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PUB-7

The title of this talk, "Photon and Electron High-Energy Physics: Present and Future" contains a contradiction: High-energy physics, usually defined as physics above the threshhold of production of unstable particles, cannot be properly separated into branches dealing with electrons and photons on the one hand, and other particles on the other. What I wish to speak about is that area of high-energy physics to which electron and photon beams from accelerators have made important contributions and are expected to do so in the future.

Before discussing specific physical problems, let me first discuss the question as to what is meant by "high-energy" electron or photon collisions in the relativistic sense. In general, when a photon (rest mass $m_o = 0$) or an electron (rest mass $m_o = 0.51$ Mev) participates in a collision it will transfer an energy ΔE and a momentum $\Delta \vec{p}$ in any given reference frame. In order to describe the process in a manner independent of the motion of the frame of reference, any physically meaningful results must depend on the covariant combination*

$$q^2 = \Delta E^2 - \Delta p^2 \qquad (1)$$

which is called the square of the "four-momentum". If $q^2 > 0$, the four-momentum is called "time-like", if $q^2 < 0$ the four-momentum is called "space-like"; these names are chosen in analogy with the relativistic space-time interval

$$\tau^2 = \Delta t^2 - \Delta x^2 \qquad (2)$$

where Δt and Δx are the time and space separation between two events.

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*We choose units in which c, the velocity of light, is unity.

If $\tau^2 > 0$ then there is a frame in which the two events are at the same place, but separated in time; if $\tau^2 < 0$, a frame can be found in which the two events are simultaneous but separated in space.

In broad terms the importance of high-energy electron physics is based on the fact that, as far as is known, electrons interact only through the electromagnetic interaction (and the approximate 10^{10} times weaker Fermi interaction); at this time experiment and theory agree exactly in all areas where this question has been put to the test. In contrast to proton, neutrons, pions, etc., electrons are not affected directly by the "strong" nuclear interaction. For this reason, again speaking generally, experiments in high-energy electron physics divide generally into three classes: 1) those processes which explore an unknown or poorly known structure, such as a nucleon or an artificially produced particle with the known action of electromagnetism (by "known" we mean the relativistic quantum description of the electromagnetic field, hereafter called QED for quantum electrodynamics), 2) the study of processes in which artificial unstable particles are created where the presence of a bombarding particle which possesses strong interaction (such as a nucleon or pion) would complicate analysis of the process, and 3) experiments which attempt to extend our range of q^2, the square of the four-momentum transfer, over which QED is known to be valid or to observe possible deviations.

Let us examine the first of these applications. The best known of these are the now classical electron-scattering experiments in which the structure of nucleons and nuclei is examined by the angular and energy dependence of the elastic and inelastic electron-scattering cross-sections. In this case, the particle studied is "real" i.e., it has existed for a long time prior to the encounter. As we shall see later a similar method can also be used on a "virtual" particle, i.e., a particle created and then destroyed during the brief interval permitted by quantum mechanics in which energy need not be conserved.

Electron scattering is commonly visualized in the analogy to the classical theory of diffraction of waves of wave length λ on an object of linear dimensions of order D. Scattering will then take place primarily into a forward cone of apex angle of order λ/D. Analyzed in more detail, classical diffraction theory shows that the angular distribution expressed in terms of the scattering angle θ is the Fourier transform of the density $\rho(\vec{x})$ of scatterers in the object; more precisely, the amplitude $A(\theta, \lambda)$ of scattering is proportional to an integral over the distribution and over the volume of dimension D given by:

$$A(\theta, \lambda) = \int \rho(\vec{x}) \exp(i\vec{k} \cdot \vec{x})\, d\vec{x} \tag{3}$$

where the scattering wave vector $\vec{k}$ is the vector difference between the initial and final wave vectors of length $\lambda/2\pi$ taken along the directions of the waves before and after scattering respectively; the magnitude of $\vec{k}$ is thus $(2\pi/\lambda)\,[2 \sin(\theta/2)]$; therefore, the scattering angular distribution effectively Fourier analyses the spatial distribution in terms of the wave number $\vec{k}$. Although there are, of course, many complicating factors, the relativistic generalization of this classical analysis relates the electron scattering amplitude to the Fourier analysis of the distribution in terms of the four-momentum transfer q^2 i.e., the larger the quantity q^2, the finer is the spatial detail of the structure which can be examined.

Let us examine this situation in the language of quantum mechanics. The actual scattering process (sketched in Fig. 1).

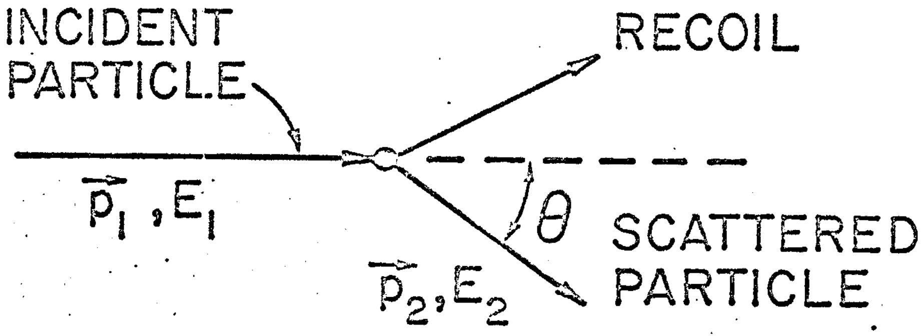


FIGURE 1

in which, say, an electron scatters from the "unknown" particle initially at rest, can also be analyzed by stating that one or more particles are exchanged which transfer the four-momentum q, as shown in Fig. 2.

