THE STRUCTURE OF NUCLEONS

. . . with the examination of the structure of the proton and neutron one is investigating a new hierarchical level in the material organization of the physical universe, related to, but underlying, the now substantially explored level of atomic and nuclear structure . . .

By L. L. Foldy

The urge to reduce the seemingly infinite variety and complexity of the visible world to some aesthetically satisfactory order has been a part of man's intellectual life since ancient times. In ancient philosophy and in modern science the natural orientation of this drive has been in the direction of understanding this variety and complexity as the natural outcome of the enormous number of combinatorial possibilities available to even a small number of basic entities subject to fixed laws of behavior. The search for these basic entities and for the strict formulation of the laws which govern them is still very much the essential fabric of physics today.

The history of this intellectual pursuit has revealed an aspect which probably was not anticipated by the ancient philosophical school which first proposed an atomistic character of the visible universe—namely, that the familiar objects and phenomena of everyday experience are not the direct and immediate consequence of the organization of the basic entities which they envisaged, but represent instead one rank in a hierarchy of organized structures, each level of the hierarchy being characterized by a degree of internal logical structure of its own, in part independent of the hierarchies lying above and below. To illustrate: the mechanics of the solar system could be understood in terms of a continuous distribution of matter characterized by mass density alone with its behavior governed by Newton's laws of motion and gravitation. At the next lower level, where internal but macroscopic properties of gross matter are examined, we have, on the one hand, the description of its elastic, thermal, electrical, and optical properties in terms of appropriate coefficients and, on the other, the achievements of chemistry in reducing the variety of substances with different physical properties—first, to mixtures of pure chemical substances, and then further to appropriate combinations of the ninety-odd chemical elements. The chemical laws of combination, in turn, suggested the first indications of a physical reality to an atomistic concept of material structure by revealing that a natural explanation of the regularities observed could be achieved in terms of elementary atoms of each chemical element when combined with rules (of then unknown origin) respecting the affinity of these atoms in forming chemical bonds. Statistical mechanics and kinetic theory gave further support to such an atomistic concept in showing how the elastic, thermal, and other physical properties of gross matter could be understood directly from such an atomistic viewpoint.

But as the atomic structure of gross matter was becoming incontrovertible, the first evidences that atoms themselves were not irreducible, and indeed possessed structure of their own, were making their appearance. The unraveling of atomic structure and its role in determining the previously arbitrary elements involved in chemical affinity and in the coefficients describing the intrinsic properties of matter on a macroscopic level—first through the discovery of the electron, the proton, and the atomic nucleus, and then through the development of quantum mechanics—was accompanied by the discovery of internal structure of the nucleus itself. The discovery of the neutron and the positron set the stage for examining this new

L. L. Foldy is professor of physics at Case Institute of Technology in Cleveland, Ohio.

level of material structure. Here something new was required: the nuclear glue which bound the nucleus together, something different from the familiar forces of gravitation and electromagnetism which had sufficed for the atom and the hierarchies of structure which lay above. When, in 1937, Yukawa proposed the meson theory of nuclear forces as the solution to this problem, the state was laid for the subject of this article. For once one admits the basic correctness of the meson theory of nuclear forces, the laws of quantum mechanics allow no alternative but that there should exist some minimum of internal structure to the neutron and proton. More of this later, but first it is necessary to mention some other developments which play an important role in what follows.

Discoveries and speculations

In Dirac's theory of the positron, Fermi's theory of beta decay involving the then hypothetical neutrino, and in Yukawa's theory of nuclear forces, there entered a new conception, an implementation of an aspect of Einstein's theory of relativity: namely, that particles (other than the photon) could be created out of energy directly, and hence that at least some of the entities found emerging from atoms (or, more specifically, their nuclei), such as positrons, electrons, and mesons, were not actually permanent constituents of the atom, but like photons were brought into existence through the conversion of available energy. The importance of this concept for the purposes of this exposition lies in the fact that, whereas the atom, and in large measure the atomic nucleus itself, could (to a good approximation) be considered to be composed of electrons, neutrons, and protons as essentially *permanent* constituents, at the next level, the internal structure of protons and neutrons, one is forced to admit the existence of a new kind of structural entity—"virtual particles" of only transitory existence, created and destroyed through the same agency which is responsible for the interactions between the particles themselves as a direct consequence of the basic quantum fluctuation phenomena associated with the Heisenberg uncertainty principle. This represents a somewhat radical revision in the very concept of material structure from what had prevailed or been envisaged earlier.

Two other developments of some importance for this subject require mention. The first is the discovery of the mu meson, which for a while masqueraded as the meson of Yukawa's theory of nuclear forces. Its significance lies not in this comedy of errors, but in the realization that here is the first particle which seems to play no significant role in the behavior of matter on a macroscopic scale. Electrons, protons, and neutrons are essential to the structure of macroscopic matter; photons and pions (the actual Yukawa particles) supply the essential forces between them; neutrinos, in their role in beta decay, determine at least the stabilities of some of the elements; positrons, antiprotons, and antineutrons provide a relativistic rounding-out of the theory of the "necessary" particles; but muons seem to play only a superficial role. Yet their symmetrical involvement with neutrinos and electrons in the theory of weak interactions suggests that they are not a minor nuisance but are involved in some essential way in the scheme of things.

The second development is the discovery in the past decade of a host of new strongly interacting particles of transitory existence whose connection with the macroscopic world is equally mysterious. The very number of such new particles, together with the evidences of their involvement in systematic symmetries with the more familiar proton, neutron, and pion, suggest strongly that what we have become used to calling "elementary particles" are not necessarily the basic structural entities of the universe but another level in the hierarchy or organization of matter. Physics is now deeply immersed in the clarification of the systematics of material organization at this level and as new unities are uncovered these must add dimension to one's views of the structure of the neutron and proton. Conversely, what is discovered about the structure of the proton and neutron has implications for the structure of this host of particles. As to the next lower level in the material hierarchy, if one exists, one can only speculate; but some of these speculations are already of such potential interest for the subject at hand as to deserve some mention below.[1]

In brief summary, with the examination of the structure of the proton and neutron one is investigating a new hierarchical level in the material organization of the physical universe, related to, but underlying, the now substantially explored level of atomic and nuclear structure. At this level, the proton and neutron are just two examples of a variety of entities which seem to be closely related and which by custom are called "elementary particles". From this point of view these two particles are not outstanding because they are fundamentally simpler than the other objects, but rather because they have been more accessible to experimental observation. That another hierarchy in the structure of matter may underlie the "elementary particles" is strongly urged by the desire for greater economy in the number of truly fundamental entities and by indications of sufficient symmetries to make such an underlying structural basis an attractive possibility. Thus, while the experimental results emerging from the study of neutron and proton will have some degree of permanence, their physical interpretation will likely be subject to revisions of a character which cannot at this time be foretold.

The meaning of structure

To turn now to our principal topic, the structure of the neutron and proton, it is perhaps appropriate to dwell for a moment on the question, "What constitutes structure?" One may have intuitive notions concerning this, but when encountering something new one cannot be certain that intuitive ideas are adequate to the situation. Thus one might immediately think in terms of a structural situation extended in space or in space-time; it is perhaps justifiable, but the possibility cannot be overlooked that there exists internal structure which is not of this character.

