam-loading of the accelerator.
5. digital-computer control of the entire accelerator and experimental areas.
6. application of klystrons as r.f. power generators at high power and high duty factor.
7. acceleration of H^+ and H^- beams simultaneously.

PHOTONS AND PIONS

The reason for calling LAMPF the "Meson Factory" is that it is designed to produce pi-mesons, the principal meson which binds the constituents of atomic nuclei *together*. Other mesons are believed to play a role in this process as well, but the most important by far is thought to be the pi-meson or pion. When pions decay, they give rise to other particles, including protons and mu-mesons. The design of LAMPF to produce copious beams of pi mesons naturally leads to emphasis on research with these basic particles. For this reason, we need to take an extended look of the nature of pi-mesons, what they do, and how they do it.

To explain the role of pions in the nucleus we begin with the relatively more familiar concept of the photon. Pions and photons, while quite different from each other, share certain characteristics.

The photon is said to be the *quantum* of the electromagnetic field. More picturesquely, we can call a photon "a particle of light." Since we know that light behaves in a wave-like way in many experiments, we immediately encounter the problem of how it is possible to speak of a "particle of light" that is also a wave. Pions and all other elementary particles, such as electrons and protons, behave in an identical way.

To speak of a photon as *being* a *particle* or a *wave* is to use loose language, at best. For the ideas "particle" and "wave" are regarded as constructs of human thought, neither of which are realizable in fact.

An idealized "particle" is an object like a geometric point, but having mass. It has no extension in space, a zero radius. Since a particle has mass within zero volume, its mass density is infinite.

We find the concept of "particle" useful in physics in many ways. For example, we can calculate the motions of stars, planets, space vehicles, earth satellites, automobiles, golf balls, and, sometimes, electrons and photons, by attributing to these entities the characteristics of the abstract idea "particle," that none of them in fact really is.

At the same time, an idealized "wave" is also an abstract idea that never exists as a physical entity. A "wave" is most easily defined mathematically, but here we describe the idea of "wave" as a periodic, regular, moving disturbance within some substance (its "medium") that supports the motion.

"Wave" tends to imply that there are two characteristics of the medium: "inertia," a property of matter that tends to keep it, once moving, in motion, and allows it to transport energy and momentum; and "springiness," a second property of matter that allows the storage of energy within a medium when it is displaced from its resting position. Thus, a wave may propagate in a violin string, a piece of steel, a pool of water, or a room full of air.

If a wave is truly repetitive, it will have a unique wavelength — the distance between identical points of wave displacement. Such a repetitive wave must have an infinite extent, since if it *ever* stops, it is not truly repetitive. But nothing in nature is infinite!

Thus, the idealized concepts "particle" and "wave" represent two opposite conceptual poles. An idealized "particle" is infinitely compact, completely localized to a point. An idealized "wave" is infinite in extent, completely nonlocalized, containing infinite energy and momentum. No wonder, then, that neither construct represents a real entity — a photon, a pion, an electron, nor a proton. To try to apply *both* ideas at the same time, however, leads to logical contradictions; Bohr's "principle of complementarity" states that only one construct at a time may be used.

Energy and Momentum

A photon is found, by experiment, to travel in vacuum with a velocity $c = 3 \cdot 10^8$ m/sec, the speed of light. It is further characterized by a frequency, a rate of vibration, denoted by ν (Greek "nu"). The time of a single vibration is the reciprocal of ν. In such a time the photon (we are now thinking of it as a wave) will travel a distance of one wavelength, λ (Greek "lambda").

Thus,

$$\lambda = c(1/\nu) \quad \text{or}$$

$$\lambda\nu = c \; ;$$

the product of wavelength and frequency is c, the velocity of light.

Furthermore, by experiment, a photon (now thought of as a particle) is found to have an energy, E, proportional to its frequency, ν.

Or $$E = h\nu \, ,$$

where h, Planck's constant, is a fundamental constant of nature named after the discoverer of this relationship.

Since $\nu = c/\lambda$, we can also write

$$E = hc/\lambda \, ,$$

and we see that the energy of a photon is directly proportional to its frequency, or inversely proportional to its wavelength. A particular photon, then, has a fixed energy, E.

Einstein discovered that energy and matter are the same thing in differing manifestations:

$$E = mc^2 \, .$$

This relation then implies that a photon has associated with it a *mass*, m,

$$m = E/c^2 \, ,$$

and since momentum p, is the product of mass and velocity,

$$p = mc = E/c = h\nu/c = h/\lambda \, , \quad \text{and note that}$$

$$p\lambda = h \, .$$

So a photon — a wave, sometimes — has a definite mass, as though it were a particle; a definite energy; and transports a definite momentum.

All of these things would be incredible, were it not that they are precisely verified by experiment.

Action at a Distance?

We say that, as the "quantum" of the electromagnetic field, the photon is responsible for electromagnetic force, how can this be?

The first discovery leading to the form of the electromagnetic-force law was made by Sir Isaac Newton — his "Universal Law of Gravitation,"

$$f = G[(m_1m_2)/r^2] \, .$$

This law, together with the mathematics of "fluxions," or calculus, invented by Newton, permitted him to calculate the motions of the planets as they had been observed by Tycho Brahe and reduced to formulae by Johannes Kepler. The law says that the "gravitational" force between two mass points, m_1 and m_2, is proportional to their product and inversely proportional to the square of the distance between them.

The law as formulated by Newton was a spectacular success and is still just what is needed for most calculations involving gravity. It left open a major question, however: How is the gravitational force transmitted, say from sun to earth, through empty space? Thus was born the idea of "action at a distance," a name for a mystery, which made it not a whit less mysterious.

Forces between electric charges were under study at about the time of Newton's death. Charles Augustin de Coulomb tried the same relationship, now known as Coulomb's Law, to describe electric force:

$$f = k[(q_1q_2)/r^2] .$$

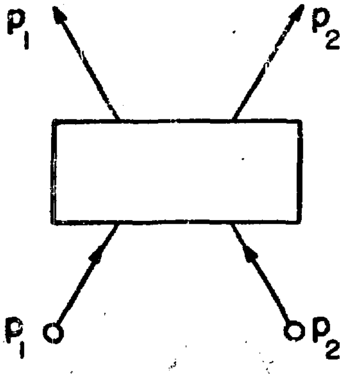
If possible, Coulomb's Law works even better than Newton's. It says that the electric force between two charges, q_1 and q_2, is proportional to their product and inversely proportional to the square of the distance r, separating them.

That the exponent of r in the denominator is exactly 2 is subject to experimental test. Its value has been verified as being 2 to 1 part in 10^{16}, showing the extent of the validity of this relationship.

Eventually it was found by Oersted that magnetic effects were intimately related to electric charges in motion. The effort to find the principles describing these effects ultimately lead James Clerk Maxwell to write his famous set of equations which describe electromagnetic phenomena. We now know that Coulomb's Law is contained in Maxwell's equations, whose validity was unaffected by Einstein's discovery of the Special Theory of Relativity, and that it describes the force between static charges.

But the question remained: How does one electric charge affect another in the case that they are separated by vacuum?

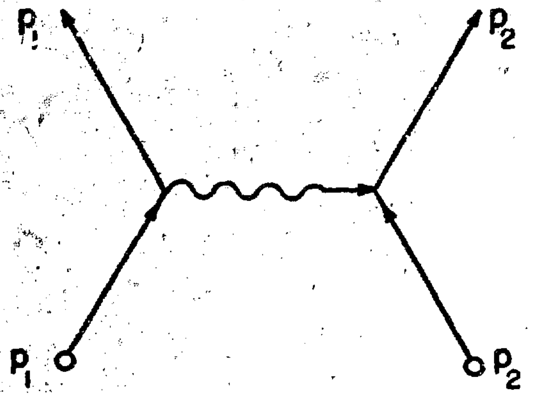
Suppose, for example, that we project two protons — positively charged hydrogen nuclei — through a region in which they interact by deflecting each other.