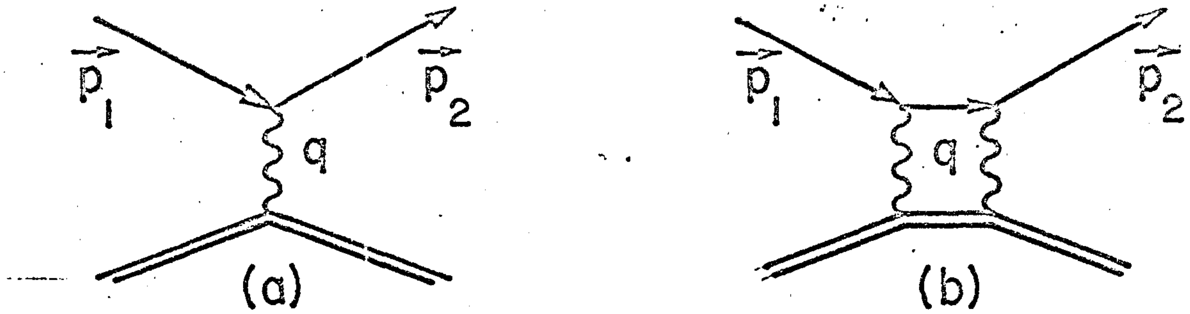


FIGURE 2

These diagrams (which I will here not use in the completely formal Feynman graph sense) are interpreted as follows: In Fig. 2, a proton (double line) approaches an electron (single line) and they affect one another through the electromagnetic field. This diagram can be described by stating that the electron "virtually" emits a photon (wavy line) which is then absorbed by the proton. The four-momentum q is then "carried" by the virtual photon.

The quantity which corresponds for high energy scattering to the diffraction amplitude $A(\theta, \lambda)$ given by eq. (3) is called a <u>form factor</u> $F(q^2)$. In the physical interaction involving scattering of an electron from an unknown structure there is in general more than one form factor if the unknown structure has spin and thus can change its spin state, or in case the unknown particle can be excited or disintegrated, i.e., if it can change its energy state.

If scattering is elastic (i.e., if the energy state of the unknown particle is not changed) and if the process can be described by only a "one-photon exchange" corresponding to the diagram of Fig. 2a, then in general two form factors, called $G_E(q^2)$ and $G_M(q^2)$ are required, the former corresponding to the case in which the spin of the particle to be explored is unchanged, and the latter to the case in which it changes by one unit of angular momentum along the axis of the momentum transfer. Figure 3 shows the values of $G_E(q^2)$ and $G_M(q^2)$ for two of the most important unknown particles: the proton and neutron. The data are those of the pioneering work of Hofstadter and collaborators combined with more modern data from Cornell, Orsay and Stanford. For reasons not discussed here the figure shows the <u>sum</u> (isotopic scalar) and the difference (isotopic vector) between the proton and neutron values of the form factors.

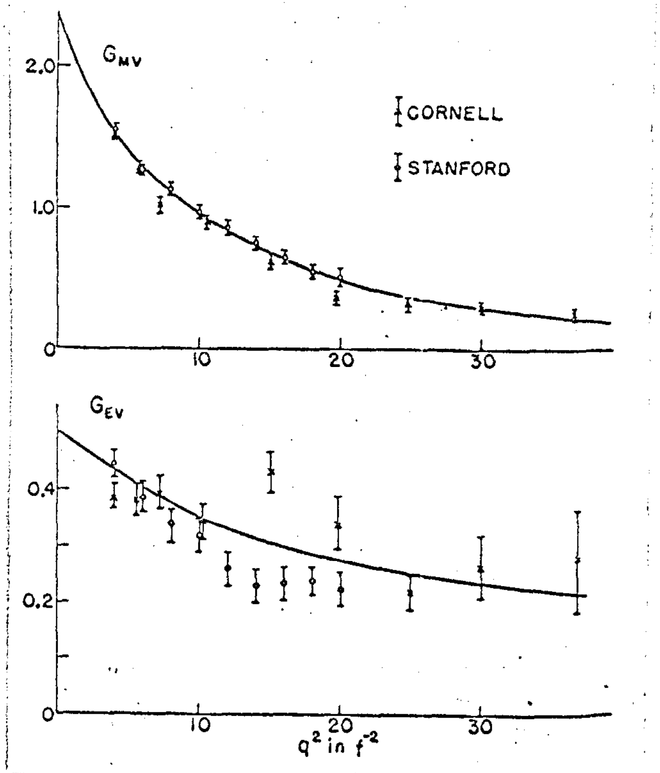


FIG. 3a. Isotopic vector form factors.