The internal symmetries of particles such as those associated with isospin or SU (3) invariance, for example, have not yet been identified as possessing a spatio-temporal connection. To postulate an isospin for a nucleon such that in pointing "up" in a hypothetical isospin space it represents a proton and pointing "down" a neutron is simply a semantic device; to discover that nuclear forces are independent of this orientation, however, would appear to endow this device with some physical reality but does not require that it has a spatio-temporal counterpart in the nucleon itself. Nevertheless, leaving such possibilities in abeyance for the moment, one can ask about the evidence for, say, spatial extension in the neutron and proton. If we find such evidence we can then inquire whether this spatial extension is of a purely static character, reflecting only a "geometrical shape" of these particles, or whether it is associated with an internal dynamics. In other words, do there exist internal degrees of freedom having some kind of analog with the internal degrees of freedom associated with an atom as a result of its being constituted of electrons? If the latter is the case it is to be expected that the system would then exhibit various internal states associated with different internal configurations; excited quantum states, in other words. One could also inquire as to the nature of the basic elements to which the dynamics has reference, the constituents of the nucleon, so to speak, and as to whether they have a permanent or transitory existence as mentioned earlier.

Straightforward as the questions appear, there are substantial conceptual difficulties in asking that experiments provide straightforward answers to them. Consider the simplest question: do protons and neutrons have spatial extension? In classical relativity there is a theorem that any system which has angular momentum must have a certain minimal spatial extension; applied to the neutron or proton this would predict a minimal spatial extension of the order of the Compton wavelength of the particle. When relativity and quantum mechanics are combined, a new difficulty arises. It does not seem possible to associate with a quantum system in a relativistic way a concept of localization which carries with it all the implications of classical localizability. There are two (at least) concepts of localizability or of associated position that can be used. One, the Dirac position concept, has the disadvantage that the process of measurement to establish this kind of localizability would immediately create other particles so one would not be localizing a single particle. The other, the Newton-Wigner position concept, has the difficulty that, if the particle is considered localized at a point in one Lorentz frame, it will not be localized in another Lorentz frame. The ambiguity in the concept of position here involved is measured by a quantity of the order of the Compton wavelength of the particle. Since the structural details of the elementary particles are, in fact, distributed over distances of just this magnitude, there will necessarily be some ambiguity in forming a space-time picture of this structure. We emphasize that the difficulty is a conceptual one: either type of position concept is internally self-consistent and can serve as an appropriate medium for expressing physical results, and once these have been formulated in one picture they are immediately transformable into the other.

Next, one may ask what qualities of a nucleon exhibit this spatial extension and to what extent are the spatial distributions of such qualities the same or different. Thus one could ask about the spatial distribution of energy density in a particle (which, in principle, but not yet in practice, could be determined from the behavior of the particle in sufficiently rapidly varying gravitational fields), or the distribution of electrical charge and current which can be determined from the particle's response to electromagnetic fields, or a host of other densities which measure the response of the particle to various other "force fields". Experimentally, of course, one would like a complete categorization of these "quality densities" in order to have a comprehensive description of the structure of a particle. In fact, one would like to extend the idea of these densities to "transition densities" associated with a change in state or nature of a particle, such as the change of neutron to proton in the case of beta decay. At a higher level still, one would be interested in polarizability effects—that is, the changes in internal density distributions induced by external influences which are sufficiently strong that higher order effects must be taken into account.

Electromagnetic structure

To approach these questions in their most familiar and experimentally best-explored aspect, let us consider first the case of charge and magnetization density. Historically, the first indication that the electromagnetic organization of the proton and neutron was more complex than that of the electron was the fact that the magnetic moments of these particles deviated very considerably from the values predicted by the simple Dirac theory of particles of spin ½. In the simple Dirac theory a charged particle has attributed to it a point charge only (from the viewpoint of the Dirac position concept). Nevertheless, the particle shows a magnetic moment and spatial charge distribution in interaction with electromagnetic fields through the characteristic kinematical feature of relativistic quantum theory, Zitterbewegung, which is intimately connected to the dualistic concept of position mentioned earlier. Even for a free particle of zero momentum, the Dirac position coordinate carries out a complicated random motion over a region of dimensions of its Compton wavelength, giving rise to a charge and current distribution over such dimensions. In the Newton-Wigner picture, the position of such a particle is stationary, but the nonlocal character of its electromagnetic interaction in this picture yields essentially the same charge and current distribution as above. It is this current distribution which gives rise to the "normal" or Dirac moment of a charged particle. A deviation of the magnetic moment from this value, therefore, may be conceived of as arising from specifically dynamical effects reflecting further structure. Such an additional moment is what is called an anomalous or Pauli moment.

A natural source of the anomalous moment of proton and neutron is provided by the Yukawa theory of nucleonic interactions. According to this theory, the internucleonic force arises from the exchange of quanta (mesons) of a new type of field (the meson field) for which the quanta have finite rest mass. The exchanged particle can be charged, giving rise to the "exchange" character of nuclear forces: a neutron changes into a proton by emission of a negatively charged meson which is then absorbed by a proton, converting it into a neutron; in the process, momentum and charge are exchanged between the two particles. The exchanged mesons are "virtual particles" in that they arise from quantum fluctuations which fail to conserve energy during the time required for the exchange, insufficient energy being available to create a "real" meson. But the same quantum fluctuations which make the above process possible require that an isolated neutron, for example, be continually dissociating into a proton and negative meson and reassociating into a neutron. Similarly, an isolated proton would be dissociating into a neutron and positive meson and reassociating. The electromagnetic structure of these particles will reflect the charge and current distributions associated with this virtual decomposition. Since the fraction of the time that a nucleon is dissociated is dependent on the strength of the interaction, and since this interaction must be strong to describe the strong nuclear forces, one would expect in particular a large anomalous moment for these particles, as observed. One would also expect the charge and current associated with the particles to be distributed over spatial regions which are of the order of the meson Compton wavelength, but even this semiquantitative prediction could be modified by strong interactions between mesons.

To confirm such a picture of the electromagnetic structure of nucleons one would like to verify the spatial distribution of charge and current which it predicts, and in particular, to show that the former differs from that expected on the basis of the Dirac theory. The natural way to do this is by the means used by Rutherford to delineate the nature of the distribution of charge in the atom, namely by studying the scattering of charged particles by such an electromagnetic structure. A first attempt in this direction was made in 1948 by groups at Columbia (under Rabi) and Chicago (under Fermi) who sought to detect an interaction of an electrostatic character between slow neutrons and electrons. Some evidence of an effect was obtained and more quantitative determinations have since been made. Unfortunately, the evidence obtained in this way was not decisive, since it was later shown that the observed result was consistent with a point magnetic moment (Pauli moment) for a particle in the Dirac picture, the electrostatic effect arising again from the combined effect of this moment and the kinematical feature of Zitterbewegung. Thus there was no evidence from this experiment that the neutron has an intrinsic charge distribution. Although the neutron does have *an intrinsic current distribution* as evidenced by its magnetic moment, the magnitude of the latter gives no indication of the spatial extent of these currents. Actually, what the neutron-electron interaction experiment shows is that the second radial moment of the charge density distribution is very small, not that the charge density in the neutron is identically zero.

