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Argonne National Laboratory

PHYSICS DIVISION

SUMMARY REPORT

December 1960

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ANL-6262
Physics
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

PHYSICS DIVISION
SUMMARY REPORT

December 1960

Morton Hamermesh, Division Director

Preceding Summary Reports:

ANL-6190 - July, August 1960
ANL-6214 - September, October 1960
ANL-6235 - November 1960

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I. EXPERIMENTAL NUCLEAR PHYSICS

I-10-1

Tandem Van de Graaff Accelerator

(51210-01)

F. Paul Mooring and Jack R. Wallace
Reported by Jack R. Wallace

A new research tool will soon be in use by the members of the Van de Graaff Section of the Physics Division. It is the 12-Mev Tandem Van de Graaff Accelerator designed and built by High Voltage Engineering Corporation, Burlington, Massachusetts.

The tandem accelerator design has evolved directly from that of a conventional Van de Graaff electrostatic generator. A Van de Graaff electrostatic accelerator has certain advantages in investigation of the properties of the nucleus. Some of these are: (1) This type of accelerator is capable of producing a tightly collimated beam of charged particles. (2) The energy of the particles emerging from such an accelerator can be varied continuously over a large range. (3) The energy spread of these particles can be kept very small ($\approx 0.05\%$).

The tandem accelerator's method of achieving higher particle energies from the same terminal voltage became possible when scientists learned how to produce negatively-charged hydrogen ions (protons to which two electrons have been attached). The principle of a tandem accelerator is to produce an intense beam of protons, accelerate them by passing them through a potential drop of about 40 kv, then pass them through hydrogen gas where they pick up two electrons. This source of negative ions is external to the Van de Graaff accelerator and at ground potential, but connected to its acceleration tube. These negative ions are accelerated from ground to the high-voltage terminal which is charged to a positive

voltage (1 to 6 million volts). In this high-voltage shell these ions are passed through a gas cell which removes the two electrons and changes the charge of the ion from negative to positive. They are again accelerated by passing through another accelerating tube collinear with the first, which runs from this terminal shell to ground. So in this way the particle has acquired an energy twice that associated with the potential difference of the terminal voltage and ground. The emerging protons are then passed through a 90° magnetic analyzer whose magnetic field is very carefully stabilized and controlled. A signal from the output slits of this magnetic analyzer is used to stabilize the voltage of the terminal shell of the tandem. The protons proceed to a switching magnet which can direct them to the various pieces of experimental equipment located in the target area.

The tandem generator will permit a logical extension of certain measurements and investigations now being carried on at our present Van de Graaff accelerator. New experiments will also be possible at these higher energies now available with the tandem. Members of the Physics Division are now planning and designing experimental equipment for use with this new accelerator.

The plan view of the experimental level (Fig. 1) of the new tandem wing of building 203 shows the location of the accelerator, analyzer magnets, and switching magnets, and the relative sizes of the various areas. The plan chosen will allow a maximum usefulness of the tandem. The emerging ion beam from the tandem can be directed through either of the 90° magnetic analyzers and then through a switching magnet which in turn directs the beam through any one of the five possible beam lines located in the target areas. This means that while a given experiment is being conducted in one target area the other target area will be free of radiation and therefore the next experiment can simultaneously be prepared and its equipment checked. Each target area has a data-recording room associated with it and there are wireways provided to carry signal cables between the two areas. Entrance into the vault and target

area while an experiment is in progress will be controlled. Doors and gates through the radiation shield will be interlocked, and radiation detection equipment will be installed to monitor the areas at all times.

The cross section through the target areas (Fig. 2) clearly shows the radiation shielding of the vault and target areas, necessitated by operations at these energies. The gamma cave in the east target area is a special room provided for experiments that require a very low external

Fig. 1. Experimental level
plan view
(basement)

Fig. 2. Cross section through target areas.

Fig. 3. Service level
plan view
(1st floor)

background. The materials used in the concrete of the walls, ceiling, and floors of this room have been selected for a minimum content of radioactive elements.

The plan view of the service level (Fig. 3) shows the area above the vault in which the accelerator is located. It will contain

the accessory equipment for the tandem, such as compressor, gas storage tanks, gas drier, gas recirculator, motor-generator sets, vacuum pump, power distribution panel, etc. The service gallery area will contain heating and ventilating equipment, a distribution system for signal and control wire, and eventually three offices on the west side.

The present construction schedule calls for the tandem wing to be completed June 15, 1961. High Voltage Engineering schedules our tandem for completion by May 1961. It is hoped that the tandem's installation will not require more than 3 months after its delivery to our site.

I-11-26 Installation and Operation of the Van de Graaff
Generator (51210-01)

J. R. Wallace

This report covers the operation of the Van de Graaff generator in the Physics Division for the period from July 1 to September 30, 1960 inclusive.

The generator was used to accelerate protons and alphas. Its voltage varied from 1.6 to 4.4 Mv. The beam currents measured at the target varied from 0.1 to 30 μ a.

The following list shows the type of experiments performed with the generator and the number of hours per experiment.

1. Neutron polarization	Elwyn, Lane	9.6 hr
2. Resonance fluorescence	Heberle, Meyer, Weinman	27.4
3. Total cross section of Co ⁵⁹ and of N ¹⁴	Huddleston, Mooring	264.4
4. " Mossbauer effect in Fe ⁵⁷ by Coulomb excitation	Holland, Lynch	208.8

5. Calibrating neutron survey counter	Anderson	40.3 hr
6. Total cross section in kev region	Hibdon	155.0
7. Fission cross section of U ²³⁶	Stupegia	37.6
8. Polarized protons from Ti ⁴⁸ (d,p)	Smither, Weinman	48.2
		<hr/>
		791.3
Startup and daily maintenance		43.0
Machine repairs and experimental setup		365.7
		<hr/>
Total time available (64 days X 16 hr + 22 days X 8 hr)		1200.0 hr

We are now trying in the Van de Graaff generator a charge-carrying belt from Fabreeka that has a longer lap joint. It was believed by their engineers that the relatively small diameter (6 in.) of our drive pulley caused more than normal flexing of the belt at the lap joint. In addition to this flexing we have conditions (high lineal belt speed plus high gas density) that lead to unusually high wind action on the lap joint in the belt. Since the failures with this belt have been exclusively at the lap, we hope this change in lap design may improve the life of the belt.

Tests with Fabreeka endless wrapped belt have been unsatisfactory so far. The different method of construction necessitated by this type of belt introduced undesirable features for our application.

We were plagued with an irregular pulsing beam which caused much unsatisfactory operation during this period. The cause of this trouble was an internal electrical leakage path (low resistance path) in the insulating drive pulley of the 400-cycle generator in the high-voltage shell of the Van de Graaff accelerator. This irregular leakage caused fluctuations in the charge removal from the charging belt and resulted in energy changes of the beam at the target.

Additional time was lost during this quarter because of a breakdown of our air compressor used for gas transfer.

I-14-21 Pulsed Beams for the Van de Graaff Generator (51210-01)

R. E. Holland, F. J. Lynch, and E. N. Shipley
Reported by R. E. Holland

PARTIAL LIFETIMES OF FIRST EXCITED STATE OF Ca^{43}

Because of recent interest¹ in the lifetime of the first excited state of Ca^{43} , we began a measurement of this lifetime by a pulsed-beam technique.² While the work was in progress, we learned of a completed measurement by Schwarzschild³ and collaborators at Brookhaven. Our measurements indicate that the mean life is less than 0.1 mμ sec, in agreement with an upper limit of 0.06 mμ sec established at Brookhaven.

