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HIGH ENERGY ELECTRON AND PHOTON PHYSICS

Exploring The Unknown With The Known

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Talk given at National Academy of Sciences Symposium "Revelations and Prospects in High Energy Physics", April 24, 1968. In the past high energy physics research with proton accelerators has been more comprehensive than that carried out with electron machines. Proton machines have been used both for the study of the interactions of the primary protons themselves as well as generators of secondary unstable particles. Electron machines have been used for studies of primary electron and photon interaction but have not served extensively as sources of secondary particles. This situation is changing greatly: Electron accelerators are entering the mainstream of high energy physics, both as tools for studying the interactions of electrons and photons, and also as sources of secondary particles.

Studies of high energy physics using electron and photon beams give in many respects much more basic information than studies involving protons. This fact is due primarily to the dominant role played in all of physical science by one of its branches, namely, quantum electrodynamics.

We have recognized several basic forces of nature, notably gravitation, the electromagnetic interaction, the nuclear strong reaction and the nuclear weak interaction; it is fair to say that at present among these only electromagnetic forces as described by quantum electrodynamics can be described completely in mathematical terms; numerical agreement between experimental and theoretical results is spectacular. It is also fair to say that all of atomic physics, all of solid state physics, all of chemistry, and probably all of biology can ultimately be considered to be a manifestation of quantum electrodynamics; in these fields of science elec-trical forces alone control the physical phenomena. The validity of quantum electro-dynamics has been demonstrated to be correct to high accuracy over the full range of distances from atomic to sub-atomic dimensions. Clearly it is a matter of the greatest interest whether quantum electrodynamics continues to be valid at the

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very smallest distances (and therefore highest energies) accessible with modern accelerators. It would be a result of extreme significance if at very small distances quantum electrodynamics would cease to be valid.

I would like to state here that thus far all experiments directed towards this question have given a null result: That is, quantum electrodynamics apparently is a valid description of the electromagnetic interaction from macroscopic dimensions down to distances as small as 10^{-15} cm. I will discuss later how this question is examined experimentally and what the prospects are for pushing the frontier of our knowledge of the validity of quantum electrodynamics still further. Let me assume for the moment that quantum electrodynamics is a valid theory; it is this fact which makes high energy physics with electron and photon probes such a unique undertaking. Since the electron, the photon, and also the mu meson and neutrino do not carry the nuclear strong interaction, and since the nuclear weak interaction is about 10^{-10} times weaker than the electromagnetic interaction, one can consider these particles as carriers of the electromagnetic interaction only when they are used as probes of structure of other elementary particle systems. In electron and photon physics we can therefore explore the unknown structures of the elementary particles and their excited states by carriers of a known interaction rather than having to explore the unknown with the unknown as is the case with an incident beam of protons.

The primary example of a fruitful exploration of an unknown structure using the electromagnetic interaction only is high energy electron-proton and high energy electron-neutron scattering. It is now known that the radius of the nucleons is of the order of 10^{-13} cm, and therefore wavelengths smaller than this number are required to explore nucleon structure. According to the Uncertainty Principle, wavelength of exploration is inversely related to the momentum transfer to the

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nucleon system in a scattering process; quantitatively, studies of nucleon structure therefore require momentum transfers greatly in excess of 100 MeV/c. Electron scattering on the proton has been carried out with all early electron machines; it was the Nobel prize-winning work of Hofstadter, using the Stanford 1-BeV accelerator, which first uncovered a proton structure differing from a point.

One can look at electron scattering on the proton in several alternate ways: Viewed as a classical diffraction process (Fig. 1) one considers the incident electron as a plane wave, each element of which scatters from a point within the nucleon which has a charge density of $\rho(\mathbf{r})$. The resultant scattering amplitude in a nonrelativistic language can easily be shown to be proportional to $\int \exp(i\vec{q}\cdot\vec{r}/\hbar) \rho(r) d^3r$ where \vec{q} is the vector difference between the incident and outgoing electron momentum. In other words, the scattering cross section of electrons on the nucleon yields the Fourier transform of the charge distribution of the nucleon. The form of the Fourier relation is a direct representation of the Uncertainty Principle: The larger the momentum transfer q in the exponent, the more sensitive will the integral be to variations of the charge density $\rho(\mathbf{r})$ for small changes in the coordinate r. In more modern terms we look at this kind of electromagnetic process by a diagram in which the incident electron "virtually" emits a photon which is then absorbed by the nucleon system (Fig. 2). Quantum electrodynamics then defines a formalism into which the structure of the nucleon enters in terms of "form factors" which are in essence Fourier transforms similar to the ones discussed previously. However, the more complete theory indicates that to describe the electromagnetic structure of the proton and neutron completely, one requires two form factors rather than one; these two numbers describe the distribution of electric charge and magnetic moment (i.e., current distribution) within the nucleons respectively.