The natural way to look further for information about charge and current distributions by the Rutherford technique is to go to higher resolution methods afforded by scattering energetic charged particles from nucleons. In the case of a fixed charge and current distribution, the scattering amplitude associated with a given momentum transfer between the charge distribution and the scattered particle is a direct measure of the space Fourier transforms of these distributions for the wavelength associated with the momentum transfer. With more energetic charged particles, larger momentum transfers and hence shorter wavelengths are accessible, and more detail can be seen in the associated distributions. For an unambiguous interpretation of such scattering data, however, one must be certain that the only important interaction between the charged particle used as a probe and the particle whose charge and current distribution are being explored is the electromagnetic one, and

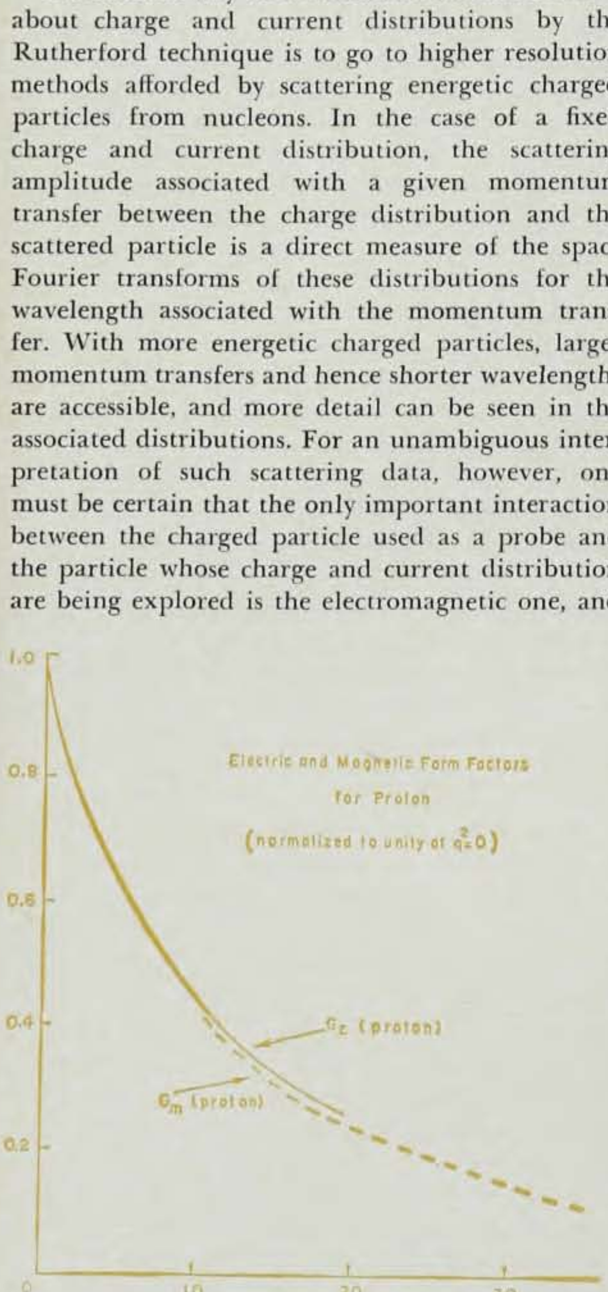


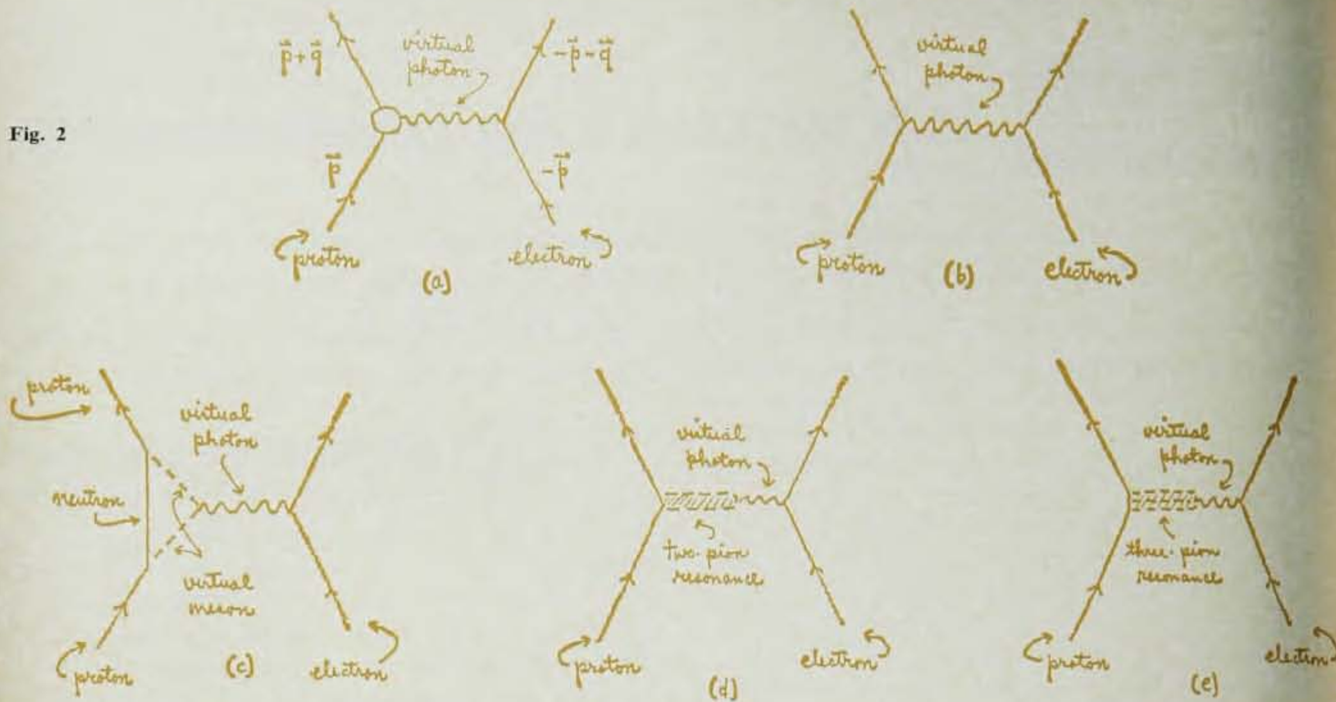
Fig. 1

further that the probe have no electromagnetic structure itself, or at least have its electromagnetic structure known. In addition, the electromagnetic interaction should be weak enough that higher order (polarizability) effects should not be important. Since the electromagnetic interaction between probe and explored particle can always be represented as the exchange of virtual photons between the two, this last condition is equivalent to saying that the scattering process is dominated by the exchange of a single photon. These conditions are satisfied (up to quite high energies, at least) by electrons and muons as probe particles.

The construction of a high-energy linear electron accelerator at Stanford finally permitted a decisive attack on this problem. In 1955 Hofstadter and his co-workers were able to demonstrate unambiguously that the charge and current distributions in the proton were indeed spatially extended over distances of the order of 10^{-13} cm. They were able to do this by showing that the ratio of the observed scattering of electrons by protons to what would be expected on the basis of the Dirac equation for a proton carrying a point charge and point Pauli moment was a rapidly decreasing function of increasing momentum transfer; this is exactly what one would expect from an extended charge and current distribution; the rate of decrease gives a measure of the actual distribution size. These and further experiments at Stanford, together with later experiments at Cornell and at the Cambridge (Massachusetts) Electron Accelerator, have yielded a quantitative determination of the essential structure functions for the proton up to momenta transfers q of the order of 2 BeV/c. These structure functions, or form factors as they are also called, represent in essence the Fourier transforms of the charge and magnetization distributions in the proton. Corresponding to the two position concepts available (the Dirac and the Newton-Wigner) there are two ways of presenting the form-factor data. The form factors which are called F_1 and F_2 are roughly speaking the Fourier transforms of the charge and magnetization respectively using the Dirac position concept, while the function called G_E and G_M are the corresponding factors for the Newton-Wigner position concept. The two sets are related by simple linear equations so that knowing one set is equivalent to knowing the other. The G-functions are directly accessible to experiment. We show a plot of the G-functions for the proton in Fig. 1. A rough characterization of the results in physical terms may be expressed as follows:

(1) The shape of the curves is such that they represent a spatial charge and magnetization distri-

Fig. 2



bution which is roughly exponential in character with a (root-mean-square) radius of about 0.8×10^{-13} cm.

