PHYSICS WITH PHOTON AND ELECTRON BEAMS: REQUIREMENTS OF EXPERIMENTERS IN TERMS OF ENERGY, INTENSITY AND QUALITY

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1. INTRODUCTION

To the eyes of an experimentalist the merit of a given beam of particles is mostly measured in terms of intensity; energy; duty cycle and time structure; momentum definition (it is important to have monochromatic beams); state of polarization; purity from other particles (a muon beam must be very pure); good emittance (which can be measured in cm × mrad); possibility of measuring the intensity with precision (monitoring, quantametry).

Let's list these qualities on the head of our Table I.

I shall go now through some recent results in the physics with electronsynchrotrons and linear accelerators, to see if one can induce which are the more urgent requirements in terms of the qualities I have listed. I will particularly refer to some recent result which were obtained by the use of the photon, the electron and the muon beams. In particular I shall profit of the Hamburg Conference which was hold last June, and of some results which appeared during Summer.

I don't have any possibility to be complete, and I only look to some facts, which seem to me convenient examples in the spirit of this Conference.

The recent Hamburg Conference indicated that phisics with electrons and photons is finding out a more and more specific role respect to the physics with proton machines, and that the relative importance of this role is increasing. I don't know how much this opinion is accepted, and I try to give arguments in favour of it.

Let's go in some standard way through the strong interactions; the physics of the form factors; the electrodynamics. These three fields, certainly the first two, never were independent. One interesting aspect of today is the increase of their reciprocal links.

2. PHOTOPRODUCTION OF STRONG PARTICLES

a) Some general remarks

The photoproduction starts from a rather general and simple consideration. From an electromagnetic point of view the proton with its virtual cloud of mesons is a charge distribution and a current distribution (its magnetic moment); the neutron is at least a distribution of currents. To study the energy levels of these particles, one can send electromagnetic waves and excite the particle, to see what comes out. The proton for instance will absorb the photon in some given multipole state, and get excited. In the same way you could classically study the properties of an electromagnetic antenna, by sending electromagnetic radiation at different angles and frequencies: you will discover for instance that your antenna is a magnetic dipole of a given resonant width, tuned around a given frequency. If you cannot put your hands on the antenna, you can hope to understand its structure and its excitation levels gy measuring the radiation reemitted from the antenna.

The situation is clear in Fig. 1; in fact our study can be expressed in a diagram like (a). Lines 1-2-3 represent the evolution of the antenna in function of time.

When we have to do with protons, the diagram is the same (Fig. 1-b). We indicate now the nucleon with N, the excited nucleon with N*. Diagram (b) is under certain circumstances the Compton effect. Of course there is an important difference: the proton is a nuclear, a strong system, ad once excited it may prefer to deexcite through nuclear channels; for instance it prefers to emit energy in a massive form, and

to create a pion: this is indicated in diagram (c), and we call it the photoproduction of a pion. As we know, quantum mechanics is rather respectful of our macroscopic intuition in the initial and final states. Not so in the intermediate states. For instance also the diagram (d) contributes to the photoproduction of a pion: in this case the pion is emitted "before" the arrival of the photon. In case you find this too strange, you can consider that pions are continuously emitted and absorbed by the nucleon, but to enter the realm of existence, the pion must receive energy; at least $m_\pi c^2$ in the center of mass: the photon just comes to supply it.

Let's go back to diagram (c). How much memory there is between the first part, A, of the process (absorption of the photon), and the second part, B, emission of the pion? Very little, *in first approximation*, apart the abvious classical and quantistic conservation theorems (angular momentum, parity, etc.).

So little that in first approximation you can excite the nucleon in other ways. The more elegant and convenient is to send a pion and to study its scattering (Fig. 1e).

Both this diagram and diagram 1(c) bring to N*, that is to an excited nucleon, that decays in one pion, or in other ways.

Both diagrams are equivalent, in first approximation, when the aim is to know the levels of N*. So that to choose photoproduction or pion scattering depends in first approximation on the facility you have home, and the quality of the beams.

Well, we know that today the study of N* is going in the hands of the pion physics, and should the electron machines justify their existance by competition of photoproduction with elastic and inelastic scattering they could go bankrupt.