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During recent months electron scattering experiments have been extended at SLAC to momentum transfers as high as 5 BeV/c, which corresponds to distances of the general order of 10^{-15} cm. Figure 3 shows the resultant form factors obtained. Several surprising facts have emerged from these recent results: The first is that the form factors continue to decrease rapidly (as the inverse fourth power of the momentum transfer even at these very high energies). Physically this means that even at this fine resolution the proton does not exhibit a core or any other central structure which would cause the scattering amplitudes to level off at high energies, or to be precise, at high momentum transfers. A second fact is that at extremely high energies electron-proton and proton-proton scattering can be very simply related.

Let me now digress briefly from discussing results to discussing experimental techniques. I would like to demonstrate that, although the style and size of carrying out experiments at the frontiers of physics has changed drastically during the last decades, the basic purposes and fundamental ideas of experimentation have not.

The type of experiment which I have discussed above is characterized by the fact that the yield, of interesting events is small; for instance, if the instrumentation is set to examine the lowest point on the curve of Fig. 3, one observes only one actual recorded event per 10^{18} electrons incident on a liquid hydrogen target in which the scattering takes place. Why is this yield so small and how is it measured? The answer to the first question is simply that elastic scattering cross sections become exceedingly small; in fact, at the point in question the cross section is comparable to that of neutrino reactions which exhibit the nuclear "weak" interaction only. The reason for this small yield is that the proton appears to remain a large diffuse structure so that scattering from different parts of the structure is not likely to interfere constructively in any particular direction of scattering. Moreover, the basic electromagnetic force is weaker than the nuclear interaction which dominates in nuclear physics.

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As far as method is concerned, we use the basic components which one has always used for this kind of investigation: A source of incident particles (in this case the Stanford Linear Accelerator), a spectrometer which sorts out the desired from the undesired processes occurring in the target bombarded by the incident particles, and a detector followed by a means of analyzing the data generated. Figure 4 shows an aerial view of the Stanford 2-mile machine which is the source of the particles. The experiments in question are carried out in one of the target buildings towards the south where the beam is deflected. Figure 5 shows the spectrometer arrangements used. The incident beam strikes the liquid hydrogen target located at the central pivot and a magnetic spectrometer rotates around this pivot. Figure 5 shows three different instruments designed to cover different ranges of scattering angle. The spectrometers are designed and built with high precision; they use magneto-optical elements to disperse the momentum of the scattered particles in the vertical plane while different horizontal production angles are being brought into foci dispersed horizontally. As a result the different particles scattered in the target are being guided along trajectories which focus inside the detector shield. A set of counter hodoscopes inside the shield then transmits this information to the data handling system. Figure 6 shows a typical data display processed by computer: The figure shows the frequency distribution of orbits entering the shield as a function of horizontal and vertical coordinates, i.e., as a function of particle scattering angle and momentum. The kinematics of the elastically scattered particles is clearly recognized: The crest of this three-dimensional representation corresponds to that relation between angle and momentum of the scattered electron required by the dynamics of elastic scattering. Notice also that this ridge is asymmetric towards lower mo-The reason is that as electrons are scattered they may, concomitant menta.

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with the scattering process, emit one or more photons (or x-rays) which can reduce the momentum of the scattered particle.

In spite of the mammoth size of instruments of this kind, the precision required and realized in this work is comparable to that attained in low energy spectroscopic studies. Energy resolution of the three instruments shown in Fig. 5 is \pm .05% and angular resolution is about 1 minute of arc. Moreover, the flux of scattered electrons to be detected is accompanied by other particles which are not of interest to the experiments in question and which may exceed in numbers those to be measured by a factor as large as 10⁶. Hence, thorough particle identification is required.

I have shown you only one of the many experimental techniques available in this field and I emphasized their similarity rather than dissimilarity with past practice. Today there are of course many other fundamentally new techniques in use in high energy physics in general, and electron and photon physics in particular, which I cannot describe here.