We conceal the interacting region because we do not know precisely how the protons interact. We see only that their momentum (mass × velocity) changes, at least in direction. We could, however, calculate the momentum change correctly by using Maxwell's equations and the Lorentz force law. But we still would be faced with the mysterious "action-at-a-distance." Can we think of a mechanism for equal and opposite exchanges of momentum?

Photon Exchange

One quite satisfactory way of accounting for action-at-a-distance is shown here:

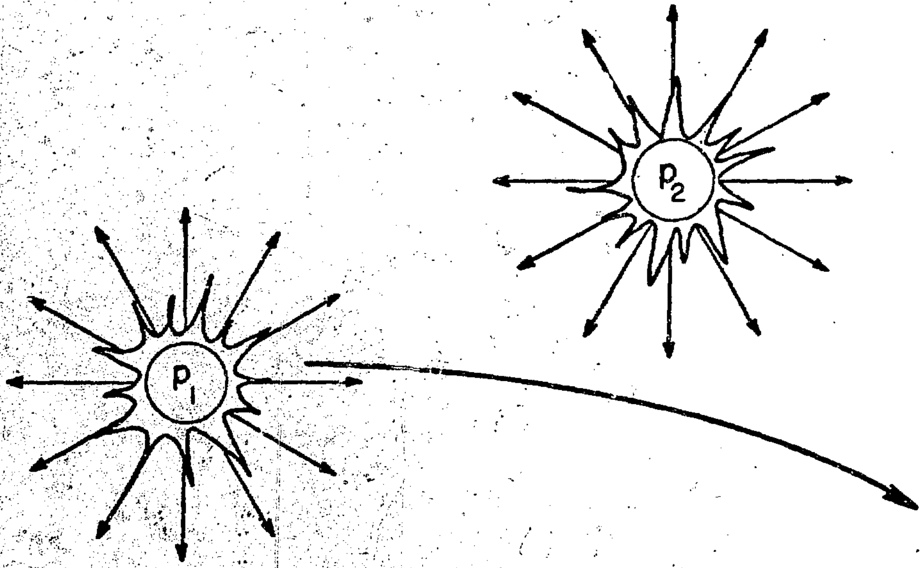


The wavy line indicates that a photon is emitted by p_1 and absorbed by p_2. The p_1 "recoils" as it fires the photon with its momentum, $h\nu/c$; p_2 is deflected as it absorbs the photon's momentum. Clearly it does not matter which proton emits and which absorbs the photon — the outcome is the same.

So the exchange of a photon — an object with characteristics both of particle and wave — can account exactly and satisfactorily for the electric force.

The "inverse square" ($1/r^2$) behavior of the electric force is automatically included in this model, since photon intensity from a point source varies inversely as r^2 — as a matter of simple geometry.

So this model accounts for *almost* everything. If it were so that the only force between protons is the electromagnetic force, that would be the end of the story. We could model protons as fuzzy balls emitting photons, and we could calculate the projectories of protons shot at one another.



In fact, if the angle of deflection is small, the photon exchange model gives quite precise agreement with experiment.

However, we find in scattering of protons by protons, and in many other similar experiments, that the photon exchange model cannot account for all the observations. What happens is that the probability of these events with large amounts of momentum exchanged between two particles is far greater than can be accounted for by Coulomb's Law — or the photon exchange model. Furthermore, the process is greatly enhanced as the energy of the projectile increases, so much so that the particles can approach each other closely in spite of their mutual repulsion due to their electric charges.

Something else is going on. At first it looks fairly easy to explain. Yet, the more we find out about this enhanced interaction, the more complicated it appears to be. It is a prime purpose of the LAMPF experimental program to help unravel this additional component, the "strong" or "nuclear" interaction, as it is known.

Nuclei and Particles

When we speak of the size of an object, and how we measure it, we mean something like this: "How near may I approach a thing before I touch it? How far away may I go and still sense its presence?"

We are accustomed to thinking of material objects as having quite definite boundaries — the edge of a table top, for instance, or the surface of a billiard ball. This appearance is really a matter of scale, or relative size. Men are so much larger than atoms (by a factor of 10^{10}) or their nuclei (by a factor of 10^{15}) that the indefiniteness of boundaries of matter on its smallest scale is imperceptible.

In a very real sense, a proton has no "electric" boundary, since the photons of its electromagnetic field radiate to infinity.

When we explore the surface of one proton with another — or if we shoot neutrons at protons, to remove electromagnetic effects (almost entirely), we find that the surface of the proton is not fuzzy, as its electric field suggests, but rather well defined — and that protons are *attracted* to protons, at least for a time, if they come sufficiently near each other.

The Meson

To account for the finite range of the "strong" interaction, which makes the radius of a proton appear to be about 1 fermi (10^{-13} cm), the Japanese physicist Hideki Yukawa, in 1935, invoked the exchange of a heavy quantum between nucleons (neutrons and/or protons). Unlike the photon, which vanishes at rest and thus has zero rest mass, Yukawa's quantum was calculated by him to have a rest mass about 200 times that of the electron. This object, with mass intermediate between that of the electron and the nucleon, was called the "mesotron" — a name later abbreviated to meson. Yukawa's mesons were found in cosmic radiation by C. F. Powell and his collaborators in 1947. Today we call them pi-mesons, or pions.

Pions occur in three charge states — positive, negative, and neutral. Our present understanding of the attractive force between nucleons is modeled by the exchange of pions of one of the three varieties.

Exchange Forces

It may not appear obvious that the exchange of quanta can account for an "attractive" force, but this result arises from a calculation first done by Yukawa that is quite straightforward. The analogy is sometimes made with a group of people bound together by playing a game of "catch." It is a rather good analogy. If we think of players throwing, from one to another, something like a baseball, we immediately see that there is a limit to the distance that exists between the players if they are to maintain their interaction. Also, if the game is played with a heavier object, say a medicine ball, the interaction distance is of necessity much smaller than it would be for a lighter ball. The range of forces is related to the mass of the quanta exchanged in a field in much the same way. The more massive the quantum, the shorter the range of the force. It was from the known range of nuclear forces that Yukawa was able to estimate the mass of the mesons that he predicted and that were later found to exist.

Presently, the measured mass of the pion is 273 m_e (electron masses) for the charged variety and 264 m_e for the neutral pion.

It is the existence of pi mesons in the atomic nucleus which makes them of great interest in the study of the nucleus and of nucleons.

Pions were first detected in nuclear emulsions in cosmic-ray experiments in 1948. They were first produced artificially in 1948 at the 184-inch synchrocyclotron at the Lawrence Berkeley Laboratory. Before the construction of the new meson factories, LAMPF, SIN, and TRIUMF, there were only about half a dozen accelerators in the world capable of producing pions. The meson factories, and especially LAMPF, will produce pion beams of intensities heretofore impossible to attain. These extremely intense beams permit scientists to devise experiments to test the details of pion theory with high precision.

Pion Facilities at LAMPF

As of 1976, there are four principal channels for pion research at the LAMPF accelerator: LEP, P^3, EPICS, and Biomed. While these channels have important differences among them, they have greater similarities. The first three names are acronyms for "Low-Energy Pion" Channel, "Pion-Particle Physics," and "Energetic Pion Channel and Spectrometer." Here we shall treat the four more or less without distinction.