In the old days, from 1947 to 1955, it was not so: the gamma beams were cheaper than the pions, and there were no pion factories at disposal, up to 20 GeV. Beyond this, the bubble chambers had not been employed yet. Today on the contrary the strong interactions are mostly in the hands of the protonsynchrotron laboratories, and will probably remain there. This is not so bad if we have other things to do: which is the case.

Let's look therefore to some results of the Hamburg Conference with two questions in mind:

A) Are there informations on the strong interactions and particles that a photon beam, and not a pion or a k beam, can give, within the present day experimental resolutions?

B) Apart from this pretent, are there informa-

TABLE I

Some qualitative indications on the requirements of the users in terms of intensity, energy and quality. The numbers on top of the columns are the present best values for the existing machines; those in parenthesis refer to machines in construction: the details on these values may be found in the proceeding of the Conference. The meaning of the abbreviations is the following:

γ = photon beam
e = electron beams
μ = muon beams
b.ch. = bubble chamber
e.s. = electronsynchrotron
p.s. = protonsynchrotron
s.d. = strong and diffraction interactions
e.d. = electrodynamic experiments
f.f. = form factor experiments
μp = physics with muon beams
l.a. = electron linear accelerator

	(1) Intensity (part/sec)	(2) Energy (GeV)	(3) Duty cycle	(4) Monochrom.	(5) Polarization	(6) Purity	(7) Emittance cm × mrad	(8) Monitoring and Quantametry
γ		e.s. 7,(10) l.a. 20,(40) s.d. e.d.	e.s. 10^{-1} l.a. 10^{-3} s.d.	5%	60% at 6 GeV b.ch. e.d.		s.d.	2-4% e.d.
e	e.s. $3 \cdot 10^{12}$ l.a. $3 \cdot 10^{14}$ f.f.	e.s. 7,(10) l.a. 20,(40) f.f. e.d.	f.f.				e.s. ~ .2 l.a. ⩽ .2 f.f. e.d.	2% e.d.
μ	p.s. 10^6 l.a. 10^{7-8} μp	p.s. 1-6 l.a. 1-10 μp	μp			$\pi/\mu < 10^{-6}$ μp		1-2%

tions that we can get more clearly by using the photon input channel, rather that the pion input?

As to question A, let's say immediately that a general reply is impossible, or not in view today. A proton is a complicated system, and the diagram (c) is only one of the simplest modes in which photoproduction may occur. So we cannot exclude in principle that the absorption of a photon may evidentiate some state that the pion scattering could not make as evident, for instance for the crowding of other states and modes. Let's rather stand on what we saw *until now*.

b) Bubble chambers

The Hamburg Conference opened with something rather unusual in photoproduction: the exploration with bubble chambers.

Around one million pictures were taken at the Cambridge electron Accelerator (1). The 12" bubble chamber with magnetic field was fed with bremsstrahlung photons of an energy up to 5-6 GeV. The beam was really obtained with a double conversion from photons to electrons to photons again; also to achieve the low intensity adeguate to bubble chambers. Consider in fact that the gamma ray beam from a machine like Cambridge has an intensity about a factor 10^7 too high for the bubble chamber when operated on the photon beam. And consider also that you can make all the high intensity experiments while the bubble chamber works.

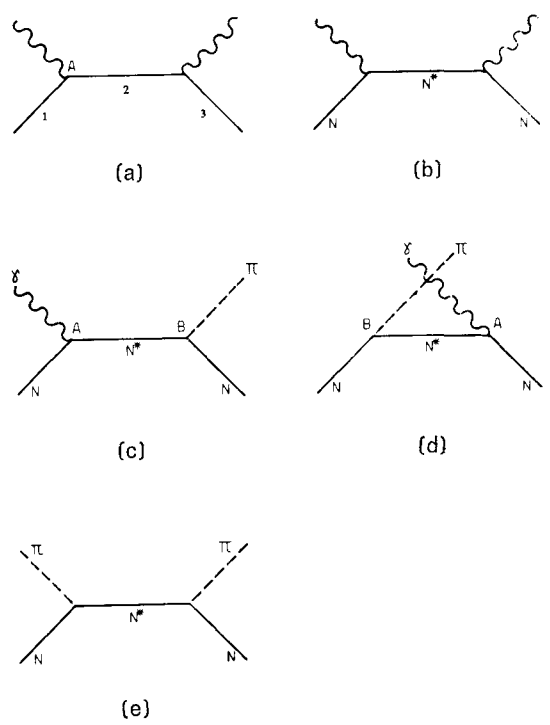

Fig. 1 - Some elementary diagrams expressing the diffusion and resonant absorption of a photon in a system of charges and currents (1a), and in the case of a nucleon (1b). Diagrams c), d): two possible modes for creating a pion in photoproduction (see text). Diagram 1(e): one of the modes to express the reaction π + nucleon $\rightarrow$ π + nucleon. Time flows from left to right.