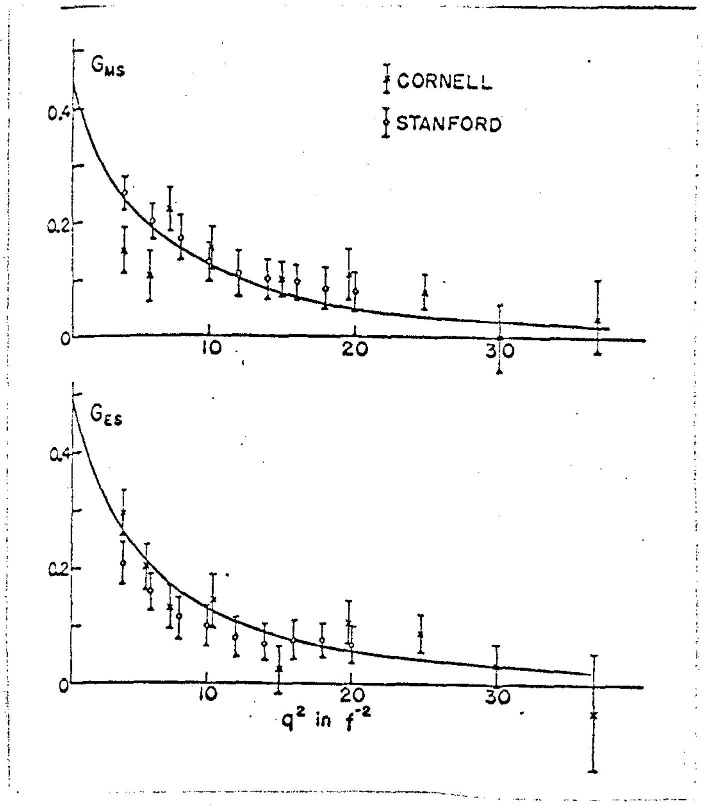


FIG. 3b. Isotopic scalar form factors

How can we understand such data and what future growth of understanding can we expect? Initially the data were interpreted in analogy to the low energy diffraction picture discussed above and thus one can construct models of charge and magnetic distributions which give some intuitive picture. More fruitful is the approach to relate the results to dynamic models of the nucleon arising from the recent discovery of "resonant" or "excited" states of nucleons. To understand the subsequent discussion, the reader should remember the general shape of the curves of Fig. 3.

Recent high energy experiments have shown that the nucleon can absorb various amounts of energy resulting in something closely akin to a set of energy levels, in analogy to excited atomic states. Excess energy would be provided by absorption of a "time like" photon, i.e., a photon gaining a larger energy than momentum transfer.

Among the excited states of the nucleons only some can contribute to the electromagnetic properties of the nucleon, due to certain selection rules involved. The most important state is the one in which the ρ-meson (spin 1; $m_o = 750$ Mev) is "oscillating" about the nucleon; this generates a resonance curve as a function of q^2 centering about a space like (i.e., excess energy) point at q^2 equal to the square of the rest mass. On the other hand we note that for elastic scattering of electrons on stationary targets $|\Delta \vec{p}| > \Delta E$, i.e., q^2 is space-like. What might happen on the time-like side, i.e., the side on which excess energy can be transferred? A conjecture which corresponds to one of the currently explored resonances of the nucleon is shown in Fig. 4.