During this work, we also observed that this state was not strongly excited by α-particle bombardment (the measurement described above was made by proton bombardment), and therefore that the cross section for Coulomb excitation was small. We were able to establish an upper limit for the cross section by comparing the yields of gamma rays from thick targets of CaCO_3 (23% Ca^{43}), CaCO_3 (normal), and V (normal). No gamma rays of 374-keV were observed from either Ca target under bombardment by 3.2-MeV α particles. Gamma rays of 342 keV from $\text{O}^{18}(\alpha, n)\text{Ne}^{21}$ produced a background which allowed us only to establish that the number of 374-keV gamma rays from the Ca^{43} target was less than 4% of the number of 323-keV gamma rays from the V target. Using the value⁴

$$B(E2) = 0.0056 \text{ barn}^2$$

¹ T. Komoda, submitted for publication in Progress of Theoretical Physics (Kyoto).

² R. E. Holland and F. J. Lynch, Physics Division Summary Report, ANL-5955, (December, 1958, January, 1959), p. 3.

³ Private communication.

⁴ K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. 28, 432 (1956).

for the reduced E2 transition probability for V^{51} and correcting for the difference in energy of the gamma rays and the difference in stopping power of the targets, we find for the reduced transition probability for first excited state of Ca^{49}

$$B(E2) < 0.000248 \text{ barns}^2.$$

The corresponding limit on the partial E2 mean life is

$$\tau(E2) > 34 \text{ m}\mu\text{sec}.$$

We infer that the short observed lifetime is due to a high partial transition rate for M1 decay.

I-58-8 Delayed Neutron Groups from N^{17} (51210-01)
G. J. Perlow, A. F. Stehney (CHM), W. J. Ramler
(CHM), and J. L. Yntema

The energy of the neutrons which follow the β -decay of 4.1-sec N^{17} was measured by means of a neutron spectrometer¹ in which the energies of proton recoils were determined in a triple proportional-counter arrangement. The energy calibrations were made with monoenergetic neutrons from $Li^7(p,n)Be^7$ at the Van de Graaff generator. The N^{17} was produced in the reaction $C^{14}(\alpha,p)N^{17}$ at a mean energy of about 25 Mev. The C^{14} was in the form of a 14-mg pellet of 41% enrichment, sandwiched in aluminum foil. Bombardment and counting were alternated by shuttering

¹ G. J. Perlow, Rev. Sci. Instr. 27, 460 (1956).

the cyclotron beam. Two groups of neutrons were observed with energies of 1.225 ± 0.060 and 0.425 ± 0.020 Mev and relative intensities in the ratio 1.6:1. Within a small energy discrepancy, these correspond to β transitions to the $\frac{3}{2}^-$ states of O^{17} at 5.38 Mev and 4.56 Mev. The higher energy neutrons reported by Hayward² would not have been observed.

A paper entitled "Delayed Neutrons from N^{17} " has been prepared for publication.

² E. Hayward, Phys. Rev. 75, 917 (1949).

I-116-1 Principles of Cyclic Particle Accelerators (51210-01)

John J. Livingood

This book presents a coherent discussion of existing varieties of cyclic particle accelerators; cyclotrons, synchrocyclotrons, synchrotrons, betatrons, microtrons, sector-focused devices, linear accelerators, and stochastic machines. These are described in sufficient detail to show their similarities, differences, and limitations.

The problem of orbit stability receives emphasis, with discussions of weak-, strong-, and sector-focusing techniques and of the means of calculating the frequencies of the associated oscillations of the orbits. The important concepts of momentum compaction, phase stability, and synchrotron oscillations are described and analyzed, and certain problems of injection and ejection are considered.

The treatment follows the development of accelerators from the simpler to the more complex. An uninitiated reader (who is assumed to understand the calculus) is led through the advances which have occurred over the years, up to the point where he has gained a solid understanding of

the underlying principles and has become equipped to read intelligently the many articles on the subject which appear in the scientific journals.

The book, of approximately 370 pages, is illustrated with 136 drawings and 28 photographs. A bibliography of about 500 items is arranged by type of accelerator, as an aid in collateral reading for those who may wish to delve deeper into theoretical aspects or to learn constructional details of particular installations.

The D. Van Nostrand Company expects to release the volume in June 1961.

II. MASS SPECTROSCOPY

II-40-7

Fragmentation of Hydrocarbons

(51300-01)

H. E. Stanton

The earlier investigations¹ of the fragmentation of hydrocarbons under impact by electrons with energies ranging up to a few kilovolts were extended to benzene and ethylene. The experimental arrangements and techniques of measurements were identical to those used for neopentane and heptane which were reported earlier.

The results for benzene are shown in Fig. 4. In Fig. 4(a), the comparison of the mass spectrum given by MA-17 and the one given in Project 44 of the American Petroleum Institute (used as a standard), for an electron energy of 70 ev, shows the usual progressive discrepancies in relative yield for the lower mass numbers, but otherwise shows a reasonable agreement, except for mass 15. The reason for the great difference (amounting to a factor of 10) is not known, and quite possibly may be partial failure of response in MA-17. The yield for this peak fluctuated rather badly throughout the experiments and any conclusions with regard to yields at mass 15 would be highly hypothetical. The yields were all normalized relative to the yield of the parent ion at mass 78⁺, the largest peak.

One notes, as with the aliphatics, that the relative yield usually shows a progressive decrease with increasing energy of the ionizing electrons and with decreasing mass number. The decreases appear to be more nearly uniform and somewhat more pronounced with benzene than they were with heptane and neopentane. With the latter molecules there were preferred modes of molecular rupture between adjacent carbon atoms, whereas the modes in benzene are less obvious, possibly because of the ring structure and the tighter binding between the carbon atoms.

¹

Physics Division Summary Report ANL-6169 (June 1960), p. 51.

Fig. 4(a). Mass spectrum of benzene bombarded by 70-ev electrons. The right-hand peak at each mass number is the result obtained by MA-17. These are to be compared with the left-hand peaks, taken as standards, which were found at the Bureau of Standards and reported in Project 44 of the American Petroleum Institute. Ordinates are the logarithms of the relative yields normalized to 100 for mass 78. (b) The mass spectra obtained from MA-17 for benzene at electron energies of 70 ev (left members) and at 2400 ev (right members). Both spectra were normalized to 100 at mass 78.

Fig. 5 (a). Comparison of the mass spectrum of ethylene as obtained on MA-17 with 70-ev electrons with a spectrum given in Project 44 of the American Petroleum Institute for electrons of the same energy. (b) Comparison of the mass spectra obtained with bombarding energies of 70 ev (left) and 2400 ev (right) for ethylene. All peaks were normalized to 100 at mass 28.

The comparison of the mass spectra, shown in Fig. 5 (a), for ethylene as given by MA-17 and Project 44, respectively, shows that the discrepancies are smaller than in any other molecule examined so far (probably because of the much smaller range of mass numbers required). However the general trend in the differences appears to be the usual one. The peak yields were again normalized with respect to the parent, mass 28^+ .

The mass spectra shown in Fig. 5 (b), taken on MA-17 with bombardment energies of 70 ev and 2400 ev, indicate a somewhat greater reduction in relative peak intensity for masses 25^+ and lower than for the other molecules. In contrast, the relative intensities of masses 26^+ and 27^+ with respect to the parent peak did not change as markedly. The changes in relative yield for these two peaks were not more than 25% throughout the range of electron energies employed. The logarithmic abscissa tends, unfortunately, to obscure changes of this order.