(2) The size and shape of the charge distribution is quite similar to that of the magnetization distribution.

(3) The fact that the curves seem to approach zero smoothly suggests that there is no "hard core" of charge (or current) inside the proton, but that all the charge and current is smoothly distributed.

Corresponding information about the neutron is not as satisfactory, but this reflects only the fact that free neutrons are not available as targets for electron scattering. By using deuterons as targets it is possible to obtain relatively clear-cut information on the magnetic form factor G_M for the neutron, but information on the electric form factor G_E is still quite uncertain. Available information concerning the magnetic form factor G_M for the neutron shows it to be essentially the same as that for the proton. It is more difficult to say anything definite about the electric form factor G_E for the neutron. Electron-scattering results from different laboratories are inconsistent and in some cases such results only determine $G_E{}^2$ so that even the sign is uncertain. The fact that the neutron has zero net charge means that G_E is zero at zero momentum transfer, while the low-energy neutron-electron interaction results indicate that it should be positive at small momentum transfers, with a definite slope. There may exist some difficulty in reconciling this low momentum transfer information with even the quite uncertain results at high momentum transfer obtained from high-energy electron scattering.[2]

Let us turn now to the question of the kind of physical picture required to understand these results. In Fig. 2(a) we have represented a Feynman diagram for the scattering of electrons by protons in the center-of-mass system. The wavy line represents the virtual photon exchanged between the electron and the proton. It carries a momentum q which changes the momentum of the proton from p to $p + q$. It also carries some angular momentum and isospin. The "blob" where it joins the proton line represents the charge and current distribution which is a "source" or "sink" for the photon. We are interested in the structure of this blob. If the proton were a structureless particle, it would be represented by a simple point charge which could absorb the photon as shown in Fig. 2(b). If the proton is sometimes virtually dissociated into a pion and neutron, then we have in addition a contribution to the blob like that shown in Fig. 2(c), where the photon is absorbed by the virtual meson; such a process is reflected in a spatial extension of the charge and current distribution in the proton. The diagram is drawn with no representation of any interaction between the two mesons into which the photon is "converted" in the process of being absorbed. Calculations on a simple model of this type have not succeeded in quantitatively describing the observed

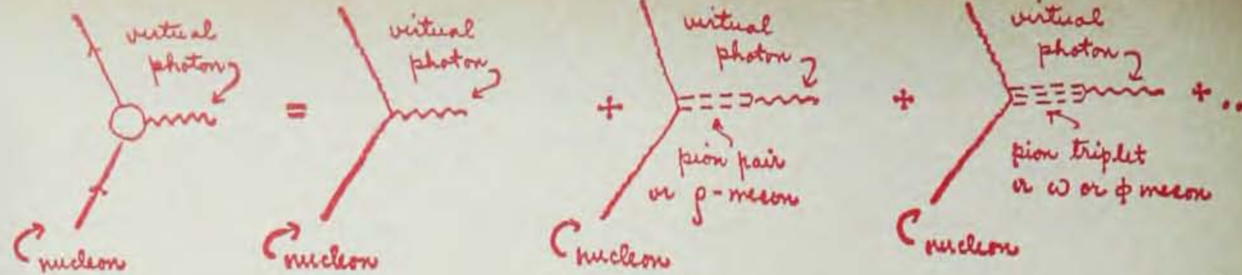


Fig. 3

form factors. If, however, there is a strong interaction between the mesons as schematically indicated by the cross-hatching shown in Fig. 2 (d), it is possible for a resonance in the pion-pion scattering to occur such that the conversion of a photon into a pair of pions takes place primarily to this resonant state. The energy at which such a resonant state occurs will have a strong effect on the rate at which form factors fall off with increasing momentum transfer. Such two-pion states contribute only to the so-called isovector part of the form factors, which means they give equal and opposite contributions to proton and neutron form factors. The isoscalar contribution which gives like-signed contributions to both proton and neutron contributions will arise from processes like that shown in Fig. 2(e) where a photon converts into three mesons. Here too, interactions between the pions of the type indicated there can lead to resonance states which seem again to be of dominant importance. Through close analysis, it was discovered that the shapes of the observed form factors could be reasonably well described if such resonances occurred in both the two-meson and three-meson exchanges at an energy corresponding to a mass of the resonant states of approximately five pion masses. This formed the basis for a *prediction* of such pion resonances, which was strikingly confirmed experimentally by the discovery of the ρ, ω, and ϕ vector mesons, of which two have a mass in the neighborhood of $5\frac{1}{2}$ pion masses and the third a mass in the neighborhood of $7\frac{1}{2}$ pion masses. There is considerable present interest in seeing how quantitatively the available experimental information can be explained in terms of the "known" vector mesons (or resonances) which can couple the photon line to the nucleon line, but a detailed analysis of these attempts is beyond the scope of this article and we summarize the situation by indicating that such analyses give promise of success, and refer the reader to Ref. 2 for details.

Rather, let us return to some more general theoretical considerations concerning the type of nucleon structure which is schematically indicated by the sketches in Fig. 3. We have indicated some of the elements which contribute to the blob where the photon line joins the proton line. A general analysis according to dispersion theory indicates that one will have additive contributions to the form factors of nucleons arising from every conceivable system into which a photon can (virtually) convert and which in turn can be absorbed by a nucleon. Besides the particular meson contributions we have indicated, there will be such structures as a nucleon-antinucleon pair or similar pairs of strange particles (hyperons). (To some extent these are already included in our vector meson exchanges, for by the same quantum fluctuation process outlined earlier, such mesons have a definite probability of being virtually decomposed into baryon-antibaryon pairs.) The form of each contribution depends on the mass of the system which couples the photon line to the baryon line and on the "strength" with which each such system is itself coupled to the two lines it connects. To apply dispersion theory to the problem at hand one must assume that the strengths decrease generally with increasing mass so that the form factors are dominated by the contributions of the lowest mass systems which can form the requisite bridge between nucleon and photon. The vector mesons we have described are then the principal contributors. From this point of view, the "inside" of a nucleon is a complex of complicated configurations of various mesons, meson complexes, baryon pairs, baryon resonances, etc., which come into (virtual) existence and disappear again as a result of quantum fluctuations; each makes some contribution, large or small, to the charge and current density of the object we call a nucleon. This is far from the relatively simple picture of the structure of the atom, where the charge and current distribution is associated with permanent and essentially stable constituents —electrons, protons, and neutrons.

Before leaving the subject of the electromagnetic structure of the nucleon we mention another source of experimental information. If we turn the diagrams in Fig. 2 "on their side" we have a representation of a different physical process, namely the annihilation of a proton-antiproton pair into a virtual photon which decomposes into an electron-positron pair. This differs from the electron-scattering process in that the square of the (invariant) momentum transfer is now negative in-

stead of positive. The amplitude for this process is expressible also in terms of the form factors described earlier, but we are now dealing with analytic continuations of these functions to values of q^2 which are negative and less than $-4M^2$ where M is the proton mass. The "integrity" of analytic functions, that is, the fact that their value in one region of the complex plane is connected with their values everywhere, means that such information is also useful in fixing the form of the charge and current distributions in the proton. Experiments of this type are in their initial stages, but eventually they should considerably enhance our information about the electromagnetic structure of the nucleon. Muon scattering and hyperfine structure in the atomic spectrum of hydrogen represent additional potential sources of information.