The experimental result discussed above relates to "elastic scattering," that is, scattering in which the incident energy is divided between the scattered electron and the recoiling proton but where the recoil proton remains in its <u>ground state</u>. As was mentioned by the previous speaker, it is now known that the proton has a "spectroscopy," that is, it has many <u>excited states</u> above the ground state, and physicists are beginning to understand the location of the energy levels, the term assignments of the levels, the selection rules gov-erning transition between levels, and the regularities of the level patterns. The principal lack is understanding of the forces which establish these levels to start with, and which govern the rates of transition between them. You may recall that this was precisely the situation near 1920 in relation to atomic energy levels before the exploitation of quantum mechanics. You may also recall that one of

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the principal experiments shedding light on this situation was the Franck-Hertz experiment. In this experiment electrons of energy of a few electron volts were passed through an atomic vapor; the energy spectrum of the transmitted electrons was explored by measuring the transmitted current as a function of the applied accelerating voltage. As shown in Fig. 7 the transmitted current then showed "bumps" or "breaks" wherever the energy of the transmitted beam had suffered a loss corresponding to the excitation of atomic energy levels in the vapor or an integral multiple of such an excitation energy. This same idea can now be applied in an energy region one-billion times higher with equally impressive results. The Franck-Hertz technique when translated to high energy electron physics is called "inelastic electron scattering" and consists of examining energy spectra of scattered electrons using apparatus essentially identical to that described above for high energy elastic electron scattering. However, here these electrons scattered on the proton have suffered energy losses corresponding to raising the proton to one of its excited states. Figure 8 shows an inelastic spectrum of this kind. You can see here in an impressive way that this new spectroscopy of the nucleon is real; that is, you can see directly the energy levels of the excited nucleon as represented by the energy loss of the scattered electron. By studying the relative height of the peaks and the magnitude of the continuum following them at high excitations as a function of momentum transfer given to the nucleon system, we can learn a great deal about the structure of the excited states. We find that the variation of inelastic scattering with increasing momentum transfer is less steep than that shown earlier in Fig. 3 relating to elastic scattering. There are in fact theoretical speculations which are now the subject of experimental study which would predict that if one added the scattering from all the inelastic channels that the resultant total cross sections would show a fall-off with momentum transfer no more rapid than that expected if the proton were a point. Inelastic scattering

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on the proton and neutron is a field in its infancy and it promises to be an exceedingly revealing one.

I have discussed how electron scattering, both elastic and inelastic, can be used to explore the structure of the nucleon, both in its ground state and in excited states. The power of the method rests on the knowledge that the electron is known to interact only through the electromagnetic force, or, in a more modern language, through the exchange of a virtual photon as shown earlier in Fig. 2. Let us look at that figure in more detail. Diagrams of this type illustrate the development of elementary particle processes in terms of the intermediate particles (here a photon) which participate in the transition. Frequently more than one diagram can represent a given reaction and all of them have to be taken into account. Diagrams of this kind have "vertices" at which the lines corresponding to different particles join. At each vertex the quantum numbers and momenta of the participating particles have to balance. However, the energy of any intermediate line (called a virtual particle) need not agree with the momentum and rest mass of the corresponding free (real) particle. Since this intermediate particle (the photon in the case of Fig. 2) lasts for a very short time only, its energy cannot be precisely defined due to the limits set by the Uncertainty Principle. Such an intermediate or "virtual" particle can thus have an effective mass differing from the real particle.

Figure 2, i. e., elastic electron scattering, illustrates exploration of nucleon structure with <u>virtual</u> photons. Obviously we can also study nucleon structure by using <u>real</u> photons directly at high energy. Thus we can use either the free electromagnetic field or the <u>virtual</u> electromagnetic field of a scattered electron to generate the new particles of modern physics. The former process is called "photoproduction"; experimentally it consists of bombarding suitable targets, usually of liquid hydrogen, with high energy photons

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in the form of x-rays produced by high energy electron impact, and then analyzing the reaction products. A great deal of work has been dedicated to such processes in the past but some exceedingly exciting results have been forthcoming lately. I can only give you a very narrow view of this wide field.