The results obtained up to this point indicate a rather simple interpretation. The reduction in relative yield of a given ionic species with respect to its parent ion (or principal fragment in the case of neopentane) under high-energy electronic impact appears to be simply correlated with the bond energy which must be broken to produce it. While, at this point, the relationship is only qualitative, one notes for n-heptane¹ that the relative yield of the principal peaks (85^+ , 71^+ , etc.) changes little in going from 70-ev to 2400-ev electrons, but the peak at mass 15^+ appears to be greatly changed. Although many of the fragments derived from these principal peaks by successive elimination of hydrogens show minor changes as a function of electron energy, there are some exceptions: 84^+ , 69^+ , 28^+ , and 26^+ . It appears that the formation of these peaks requires the breaking of a more energetic bond than does the removal of a second hydrogen from a smaller fragment. Since the C-C single bond is about 3.5 ev and the simple C-H bond around 4.3 ev, the earlier experiments did not distinguish between these two values.

But on considering the present results, Figs. 4 and 5, the effect of bond energy becomes clearer. All the peaks in benzene for mass number 63 and below (except the erratic peak at mass 14) showed a comparatively large drop in relative yield as the bombarding energy of the electrons was increased. The formation of these peaks involved the rupture of at least one C-C bond with an energy of about 5.2 ev. Actually more energy was involved since production of a fragment involves not only breaking the ring but also release from the radical so formed. A similar statement applies for ethylene since the formation of fragments with masses 15 and below requires the rupture of a double bond with an energy of about 6.3 ev. Again in both mass spectra, the removal of one or two hydrogens from the molecule does not seem to be very sensitive to electron energy; but as more hydrogens are removed, further removal becomes relatively less probable as the electron energy increases.

There were three peaks that showed distinct high-energy components and others that gave strong indications of some kinetic energy of formation. At the lower electron energies, the mass-15⁺ ion from benzene showed a well resolved peak at high kinetic energies, with a maximum at 2.3 ev, a width at half maximum of about 0.5 ev, and an amplitude of about two thirds of the amplitude of the peak at thermal energies for the same mass. This ion can be formed from benzene only by an extensive rearrangement, since the CH₃ radical is not a part of the structure of the parent molecule. There remains the possibility that an impurity was responsible for the peak, but this seems doubtful.

Ethylene gave two peaks with high-energy parts. One, at mass 14⁺, which represented a rupture of the double bond, had a maximum at about 2.5 ev and a width at half maximum of about 1.5 ev, but very low intensity. It seems unlikely that this is a spurious result caused by a nitrogen impurity.

The ethylene fragment peak at mass 13⁺ also showed a small

unresolved high-energy component with a maximum around 2 ev. Finally, the peak at 12^+ had a high-energy tail which indicated some kinetic energy of formation. It seems probable that when the fragmentation of ethylene involves the separation of the two carbon atoms there is some kinetic energy of formation.

IV. PLASMA PHYSICS

IV-10-1

High-Frequency Plasmas

(54100-01)

Albert J. Hatch

The purpose of this report is to outline the plasma research program at Argonne and to show its relation to the over-all field of plasma physics.

There are two lines of research being followed, one major, the other minor. The major research is an experimental study of basic properties of low-pressure plasmas produced in high-frequency electric fields which are approximately uniform in space in the absence of plasma. Most of the work to date has been on the high-frequency plasmoid phenomenon. The minor research is a theoretical study of the interaction of plasmas with non-homogeneous high-frequency electromagnetic fields, with special emphasis on rf containment of plasmas.

OSCILLATORY PHENOMENA IN PLASMAS

A plasma is a dynamic physical system made up of electrons, ions, and neutral gas atoms (or molecules) in which the electron and ion densities are usually approximately equal. The fraction of ionization can extend from as low as about 10^{-8} for weakly ionized plasmas to almost 1 for fully ionized plasmas. The characteristics of a plasma which distinguish it from other physical systems arise mainly from two classes of phenomena that involve both the individual and the collective behavior of the plasma constituents.

One class of phenomena is the short-range interactions between the individual constituents of the plasma, especially between the electrons and atoms. These interactions include short-range hard-sphere elastic collisions, inelastic collisions, recombination, electron attachment,

and interaction with solid surfaces.

The other class of phenomena is the individual and collective response of the electrons and ions to long-range electric and magnetic forces. These forces may originate either from externally applied fields or from the internal collective behavior of electrons and ions themselves. Among the phenomena included in this class are the transmission and reflection of electromagnetic radiation through plasmas, containment of plasmas by magnetic and electromagnetic fields, and several species of electron and ion oscillations, including cyclotron resonance. It is to this class that the plasmoid and containment phenomena belong.

Plasma-electron oscillations are one of the long-range force phenomena which have been the subject of much research since their discovery over 30 years ago. Tonks and Langmuir¹ showed in 1929 that these oscillations occur in a one-dimensional system at the radian frequency $\omega_p = (ne^2/m\epsilon_0)^{1/2}$, where n = electron density, e and m are the charge and mass of the electron, and ϵ_0 is the permittivity of free space. Such oscillations in dc-or pulse-excited plasmas result from charge density gradients; in rf-excited plasmas they result from a combination of oscillating charge density gradients and response to the rf excitation. For the range of electron densities normally encountered in laboratory plasmas, the frequencies of plasma-electron oscillations are in the nominal range of 1 to 10 000 Mc/sec.

Most of the experimental research on plasma-electron oscillations has been performed in dc-excited plasmas, a species of plasma which imposes severe limitations on many (but not all) types of such observations, mainly because the oscillations are merely a by-product of the

¹ L. Tonks and I. Langmuir, Phys. Rev. 33, 195 (1929).

more prominent dc plasma mechanisms. One is therefore justified in the conjecture that this is a situation which has perhaps seriously hampered the advance of our knowledge of oscillatory phenomena in plasmas. Indeed, it is generally recognized that plasma oscillations are currently one of the least understood of the important basic phenomena of plasma behavior.

It is axiomatic in physics that the study of the oscillatory properties of a physical medium can usually be performed most expeditiously by exciting the medium at frequencies in the vicinity of its resonant and/or cutoff frequencies. Thus one is led to expect that phenomena involving electron oscillations should become very prominent, perhaps even dominant, in plasmas excited by frequencies in the megacycle range. This expectation appears to be at least partially confirmed by the many types of unusual phenomena observed in rf-excited plasmas at low pressures. Further confirmation is emerging from the detailed experimental study of the internal characteristics of the various phenomena.

HIGH-FREQUENCY PLASMOIDS

There are three major plasma mechanisms which occur in high-frequency plasmas at low pressures, namely, diffusion, plasmoids, and multipacting, listed in order of decreasing pressure.

The diffusion mechanism—so named because the dominant mechanism of electron loss is by diffusion to the tube walls and electrodes—occurs throughout a wide range of plasma parameters, i.e., pressure, tube dimensions, and applied frequency. Although diffusion has been studied mainly as a breakdown mechanism, certain theoretical aspects of its role as a plasma mechanism have also been developed and correlated with experimental observation.

From the standpoint of appearance, the most unusual rf plasma phenomena at low pressures are the high-frequency plasmoids first reported by R. W. Wood² in 1930. A high-frequency plasmoid is a region

² R. W. Wood, Phys. Rev. 35, 673 (1930).

in a high-frequency plasma that has a definite sharply bounded form—e.g., a spheroid, spindle, disk, or pear shape, depending mainly on the plasma tube configuration and the pressure—within which the luminous intensity of the plasma is usually noticeably higher than that of the surrounding plasma. Although Wood suggested that the plasmoids were a manifestation of an oscillatory phenomenon, his observations did not include any confirmatory evidence for this hypothesis. Recent studies at Harwell,³ Saclay,⁴ and Argonne,⁵ however, now tend to confirm Wood's hypothesis and are starting to reveal some of the details of the oscillatory mechanism.