In each of these pion channels, pions are extracted from a target placed in the proton beam of the accelerator. In fact, LEP and EPICS use the same target. The proton beam, passing at high energy through a material target, "knocks" the pions out of the nucleus. The pions leave the target with a broad spread of energies. But it is much easier for a physicist to do his experiments with a beam of particles that has a single energy. The reason for this is that if the energy width of the beam is large, a great variety of processes may occur in the experiment at once, making it difficult to unravel the multiple effects.

Thus, the purpose of each of the three pion channels is to transport a selected pion group with a particular energy and momentum to the experimenter, and to bring the beam to a focus at some convenient point in his "cave." While the design and construction of a pion channel is a task of considerable magnitude, it is in theory quite straightforward.

From the time of their creation until they decay into muons, pions exist, on the average, 26 nanoseconds, or 26 billionths of a second. But the average pion does not live 26 nanoseconds. An given pion may decay immediately upon leaving the target, or it may live several times 26 nanoseconds. At the speed of light, an object moves about one foot in one nanosecond. At first glance, therefore, if the channel is 26 feet long (and all of them are at least this long), it would seem that about two-thirds of the pi mesons will decay before they exit the channel.

But this is not the case. The reason is that, since the pions move at velocities comparable with the speed of light, their own "clocks" run slower than do those in the laboratory; hence, the pions gain a moderate extension of their lifetimes. Typically, this factor may be two or three times the 26-nanosecond lifetime. At the same time, because of another relativistic effect, the pions passing through the channel appear to gain mass by the same factor by which their lifetime is increased. This means that the magnet designer must provide a larger magnetic field to bend and focus the pion beam than he would expect to do if he were not acquainted with the concepts of relativity. Since the experiments require a range of speeds in each of the channels, and since mass and lifetime vary with speed, the designer has a challenging problem in optimizing the length and shape of the channel.

There is yet more to the problem, however. Not only are pions knocked out of the nuclei in the target, many of them decay in different directions into muons, or mu-mesons, of different mass. Furthermore, protons from the primary beam may scatter from target nuclei, or protons having momenta which overlap those of the desired pion beam may be knocked out from within the nucleus. The same is true of electrons — they are not knocked out of the nucleus, but may be produced in the channel as pions, muons, and protons proceed down it.

The experimenter would like to have a beam of pure pions. It is his job to design his experiments so that he can tell the difference between the particles that he wishes to study and those that he does not. Fortunately, there are differences among the various particles which impinge upon experimental apparatus that make it possible to distinguish them. What we have said above of pions is equally true of the other particles used for experiments — muons, neutrinos, protons, neutrons, and photons.

Experiments with Pions

Having gained some notion of how pion beams can be formed, we now look at some of the kinds of experiments which can be done with them.

The intrinsic nature of the pion itself is of great interest: How do isolated pions behave? To this point we have discussed only π^+ and π^-, the charged (positive and negative) pions. We shall return to these two shortly, after we have looked at their neutral counterpart, π^0.

The neutral pion, π^0, has a much shorter mean life than $\pi^\pm$, 10^{-16} sec *vs* 10^{-8} sec. Usually π^0 decays into two photons, or gamma rays; however, there is nothing to forbid its decay into more photons, or other decay schemes, such as:

$$\pi^0 \rightarrow \gamma + \gamma + \gamma$$

$$\pi^0 \rightarrow \mu^+ + \mu^-$$

$$\pi^0 \rightarrow e^+ + e^- \ .$$

Other decay schemes are also easily imagined. A theory of pions must explain why a particular decay mode is favored — and why other decay modes can occur.

The prevailing decay scheme of the charged pions, $\pi^\pm$, on the other hand, leads to muons, neutrinos (ν), and antineutrinos ($\overline{\nu}$), thus:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \ .$$

Many other decay modes are also possible, two of which are:

$$\pi^+ \rightarrow \pi^0 + e^+ + \nu_\mu$$

$$\pi^+ \rightarrow e^+ + \nu_e + \gamma .$$

Of course, there are counterpart decays for π^-.

What one does is to observe free pions and measure the mode of their decay, its frequency relative to other decay modes; then one must construct models of pions that reflect the experimental observations.

Pions are thought to be stable within the nucleus. Perhaps the greatest of the riddles is why the free pion is unstable, why it decays at all. On this point it is worth noting that the π^0 mean life of 10^{-16} s and the $\pi^\pm$ mean life of 26 ns ($2.6 \cdot 10^{-8}$ s) must be considered in context. The time required for light, travelling $3 \cdot 10^{10}$ cm/s, to traverse a nucleus, of about 10^{-13}-cm diameter, is approximately 10^{-23} s. When we compare this time to the π^0 mean life, we see that the π^0 lives 10^7 "nuclear transit times" and the $\pi^\pm$ lifetime is $2.6 \cdot 10^{15}$ "nuclear transit times," so that pions do, in fact, exist outside the nucleus for quite a long time, as the nucleus reckons time. From this viewpoint, pion lifetimes are long. The appearance that pions give to man of a brief and evanescent existence is a consequence of man's desire to measure time on the scale of his own heartbeat.

Pions as Waves

In considering the energy and momentum of photons, we derived the relationship between momentum (p) and wavelength (λ),

$$p\lambda = h .$$

This famous equation was first given in 1923 by Louis de Broglie, and bears his name. De Broglie suggested that what is true for a photon, a "particle of light," might also be true for particles of matter — electrons, protons, pions, and so on. More specifically, the idea is that a definite wavelength is associated with a given value of momentum. In other words, particles may behave like waves, under suitable conditions.

That such is the case was verified at Bell Labs in 1923 by C. J. Davisson and L. H. Germer, and by John Thompson at the Cavendish Laboratory, who independently demonstrated the wave-like interaction of electrons with the regularly spaced crystalline arrangement of atoms in metallic gold.

This simple but elegant equation is the foundation of "wave mechanics" or "quantum mechanics," a description of the world on the scale of atoms and nuclei that has met with tremendous success — more in atomic than in nuclear physics, but nonetheless great success. Major contributors to the development of quantum mechanics were Schroedinger, Heisenberg, Pauli, Bohr, Einstein, Gamow, and Dirac — and there have been many other important contributors since the 1920s.

In 1976 our best description of the behavior of pions is in terms of their wave-like behavior as they interact with nucleons or nuclei. It is likewise the case that nucleons — neutrons and protons — are best described by wave mechanics.

In the de Broglie relation, $p\lambda = h$, h is Planck's constant, a constant of nature. The value of h is such that λ is exceedingly small when p has a value comparable to momentum values of direct experience. Only on the scale of nuclear particles, where masses are miniscule, does the de Broglie relation assert itself. It turns out that when one uses pions or protons or neutrons of "medium energy," 100 to 1000 MeV, their de Broglie wavelengths, λ, are about the size of nucleons. Pions then can probe the structure of nucleons or nuclei. With lower energy (and/or momentum), the wavelength is too large, too gross, to allow one to study details of nuclei and nucleons; and at much higher energies and momenta, the wavelength is such that only the structure of nucleons can be seen.

The LAMPF Accelerator thus is designed to produce pions with wavelengths suitable as nuclear probes.