When a photon is incident on a proton target, one can frequently describe the process by a mechanism of the kind shown in the next diagram (Fig. 9). The electromagnetic field of the incident photon creates a new particle which is emitted <u>forward</u> and another particle which is then absorbed by the nucleon. If one of these particles is positively charged, the other one must be negative. Similarly,quantum numbers other than electric charge must be conserved with those of the photon. If one studies the angular and energy distribution of the outgoing particle, one obtains a great deal of insight into the nature of the exchanged particle which may or may not be a real particle existing in nature. Experiments of this kind have recently been extended into the 20 GeV range of energy; the results indicate that the family of exchanged particles which is required to explain the observed phenomena must be considerably richer than the group of particles which has been discovered in their free state.

Another equally powerful method of examining nucleon structure with photons is to look at production of new particles in the <u>backwards</u> direction. A corresponding diagram is shown in Fig. 10. The particle exchanged between the incoming photon and the outgoing secondary particle has to be an excited state of the nucleon, and therefore one would expect that the energy spectrum of the outgoing particle would exhibit similar bumps as those shown before in the inelastic spectra in electron scattering. Figure 11 shows this is indeed the case; we thus have another new and independent tool for examining the spectroscopy of the nucleons.

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Finally, I would like to mention a new and very interesting field in high energy electron-photon physics: This is the relation of photon physics to some of the most recently discovered particles in physics, the so-called Vector mesons. Vector mesons are particles of exceedingly short lifetime of the general order of 10^{-23} seconds which have the same quantum numbers as the photon, which is the carrier of the electromagnetic force and which has zero rest mass; in contrast the Vector mesons have a large rest mass which, in the case of its most prominent member, the rho meson, is 1500 electron masses. It is therefore possible in high energy collision to "create" a Vector meson in a collision between a high energy x-ray photon and a nucleus without exchanging anything but energy, since the quantum numbers of the outgoing Vector meson and the incoming photon are the same. As a consequence, the nucleus on which this transformation takes place can be left in its ground state, and therefore all the constituents of the atomic nucleus, that is all the neutrons and protons, can act coherently in producing the reaction. A diagram illustrating this process is shown in Fig. 11. For this reason the production cross section by photons of such Vector mesons may become large if one uses targets of high atomic number. This is indeed the case; the next figure shows some of the curves documenting this process (Fig. 12). Note that for very large atomic numbers the rate of increase of the cross sections turns down again; this is due to the absorption of the ρ -mesons when traversing the larger nuclei. We can thus derive from these experiments the interaction cross section of the ρ -meson with nuclear matter – really a remarkable feat if one considers that ρ -mesons live only for 10^{-23} sec !

A great deal can be learned from studying production processes of this kind; however, any process in which a proton is a target and in which a new unstable particle is formed will necessarily suffer from some complexity. The reason is that

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baryons (i.e., protons, neutrons or hyperons) are conserved in any process; therefore a proton or another baryon will remain in the final state and therefore the study of the new, unstable particle will be complicated by its interaction with the proton. It would be very nice indeed if one could invent a means to create these new particles out of pure energy, that is, without the presence of any kind of material target at all. Fortunately, in recent years we have discovered just how to carry out such a pure process and this is the use of colliding electron and positron beams. If electrons and positrons collide they can annihilate into a variety of products; at low energies the products will be two or three photons. However at high energies electrons and positrons can also annihilate into any other energetically possible combination of final particles which conserve the applicable quantum numbers.

Let me give you an example again in terms of the rho meson which, as mentioned above, disintegrates very rapidly into two pi mesons. If an electron and positron collide, a virtual photon can be formed which in turn can become a rho meson (having the same quantum numbers as the photon!) which then can disintegrate into two pi mesons. This chain of events is shown in Fig. 13. We therefore have a process where <u>nothing</u> is left over in the final state except the new, unstable particle, and its properties can be studied without complication from other influences.

But how do we do this? How do we produce collisions between electrons and positrons since positrons do not occur in nature? A first answer might be to build a positron accelerator and let the positron beam hit electrons contained in ordinary atoms. It is indeed possible to accelerate positron beams with an electron accelerator; in fact, the SLAC two-mile accelerator does produce a very intense beam of positrons up to an energy of about 12 GeV. However, the difficulty is that if a beam of electrons of energy E hits a stationary electron of mass m, then according to the Special Theory of Relativity the energy available in the reaction is given by $\sqrt{2 \text{ Emc}^2}$. This quantity is generally small since most of the energy of the electron is used up to set the common