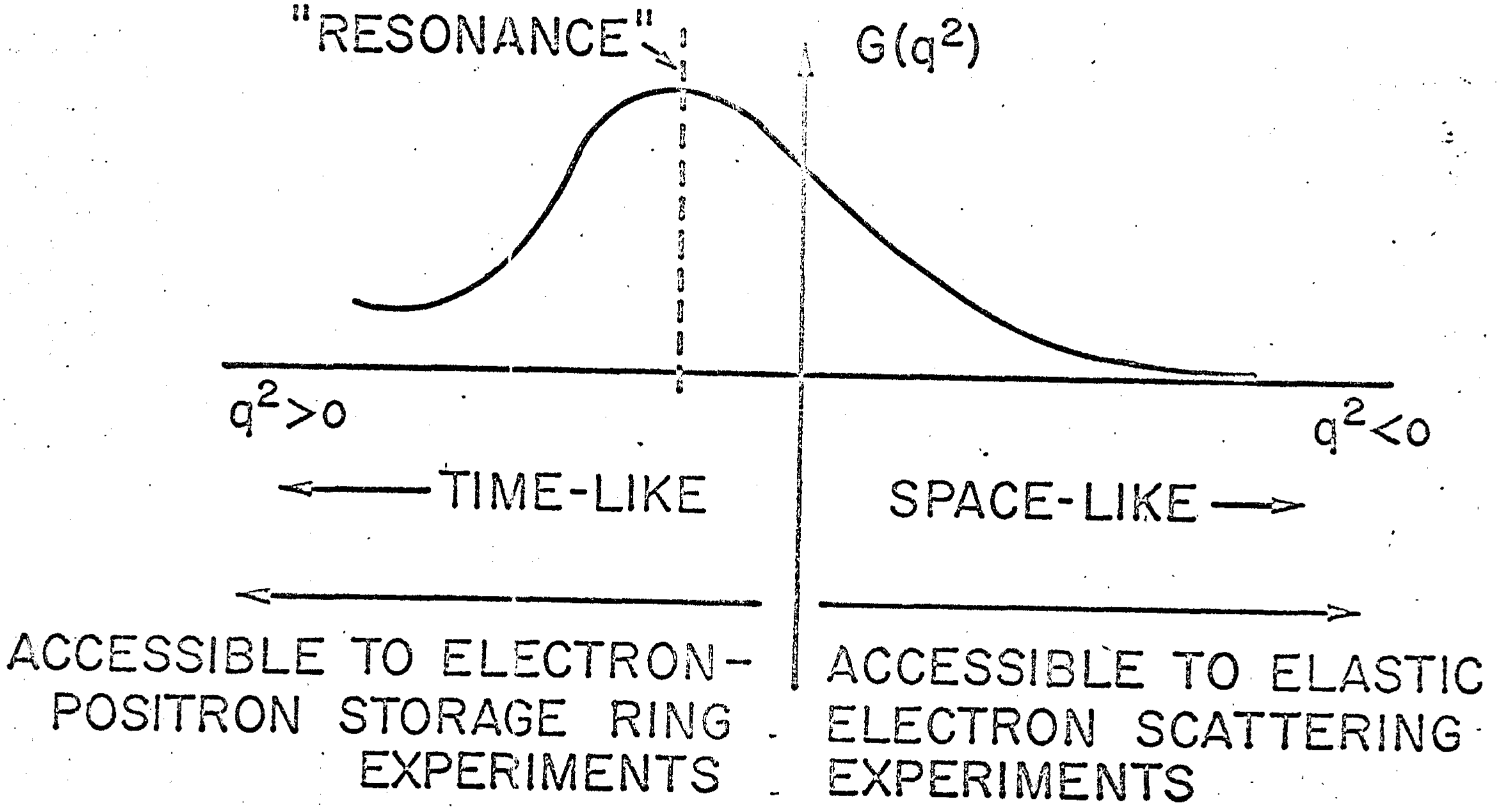


FIGURE 4

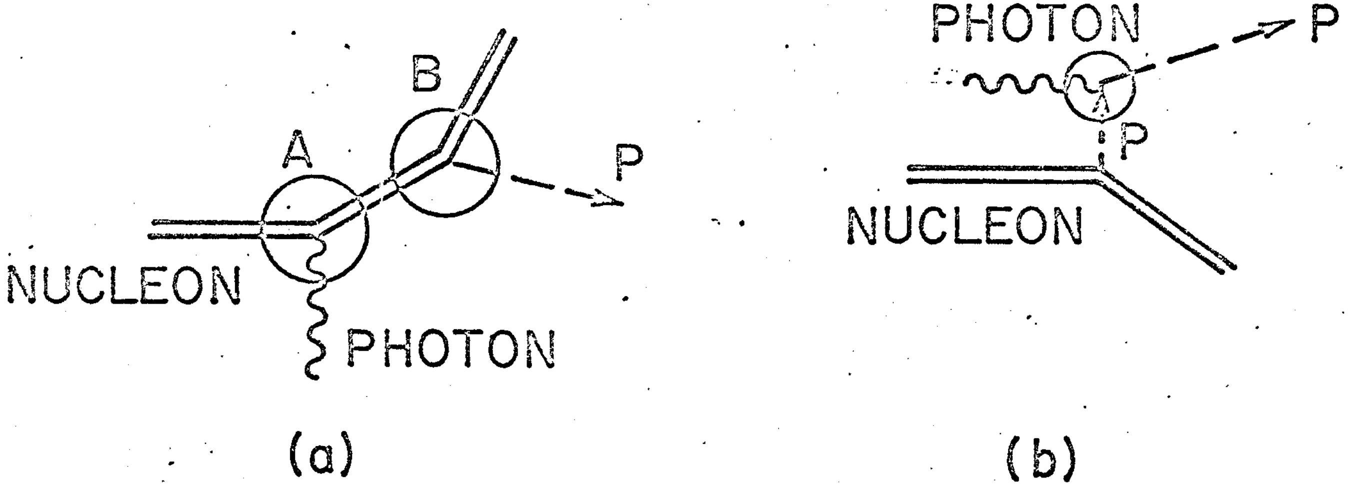
The elastic scattering thus measures the tail of the resonance curve. At present a single resonant nucleon state is not sufficient to fit the data; this may be due to higher mass resonant contribution, to inadequacy in calculation, or due to inadequacies of the model of Fig. 2a in which only one photon is exchanged.

This latter question can be analyzed by substituting positrons for electrons in scattering experiments; if diagrams like Fig. 2b contribute, negative and positive electron scattering cross sections will differ; such experiments (instituted by J. Pine and collaborators) are in progress and there are indications of such differences for large values of q^2.

I have outlined how in the past electric electron and positron scattering have illuminated the nucleon structure problem and formed a direct link to the resonances discovered in strongly interacting particle systems. What then is the future? Clearly much more work of the kind indicated needs to be done; in particular the situation in relation to neutron structure is still quite unsatisfactory since, in the absence of free neutron targets, complications introduced by the deuteron structure seriously limits reliable analysis. Moreover, there are already indications that analysis will become progressingly more difficult as q^2 increases in the space-like direction: first there is the contribution of more complex mechanisms, such as the one shown in Fig. 2b. Secondly, unless there will be new high mass resonances discovered which contribute to the scattering, the cross section will continue to decrease at high energies and thus the data rate of experiments will go down. Thirdly, as we go to higher values of q^2 the validity of QED is no longer established and such questions become intertwined into the study of particle structure. Finally, time-like values of q^2 are inaccessible to electron scattering and hence, as seen in Fig. 4, the role of resonances has to be inferred by far away measurements on the q^2 axis. We will return later to experimental techniques involving collisions between electrons and positrons traveling in opposite directions; these have bearing on extending structure information along the time-like portion of the q^2 axis and also to examine the validity of QED.

How do we examine the structure of particles which are themselves unstable? A possible answer lies in certain types of photo- and electro-production experiments involving such particles.

Photo production of pions has been one of the earliest successful applications of electron accelerators; in fact the first information of the interaction between pions and nucleons have been inferred from the behavior of photo-production cross sections. Phto-production of unstable particles can proceed, in broad terms, via the two alternate methods sketched in Fig. 5.



(a)

(b)

FIGURE 5

In diagram 5a the photon interacts at A through its electromagnetic field with an electric or magnetic property (charge or magnetic movement) of the nucleon. The resultant excited nucleon then disintegrates at B into a nucleon and the particle P. The resultant production rate then depends on the forces acting at B between the particle P and the nucleon, i.e., on information similar to that gained from scattering experiments of particles P generated as an external beam from an accelerator, scattered in a hydrogen target.

The absorption of a photon of zero rest mass corresponds to a four-momentum transfer $q^2 = 0$, hence the absorption at A will give no new information. However, corresponding to each photon - absorption process there is also an inelastic electron scattering process, i.e., instead of absorbing energy from the field of a free photon, the process can be induced by absorbing the field from a rapidly moving electron. In this case Fig. 5a changes schematically to the form shown in Fig. 6.