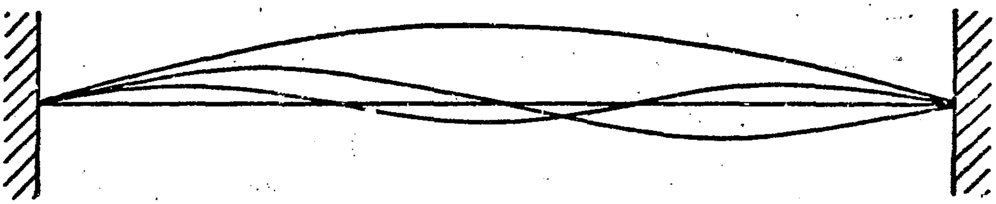
Resonance: The Pion-Nucleon System

We have said above that a wave requires a "medium" for its propagation, a quality of space which combines elasticity, or "springiness" and inertia, the propensity to store energy of motion. The material, whatever it is, of which atomic nuclei and their constituent particles, nucleons, are made might well be expected to share these properties. It is possible for waves to propagate in nuclear matter, of the sort which represent pions in motion.

If we consider a material object on our own scale — for example, one designed to vibrate musically — we find that such a thing does not respond equally to waves of all wavelengths, or frequencies. Caruso is supposed to have been able to shatter a wine glass with the sound of his voice. If he could, he had not only to sing loudly enough, but at precisely the pitch which matched a vibration of the glass at which it would absorb energy, causing its walls to vibrate at large amplitude, finally breaking with the stress.

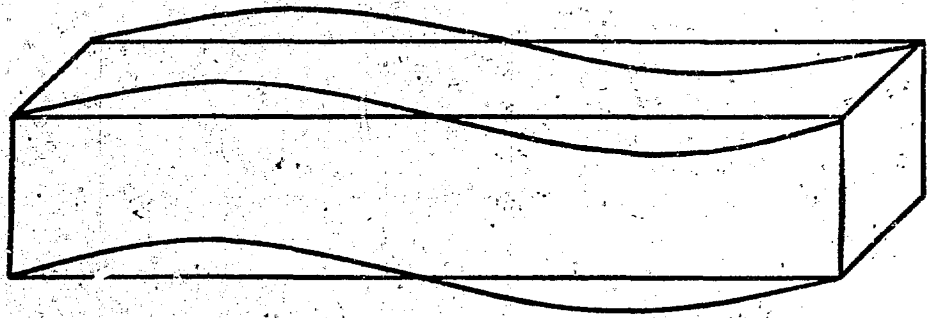
A less powerful singer might also match the vibrations of his voice with the glass, perhaps without breaking it. This matching of vibrational frequencies is called resonance. It occurs widely in nature. In particular, it occurs when pions interact with nucleons. We shall look at this process in greater detail, to see how it may help us to understand the "shape and size" of nucleons.

Any material object which propagates waves — sound, light, or matter — and which has "shape" or boundaries, will have characteristic wavelengths at which it can vibrate with large amplitude. These wavelengths are defined by the shape of the object. In the simplest, one-dimensional case of a vibrating string, the wavelengths are determined by the condition that a half-wave, or an integral multiple of half-wavelengths, must fit the length of the string, thus:



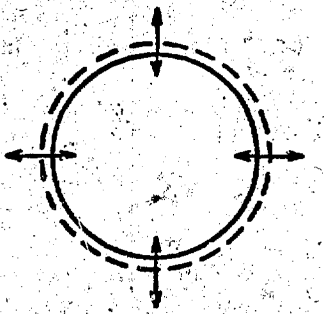
$n(\lambda/2) = L$, *where n is an integer.*

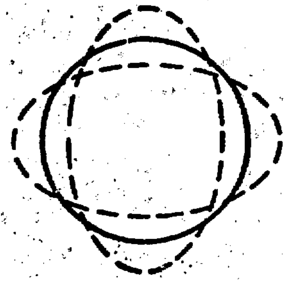
In two or more dimensions the resonant wavelengths are more complex. A simple example is the case of a rectangular bar of metal:



The bar may vibrate in each dimension independently, and it may also have motions which cooperate in two or three dimensions.

The vibrations of a sphere are similarly complex, the simplest mode being a pulsing motion in which the radius oscillates uniformly. The three-dimensional vibrations of a sphere are useful in describing possible motions of nuclei. A few simple examples are sketched below. It is to be understood that the waves, be they matter or not, propagate within the sphere:





We have seen that, for photons,

$$\nu\lambda = c$$

and for matter waves (pions, for example)

$$p\lambda = h\ .$$

This relation is true for photons as well. Thus there is a correspondence between ν and p, and c and h. Protons have a momentum, p, proportional to their frequency, ν, as do other particles of zero rest mass.

For particles with nonzero rest mass, the momentum, p, plays the role of frequency, since p has associated with it a definite wavelength, $\lambda = h/p$.

The relationships among momentum, rest mass, and energy are given by:

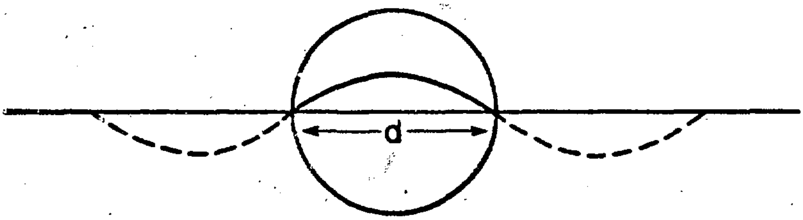
$$E^2 = p^2c^2 + m_0^2c^4 \quad \text{and}$$

$$E = T + m_0c^2 ,$$

where m_0 is the rest mass, T is the kinetic energy, and E is the total energy of a particle.

A Simple Resonance

Suppose a pion impinging on a nucleon has a wavelength such that it "fits" into the nucleon, as shown:



$d = \lambda/2$

If $d = \lambda/2$, then

$$d = h/2p \quad \text{and}$$

$$p = h/2d \; .$$

The diameter of a nucleon is about $2 \cdot 10^{-13}$ cm = 2 fermis. [$\hbar c = hc/2\pi = 197$ MeV-fermi.] It then turns out that

$$pc = 309 \text{ MeV}$$

$$E = 339 \text{ MeV}$$

$$T = 200 \text{ MeV} \; .$$

That is, a pion impinging on a nucleon with a kinetic energy of 200 MeV will "resonate" with the nucleon.

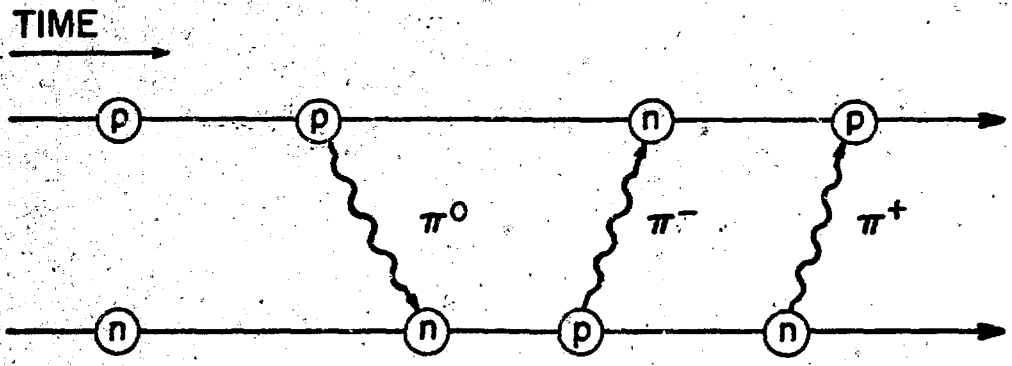
This very rough model gives astonishing, perhaps somewhat accidental, agreement with experiment. At about 190 MeV, the (3,3) resonance, first observed and named by Enrico Fermi, occurs. It is also called the (3/2, 3/2) resonance or Δ_{1237}. It was the first observed pion-nucleon resonance and has continued to be studied in detail since Fermi first discovered it. The (3,3) resonance has the lowest observed energy for a pion-nucleon interaction, just as this model would predict.