Multipacting is a low-pressure high-frequency quasi-oscillatory mechanism—i.e., nonharmonic—in which the electron transit

Fig. 6. High-frequency plasma domains in dry air. These plasmas are established between plane-parallel aluminum electrodes, 23 cm in diameter and 15 cm apart, at a frequency of 15 Mc/sec.

time between electrodes is nominally $\frac{1}{2}$ -cycle and electron multiplication is by secondary emission due to electron impact, on the electrode surfaces, with energies of the order of 50 ev or more. Although the mechanism lacks certain important attributes ordinarily associated with plasmas, especially a random electron distribution in phase space, it nevertheless has other characteristics that are measurable by the same

³ E. R. Harrison, J. Electronics and Control 5, 319 (1958). (Harwell work.)

⁴ R. Geller, Compt. rend. 249, 2749 (1959). (Saclay work.)

⁵ A. J. Hatch, Proceedings of the Fourth International Conference on Ionization Phenomena in Gases 1, 314 (North-Holland Publishing Company, Amsterdam, 1960).

diagnostic techniques as are used in "real" plasmas and therefore is a useful neighboring mechanism to the plasmoids.

The present research is aimed at studying high-frequency plasma and plasmoid phenomena in the gap between the diffusion domain and the multipacting domain as shown in Fig. 6. This map of the plasma domains is by no means complete; it has been filled in only enough to provide an orienting reference for the present studies, and there are several subdomains which have been recognized but have not yet been explored in sufficient detail to be included.

Some idea of the variety of high-frequency plasma phenomena at low pressures can be gained from examination of the plasma photos in Fig. 7. The plasmas shown in the top three photos are in the diffusion domain. Of these, the only one for which there is a satisfactory published theoretical description⁶ is the doubly striated plasma at 50μ . The plasma shown in the $13\text{-}\mu$ photo is in the vicinity of the transition at the mean-free-path limit, shown in Fig. 6, where the electron mean-free-path is equal to the characteristic diffusion length. Two stages in the appearance of the high-frequency plasmoids are shown in the photos at 1.0 and 0.3μ . The spheroidal dark sheath which delineates the plasmoid seems to present a paradoxical situation in that although plasma boundaries ordinarily tend to become less distinct as pressure is reduced, this one becomes more distinct. In the $0.3\text{-}\mu$ photo the sheath width is of the order of 0.002 of the electron mean-free-path. Densitometer measurements of the negative from which this photo was made show that the luminous intensity of the dark sheath ($D = 0.295$ arbitrary units) is less than that of both the immediately adjacent

⁶ W. P. Allis, S. C. Brown, and E. Everhart, Phys. Rev. 84, 519 (1951).

Fig. 7. Photographs of high-frequency plasmas and plasmoids.
The parameters are the same as in Fig. 6.

surrounding plasma ($D = 0.300$) and the plasmoid interior ($D = 0.340$). The increasing prominence and distinctness of the plasmoids as the abrupt extinction boundary is approached (maintaining voltage in Fig. 6) suggests that we have here either an isolated freakish mechanism of no fundamental importance (there are many such in plasma physics) or a beautiful manifestation of a significant and fundamental plasma property (there are also several of these in plasma physics).

The experimental study of the high-frequency plasmoids involves measurements of the axial variation of luminous intensity, dc and rf potentials in the plasma, and electron and ion density, all as functions of applied rf potential, frequency, electrode separation, and gas pressure. The experiment is a clean one in the sense that the plasmas are produced in the homogeneous electric field between large-diameter plane-parallel electrodes; thus, to the first approximation the oscillatory phenomena occur parallel to the axis and the axial observations can be correlated directly with one-dimensional axial theory.

The results of the studies appear to point toward one paramount conclusion, namely, that the mode transitions in Fig. 6 mark the changeover from oscillations of free electrons in a "normal" plasma to oscillations of bound electrons in the plasmoid domain. The equation of motion of an electron in a one-dimensional plasma produced by a field $E \exp(j\omega t)$ is

$$\ddot{x} + \nu_m \dot{x} + \omega_p^2 x = (e/m) E \exp(j\omega t), \quad (1)$$

where ν_m is the collision frequency for momentum transfer (elastic collisions). The solution of this equation is

$$x = \frac{(e/m) E \sin \theta}{\omega \nu_m} \exp(j\omega t), \quad (2)$$

where

$$\tan \theta = \frac{\omega \nu_m}{\omega_p^2 - \omega^2} \quad . \quad (3)$$

This solution represents a forced oscillation. At sufficiently low pressures the damping term $\nu_m \dot{x}$ in Eq. (1) becomes negligible, and the solution above reduces to

$$x = \frac{(e/m)E}{\omega_p^2 - \omega^2} \exp(j \omega t) \quad . \quad (4)$$

When $\omega_p^2 < \omega^2$ the electrons are considered as free and oscillate under the major influence of the externally applied driving force. When $\omega_p^2 > \omega^2$ the electrons are considered as bound and oscillate under the major influence of a force developed internally by charge separation, although the frequency of oscillation is still controlled by the external driving force. The binding force in the plasmoid is due to its positive dc potential which arises from the relatively mobile electrons being lost to the tube walls at a higher rate (initially) than are the relatively slow ions. As the transition from free to bound oscillations occurs, Eq. (4) shows that the phase of the electron motion theoretically undergoes a shift of 180° . Associated with this shift is a phase shift in the self potential of the oscillating electrons. Such a phase shift has been observed experimentally in the vicinity of the transitions shown in Fig. 6.

Considerations based on this bound electron mechanism and supported by measurements of the axial profiles of dc and rf potentials have recently led to an explanation of the axial part of the dark sheath around the plasmoids which can be summarized by referring to Fig. 8. Here are plotted representative curves showing the axial profile of the instantaneous axial rf electric field for the three cases of no plasma, normal plasma, and the high-frequency plasmoid. In the case of no plasma the electric field

is uniform. In the normal plasma the electric field has the same sign all along the axis even though its magnitude may vary. In the plasmoid case, however, the sign of the electric field inside the plasmoid is opposite to that outside the plasmoid. Thus in Fig. 8 the electric field has two zeros located approximately at the plasmoid dark sheath. In the immediate vicinity of these two zeros there is a small zone within which the rf electric field is less than a "threshold" value required to cause gaseous ionization. These two zones correspond to the axial part of the plasmoid dark sheath. The axial dc field has its

maximum value just inside the plasmoid sheath and this is where the electrons oscillating inside the plasmoid receive their turn-around acceleration. The sheath can therefore also be considered as the zone within which the energy of the plasmoid electrons is below the ionization energy of the gas. The oscillatory motion of the electrons inside the plasmoid is generally not simple harmonic because most of the turn-around acceleration occurs only within the narrow sheath. However, as the conditions of operation in the plasmoid approach the maintaining voltage at low pressure and applied emf as shown in Fig. 6, the ratio of the sheath width to the plasmoid width increases and the electron motion is believed to become more

Fig. 8. Axial profiles of rf electric field representative of the three cases indicated. The dark-sheath zones in the plasmoid case occur at the field zeros which result from the phase reversal of the field inside the plasmoid.

nearly harmonic.