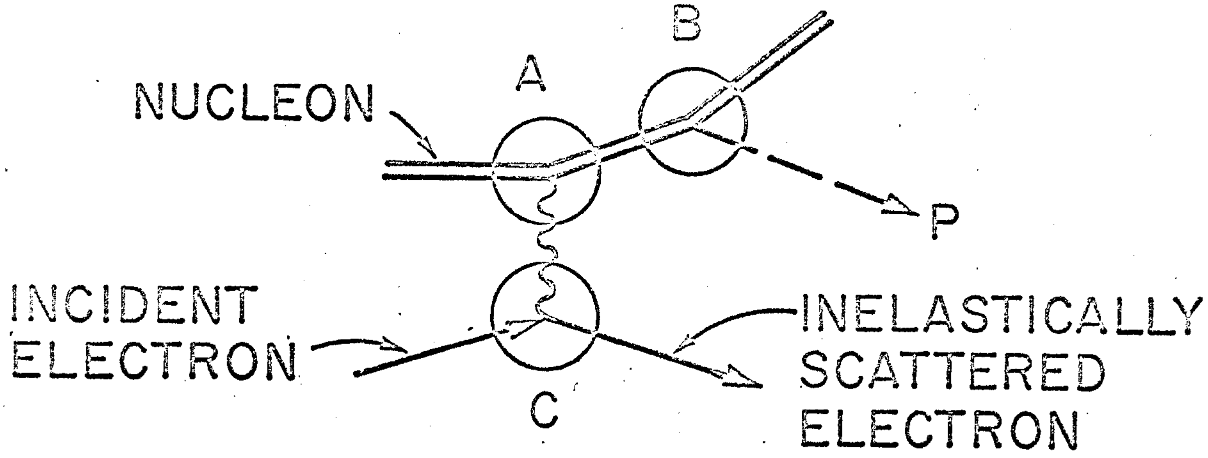


FIGURE 6

In this case $q^2 \neq 0$; in fact the part of the process involving the interaction at A and C are very similar to the ordinary electron scattering process of Fig. 2. Hence inelastic electron scattering can also give information on nucleon structure.

The second mechanism for photo-production of single particles is shown in Fig. 5b. Here the photon is absorbed by the created unstable particle and thus the interaction is between the electromagnetic properties of this new particle and the field of the photon. If, as above, we substitute the field of an inelastically scattered electron for that of the photon, we find that the resultant scattering amplitude depends on the structure of the unstable particle. Hence, such an electro-production process constitutes a "virtual target" of unstable particles for electron scattering. Successful exploitations of this scheme depends on isolating this process from other reaction channels; this should be possible in the future.

We thus find that photo-production of unstable particles has taught us a great deal about the interaction of these particles with nuclei and about the structure of these particles themselves, and will continue to do so.

Production of more than one particle opens up a new series of interesting phenomena. I shall only discuss two: electromagnetic pair production and "peripheral production". Electromagnetic production of electron-positron pairs is the well-known process by which gamma rays of energy above 1 Mev can "materialize"; it becomes the dominant absorption process for high energy electromagnetic radiation. A gamma ray by itself cannot convert into a pair of positive and negative particles and still conserve energy and momentum; a third, preferably heavy particle has to participate to absorb the recoil. Since this third particle (in general the nucleus of the nuclear species under gamma ray bombardment) can absorb the recoil just through its electrostatic field, the entire process is "all electromagnetic", i.e., it can be totally analyzed in terms of well understood electromagnetic forces. Clearly the same type of theory adjusted only for the mass and spin of the charged particle pair to be produced can thus predict a production rate of any particle through this mechanism. The process has been verified for muons (in addition to electrons) and thus lends itself well to a systematic particle search. Such a search has recently been carried out at Stanford for particles intermediate to the electron and muon mass with (not unexpected) negative results; depending on observational techniques such a search can be continued in the future to higher masses. Of practical consequence is the production of pure high intensity muon beams; beams thus generated have a much smaller pion contamination than beams produced by the decay of primary pions.

Let us now consider a "peripheral" collision. We noted that as the energy of a photon becomes very large, a pion pair can be produced "almost" in vacuo with only a small unbalance of momentum absorbed by a target nucleus (Fig. 7).

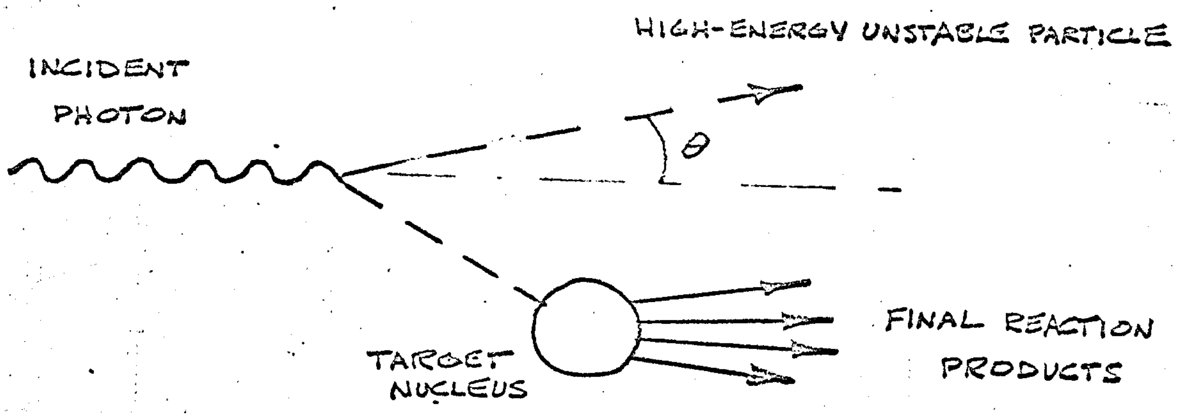


FIGURE 7

We can thus consider a process in which only one of the pair fragments escapes while the other fragment interacts with the total cross section on the target nucleus for the particle in question. The resultant cross section is quite large in the forward direction and in fact is likely to exceed the production cross section of corresponding particles by protons for secondary particles of energy near that of the bombarding particle; comparative cross sections are shown in Fig. 8. As a result high energy electron accelerators will become highly competitive "factories" for secondary particles, including pions, k-particles, neutrinos, etc., in contrast to the situation at lower energies where proton machines are superior in this respect.