What is wrong with this model? Aside from being mathematically naive, there is no reason to assume that the density of nuclear matter is uniform in a nucleon, although this is the simplest assumption and is, therefore, appealing. Furthermore, the nucleon may well have other modes into which a pion wave would fit; in fact it turns out that there is a very large number of "resonances" involving mesons and nucleons, the study of which won a Nobel prize for Luis Alvarez in 1968. The list, in fact, seems to have no end as we would expect if this model is valid.

Of course, we have not shown how the energies of the higher resonances are to be calculated — but neither has anyone else! This is one of the central problems of theoretical particle physics — the creation of a model whose properties will agree with experiment, including the precise prediction of resonant energies.

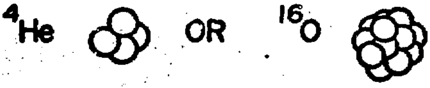
Pions and Nuclei

Atomic nuclei are thought to consist of nucleons, pions, and perhaps other mesons. The binding together of nucleons can be accounted for in part by pion exchange. For example, the least complicated nucleus having more than one nucleon is the deuteron; it consists of two nucleons (a proton and a neutron) exchanging pions, thus:



As shown, the nucleons may, through pion exchange, also exchange their charge state.

The deuteron is loosely bound, by only 2.2 MeV, so that the nucleons are, on the average, further apart than they are in a more compact nucleus, say



Nucleons maintain their identity within nuclei as individual nucleons. Hence they can resonate with incident pions in an individual sense. This means that we should observe the (3,3) resonance whatever the target nucleus, and in fact we do. The (3,3) pion-nucleon resonance is observed in all nuclei.

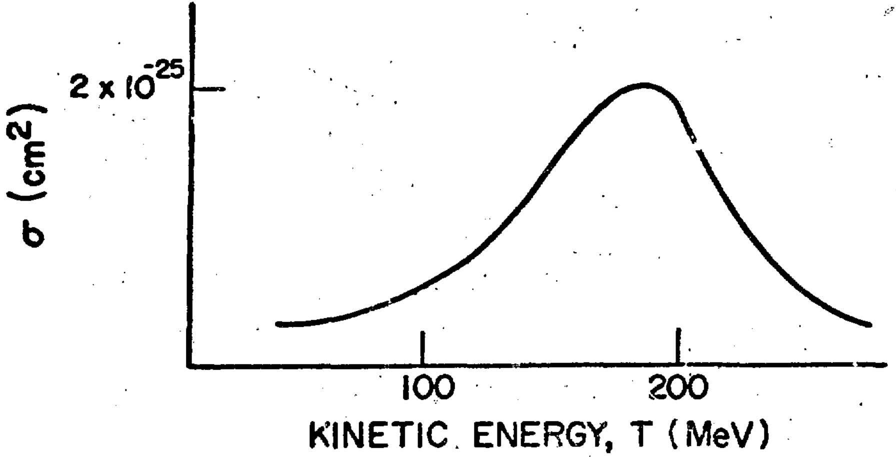
However, it also turns out that the shape and energy of the (3,3) resonance depends upon the target nucleus. We might guess that it would, since any single nucleon participating in a resonance might well be affected by its surroundings. There is also the possibility that more than one nucleon might participate in the resonance, and this would likely lead to differences from the pion single-nucleon resonance. It is a fundamental problem of the theory of the pion-nucleus interaction to make a model whose predictions agree with the observed energies, widths, and magnitudes of the (3,3) resonance.

It is a property of resonant systems that if they dissipate or radiate energy rapidly, their "tuning" or resonance is broad; and conversely, if the resonance is sharp or narrow, it lasts a long time. This is a perfectly general result for waves. In wave mechanics it takes the form of the Heisenberg "uncertainty principle":

$$\Delta E \, \Delta t \geq \hbar \qquad (\hbar = h/2\pi) \, .$$

That is, the energy width of a resonance times its duration exceeds $\hbar$, a fundamental constant of nature.

The (3,3) resonance is quite broad in energy, which means it lasts only a very brief time. It looks like this:



The width indicates a duration of 10^{-23} s, or about the time it would take a pion, considered as a particle, to cross a nucleon. This resonance exists only very briefly indeed.

Nuclear Excitation by Pion Bombardment

Since the pion is to a large degree responsible for the forces within the atomic nucleus, its use as a probe of nuclear characteristics is natural and reasonable.

Nuclear excitation means the addition of energy to a nucleus above that which it normally possesses in its state of lowest energy — its *ground state.* An excited nucleus may lose energy by emitting one or more particles, where photon is included in the meaning of "particle." Thus, for instance, an energetic pion may excite a nucleus, and be re-emitted; or a photon, nucleon, or a nucleus (d, T, ^{3}He, ^{4}He) may be emitted as a result of pion excitation. Of course, the pion may simply be scattered elastically as well. Reactions of this kind are denoted as below, where T represents a target nucleus, T* an excited T, and R_n a resultant nucleus differing from T in nucleonic composition:

$T\,(\pi,\pi)\,T$	elastic scattering
$T\,(\pi,\pi')\,T^*$	inelastic scattering
$T^* \rightarrow T + \gamma$	

$T(\pi,p)R_1$

$T(\pi,d)R_2$

$T(\pi,t)R_3$

. . . and so on. Inside the parentheses, the first symbol denotes the incident particle, the second the emitted particle.

A large number of reactions like those above can be imagined, and efforts to test them are under way at LAMPF. As we have already noted, physics is an experimental science; the object of the LAMPF experiments is to test theory against experimental results.

Similar experiments are being performed using protons from the primary beam as nuclear probes. In addition, the liquid deuterium target in Area B produces neutrons of high energy, which can also be used as probes of nuclear structure.

Studies of nuclei made by bombarding them with pions can be better understood by analogy. Consider, for example, a large bell, whose natural vibrations are determined by the size, shape, and material of which it is made. Although the bell will respond to some degree to any frequency exciting it, its "natural" frequencies are those at which it vibrates most strongly. Their relative intensities depend also on where, and with what, the bell is struck. Now, one can imagine an experiment with a bell in which it is struck at every point of its exterior with a variety of projectiles, hammers, and mallets, and the resulting sounds sent electronically for analysis to a remote location. If the analyst is a competent theoretical physicist, he may come up with a model of an object which behaves very much like the bell. The model may not look like the thing it attempts to describe, however, and to the extent that it does not, further experimentation will distinguish the model from the true object.

In the same way pi mesons of varying energy are used to study the atomic nucleus. Varying the energy and momentum implies that the wavelength of the projectile is varied. In the nuclear case the pion may be refracted, that is, scattered; or it may enter into some cooperative motion with the interior components of the nucleus. Just as for the bell, the nucleus has favored wavelengths at which matter waves within it may vibrate. The experimenter is of necessity remote because of the miniscule size of the nuclei. And, while it is not usual to study bells by hitting them with sufficient energy to break off pieces from them, it is of interest to see how a nucleus fragments in order to learn what is in it. For instance, if nuclear bombardment causes the emission of a ^{4}He nucleus (alpha particle), there is a strong presumption that, at least some of the time, part of the nucleus is organized into an alpha particle. The same is true, or course, of other particles which are emitted.

If the energy of an incident pion goes only into organized motion of the constituents of the nucleus, it can be observed as the emission of gamma rays (photons) when the nucleus returns to its unexcited or ground state. In this way one can determine the natural frequencies of the nucleus. And, as was the case for the (3,3) resonance, measuring the energy width of a nuclear resonance, (ΔE), determines its lifetime.