Gravitational and weak interactions

We have remarked earlier that one is also interested in the distribution of other physical quantities of the nature of densities inside nucleons. The energy (and momentum) density distribution, while in principle determinable, is far from being accessible experimentally at the present time. In analogy with the electromagnetic case one would like to explore scattering in which a single gravitational quantum

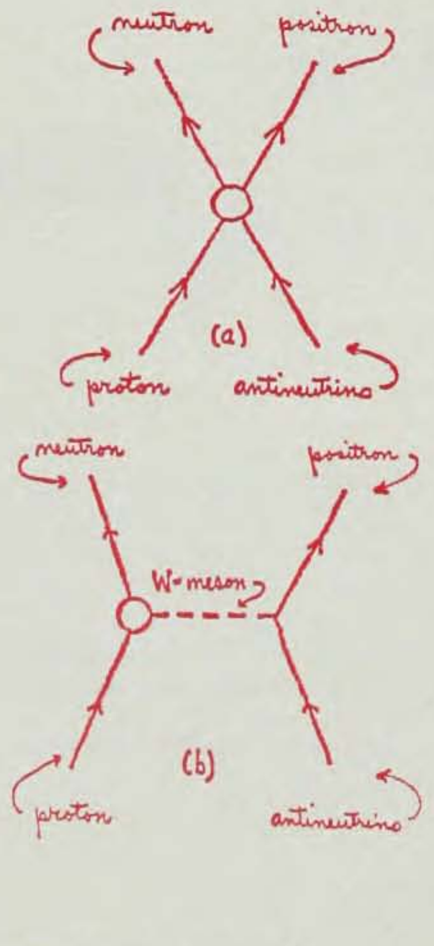


Fig. 4

is exchanged between the nucleon and the probe particle. Unfortunately there do not seem to exist particles for use as probes in which some other kind of quantum exchange would not dominate the scattering process, and if such did exist, the weakness of their interactions would appear to pose problems for their detection. The prospects for obtaining information of this kind are therefore grim. We mention this process here only to illustrate a general principle: Electric charge and current densities are sources and sinks for electromagnetic quanta (photons) and can be explored by examining processes in which a single photon is exchanged, as indicated earlier. The energy-momentum density tensor is a source and sink for gravitational waves, and hence its spatial distribution could be explored by processes in which single gravitational quanta are exchanged. Generalizing this idea, we see that we can examine the source and sink density for any field by an analogous process. Therefore, let us look at other situations where a corresponding interpretation is possible.

The question of ensuring that only single quantum exchange takes place in a scattering process is simpler in those situations where the interactions mediated by the quanta of the field are relatively weak. This immediately brings to mind the so-called "weak interactions" which are responsible for such processes as beta-decay, muon decay, muon-capture, etc. Consider, for example, the process illustrated in Fig. 4 (a) in which an antineutrino interacts with a proton to yield a neutron and a positron. It has been proposed that this interaction is actually mediated by a vector meson field as shown in Fig. 4 (b), but there is no direct evidence for its existence at the present time. If such a meson field exists, its quanta (the so-called W mesons) must have a mass considerably greater than the mass of the proton. Whether or not it exists it is conceptually possible to visualize the interaction to take place as shown in Fig. 4 (b), since the W meson serves essentially to transfer momentum, and in this case electric charge as well, between the leptons and the nucleons. The sources and sinks of this meson field will be "currents" associated with the leptons on the one hand and the nucleons on the other. If no W mesons exist we have a direct interaction between these "weak currents," as they are called, but we can explore their structure just as well by the same techniques that would be applicable in the case W mesons do exist, and these techniques would be in close analogy to those used in the electromagnetic case. What we need to do is to determine how the amplitude for the process described depends on the momentum

transfer involved in the process. Describing these by appropriate form factors, the Fourier transforms of the latter would be related to the spatial distributions of these "weak currents."

Let us first note some differences between the present case and the electromagnetic case. First, there is a charge transfer in the process which means that the nucleon must change its isospin in the process of emitting a W meson. This means in turn that the associated weak current here involved will now have only an isovector part rather than an isoscalar part as well as in the electromagnetic case, or stating the result more conservatively, only the isovector part of the current plays a role in this process. Furthermore, we know from various sources that there are two basic kinds of weak interactions, the vector and the axial vector. This means there will be two kinds of weak currents, one of a vector character and one of an axial vector character. Feynman and Gell-Mann have proposed that the vector currents are conserved currents of the same character as the electromagnetic current, and that they are in fact just the "charged components" of the isovector current of which the "neutral component" is the ordinary electromagnetic current. By charged and neutral components is meant here that the currents are associated with a change in charge or no change in charge of the nucleon. This proposal has been strikingly confirmed in beta-decay experiments and by the relationship between beta-decay and muon-decay. In these experiments only relatively low momenta transfers are involved between the participating nucleons and leptons. If the Feynman–Gell-Mann scheme is indeed correct, the form factors associated with the vector weak currents should be the same as the electromagnetic form factors even for large momentum transfers. A detailed confirmation of this would be a striking triumph for the Feynman–Gell-Mann hypothesis and would suggest that there exists only one vector current associated with elementary particles to which all vector fields are coupled, though with different strengths. On the other hand there is no electromagnetic analog to the axial vector currents involved in the weak interactions. These currents are also described by form factors whose momentum-transfer dependence it would be of interest to determine. Unfortunately, the neutrino experiments which have been carried out so far at Brookhaven and CERN are not yet of the character to shed direct information on these questions. One can look forward hopefully, however, to the day when the structure of the weak currents in nucleons will be studied with neutrino beams in much the same way as the electromagnetic structure is currently being probed with electrons.

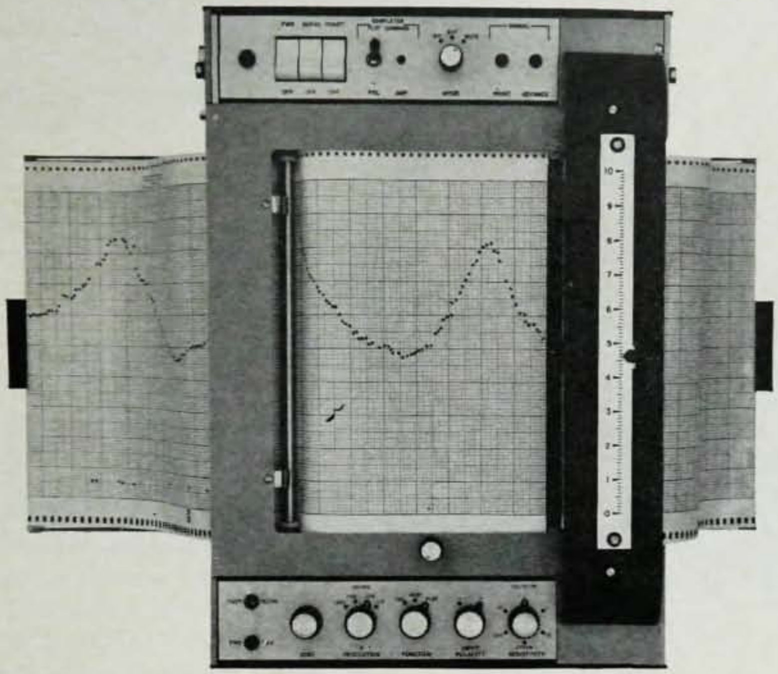
On the theoretical side we may remark further that if the Feynman–Gell-Mann picture of the weak vector current is correct and its physical extension in space corresponds to that of the electromagnetic current, then again this extension arises primarily from pion pairs, or more explicitly the pion resonance called the ρ meson, (only isotopic spin-1 mesons can now contribute so that the ω and ϕ would not contribute), as the bridge between the nucleon and the hypothetical W meson. Thus the physical picture of the nucleon which would emerge from determining these form factors would not be essentially different from that described above as revealed by the electromagnetic structure.