Finally, I would like to discuss experiments which aim to extend the range over which the correctness of QED has been established. Presently QED is known to be correct through experiments covering the range from very large interaction distances down to intervals as low as a small multiple of 10^{-14} cm. By the uncertainty principle examination of physical properties at small distances requires large transfers of momentum or, relativistically, four-momentum. In addition experiments designed to examine this question should, if possible only involve electrons, photons or muons because these are the only particles not interacting through nuclear forces; since in general nuclear forces are larger than electromagnetic interactions, such forces would obscure observation of possible deviation from the laws of electromagnetic interaction. Actually, some of the experiments involving protons can be interpreted as setting limits to QED; this can be done by comparing the results of different experiments in which the proton enters in the same manner, but in which different electromagnetic processes are involved.

If proton targets are not involved then limits of electrodynamics can be explored either by a) comparing the electromagnetic properties of the "free" electron or muon with QED, b) studying collision between electron or muon beams

PION YIELD PER 25 BEV PARTICLE

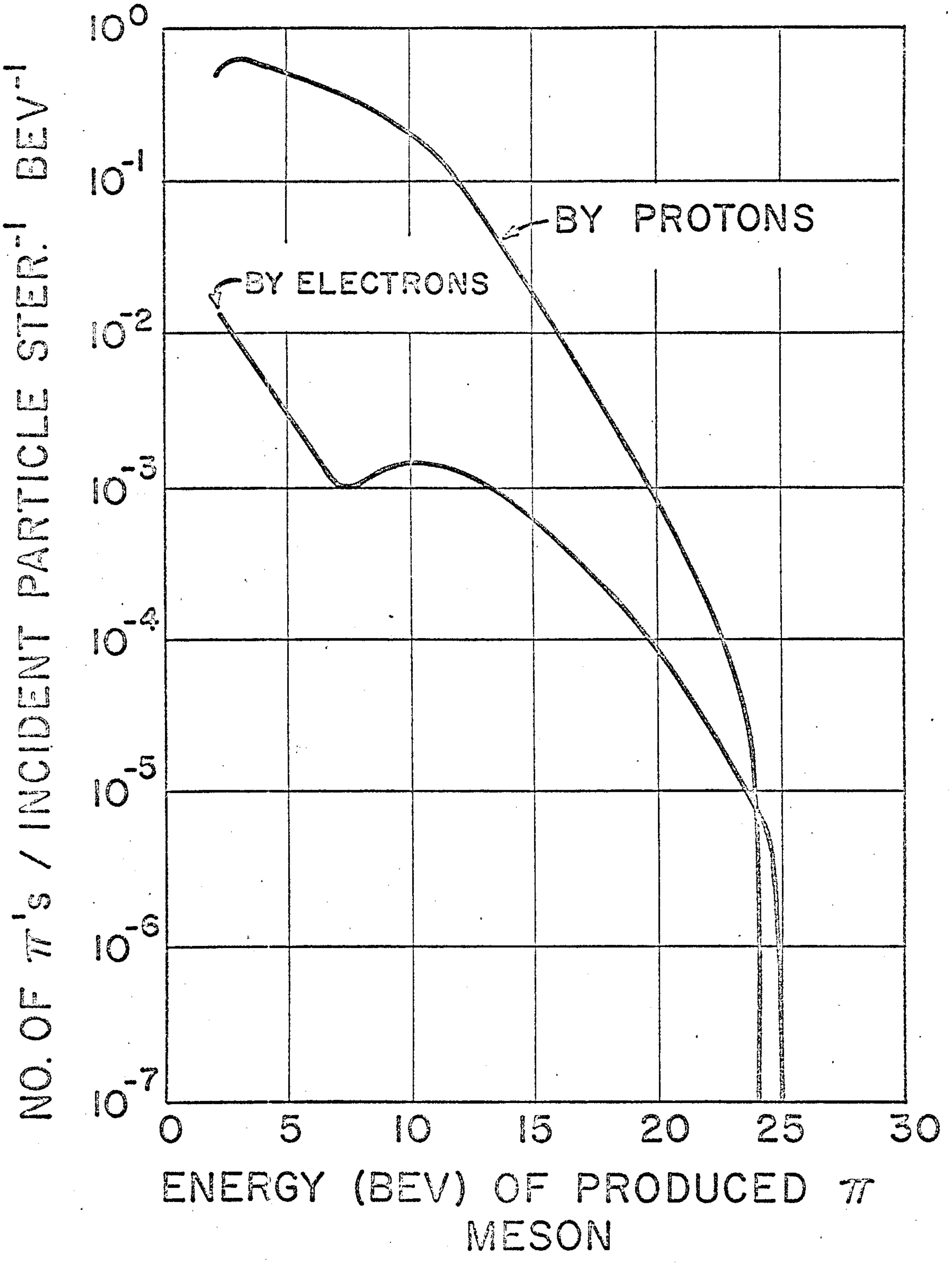


FIGURE 8

with electrons at rest, c) experiments between colliding electron beams. Of greatest importance in the first category is the CERN experiment on the g-factor of the muon; I will not have the opportunity to discuss this beautiful result here beyond stating that no deviations from QED were observed.