This technique is itself not new, it having been used for some forty years with protons, neutrons, and gamma rays as the nuclear probes.

What *is* new at LAMPF is the use of pions to probe the nucleus in detail; pions offer some unique advantages as nuclear probes.

One of these comes from the lack of intrinsic angular momentum or "spin" of pions. Nucleons, unlike pions, possess spin of magnitude $\hbar/2$. Spin gives rise to magnetic properties which, in the case of protons (among the easiest of particles to accelerate) include a magnetic moment. This magnetic moment interacts with the magnetic fields of the proton and of nuclei, complicating its behavior in ways that are well understood but that nonetheless are a hindrance to the understanding of nuclear forces. Thus, pions have the advantage of a simpler interaction with nuclei.

Since their spin is zero, pions are classed as ***bosons****, along with other mesons, photons, and* gravitons, the latter being the predicted but as yet unobserved gravitational analogy of the proton and the pion. Bosons have the property that any number of them can aggregate in the same quantum state. *Fermions*, on the other hand, may not be in identical quantum states. Thus a pion, upon entering a nucleus, may share a state with pions already there. Protons and neutrons, being fermions, are *excluded* from states already occupied by other nucleons. Hence it is possible for a pi meson to explore nucleonic behavior in ways inaccessible to nucleon probes.

Charge Exchange: Nuclear Transmutation

We have already noted that pions occur in three charge states: π^+, π^0, and π^-. It is possible to inject one or another of these pions into a nucleus and have a different one emerge — thus converting one or two nucleons within the nucleus to a different charge state. That is, neutrons might be changed to protons, or *vice versa*. For example:

$p\ (\pi^-,\pi^0)\ n$

$n\ (\pi^+,\pi^0)\ p$

$d\ (\pi^+,\pi^0)\ 2p$

$d\ (\pi^-,\pi^0)\ 2n$

$^3He\ (\pi^-,\pi^+)\ 3n$

$^3H.\ (\pi^+,\pi^-)\ 3p$.

Some truly exotic nuclei can be made by *double charge exchange* (π^+,π^-) or (π^-,π^+). For instance:

$^6Li\ (\pi^-,\pi^+)^6He$

$^{12}C\ (\pi^-,\pi^+)^{12}Be$

$^9Be\ (\pi^+,\pi^-)^9C$.

Systems like 2p, 3n, ^{6}He, ^{12}Be, and ^{9}C are not stable, so these unlikely objects soon separate or decay. However, an adequate theory of nuclear structure must predict how long these systems last, what, if any, excited levels they have, and into what they decay. With these reactions of pions with nuclei, LAMPF opens an entirely new field in the study of nuclear structure.

Muons and Neutrinos

We have noted above that π^+ and π^- have a mean lifetime of 26 ns. When a charged pion decays, most often (>99% of the time) it goes as follows:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

where μ (Greek "mu") is the symbol for muon, and ν (Greek "nu") represents the neutrino. The subscript on ν indicates that this neutrino differs from the "electron neutrino" of beta-decay, and $\overline{\nu}$ means "anti-neutrino," ν and $\overline{\nu}$ differing only in the direction of their spins, or helicity.

Muons exist for a much longer time than do pions: 2.2 microseconds. When muons decay, the reactions usually are:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \,.$$

The $\mu^\pm$ goes to its electron (e) counterparts, electron and positron, and two neutrinos, one of each variety.

Unlike pi mesons, muons have spin ħ/2, a property which they share with protons, neutrons, electrons, and neutrinos. All of these particles are fermions; all are affected by the Pauli "Exclusion Principle," which states that no two like fermions may occupy identical quantum states.

The π and μ were named by Enrico Fermi, a story worth recalling. When Yukawa, in 1935, predicted the existence of the mesotron, later shortened to meson, he was able to predict only that the mass should lie in the range of 200 to 300 electron masses. Shortly before this prediction was made, a meson of the predicted mass was found in cosmic radiation by Anderson and Neddermeyer, who were unaware of Yukawa's prediction at the time of their discovery.

At first it was assumed that this new object was Yukawa's meson, but a difficulty was soon perceived, namely that the meson discovered by Anderson and Neddermeyer, supposedly responsible for the nuclear force, showed no interaction at all with nuclei — it was simply an electromagnetic particle like the electron in every way except for its mass.

It was 1947 before the meson actually predicted by Yukawa was found by C. F. Powell and his collaborators. (Subsequently both Yukawa and Powell received the Nobel Prize for their work.) Powell, using photographic emulsions flown at high altitude, found evidence of mesons being produced by proton collisions with atmospheric nuclei, almost as they are produced at LAMPF today. This meson, the Yukawa meson, had a mass 273 times that of the electron, within the range of Yukawa's prediction.

Shortly thereafter, mesons were created artificially. Fermi named them π (Greek "pi") for primary, and μ for meso, or intermediate-meson.

We now understand why only muons are found at the earth's surface in cosmic radiation (and pions only very rarely). The pion's mean life, even if it is extended a thousand fold by relativistic time dilatation, is too short for the pion to go more than about 10,000 m; but pions decay to much longer-lived muons, and these are what we find at sea level.

Properties of some elementary particles are given in Table I:

TABLE I

PARTICLE PROPERTIES

Particle	Rest Mass (MeV)	Mean Life	Spin ($\hbar$)
γ	0	∞ (Stable)	1
ν	0	∞ (Stable)	1/2
$e^{\pm}$	0.511	∞ (Stable)	1/2
$\mu^{\pm}$	105.66	$2.2 \cdot 10^{-6}$ s	1/2
$\pi^{\pm}$	139.57	$2.6 \cdot 10^{-8}$ s	0
π^{o}	134.96	$0.84 \cdot 10^{-16}$ s	0
p	938.28	∞ (Stable)	1/2
n	939.57	918 s	1/2

MUONS AS NUCLEAR PROBES

Physicists have wondered how muons ought to fit into the scheme of things since they first were found. Their mean life of 2.2×10^{-6} s is long enough to permit them to have well-defined properties: mass, charge, spin, and so on. For this reason, they are classified as "stable" particles.

The puzzle lies, however, in "what muons are good for," to put it colloquially. Except for their mass, muons might as well be electrons. Both emit photons as they go from one to another quantum state within an atom; both can participate in chemical binding. The more massive muon orbits nearer a nucleus, its radius being less in proportion to its mass (1/207) as compared to an electron's radius. For the same reason, chemical binding by muons leads to very small molecules, so small that the component atomic nuclei sometimes overlap, or "touch."

As the charge of the nucleus increases, so does its radius, and so does its attraction for the muon; at about $Z = 20$ (calcium), the orbiting muon has a radius equal to the nuclear radius, and for still heavier nuclei, the muon orbits inside the nucleus. This is indeed curious, considering that nuclear matter is denser than water by a factor greater than 10^{14}. Yet the muon, responding only to electromagnetic forces, zips through this extraordinarily dense nuclear matter sensing only protons, and those only by their electric fields. Therefore, transitions between orbits in muonic atoms give information on the distribution of protons inside the atomic nucleus.

NEUTRINOS

Postulated by Wolfgang Pauli and named by Enrico Fermi, the neutrino (little neutral one) was not observed experimentally until 1956, when it was detected by Reines and Cowan and their co-workers. Pauli recognized that the existence of the neutrino would explain why electrons or positrons emitted in beta decay from an atomic nucleus do not have a unique energy. Rather, they have a spread in energy from a maximum down to the limits of measurement. Neutrinos are exceedingly difficult to detect; it is this property which gives the "weak interaction" its name. It is weaker than the nuclear interaction by a factor of about 10^{10}. Pauli correctly guessed that neutrinos would in fact be very difficult to detect, since none had ever been seen.