Strong interactions

Having remarked on the electromagnetic, the "gravitational," and the weak-interaction structure of the nucleon, we must turn now to the only remaining class of known interactions—the so-called strong interactions. Here the problem is complicated by the fact that these interactions are so strong that it is not easy to see how to isolate contributions to scattering or interaction processes associated with the exchange of a single quantum or particle. What makes it possible to attempt some kind of analysis is the fact that the range of the interaction associated with the exchange of a particle or system of particles between the interacting systems is inversely proportional to the mass of the exchanged system. Thus the longest-ranged interaction is that associated with the lightest exchanged systems. In the case of nucleon-nucleon scattering, for example, the lightest system of strongly interacting character is a single pion and its exchange should then dominate the interaction at large impact parameters. At somewhat smaller impact parameters the exchange of two pions would become important. The existence of the strong interaction between two pions which give rise to the meson resonance we call the ρ meson, means that two-pion exchange contributions tend to take place in these resonant states, corresponding to single ρ meson exchange. Since the mass of these is about four times the pion mass, there exists a substantial range of impact parameters where only the single pion exchange should be important. The problem is then to isolate these large impact parameter collisions from the close collisions. In general, this means that it must be possible to construct wave packets representing the colliding particles whose spatial extent is substantially smaller than a pion Compton wavelength. This in turn requires the

World's fastest / most accurate / most compatible

ANALYZER PLOTTER



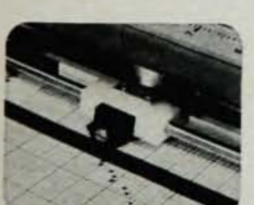
The Model 6550 OMNIGRAPHIC™ Recorder is designed to read out the memory of multi-channel analyzers, average transient computers and digital oscilloscopes. It has been specifically developed to replace slow speed X-Y recorder—null detector combinations when high plot rates are desired to save computer time and where it is desired to selectively resolve any number of channels.

SPEED 1200 points per minute. A 400 channel analyzer record may be obtained in just 25 seconds. A 512 channel record in 30 seconds. 100 channels in only **6 seconds.**

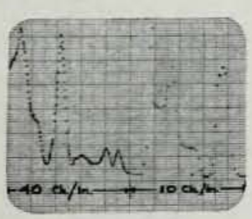
ACCURACY .15% of full scale with .1% repeatability. And this accuracy is at the instrument's full speed; for each point is printed **only** when the instrument has reached a null condition.

COMPATIBILITY Front panel controls facilitate usage with **all known** multi-channel analyzers, average transient computers and digital oscilloscopes. Since pulse inputs are used, the analog staircase generator is by-passed in the computer, and no X (chart) axis calibration is necessary.

RESOLUTION Channel resolution can be spaced at .025, .050, .075 and .100 inch to insure channel identification. Spacing can be changed at will and during course of the recording if some area is of more pertinent interest. Z-fold chart packet permits desired resolution for any number of channels on a continuous record. Chart folds or tears to **notebook size** record.



4 character plotting



Variable resolution

Ease of loading

Z-Fold paper

houston OMNIGRAPHIC corporation

a subsidiary of houston instrument corporation
4950 Terminal Ave. / Bellaire, Texas 77401
(713) 667 7403 / cable HOINCO / TWX (713) 571 2063

IN EUROPE: Houston Instrument N.V. Keizersgracht 450, Amsterdam, Holland, Tel. (020) 238138

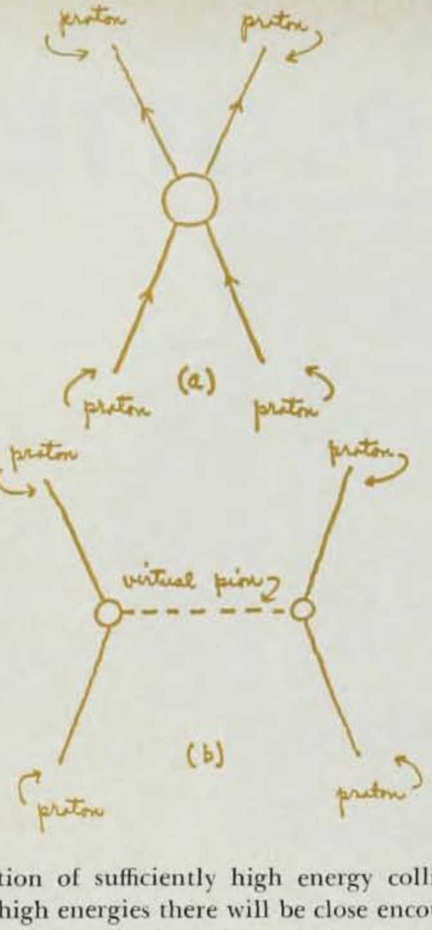


Fig. 5

examination of sufficiently high energy collisions. Even at high energies there will be close encounters as well as distant encounters. To isolate the distant encounters attention must be focused on those collisions in which the orbital angular momentum is sufficiently large for a given incident energy that close encounters are no longer possible. In cases where the energy is sufficiently high that the total scattering amplitude involves so many angular momentum states that the contribution of the few small angular momentum states which involve the effect of close encounters is relatively small, we may effectively accomplish the same result. Thus, by this means one can effectively study the strong interaction structure of the outer fringes of particles like nucleons, their periphery so to speak, whence, the name "peripheralism" for the general study of such processes.

Consider first in more detail the nucleon-nucleon elastic scattering process as shown in Fig. 5(a). The momentum transfer involved in the scattering will take place through the exchange of systems like a single pion, a ρ meson, etc. We would like to isolate the one-pion contribution exhibited in Fig. 5 (b). The blobs at the vertices in this figure now represent the structure or distribution of source strength for absorption or emission of a pion by the nucleon, and determines the "strength" of the interaction associated with a given momentum transfer, or a form factor in the same sense as in the electromagnetic case that we discussed earlier. The difference is that we are now examining a "pseudoscalar" source function or current rather than a vector current from the point of view of relativistic transformation properties. If we consider scattering at energies up to a few hundred MeV, then one can make a phase shift analysis of the scattering amplitude. The phase shifts for higher angular momentum states will be dominated by the single-pion exchange contributions to the force and therefore will give us some information about these blobs. At these energies, however, about all we can determine is the total strength of the source, that is the form factor for small momentum transfer, which is effectively what we call the pion-nucleon coupling constant g; it plays the same role for meson emission and absorption as the total charge e does for photon emission and absorption.

To find out something about the momentum transfer dependence of the form factor one would have to go to higher energies where larger momenta transfers are possible. Here one encounters a difficulty which has limited the effectiveness of "peripheralism" in yielding results free of ambiguity. This is the onset of a substantial cross section for inelastic processes even in peripheral collisions—processes like pion production or production of strange particles. Whenever such inelastic processes occur they react back on the elastic processes to yield an imaginary part of the scattering amplitude. This imaginary part cannot arise from single pion exchange but requires at least two pion exchanges for its description. The fact that the imaginary part of the amplitude becomes comparable to its real part indicates then that the basic assumption of the peripheralism approach is breaking down.