Experiments of the second class suffer from the fact that the values of q^2 which can be reached if a light particle, such as the electron, is struck at rest, will be very small even at a very high incident energy. Specifically, the value of the four-momentum transfer q^2 if a particle of rest mass m_o is struck by a very energetic incident particle of energy E_o is given by

$$q^2 = - 2m_o E_o \quad . \tag{4}$$

which, in MeV becomes just $q^2 = - E_o$ for an electron. Hence, a 10 GeV electron striking an electron at rest will produce a q value of only $- (100 \text{ MeV})^2$. Hence, such electron "knock-on" experiments will extend our range of knowledge about QED only for very high incident energies indeed.

Our greatest hope of examining the validity of QED further lies in colliding beam experiments. Such experiments are in progress at Stanford and by the Frascati, (Italy) physicists using their storage ring at the French electron linear accelerator at Orsay. Figure 9 shows a diagram of the Stanford intersecting storage ring arrangement. Electrons are injected into each ring separately from a linear accelerator and stored in each ring. Collisions occur in the common straight section between the rings.

Of possibly greatest interest are the future experiments in which electrons and positrons are stored in a single ring and are allowed to collide in specified interaction regions. When an electron and positron collides, one can obtain both time-like and space-like momentum transfers, and thus test the validity of QED in both of these regions. The reason time-like values of q^2 are accessible if

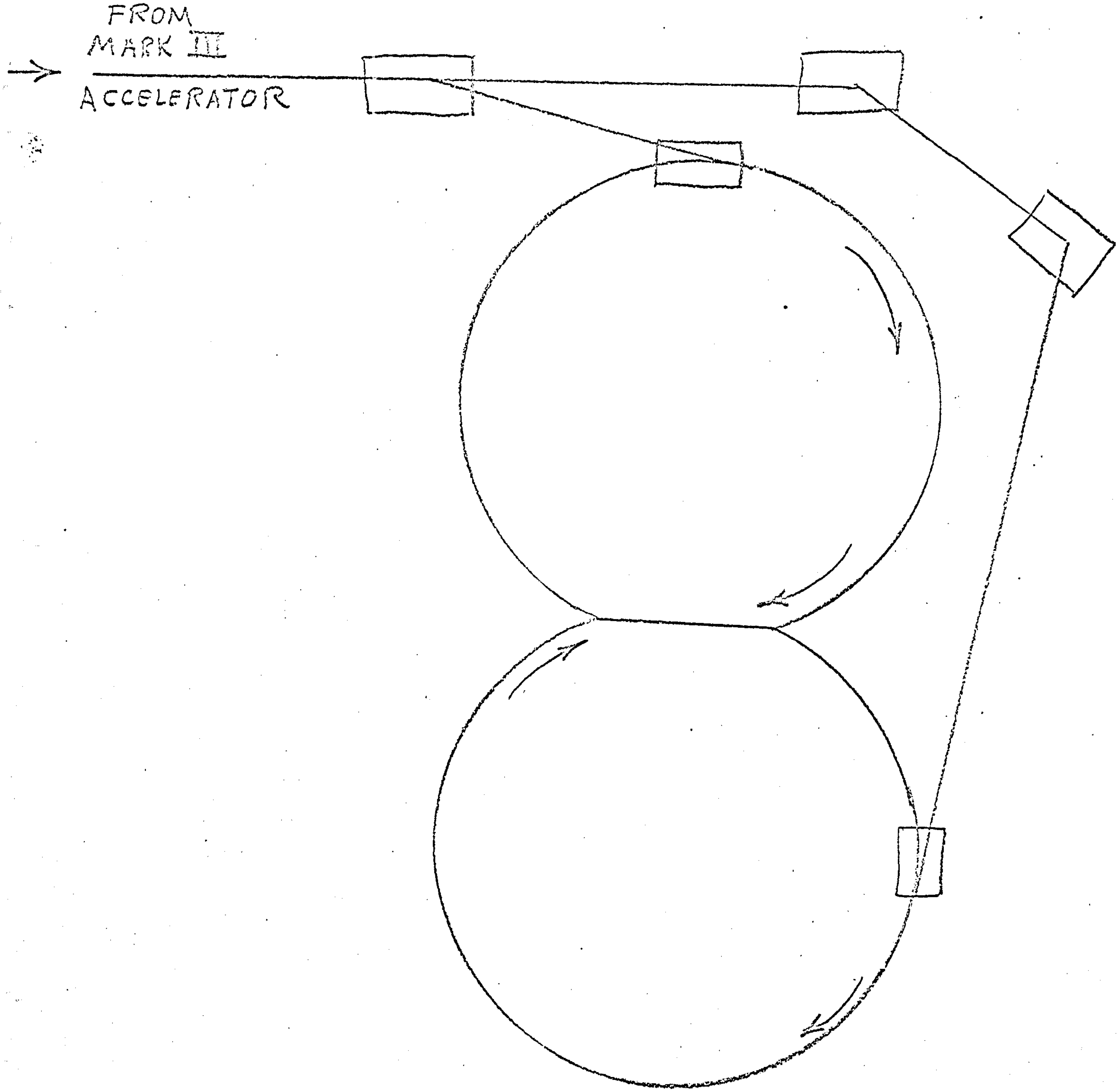


FIGURE 9

electrons and positrons collide while they are not accessible if particles of like charge are involved, is that electrons and positrons can annihilate, and thus energy can be given up which can be larger than the transfer of momentum; therefore for $e^- - e^+$ collisions we can have:

$$\Delta E \gtrless |\Delta \vec{p}|$$

At sufficiently high energy, the time-like transfers lead to reactions like these:

$$\begin{aligned} e^- + e^+ &\to \gamma + \gamma \\ &\to \mu^+ + \mu^- \\ &\to \pi^+ + \pi^- \\ &\to p^+ + p^- \\ &\to \kappa^+ + \kappa^- \\ &\to \text{states involving more than two particles.} \end{aligned}$$

Electron-positron storage rings thus produce a "laboratory" in which pairs (a larger number) of otherwise unavailable particles can be maintained and their interaction studied.