In 1962, a group from Columbia University and Brookhaven National Laboratory showed that there are in fact two kinds of neutrinos. One of these arises when an electron or positron is the product of beta decay, as in the reaction:

$$n \rightarrow p + e^- + \overline{\nu}_e \ .$$

The subscript "e" on the Greek letter nu (ν) indicates the connection of this variety of neutrino with electron-positron events.

The second neutrino is involved, for example, in the reaction:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \ .$$

The subscript μ identifies the μ-neutrino. Each of the two kinds of neutrinos has associated with it an antineutrino, designated by a bar over the nu, thus: $\overline{\nu}$. Neutrinos, like electrons and muons, have spin $\hbar/2$. These three are known as "leptons" and are subject to the conservation law that the total number of leptons in any reaction is an invariant constant, if in the accounting particles count as plus one, antiparticles as minus one.

The strength of the weak interaction is such that a neutrino passing through a diameter of the earth has but one chance in about 10^{12} of producing an interaction. Thus, whatever his other qualifications may be, a researcher doing neutrino experiments must above all else be patient.

The LAMPF accelerator is a copious source of both electron and muon neutrinos. One experiment in which this source will be used is intended to resolve the mystery of why the sun, which is thought to derive its energy from nuclear energy involving catalytic reactions which should produce large numbers of neutrinos appears to emit no neutrinos at all. Aside from its great importance to the understanding of elementary matter, knowledge of the neutrino might assist in understanding new ways to produce energy from the fusion reactions that are thought to occur in the sun.

NUCLEAR CHEMISTRY

The dividing line between physics and chemistry is hazy and indistinct. Physicists sometimes define their science as "the study of matter and energy." They frequently study systems of very great simplicity in the hope of understanding the basic laws of matter and energy.

One chemist has said that nuclear chemists tend to study much more complex problems than do physicists. Another chemist has defined his science by saying "chemistry is what chemists do." It is certainly the case that quite often an experiment is regarded as nuclear physics or nuclear chemistry depending on whether the experimenter is a physicist or a chemist.

The two subjects are in fact very closely related. A brief look at the history of the two sciences may help to show the interrelationship.

The earliest chemists were alchemists, their goal to discover "the philosopher's stone" and to perfect the transmutation of elements. But nuclear transmutation was first carried out by Lord Rutherford, a physicist, in 1915. (For this discovery, Rutherford received the Nobel Prize in Chemistry!) The conversion of one element to another is now routine in nuclear reactors and accelerators and in many experiments at LAMPF.

Once a sufficiently large number of elements became isolated and understood, the Russian chemist Mendeleev organized the periodic table of the elements. This important discovery helped science to understand why certain "families of elements" behave similarly in chemical reactions. Elements became grouped into such collections as the alkali metals (lithium, sodium, potassium, rubidium, cesium) or the noble gases (helium, neon, argon, xenon, and krypton). The periodic table is in fact organized around the structure of the outer electronic orbits of the elements. The British physicist, Moseley, found a way of measuring the number of protons in the nucleus by looking at the x rays produced by the elements. Chemistry is the science of the interaction of outer orbital electrons, this interaction causing the joining together of atoms to form molecules. In a naive sense, therefore, chemistry is a science involving only electromagnetic forces, and deals with compounds from the simplest, like table salt, to the large and complex molecules of which living matter is made.

Historically, chemists have tended to regard the periodic table as their own territory. However, the British physicists Aston and Dempster invented the mass spectograph, which showed that atoms of some elements that are assigned a single place in the periodic table actually differ in their mass and in other important ways. These different varieties of a given element are called "isotopes." Although their nuclei have the same number of protons, and thus the same amount of positive nuclear charge, and the same number of electrons, the atomic nucleus has varying numbers of neutrons. Thus, the mass of the atom and that of its nucleus is different for different isotopes. There are also other, less obvious differences, such as the magnetic properties of the nucleus and its spin angular momentum, which affect the chemical combining properties of a given isotope. Mendeleev's original table of the elements was eventually filled with naturally occurring species of atoms. But the discovery of isotopic differences and the production of artificial nuclei has extended that number to well over 1000 isotopic species. Probably the great bulk of this work has been accomplished by nuclear chemists. The search for new elements has resulted in several Nobel Prizes, including the award to Fermi in physics and those to Urey and Seaborg and MacMillan in chemistry, although MacMillan is a physicist.

Nuclear chemists from more than a dozen universities and national laboratories work at LAMPF studying nuclear transmutation and the creation of new isotopes. In one set of experiments (Dropesky *et al.*) pi mesons are used to remove one or two neutrons or protons from a target nucleus. If the number of incident pi mesons is known, and the number of resulting nuclei is measured, along with the target characteristics, it is possible to calculate the probability for nuclear transmutation by pi mesons. The results thus obtained must then be explained in terms of theoretical models of the nucleus. A quite successful beginning has been made on this group of experiments.

If energetic pions or protons are incident upon a complex, massive, and large nucleus, the nucleus may be split into two or several fragments, the process being known as fission or spallation. Numerous experiments at LAMPF are designed to study the probabilities of these kinds of events. For instance, pi mesons have bombarded uranium and the resulting yield of ^{24}Na, a radioactive isotope of sodium, was measured. This particular experiment required the use of "wet" chemistry, the conventional kind of chemistry involving analytical separations, in addition to the techniques of nuclear physics.

RADIOBIOLOGY AND MEDICAL APPLICATIONS

Living organisms are the most complex chemical processing plants known. Because at LAMPF we are interested in the interactions of radiations with humans, we shall choose the human organism as our example.

Each cell of a living human being contains within its nucleus the double helix of DNA, which is believed to encode the complete genetic description of the individual. Although the code is imperfectly understood, there are specific examples known for which a flaw at a particular site in the DNA molecule produces a disease as, for example, sickle-cell anemia. The information is encoded in the arrangement of the base pairs AT (adenine-thymine) and CG (cytosine-guanine). The arrangements of these base pairs are analogous to the encoding of information in binary form on a magnetic computer tape, for example. A rearrangement of the sequence of bases could and probably does lead to a genetic error that may be trivial or may be fatal or may lie somewhere in between.

Within the cytoplasm of the cell are complex molecules known as enzymes. Approximately 3500 enzymes are produced in the human organism. Enzymes act as catalysts in the production of chemical reactions within the cell or outside it without themselves being chemically altered.

There are also many other molecules of considerable complexity that make up parts of living cells. For example, the cell membranes are composed in part of phospholipids, fatty molecules. Proteins are another example of a complex molecule that the organism requires for its continued existence.

Radiation of all kinds interacts to some degree with living material. Since living organisms depend upon chemical reactions for their existence, the greater the ability of radiation to disrupt the chemistry, the greater will be its effect upon the organism. Another way of saying the same thing is that the greater the degree of ionization produced by a given radiation, the greater will be its effect on living tissue.

Ionization in chemistry causes the breaking of chemical bonds or the rearrangement of molecules or both.

Because of certain of its unique characteristics, two of the product radiations at LAMPF are of particular interest in radiobiology and medicine: the negative pi-meson and the negative muon. Each of these particles has a negative electric charge equal to that of the electron. They are, however, much more massive than the electron, 273 and 206 times, respectively. As already noted, they can orbit the positive nucleus of an atom at a distance much less than the corresponding electron radius. As already explained, the negative muon orbiting a nucleus emits photons of energy characteristic of the nucleus upon which it is captured. This property makes it useful as a chemical probe of living tissue, for it is possible to make a chemical analysis of many of the elements in tissue by using muons without giving the organism an excessive dose of radiation.