This problem appears somewhat less severe if one applies the peripheralism approach to an inelastic process such as that illustrated in Fig. 6, where we have the conversion of a pion into a

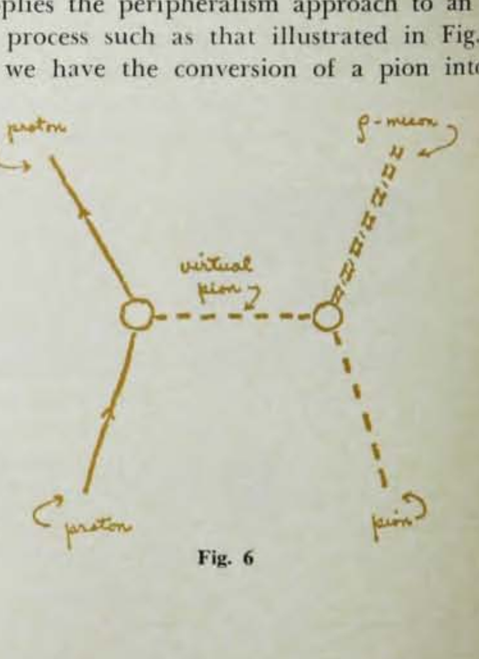


Fig. 6

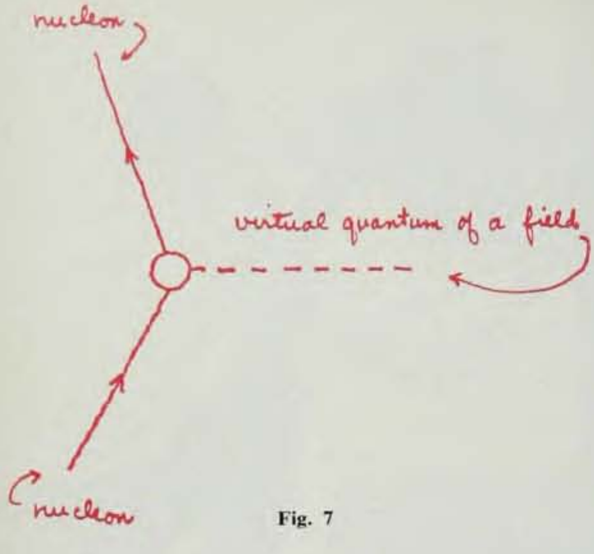


Fig. 7

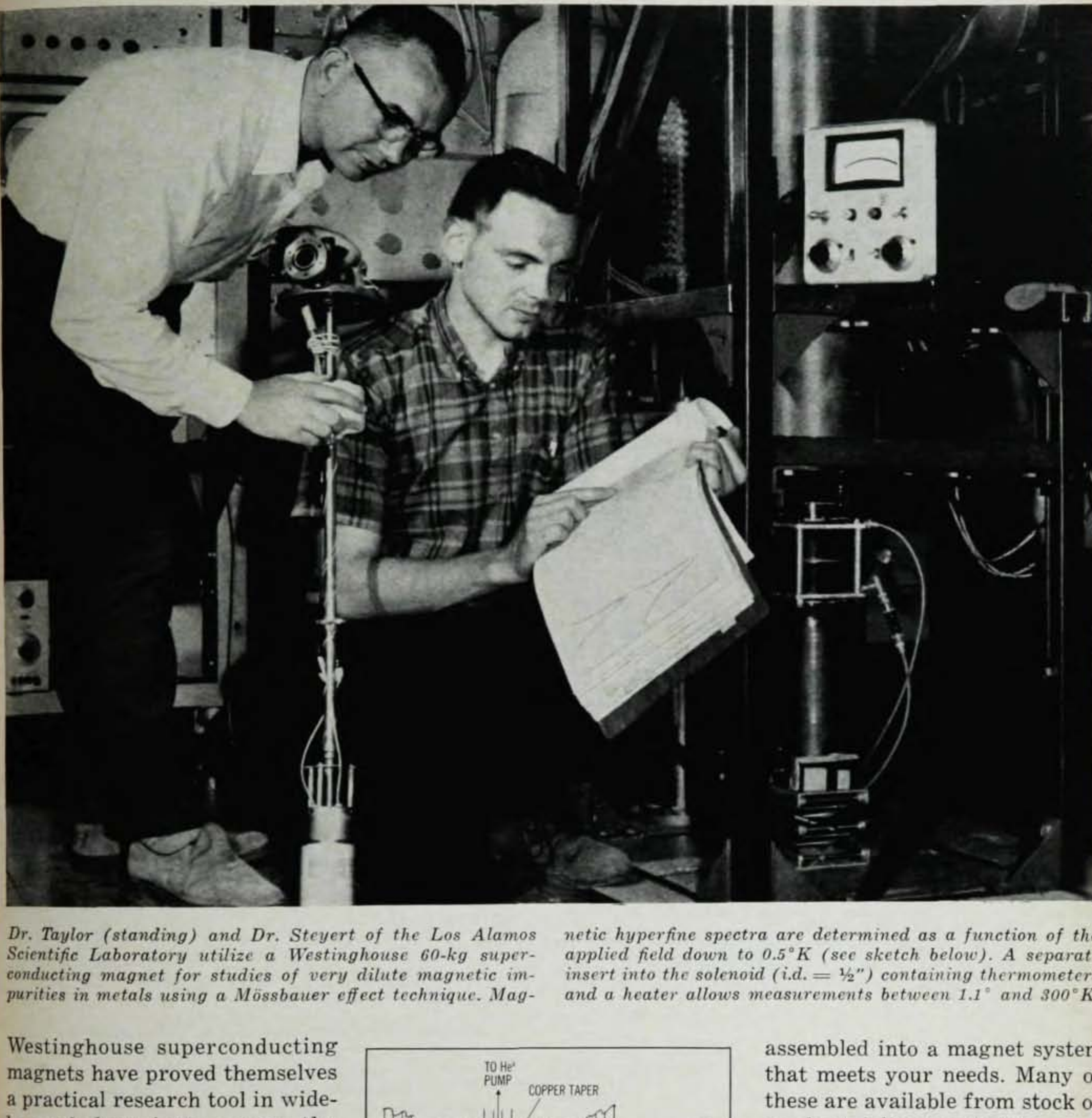
ρ meson through a collision with a proton. One conjectures that the required momentum transfer in the process arises from the exchange of a single pion. In this case, however, there are two unknown blobs whose structure in terms of form factors is involved in the amplitude for the process. Furthermore, the reactions of other inelastic processes on this inelastic channel are still quite substantial in reducing the probability that this particular process can occur. Thus a decrease of the cross section for this inelastic process with increasing momentum transfer will reflect not only the drop in the form factors associated with the two vertices where the exchange pion is emitted and absorbed but also the distortion of the waves representing the incident and emitted particles as a result of absorption produced by competing inelastic processes. While the peripheralism approach to high energy reactions is substantially increasing our insight into the essential elements that make up these processes, it still suffers from strong limitations insofar as allowing one to analyze quantitatively each element that enters, as for example, the momentum-transfer dependence of the form factors for pion emission or absorption. There exists, in fact, a close similarity between the methods of peripheralism in elementary particle physics and the study of direct interactions in nuclear physics and a substantial similarity between the nature and quantitative accuracy of the conclusions which can be drawn in the two cases.[3]

To summarize, then, the type of nucleon structure analysis we have been discussing is the determination of the spatial distribution of source functions for various types of fields which may be coupled to a nucleon—or, in more general terms, the form factors which characterize a vertex like that shown in Fig. 7. Here the two full lines represent a nucleon (more generally, any baryon) entering and emerging from the vertex "on the mass shell" (which means that the relation between the momentum and energy of the baryon is that of a free particle). The dashed line entering the vertex represents a virtual quantum of some field which transfers the requisite energy and momentum to the baryon along with charge, isospin, strangeness, etc., as selection rules may demand. For each fixed set of quantum numbers required to characterize the incoming and outgoing baryon states, the dependence of the associated vertex function on the invariant momentum transfer to the baryon represents a form factor which can be interpreted as a Fourier transform of the source function for the field with which the virtual quantum is associated. In the case where the virtual quantum is a photon, one has now a fair determination of this source function for nucleons except for the case of the charge distribution in the neutron. For the "weak currents" which are the sources of the hypothetical W mesons which mediate the weak interactions, and for the source functions of the strongly interacting meson fields, there remains much to be done experimentally and theoretically, but in general many of the means are at hand for the vigorous prosecution of such a program.