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center-of-mass of the particles into motion, and very little of it goes into the energy of the interaction. Numerically the 12-GeV positron beam produced by the SLAC accelerator would only produce a reaction energy of 110 MeV which is inadequate to study any of the processes of interest and which specifically would be insufficient to create a particle like the rho meson. The situation is vastly improved if one were to produce two accelerators, one accelerating electrons and one positrons, and bring these two beams into collision. In that case the center -of-mass remains at rest and the sum of the energies of the two beams is entirely available for the reaction. This is the basic idea underlying "colliding beam" accelerators. Energetically this argument is all right, but from the point of view of intensity we are dealing with a serious problem since the density of a practical electron beam is too small; it is lower than the density which one attains in a good laboratory vacuum (1.) Therefore collisions between two external linear beams would not produce a sufficient reaction rate. However, this problem can be solved by storing both beams in what is known as storage rings, that is, annular magnetic fields which can confine and store the beams. In that case, the two beams can cross one another repeatedly and the resulting increase in reaction rate, combined with the simplicity of the reaction and the high reaction energy, makes such storage-ring, colliding-beam devices very attractive indeed. Colliding-beam installations successful in doing important physics experiments were built first in this country but in recent times initiative in this field has been shifted to Western Europe and the Soviet Union.

Figure 15 shows such an installation located at Novosibirsk which stores negative electrons and positrons at an energy of 750 MeV. Figure 16 shows one of the results obtained with this device. The measurement determined the rate of the reaction which I discussed previously, namely, the formation of a rho meson and its subsequent disintegration into pi mesons resulting from electron-positron collisions. The curve shows this rate as a function of the energy of the particles

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stored in the two rings. You can see that a very pure resonance curve results from which both the energy and the width of the rho state can be deduced. Interestingly enough, these numbers differ from those inferred from experiments on the rho meson with conventional accelerators, indicating that interactions of the final rho meson with the other final products, unavoidable when proton targets are used, had distorted the earlier results. Colliding-beam accelerators are thus indeed a very valuable and unique addition to electron and photon physics and probably constitute the ultimate tool for "exploring" the unknown particles with the known forces of electrodynamics because they permit the greatest possible isolation of the unknown object.

Thus far I have strictly adhered to my topic: "High Energy Electron and Photon Physics - Exploring the Unknown With the Known", whereby by "known" I mean quantum electrodynamics. But is this basic premise really true? Do we know that quantum electrodynamics remains valid at the exceedingly high energies and small distances which constitute the sphere of interest of high energy physics? As mentioned before, quantum electrodynamics has been verified quantitatively over an unprecedented large range of energies and distances ranging to energies in the GeV region and distances down to 10^{-15} cm. Naturally there is a great deal of interest to push these boundaries still further, that is, to explore whether quantum electrodynamics is valid at distances even smaller. To put it into more elementary terms: We wish to explore whether Coulomb's law, which implies that the electrostatic potential would vary inversely with distance from a point source, would still continue to increase at these exceedingly small distances. Beyond one's natural curiosity in extending our knowledge of the range of validity of any physical law, including quantum electrodynamics, there also are more specific incentives for examining this question. The most important of these remains the fact that quantum electrodynamics when applied to truly "point" charges

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generates mathematical divergences; these can be subtracted out so as not to affect physical results; the question remains, however, whether they cannot be avoided altogether. Therefore one is led to speculate whether in some way that Coulomb's law may cease to be valid at very small distances. It may, of course, be that posing the question of the origin of an electromagnetic mass is not meaningful. The existence of such questions gives additional impetus to examine the range of validity of electrodynamics at small distances and therefore high momentum transfers. Unfortunately, experiments to examine these questions are difficult. For one thing, such experiments have to be designed so that the influence of unknown or poorly known structures (such as that of the proton or other hadrons) on the desired result are avoided. Experiments to examine the validity of quantum electrodynamics are therefore those which either involve only photons, electrons or muons, or involve protons only in such a way that the effects of proton structure can either be eliminated or neglected.

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In addition, if we believe in the basic assumptions of special relativity, then the momentum which defines the sensitivity of the experiment must be the so-called fourdimensional momentum q involved in the process; the square of its magnitude is given by $q^2 = E^2 - c^2p^2$ where E^2 is the energy involved and p^2 is the ordinary, threedimensional momentum. It can be shown that this quantity is always the square of the rest mass of the particle involved; this is 0 for the free photon and is small for particles like the free electron and muon, which do not carry nuclear interactions but interact through the electromagnetic and weak interaction only. However, if we invoke processes in which these particles are virtual rather than real, then this critical quantity may become large. Thus, the kinematical conditions must be such that electrons, muons or photons are involved in a virtual state having a large "four-momentum" q.