Negative pi-mesons differ from muons in the major respect that they interact with nucleons via the "strong" or nuclear interaction. Thus when a negative pion comes sufficiently close to an atomic nucleus, an interaction occurs which results in the vanishing of the pion together with the conversion of its rest mass to energy. The nucleus separates into two or more fragments in one of a large number of possible ways. These events are called pion "stars" because of their characteristic appearance in nuclear emulsion.

The fragments resulting from pion absorption are highly ionizing and therefore highly disruptive to the chemistry of living cells. On the other hand, before the pion attaches to a nucleus and creates the "star," it is, relatively speaking, a particle of fairly low ionization. Since it is charged, the negative pion is affected by electric and magnetic fields, and therefore may be steered readily to a place at which it is desired to deposit its major ionizing energy. These characteristics make the negative pion a particularly interesting candidate as an agent for treatment of cancer by radiation.

As of 1976, trials have been made on many living systems, including humans, to test the possible usefulness of negative pi-mesons in radiation therapy. As was thought should be the case, pi-mesons appear to interact with higher effectiveness than does a similar dose of x radiation. Therapeutic trials have not yet begun, but there is good reason to believe that pi-mesons will turn out to be extraordinarily useful in treatment of tumors that are otherwise very difficult to treat, because of the pion's steerability and high-radiation dose when it comes to rest.

Successful tests have been made of the usefulnesss of negative muons' mesonic x rays in measuring concentrations of essential trace elements in living tissue. These trials indicate the method to be successful, its application depending upon its usefulness in clinical medicine.

RADIOISOTOPE PRODUCTION

The chemical identity of an element is established by its nuclear charge, i.e., the number of protons in its nucleus. Nuclei also contain a variable number of neutrons. (In the naturally occurring stable isotopes, the number of neutrons is about equal to the number of protons.) For larger and heavier nuclei, there tends to be a preponderance of neutrons over protons.

If the number of neutrons in a stable element is changed by perhaps only one, two, or three, the element will maintain its chemical identity but will become radioactive. If it has too many neutrons, it will tend to emit electrons, thus increasing its positive charge and restoring the balance of protons to neutrons. On the other hand, if the number of neutrons is too few, positrons will be emitted, decreasing its positive charge and again restoring the natural balance. In either case, as the nuclear charge changes, the chemical identity of the element also changes.

Nuclear reactors have within them a surplus of neutrons. Radioisotopes produced in nuclear reactors invariably have, therefore, neutron-rich nuclei which emit negative electrons (beta particles). Any source of neutrons can be used in making radioisotopes; LAMPF is no exception. At its designed beam intensity of one milliampere, 6×10^{15} protons per second impact the beam stop, having lost at most 100 MeV of their initial 800 MeV of energy. Each stopping proton will produce about 30 neutrons, giving a total of about 2×10^{17} per second, one of the most intense neutron sources ever created. The greater the source strength, the easier it is to produce radioisotopes of short half-life. For this reason, LAMPF is a copious source of commercial radioisotopes, making many of them available in quantity for the first time.

At the same time, the primary proton beam can be used to knock neutrons out of a target nucleus, producing radioisotopes that are positron emitters. Relatively few positron-emitting radioisotopes are available on the market today, because most radioisotopes are made in reactors. Positrons annihilate with negative electrons, causing the emission of two gamma-ray photons of energy 0.511 MeV, which, to conserve linear momentum, leave the point of annihilation in precisely opposite directions. Counters can be used to establish the line of flight of the two photons. Many such measurements permit the localization of the origin of emission of the positrons. Thus the use of positron emitters may be very advantageous. For example, it may be possible to visualize a vascular bed by injecting into the blood stream a positron emitter, the radioisotope sodium-22. Also, as the two photons are emitted simultaneously, if the requirement is put on the system that they be detected in time coincidence, the background is greatly reduced. For both of these reasons, the market for positron emitters is very large and is mostly unsatisfied at present. LAMPF may become the primary supplier to meet this need.

MATERIALS TESTING

Just as radiation can alter the molecular structure of the constituents of living tissue, radiation can also change the structure of all other materials. Radiation is not the only agent that can effect these changes; thermal cycling and work-hardening are similar effects. It is important to test materials that are to be used in intense radiation fields by placing them in environments which simulate as nearly as possible the actual environment of use, perhaps even to the extent of exaggerating the cause of deleterious effects.

LAMPF could be used for such tests by irradiating specimens with the high-neutron flux produced at the beam stop, in the way that radioisotopes are produced. Moreover, recent studies indicate that the extent and kinds of damage to be expected from irradiation with the main proton beam should correlate with that produced by neutron damage, except that it will be produced at a much greater rate. Thus, LAMPF may provide some important answers to the problems faced by the designers of fast-breeder and fusion reactors, because these problems presently appear to be related mostly to materials engineering.

LAMPF MANAGEMENT AND THE LAMPF USERS GROUP, INC.

Because of its size, scope, and cost, and because the problems which it addresses cross many disciplines and are of interest to the entire international scientific community, LAMPF was from its beginning visualized as a national and international facility. Qualified scientists from any country in the world are welcome to use LAMPF. Since its conception and initial funding, the design of LAMPF, especially with regard to experimental facilities, has reflected the advice of potential users. A great deal of effort has been spent at Los Alamos to ensure that the completed facilities will be responsive to the needs of visiting scientists, whose recommendations reflect the requirement of experiments designed to answer some of the most important questions in physics, chemistry, and life sciences.

The first organizational meeting of the LAMPF Users was held in 1968. Annual meetings are held in November. It soon became apparent that important advantages were to be realized by incorporating LAMPF users into a nonprofit corporation; this was done in 1972. The LAMPF Users Group, Inc. has an elected board of seven directors. There are in 1976 some 1100 members of the LAMPF Users Group, from 331 institutions and 20 foreign countries.

The users of a particular channel or beam facility are separately organized into "Working Groups," each of which elects a representative to the Technical Advisory Panel, which meets at least annually with the Director of LAMPF and his staff. This mechanism provides a valuable communications channel from users to LAMPF management and *vice versa.*

An independent Program Advisory Committee (PAC), is appointed by the Director of LAMPF to review proposed experiments and advise the Director of LAMPF as to the validity of the experiments and the priority that should be placed upon them relative to beam time and facility availability. Nominations to this committee are made by the Board of Directors of the LAMPF Users Group. In addition, certain members of PAC are *ex officio*, including representatives from the U.S. Energy Research and Development Administration (ERDA) and the National Science Foundation.

The MP-Division of the Los Alamos Scientific Laboratory operates and maintains the LAMPF accelerator and its experimental facilities, and also has its own concurrent research program in Group MP-4. Group MP-3 is charged with "practical applications." Except for these two groups, the overlap of personnel in MP-Division and in the LAMPF Users Group, Inc. is slight.

MP-Division is divided into the following groups, with functions as indicated by their titles:

MP-1 Electronic Instrumentation and Computer Systems
MP-2 Accelerator Operations
MP-3 Practical Applications
MP-4 Nuclear and Particle Physics
MP-7 Experimental Areas
MP-8 Engineering Support
MP-9 Accelerator Systems Development
MP-10 Large Spectrometer Systems
MP-11 Accelerator Support
MP-12 Injector Systems
MP-13 Beam Line Development

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