Equation (1) is applicable to a wide variety of high-frequency plasma mechanisms. At pressures well above the mean-free-path limit in Fig. 6, the collision damping term $\nu_m \dot{x}$ becomes important whereas the quasi-elastic term $\omega_p^2 x$ is negligible and the resulting equation enters into the theory of the diffusion mechanism. At very low pressures, at which both $\nu_m \dot{x}$ and $\omega_p^2 x$ are negligible, the resulting expression $\ddot{x} = (e/m) E \exp(j\omega t)$ can be used to describe either undamped free electron oscillations or the multipacting mechanism by appropriate choice of the boundary conditions. The Tonks-Langmuir type of plasma-electron oscillation as observed in dc-excited plasmas can be considered as another special case of Eq. (1) in which $E = 0$ and ν_m is negligible. Here the cohering effect of $E \exp(j\omega t)$ disappears, thus explaining why the oscillations become difficult to observe. By considering both the plasmoid oscillations and the Tonks-Langmuir oscillations as limiting cases of Eq. (1) which result mainly from sheath effects, and which differ only to the extent of the presence or absence of a cohering field, one can now see the justification of Wood's hypothesis that the two phenomena are very closely related.

PLASMAS IN NONHOMOGENEOUS ELECTROMAGNETIC FIELDS

The achievement of controlled thermonuclear reactions requires—among other things—the isolation of an extremely hot dense plasma from the material walls of a container. The static or pulsed magnetic fields used for this purpose in most experiments to date have had the flaw of permitting instabilities to develop with a rise time of the order of a microsecond. One method of suppressing the instabilities is to reverse the containing field in a period shorter than the rise time of the instabilities, a method which requires the use of high-frequency fields.

Several possible containment methods using the nonhomogeneous fields in resonant cavities have been proposed. The principle of such containment has an analogy in the formation of sand patterns along the

nodal lines of 2-dimensional vibrating plates or membranes--the Chladni sand figures. Plasmas are likewise expected to be concentrated or contained in the vicinity of the nodal points of the electromagnetic fields in 3-dimensional cavities.

One type of containment by cavity fields, which has been known for several years, arises from the Lorentz force exerted on an individual charged particle in an electromagnetic field. This force on electrons is derivable from a scalar potential

$$\Phi = \frac{1}{4} \frac{e^2}{m\omega^2} \langle E^2 \rangle_{av} , \quad (5)$$

where $\frac{1}{2} \langle E^2 \rangle_{av}$ is the time-averaged square of the electric field, $\langle \mathbf{E} \cdot \mathbf{E} \rangle_{av}$. Such Φ potential wells are known to occur in cavity fields of the electric quadrupole type but their containment capabilities are limited to low-density plasmas in which $\omega_p < \omega$.⁷

The possibility of containing high-density plasmas in the nonhomogeneous fields of resonant cavities has received sporadic attention during the past few years, but none of the proposed containment schemes has shown any firm promise of scientific feasibility, to say nothing of economic feasibility. An analog experiment⁸ was performed about a year ago at Argonne, however, in which the equilibrium properties of dense plasma cores as simulated by copper spheroids were studied in a resonant cavity. From this experiment a new and significant result emerged, namely, that cavity fields of the magnetic quadrupole type might have the requisite

⁷

The comparative values of ω_p and ω are a commonly used criterion of relative plasma density. When $\omega_p < \omega$ the applied field will penetrate the plasma; when $\omega_p > \omega$ the field is appreciably attenuated inside the plasma.

⁸ A. J. Hatch and J. W. Butler, Bull. Am. Phys. Soc. 5, 324 (1960).

equilibrium and containment properties. More recently, theoretical studies have demonstrated that for very small (point) test spheres of radius r_0 the magnetic quadrupole and higher magnetic multipole modes in cavities possess potential wells which can be represented by the scalar point function

$$\mathcal{V} = 2\pi r_0^3 \left(\frac{1}{2} \mu_0 \langle H^2 \rangle_{av} - \epsilon_0 \langle E^2 \rangle_{av} \right). \quad (6)$$

To the extent that such a test sphere can be considered as representative of a dense plasma, these modes are theoretically capable of containing dense plasmas.

Calculations of the rf power necessary to contain thermonuclear plasmas at pressures of hundreds of atmospheres in such potential wells are discouraging. However, pressures of the order of dynes/cm² are achievable with relatively modest rf power. The effects of such pressures on plasmas in the micron pressure range should be observable provided their manifestations are not obscured by competing effects. Thus, from the point of view of basic plasma physics, the main problem is that of the interaction of plasmas with electromagnetic fields, which now takes on added interest because of the theoretically predicted existence of Φ and $\mathcal{V}$ hills and wells in nonhomogeneous fields. This work is receiving continued attention as a likely area for more intensive experimental and theoretical work in the future.

V. THEORETICAL PHYSICS, GENERALV-13-1 Spin-Orbit Splitting and Pion Theoretic L-S Potential (51210-01)Akito Arima, Masao Sugawara, and Tokuo Terasawa^{*}

Concerning the origin of the spin-orbit coupling in nuclei, two of the present authors have recently shown that the second-order effect due to the tensor force is fairly large in light nuclei.¹ The same effect has also been shown to give roughly the observed doublet splittings in heavy nuclei.² However, the numerical results depend strongly on the nuclear radii assumed. If the tensor force suggested by the meson theory is assumed³ and the nuclear radii are chosen to fit the difference between the Coulomb energies of the mirror nuclei⁴ and the electron-nucleus scattering,⁵ the doublet splittings due to the tensor force amount to one-fifth to one-half the observed values. If the nuclear radii are reduced by 20% or less, the corresponding effect can produce the observed values. Therefore, we have stressed the importance of the tensor force and have concluded that the tensor force explains considerable amounts of the observed splittings.¹

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¹ T. Terasawa, *Progr. Theoret. Phys. (Kyoto)* 23, 87 (1960); A. Arima and T. Terasawa, *Progr. Theoret. Phys. (Kyoto)* 23, 115 (1960); A. Arima to be published in *Nuclear Phys.* 18. This has also been investigated by Wigner and Feingold: E. P. Wigner, *Symposium on New Research Techniques in Physics*, Rio de Janeiro, 1952; A. M. Feingold, *Phys. Rev.* 101, 258 (1956).

² S. Takagi, W. Watari, and M. Yasuno, *Progr. Theoret. Phys. (Kyoto)* 22, 549 (1959); B. Jancovici, *Progr. Theoret. Phys. (Kyoto)* 22, 585 (1959).

³ L. Hulthén and M. Sugawara, *Handbuch der Physik* (Edwards Brothers, Ann Arbor, 1943) Vol. 39. Concerning the pion theoretic potentials, the works before 1956 are summarized in *Suppl. Progr. Theoret. Phys. III* (1956), edited by M. Taketani.

⁴ B. C. Carlson and I. Talmi, *Phys. Rev.* 96, 436 (1954).

⁵ R. Hofstadter, *Revs. Modern Phys.* 28, 214 (1956).

The purpose of the present note is to report that the pion-theoretic L-S potential can give other large fractions in such a way that the over-all effects just explain the observed splittings without changing nuclear radii.

It has been known that a strong L-S potential can produce large doublet splittings in nuclei.⁶ Several authors have in fact shown recently that the phenomenological L-S potential due to Gammel and Thaler⁷ can give large splittings, even values which are much greater than observed.^{8,9} Here arises the question of how large the splittings due to the pion-theoretic L-S potential can be. This potential is weaker than that of Gammel and Thaler, but still not negligibly small. In this note we assume the L-S potentials that were derived recently by Okubo and one of the present authors.^{10,11} We also have reinvestigated the Gammel-Thaler potential as a check on the previous work.

We consider those light nuclei which are closed shells plus or minus one nucleon: He^5 , N^{15} , and O^{17} . As for the nuclear wave functions, the harmonic oscillator model is assumed for simplicity in calculations.¹ The first-order perturbation expressions for the doublet splittings are written as

⁶ J. P. Elliott and A. M. Lane, Phys. Rev. 96, 1160 (1954); R. J. Blin-Stoyle, Phil. Mag. 46, 973 (1955); C. A. Pearse, Phys. Rev. 106, 545 (1957); B. P. Nigam and M. K. Sundaresan, Phys. Rev. 111, 284 (1958).