On the conceptual side, the picture of a nucleon which must be associated with such form factors is not easy to visualize. As a consequence of quantum fluctuations, the physical nucleon must be pictured as passing through a disorderly sequence of virtual states in which it is dissociated into those various combinations of strongly interacting particles which selection rules allow, each of these possible states making its contribution, large or small, to the form factors. The transitory existence of these "virtual particles" and their considerable variety then yields a picture far more complex than the relatively orderly picture presented by the electronic structure of the atom.

The proliferation of the number of particles which we have become habituated to terming elementary—the nucleons, hyperons, baryon resonances, mesons, and meson resonances of various characters—has raised the question whether there may exist an underlying dynamical structure for them, a lower hierarchical level in the structure of matter in which the observed "elementary particles" are composites of even simpler entities. Such speculations have been greatly strengthened by the recent uncovering of remarkable symmetries between these particles. The famous SU (3) symmetry of

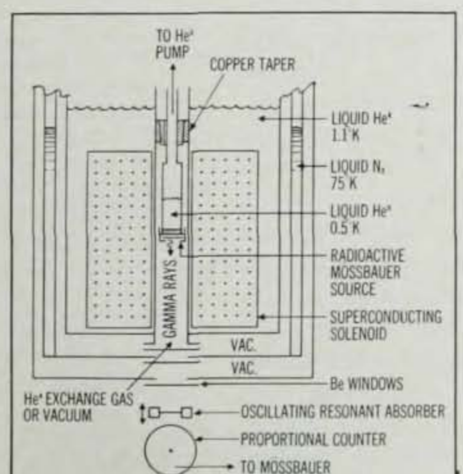
Now—superconducting magnets up to 100 kilogauss: portable, safe, easy to set up and use



Dr. Taylor (standing) and Dr. Steyert of the Los Alamos Scientific Laboratory utilize a Westinghouse 60-kg superconducting magnet for studies of very dilute magnetic impurities in metals using a Mössbauer effect technique. Magnetic hyperfine spectra are determined as a function of the applied field down to 0.5°K (see sketch below). A separate insert into the solenoid (i.d. = ½") containing thermometers and a heater allows measurements between 1.1° and 300°K.

Westinghouse superconducting magnets have proved themselves a practical research tool in widely varied projects across the country. Capable of producing stable field intensities up to 100 kilogauss, they are completely self-protecting and require no training to use. They are adding important new flexibility to many investigative techniques—at an operating cost much lower than conventional electromagnets.

Westinghouse offers a wide range of cryogenic solenoids and components which can be quickly



assembled into a magnet system that meets your needs. Many of these are available from stock or on short delivery schedules.

For answers to your questions and new literature on superconducting magnets in the fields of physics, chemistry, biology and medicine, call or write Ed Mullan, Westinghouse Cryogenics Department, Box 8606, Pittsburgh, Pa. Phone (412) 391-2800, Ext. 673.

J-09203

You can be sure if it's Westinghouse

Gell-Mann and Ne'eman, allow the grouping of the nucleons together with the Σ and Λ particles into an octet of particles related to each other in a way analogous to that in which the neutron and proton have been related in nuclear physics. Ten of the baryon resonances allow a similar grouping into a "decuplet". The pseudoscalar mesons can be similarly grouped into an octet, while the vector mesons constitute an octet and a singlet under this symmetry. The even more recently studied SU (6) symmetry allows the octet and decuplet of baryons to be combined into a single grouping and all of the aforementioned mesons to be similarly combined. What is most intriguing is that the group-theoretical structure of these multiplets is such as to allow these baryons and baryon resonances to be considered as composites of one (or perhaps several) triplets of more fundamental particles which are variously called quarks, aces, fundamental triplets, etc. The particles of an elementary triplet would be the basic carriers of the entities which we call charge, baryon numbers, isospin, and strangeness and would carry half-integral spin. The baryons of the octet and decuplet would then be composites of three such basic triplets, their differing isospins, strangeness, and spin arising from the various combinations of these quantities which can be formed from the different combinations of triplet particles that can be assembled with like spatial symmetry. The mesons, both vector and pseudoscalar, would similarly be constructed from a member of a basic triplet bound to an antiparticle of a basic triplet.

This is not the place to go into details of such schemes, and some of what is known has been ably summarized by other authors.[1] What is pertinent to our particular subject is the light that is thrown on the question of the source functions or form factors for the particles which we presently call elementary, including the nucleons. It has been found that the electromagnetic currents fall neatly into the classification scheme afforded by these symmetry properties, and that the same is true of the "weak currents" and also of the "strong currents" which are the sources of the vector mesons. This suggests that the structure of these currents has a form which is similar to (but not necessarily identical with!) the superposition of currents associated individually with the basic triplet particles themselves. If in fact such a superposition held, at least approximately, then the form factors of all these particles could be related to the form factors associated with the basic triplets themselves. Such simplicity is perhaps too much to hope for, but in any case the relations between different particles illuminated by these underlying symmetries are reflected in corresponding relations among their form factors; this could greatly reduce the amount of experimental work which needs to be done in order to obtain a comprehensive picture of the internal structure of elementary particles.

A striking example of the power of these symmetry ideas is the following: In the proposed SU (6) symmetry scheme, the simplest assumption about the transformation properties of the electromagnetic currents yields the prediction that the static magnetic moment of the neutron is minus two thirds that of the proton, a result confirmed by the experimental values to a few percent. From a straightforward extension of this assumption, the identity of the magnetic form factors for proton and neutron, as observed, also follows. The magnetic moment of the lambda particle is also predicted and is consistent with the crude experimental results presently available. Many other predictions concerning the various form factors of the members of the baryon octet and decuplet can be made which are currently beyond the range of experimental verification.

There seems little doubt that approximate symmetries among the elementary particles exist and probably have some significance. Whether the attractive picture of basic triplets as the underlying basis of these approximate symmetries will survive depends in part on the actual observation of the triplets. Since their masses are necessarily large, it is possible that we must await a new generation of high-energy accelerators before we can transmute this theoretical speculation into substantial experimental fact, or perhaps the cosmic rays will again serve us in the admirable way they have in the past.

References

1. Two popular expositions of present knowledge and trends in elementary-particle physics which may be useful as background reading on this subject for the nonspecialist are: M. Gell-Mann, "Particles and Principles", *Physics Today*, November 1964, p. 22, and G. F. Chew, M. Gell-Mann, and A. H. Rosenfeld, "Strongly Interacting Particles", *Scientific American*, February 1964, p. 74. A more technical review of elementary-particle symmetries, but not including the more recent SU (6)-induced symmetries, is contained in R. E. Cutkosky, "Symmetries Among the Strongly Interacting Particles", Ann. Rev. Nucl. Sci., **14**, 175 (1964).
2. For a recent review of experimental data on electromagnetic form factors of nucleons and their theoretical analysis, see R. R. Wilson and J. S. Levinger, "Structure of the Proton", Ann. Rev. Nucl. Sci., **14**, 135 (1964).
3. Some recent work in peripheral reactions is discussed in the article "Peripheral Production and Decay Correlations of Resonances" by J. D. Jackson, Revs. Modern Phys., **37**, 484 (1965).