Time does not permit me to give an exhaustive summary of the experiments which fulfill these various requirements. The most important ones have been the study of electron-positron pairs produced at large angles by high energy incident photons, study of

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the gyromagnetic ratio of the muon, and study of electron-electron collisions in collidingbeam experiments. The first experiment, wide angle electron-positron pair production, has been investigated at laboratories in the United States and Western Europe. For some period of time one of these experiments seemed to give clear indication of a violation of the laws of quantum electrodynamics but more recent and careful determinations indicate one of these experiments seemed to give clear indication of a violation of the laws of quantum electrodynamics but more recent and careful determinations indicate complete agreement. These studies of wide angle pair production process form one of our principal anchor points at this time giving the smallest distance over which the laws of electrodynamics seem to remain valid. Our most stringent limit derived from a purely electrodynamic process on this question comes again from storage ring studies. Figure 17 shows an experimental configuration originating from a collaboration between Princeton and Stanford Universities by which electrons are stored in magnetic rings which have a common section. Electrons are stored in each ring at an energy of 550 MeV and make collisions in the common section. The collision cross section is studied as a function of the angle between the emerging electrons and the incident collision path. Figure 18 shows the agreement between the observed data and the predictions from quantum electrodynamics calculations. As can be seen by inspection, and as can be verified by more quantitative statistical analysis, agreement between experiment and theory is excellent. We thus conclude from these and other experiments that at this time quantum electrodynamics remains a quantitative theory whose validity extends all the way from the largest macroscopic distances to sub-atomic distances of a small multiple of 10^{-15} cm. At this time an experiment bearing on the validity of quantum electrodynamics at small distances through measurement of the gyromagnetic ratio of the muon exhibits a small discrepancy, but this experiment is sufficiently complex to require independent verification. We can thus conclude for the time being that high energy electron and photon beams remain a tool with which we can explore the unknown structure of the new sub-atomic particles with known forces.

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Figure Captions

- 1. Nonrelativistic electron-proton scattering wave description.
- 2. Feynman diagram of electron-proton scattering.
- 3. Plot of SLAC electron-proton scattering data expressed as a "form factor."
- 4. SLAC aerial view.
- 5. Interior view of target area with spectrometers.
- 6. Counts recorded in spectrometer hodoscope produced in elastic scattering. These data are plotted by computer and show the momentum of the scattered particle and its production angle. Note the "radiative" tail.
- 7. Results of a Franck-Hertz experiment in mercury vapor. The transmission of an electron beam as a function of electron beam voltage is shown.
- 8. Inelastic electron spectra observed at SLAC with a primary energy of 10 BeV at a scattering angle of 6° .
- 9. Forward photoproduction of a positive particle. The incident photon produces a "pair" of particles; the positive particle is emitted forward while the negative particle reacts with the proton.
- 10. Backward photoproduction. The incident photon interacts with the current of the baryon which has emitted a new particle in the backward direction.
- 11. Backward photoproduction of single neutral pions. (DESY data)
- 12. Photoproduction of a Vector meson (the ρ -meson disintegrates into a pion pair).
- 13. Coherent photoproduction of ρ -mesons by photons on various elements, shown for various momenta.
- 14. Production of a ρ -meson in electron-positron collisions. Note the absence of nucleons in process.

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- Storage-ring, colliding-beam installation (VEPP-2) at Novosibirsk, USSR.
 Electrons and positrons each of 750 MeV are stored.
- 16. Novosibirsk ρ resonance observed in VEPP-2.
- 17. The Stanford-Princeton colliding beam installation. Electrons each at an energy of 550 MeV are stored in the two rings and collide in the common section.
- 18. Data taken in the electron-electron storage rings of Fig. 17. The experimental points are the observations on elastic electron-electron scattering as a function of angle. The solid horizontal bars are the predictions from quantum electrodynamics. The dashed lines correspond to breakdown models of QED at distances of the order of 10^{-14} cm.





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FIG. 2



Fig. 3



Fig. 4



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FIG. 6



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FIG. 7



Fig. 8



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FIG. 9



FIG. IO





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FIG. 12



FIG. 13





FIG. 14



FIG. 15



Fig.16



Fig. 17



FIG. 18

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