⁷ J. Gammel and R. Thaler, Phys. Rev. 107, 291 (1957); 107, 1337 (1957).

⁸ J. Sawicki and R. Folk, Nuclear Phys. 11, 368 (1959); J. Sawicki, Nuclear Phys. 13, 350 (1959).

⁹ G. E. Tauber and T-Y. Wu, Nuclear Phys. 16, 545 (1960). The authors are very grateful to Professors T-Y. Wu and G. E. Tauber for informing them of the results of their work before publication.

¹⁰ M. Sugawara and S. Okubo, Phys. Rev. 117, 605 and 611 (1960).

¹¹ Recently M. Taketani and S. Machida derived the L-S potential due to the pion theory. The authors would like to express their thanks to Professor S. Machida for his kindness in informing them of the results.

$$\Delta E_p = -\frac{9}{2} \langle 1p | V_- | 1p \rangle \quad (1)$$

$$\Delta E_p = -\frac{27}{4} \langle 1p | V_- | 1p \rangle - \frac{15}{4} \langle 1d | V_+ | 1d \rangle \quad (2)$$

and

$$\Delta E_d = -\frac{15}{2} \langle 1p | V_- | 1p \rangle - \frac{3}{4} \langle 2p | V_- | 2p \rangle - \frac{21}{2} \langle 1f | V_- | 1f \rangle - \frac{15}{4} \langle 1d | V_+ | 1d \rangle, \quad (3)$$

where Eqs. (1) and (3) refer to the cases of one nucleon outside closed shells in the orbits 1p and 1d, respectively, and Eq. (2) refers to the case of N^{15} or O^{15} . In these equations

$$\langle n\ell | V_{\pm} | n'\ell' \rangle = \int_{r_c}^{\infty} R_{n\ell}(r) R_{n'\ell'}(r) V_{\pm}(r) r^2 dr, \quad (4)$$

where $R_{n\ell}(r)$ is the relative wave function defined in reference 1 and $V_{\pm}(r)$ are the coefficients of the L-S operator in the two-body nuclear potential in the triplet even and odd states, respectively, L and S being the relative orbital and total spin angular momentum operators of the two-nucleon system. Since $V_{\pm}(r)$ diverges very badly as r goes to zero, and also the relative wave function $R_{n\ell}(r)$ of the two nucleons should vanish inside the hard-core radius, we have assumed a zero cutoff in Eq. (4) at r_c equal to three tenths of the Compton wavelength of the pion.

The results are shown in Fig. 9, as functions of the parameter ρ which is proportional to the nuclear radius and is defined in reference 1. If the wave functions of the pure harmonic oscillator model are assumed, an experimental value ρ_c can be determined from the difference between the Coulomb energies of the mirror nuclei.⁴ We have extended calculations toward the smaller side of the nuclear radius since one

Fig. 9. First-order doublet splitting ΔE for He^5 and Li^5 , N^{15} and O^{15} , and O^{17} and F^{17} , against ρ which is proportional to the nuclear radius and defined as $(2/\nu)^{\frac{1}{2}}$ and $\nu = m\omega/\hbar$, m being the nucleon mass and ω the angular frequency of a harmonic oscillator. Vertical lines indicate the value of ρ_c that is determined from the difference between the Coulomb energies of the mirror nuclei. The G-T curves refer to the Gammel-Thaler potential (reference 7) and ps and pv curves are the effects of the pion theoretical potentials (reference 10) with ps-ps and ps-pv couplings, respectively. Dotted lines are second-order effects due to the pion theoretical tensor force and have been taken from reference 1. Experimental values are indicated by horizontal lines (or a shaded band).

can argue that taking $\rho < \rho_c$ may be reasonable because of the admixture of higher states due to higher-order perturbations and the short-range correlation.

It is very interesting that the L-S potential suggested by the pion theory¹⁰ can produce the large doublet splittings, especially in the ps-pv case. Even in the ps-ps case, the contribution has the same order of magnitude as that due to the tensor force. The Gammel-Thaler L-S potential⁷ seems to give splittings that are somewhat too large. The even-state L-S interaction is considerably less important in producing doublet splittings than the odd-state interaction. Therefore, as far as the odd-state L-S potential is attractive, the sign of the splitting is correct, and this is the case in all potentials assumed.^{7,10} Because of the short-range nature of the L-S potentials, one might think that our zero cut-off procedure in Eq. (4) might lead to a serious overestimate compared with the case in which a proper correlation

function is introduced into the wave function $R_{nl}(r)$ in Eq. (4). We have, therefore, compared our result with that of Tauber and Wu,⁹ who used the G-T potential and introduced the correlation function. Our result is only about 10% larger than their result in N^{15} at the same ρ . Therefore our result cannot be too much of an overestimate. We have also estimated the magnitude of the second-order effect. The effect can be calculated in the same way as is outlined in the previous papers.¹ A nucleon inside the closed shell interacts with the outside nucleon and both can jump into higher orbits. The second-order correction to the doublet splitting is finally given by

$$\Delta E_p^{(2)} = -\frac{9}{8} \sum \frac{1}{N\hbar\omega} \left\langle 1p \mid V_- \mid N+1p \right\rangle^2 \left(1 - \frac{1}{2^{2N}} \right),$$

where ω is the angular frequency of a harmonic oscillator. The correction $\Delta E_p^{(2)}$ is estimated only for the G-T potential and at $\rho = 2.4$. It has the opposite sign to ΔE_p given by Eq. (1) and is about 25% of ΔE_p , or less. We may hope that the higher order corrections would not affect our results drastically.

As the conclusion, the doublet splittings are adequately explained in all three nuclei considered in terms of the combination of the second-order effect due to the tensor force and the first-order effect due to the L-S potential, both of which are suggested by the present pion theory,^{3,10} if the ps-pv coupling is assumed and also the nuclear radius is chosen at ρ_c . The splittings obtained from the ps-ps theory seem to be somewhat small, while those from the Gammel-Thaler potential seem too large for the same ρ . However, the smaller ρ may be more reasonable, as we have discussed before. Thus, it is certainly premature to rule out the ps-ps case on this basis alone. We also recall that the derivation of the L-S potential in the ps-ps coupling contains certain ambiguities. Therefore, we certainly cannot discriminate the ps-ps and ps-pv couplings. Our positive statement is that the shell-model doublet splittings do not indicate any urgent need for introducing

phenomenological L-S potentials besides those already expected from the pion theory.

V-42-1

Geometric Theory of Charge

(51151-01)

H. Ekstein

The "explanation" of electricity has been an age-old dream of physicists. Students of the history of physics know about one-fluid and two-fluid theories of electricity and about mechanical ether theories. The path of physics is strewn with skeletons of such theories. After many failures, physicists have resigned themselves to consider electricity as a phenomenon of its own, not reducible to or explainable in terms of other phenomena. But, as cocks cannot stop crowing, so physicists cannot stop trying to simplify the picture of nature, i. e., to decrease the number of separate assumptions needed.

The present paper tries to deduce the more basic aspects of electricity from such prime principles as relativistic covariance and principles of quantum mechanics. What are these basic aspects? First, the existence of two distinct types of particles, such as electrons and positrons, that have identical mechanical properties. Second, the existence of a conserved quantity (the charge) which would be just the difference between the numbers of positive and negative particles if there were only electrons and positrons in the world, but which has a more subtle meaning in the presence of other particles such as protons and antiprotons. Third, the curious fact that the charge never changes as the result of any measurement. This is more than a conservation property, for the energy (which is conserved) may well be changed by an external measuring system. This

"superconservation" property of electric charge is expressed by a "super-selection rule."