I hope that this only too sketchy outline of the field of high energy electron and photon physics has at least indicated that this is a vast and as yet very incompletely explored field.

Since the degree to which the field can be explored is so much related to the available high energy sources, I should like to conclude with a slide which indicates the coverage over the often-mentioned variable q^2 now available and to be available as machines now under study or construction, are completed (Fig. 10). Study of the figure will impress you both with the power of the new very high energy electron accelerator but also the potential value of storage rings. As is usually the case in physics these two classes of instruments are not in competition for solving the same problem, but will complement one another in defining fruitful areas of research.

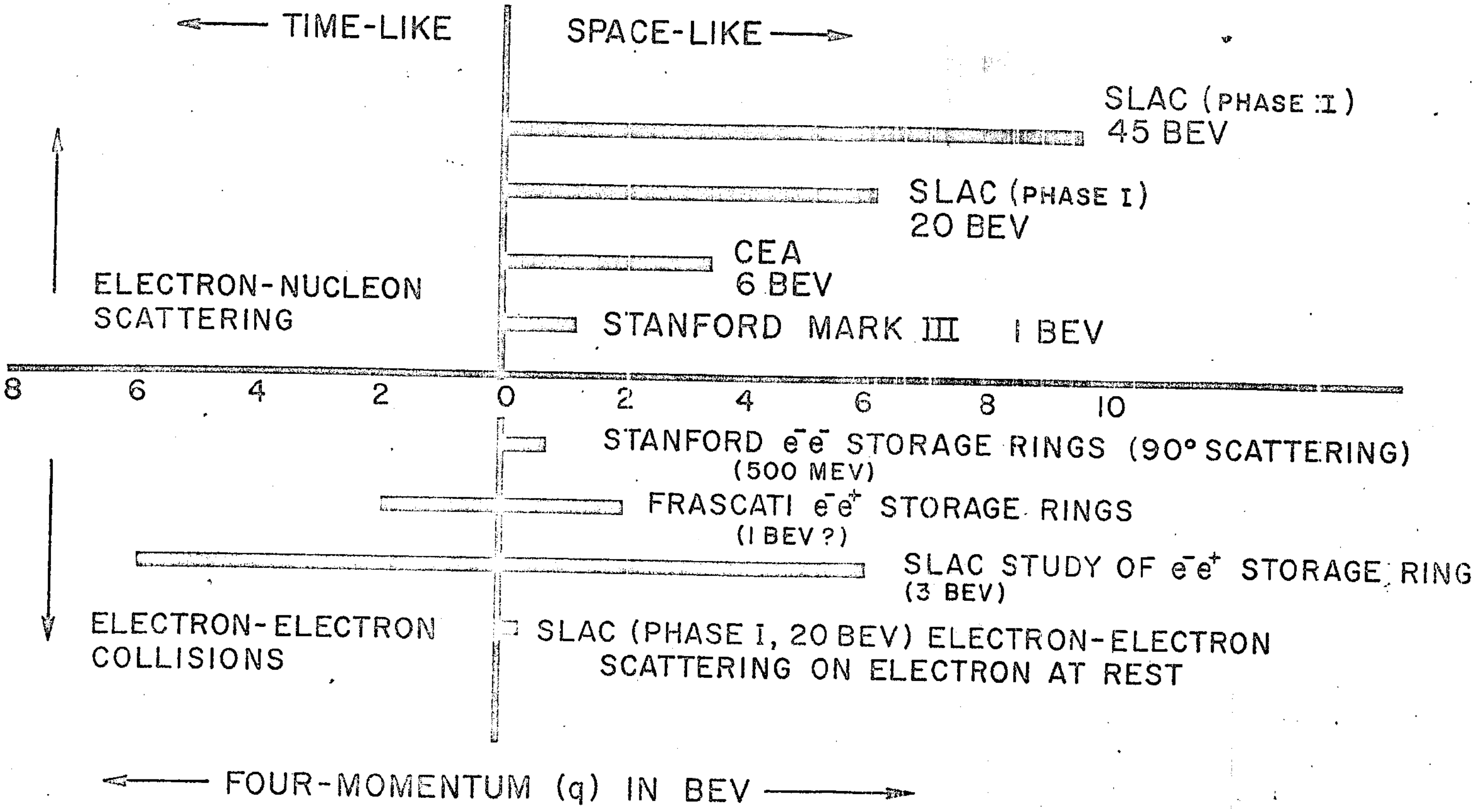

TIME-LIKE
SPACE-LIKE
SLAC (PHASE II) 45 BEV
SLAC (PHASE I) 20 BEV
CEA 6 BEV
STANFORD MARK III 1 BEV
ELECTRON-NUCLEON SCATTERING
8
6
4
2
0
2
4
6
8
10
STANFORD e⁻e⁻ STORAGE RINGS (90° SCATTERING) (500 MEV)
FRASCATI e⁻e⁺ STORAGE RINGS (1 BEV ?)
SLAC STUDY OF e⁻e⁺ STORAGE RING (3 BEV)
SLAC (PHASE I, 20 BEV) ELECTRON-ELECTRON SCATTERING ON ELECTRON AT REST
ELECTRON-ELECTRON COLLISIONS
FOUR-MOMENTUM (q) IN BEV

FIGURE 10