The main assumption is covariance of natural laws under the full Lorentz group, including space and time reversal. This assumption, together with some of the basic principles of quantum mechanics, is surprisingly powerful for the analysis of one-particle systems, in that it restricts the number of possibilities. One of the oldest examples of this power is the prediction that spins can be only integral or half-integral—not of any intermediate value. The type of statements in a theory of this kind ("Wignerism" for short) is not mainly "if A, then B," as in dynamical theories (e.g., Newton's equations). It is rather: "A or B may exist, but not C" (e.g., the spins may exist only with the values mentioned above). This can be provided by principles that restrict the number of a priori possibilities. The purpose of the game is not just to postulate a scheme that is consistent with experiment, for the simplest such statement would be: "Anything may exist." The success of such a theory is measured by the number of conceivable objects forbidden by theory provided that, in fact, they are not observed. This should be accomplished by use of the smallest possible number of principles or assumptions. A figure of merit of the theory might be

$$M = \frac{\text{number of excluded possibilities}}{\text{number of assumptions (or principles)}} \quad .$$

A less quantitative criterion used by judges in theory-beauty contests is the "simplicity" or "elegance" or "plausibility" of the principles. It is indispensable to make such a requirement, because it is technically always possible to summarize any number of statements by the symbolic equation $X = 0$.

The set of principles which we use can claim plausibility because each of them is (almost) separately and directly verifiable, i.e., the observable implications of the principles can be tested more or less

directly. This is very different from a quantum field theory, for which the set of all assumptions may (or may not, we do not know) lead by a complicated mathematical procedure to predictions comparable and consistent with experiment.

Furthermore, a great effort is made to accept only the most general assumptions that imply observed results. A good example of this effort is the history of the mathematical formulation of symmetry in Hilbert space. It was originally assumed that operators must form a representation of the symmetry group. This assumption indeed implies the observed symmetries of observable quantities, but it is not the most general assumption that accomplishes this purpose. Therefore, the assumption was modified to loosen the connection demanded between group and operators. The currently accepted requirement is that the operators must form a co-representation, up to a factor of modulus unity, of the symmetry group. This means (1) that instead of mimicking the group multiplication table

$$L_1 L_2 = L_{12} \quad (1a)$$

$$U(L_1) U(L_2) = U(L_{12})$$

the operators $U(L)$ must only satisfy an algebra

$$U(L_1) U(L_2) = e^{i\delta(L_1, L_2)} U(L_{12}) ; \quad (1b)$$

(2) that the operators do not have to be unitary but that some of them may be antiunitary. That is, instead of having the linear property

$$U(af + bg) = a Uf + b Ug$$

(where a, b are numbers and f, g are vectors in Hilbert space), the operators may have the antilinear property

$$U(af+bg) = a^* Uf + b^* Ug .$$

This less restrictive mathematical requirement also implies the observed symmetry properties but, being less restrictive, allows for more possibilities, some of which we know to be realized. The currently accepted formalism may still be too restrictive. At any rate, one of the main preoccupations of Wignerists (or Wignerianers ?) is the avoidance of restrictions imposed for mathematical convenience rather than by physical principles.

One of the main assumptions is that one-particle states are to be described by irreducible representations of the Lorentz group.¹ The justification for this assumption is as follows. It can be shown (a) that the operator $P_\mu P_\mu$ (where the P_μ are the generators of the space-time translations) commutes with all group operators, and (b) that in irreducible representations (Schur's lemma) such an operator is a constant, i.e.,

$$P_\mu P_\mu = -m^2 .$$

It follows that the time-translation operator P_0 can, in an irreducible representation, be expressed as a function of the space-translation operators P_k :

$$P_0 = (P_k P_k + m^2)^{\frac{1}{2}} .$$

In this case, the time-translation is therefore a function of space-translations, and therefore any state

¹ A terminological note: (1) While, as mentioned above, we are now looking for corepresentations up to a factor rather than for representations, we will still use the short word "representation." To avoid ambiguity, we may refer to "proper representation" when we really mean representation. (2) French physicists have long referred to the Lorentz group as the Poincaré group. For NATOamity as well as for historic justice, we should accept this change of name, for Lorentz had really nothing to do with the group. The credit may be split between Poincaré and Einstein, but so many things bear Einstein's name that it is only fair to attribute the group to Poincaré.

$$e^{-iP_0 t} \psi$$

which develops in time t from an initial state ψ may be obtained also by an appropriate linear combination of space-translated vectors

$$e^{iP_k x_k} \psi .$$

Stated crudely: an initial state described by an irreducible representation does not "essentially" change during time-development, because the later states are just linear combinations of the space-translates of the initial state. This is (almost) an experimental test of irreducibility.

Stable one-particle states meet this specification; two-particle states do not, because—for instance—no space-translation of an electron-positron system will produce gamma rays. Also, unstable particles do not really meet the requirement, because (as another example) no space-translation of a π^0 will produce gamma rays. Nevertheless, it is usual to consider unstable particles as being approximately described by irreducible representations. Thus, the primary subjects of symmetry theory are the simplest systems (one-particle states) that are described by irreducible representations. One should expect that the enumeration of the irreducible representations of the Poincaré group will predict the general properties of all particles.

To what extent has this expectation been realized? One of the striking facts about elementary particles is that they often occur in doublets—electrons and positrons, positive and negative pions, etc. Until recently, the only irreducible representations known attributed only one linearly independent state to a spinless particle with given mass and momentum, two to a spin- $\frac{1}{2}$ particle, and, more generally, $2s + 1$ linearly independent states to a particle with spin s . If this were true, the introduction of electric charge as a separate and superimposed entity would

indeed be indispensable—or else how can the existence of two mechanically equal copies for the electron be explained?

Of course, pure symmetry theory does not exclude the possibility of two irreducible representations with exactly equal mass and spin, but this would be an accident. If we wish to obtain nontrivial restrictions from symmetry theory, we must adopt the principle: accidents don't happen.

Fortunately, the complete theory of symmetry is richer, and it does provide for the possibility of two such states; in technical language, there exist irreducible representations in which there are two linearly independent vectors with given momentum, mass, and spin projection on the momentum. Thus, we can explain the existence of positive and negative particles with equal mechanical properties.

What is more important is that there are only two such linearly independent states possible in an irreducible representation. This (on the assumption that we are justified in equating the charge doublets to the doublets predicted by the theory) predicts that there can be only doublets, and not triplets, quadruplets, etc. This prediction is indeed in agreement with experiment, although approximate multiplets of higher order exist, e.g., the neutral pion in addition to the two charged ones—but its mass is not quite the same.

It is encouraging that purely geometric considerations explain the dual (rather than triple or sextuple) nature of electricity. However, the "doubled" representations of the theory are too numerous; they allow for too many possibilities.

Another physical principle will be needed to obtain nontrivial results. After the painful experience of parity-nonconservation, most physicists will agree that invariance principles should be tested experimentally before they are raised to the dignity of fundamental postulates. But, before being verified, a principle must be expressed in an experimentally verifiable way. The principle of time-reversal invariance, as ordinarily stated, does

not satisfy this requirement, and an additional or more complete formulation is needed.

To see how time-reversal differs from other invariances, let us restate clearly what is meant by invariance or symmetry of natural laws. This statement will avoid the use of coordinates. These are sometimes useful, but always arbitrary conventions and their introduction at this point tends to obscure the simple intrinsic meaning of the statements.

Given a state Ψ specified by a complete set of measurements at one time (say, $t = 0$), there exists an image state $\Psi' \equiv U(L)\Psi$ induced by an invariance element L . In our scheme, L includes the set of all length-preserving mappings of space-time into itself. The state $U(L)\Psi$ is obtained from Ψ by making a certain type of change in the equipment which produced Ψ , this change being determined by L as follows. If L is a translation, the equipment is to be transferred to another point without rotation. If L is a space-rotation, the equipment is to be rotated with respect to its former position. If L is a "proper" Lorentz transformation, the producing equipment is to be put on a moving support. The prediction of the invariance principle is then that all measurements made at all times on Ψ' will be related to those made on Ψ in the simple way implied by the geometric meaning of L . For instance, the observed values on $U(\text{Tr})\Psi$ (Tr being a space translation) will be numerically equal at points $\text{Tr } P$ to those made at points P in the original experiments on Ψ . The implication of other invariance operations will be sufficiently clear by analogy to this.

The one exception to this operational interpretation of invariance is time-reversal. What is the instruction for the preparation of a state $U(T)\Psi$? One occasionally finds textbook statements about "letting time run backward" but this is clearly a manner of speaking and not an operational instruction.

Consider first the classical case. The statement is: given that a classical state Ψ_i (specified by positions, momenta, and possibly intrinsic angular momenta of all particles at one time) evolves into a state

Ψ_f after a time t , then there exists a state $T\Psi_f$ which evolves into a state $T\Psi_i$ during time t . The statement is empty unless an instruction for the preparation of any state $T\Psi$ corresponding to a given Ψ is provided. The statement would be empty if this instruction had to rely on a specific theory, since symmetry statements should be imposed on a theory, and not be deduced from it. In fact, the instruction is easy to formulate: $T\Psi$ is obtained from Ψ by reversing all momenta and angular momenta and leaving the positions unchanged.

In this purely empirical form, the statement is verifiable, and has been verified to a large extent. The essential point is that a directly verifiable statement of time-reversal invariance has to be made in terms of a geometric operation (180° rotation).

For at least a restricted set of (improper) quantum mechanical states, the classical statement can be immediately adapted: For a one-particle state which is a simultaneous eigenvector of momentum $\underline{p}$ and of the projection s of the angular momentum ($s = \underline{J} \cdot \underline{p} / |\underline{p}|$) on it, the time-reversal operator is equivalent to a 180° rotation with respect to a direction normal to $\underline{p}$, i.e.,

$$\begin{aligned} U(T) \Psi_{\underline{p}, s} &= e^{i\alpha} U(R_{\underline{p}}) \Psi_{\underline{p}, s} \\ &= e^{i\beta} \Psi_{-\underline{p}, s}. \end{aligned} \quad (2)$$

In this form the statement is in agreement with observations as well as with all theories of elementary particles considered in the past. In the case of the "doubled" representations, however, not all simultaneous eigenvectors of $\underline{p}$ and s satisfy Eq. (2) and therefore we have to impose it as a condition on states.

The fact that some vectors in Hilbert space do not represent physically realizable states is not new but still unfamiliar to most physicists. In conventional quantum mechanics as formulated by Dirac or

von Neumann, there was a one-to-one association between the rays of Hilbert space (i.e., the vectors multiplied by any phase $e^{i\delta}$, since phases are not observable) and observable "pure states." This is part of the conventional set of axioms.

However, this axiom cannot be correct. It is known that a rotation through 360° produces a vector $-\Psi$ for a spin- $\frac{1}{2}$ system, but a vector $+\Psi$ for a spinless system such as the vacuum. By itself, this is not disturbing since phase factors ± 1 are not observable. But if we consider a vector $\Psi_0 + \Psi_{1/2}$, a linear combination between the vacuum state and a state of spin $\frac{1}{2}$, then a rotation through 360° produces $\Psi_0 - \Psi_{1/2}$, which is not equal to the original vector even up to a factor of unit modulus. Yet, a rotation through 360° cannot possibly change the physical nature of a system! We must conclude that, although $\Psi_0 + \Psi_{1/2}$ is a well-defined vector in Hilbert space, it does not correspond to a realizable state. This does not exclude the existence of a system that sometimes gives the result 0, and at other times the result $\frac{1}{2}$ for the observed value of the angular momentum. Such a system might be described by a statistical (incoherent) mixture of spin-0 and spin- $\frac{1}{2}$ states. Contrary to conventional quantum mechanics, the Hilbert space of physics has holes in which vectors languish without the dignity of states.

Our principle, which requires an experimental verifiability of time-reversal symmetry, relegates many vectors to this purgatory of non-states. In particular, all but one of the "doubled" representations turn out to have no states at all, and can be discarded. This is the desired result of a physical principle in a symmetry theory: it restricts the number of possibilities.

The remaining "doubled" irreducible representation has some states, but most of it is in purgatory. In technical language, there is a superselection rule within the irreducible representation. Two subspaces, each of which is irreducible under the restricted Poincaré group,

are separated by superselection, i.e., linear combinations of vectors from the two subspaces are not states. Obviously, we identify the vectors in the two subspaces with positive and negative particles, respectively, and we have—from general principles only—deduced or "predicted" the superselection which is consistent with observations.

The superselection rule can be extended deductively to many-body states. It then states that systems having different values of the difference between the number of positive and of negative particles (i.e., systems for which $n_+ - n_- \neq n'_+ - n'_-$) are separated by superselection. One obtains also the "superconservation" of a quantity Q (charge) which is proportional to the difference between the numbers of positive and negative particles.

The two one-particle subspaces are connected by the operator that represents space inversion, i.e., the mirror image of a positive particle is a negative particle, and the mirror image of a neutron is an antineutron. One should expect, on the basis of this symmetry property, that in some experiments the positive particle will reveal its lack of mirror symmetry.

In one sense then, the pure symmetry theory predicts the Wu experiment. It is ironic to reflect that if these considerations on the basis of assumed full relativistic symmetry had been carried out in 1940—and there is no reason why this could not have been done—physicists would have expected results of the "parity-nonconservation" type just because of inversion symmetry of natural laws.

Work on this project has been completed and the results have been published in a report entitled: "Geometric Theory of Charge," H. Ekstein, Phys. Rev. 120, 1917-1924 (December 1, 1960).

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PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

DEPARTURES

Dr. Akito Arima joined the Physics Division as a Resident Research

Associate on September 14, 1959. He has been interested in spin-orbit splitting and tensor force, spin-orbit splitting and pion theoretic L-S potential, and the influence of short-range two-body interactions on the equilibrium deformation of nuclei (Project V-13). He terminated at ANL on December 7, 1960 to return to the Institute for Nuclear Study, University of Tokyo, Tokyo, Japan.

Drs. Herman A. Tasman joined the Physics Division as a Resident Re-

search Associate on May 31, 1960. He has collaborated with W. A. Chupka and J. Berkowitz on high-temperature thermodynamic studies with a mass spectrometer and on development of a double oven for studying fragmentation and dissociation resulting from ionization by electron impact. He terminated at ANL on December 19, 1960 to return to the Laboratorium voor Massaspectrografie, Amsterdam, the Netherlands.

Dr. Malcolm Macfarlane joined the Physics Division as a Resident Re-

search Associate on November 2, 1959. He studied stripping reactions as indicators of the structure of light and intermediate nuclei (Projects V-9 and I-22), pairing forces in nuclei, and, in collaboration with R. D. Lawson, a rotational model for Fe^{57} . He terminated at ANL on December 30, 1960 to join the Physics Department of the University of Rochester.