This is the biggest unbiased experiment that was done with gamma ray beams. The pictures were examined and classified in:

— strange particles,

— vector mesons (ρ, ω etc.),

— nucleon, isobars,

— multipion production and other complex reactions...

A similar effort is now in course at Desy, and a campaign with bubble chambers is in program at SLAC, on the photons and the secondary beams.

I do not enter in the details of the results, which deserve much consideration. Only a few remarks. Which is the position of these explorations respect to questions A and B? Until now the reply is toward the no: nothing unexpected; nothing unique. We are still at the first approximation, and no dramatic "breakdown" respect to the landscape already taken by the pions came out (apart some evidences, like the low production of the ω (omega) which is of interest). Of course the resolution is less than in the case of the pictures taken under pion and keon bombardment, the energy of the photon being a priori unknown.

But we must wait, for the method in itself is not to a dead end, and may become important for a few reasons:

— One reason is that the knowledge of the total photoproduction cross section is a fundamental information, while the scanty information on σ total is a characteristic defect of the photoproduction. This is obviously due to the bremsstrahlung spectrum of the photons, and to the difficulty to obtain the total photoproduction cross section through absorption measurements with counters. The bubble chamber, being a 4 π detector, may resolve the problem. The knowledge of the total cross sections will at the end allow a definite comparison between the amplitudes for pion and photoproduction.

— Another is that the increase in statistics may give rather precise relations among the amplitudes of different resonances and channels. These relative amplitudes are a good check of the present theories of strong interactions. Something already is coming out (1).

— Another is obvious and fundamental; with counters you mostly examine situations with already known particles and states. With the bubble chamber you can find new personages. For instance: we shall see in § 2,d) of a nice experiment on the diffraction photoproduction of the ρ; but it is important (for instance to "correct" electrodynamics) to see if there are other vector bosons, and to measure the total photoproduction cross section for all possible vector bosons: the bubble chamber might be the right instrument to do this.

— Another is the possibility of making precise physics on the neutron, by using a deuterium filled bubble chamber (for instance the reaction $\gamma + n \rightarrow \pi^- + p$ with a spectator proton).

So, what do we desire in future for our bubble chambers? How can we help? I think that the first requirement is a clear kinematics, that is to have at disposal monochromatic beams of photons, and without much background, so that the mass of a neutral body can be determined, at least in the simplest cases. This may be very difficult, and we'll listen at this conference to know what we can hope. But let's write down this important request in Table I (a mark b.ch. in the column 4).

One method could be the crystal diamond technique, which was started in Frascati and is now progressing so well at Desy (2); another the positron annihilation, etc. The problem is to eliminate the unwanted bremsstrahlung background: this is a nice and difficult problem. It would also be a big advantage to use a polarized photon beam (2): this goes together with monochromatism in the crystal technique. Let's put this desire in Table I, column 5, for it seems that it is coming to reality rather fast.

c) Photoproduction of pions and η's

These last years brought a large contribute of refined but more conventional, from the point of view considered here, photoproduction cross sections at all energies. For instance the single photoproduction of π's at high γ ray energies, and the consequent spectroscopy of the excited states N* of the nucleon; the double photoproduction of π 's, and the photoproduction of other resonances and states.

The photoproduction of the meson resonances may be rather illuminating on the type of contribute of the gamma ray beam to the strong interactions, respect to the questions A and B we put a moment ago.

We give now a pair of examples, on the eta and the rho photoproduction. Let's take the photoproduction of the eta first.

Respect to question B. The eta (3) is neutral (mass 548 MeV, spin 0, negative parity) and is well produced in a $\gamma + p \rightarrow \eta + p$ (4) process. Its presence may be rather well recognized in by the measurement of the proton in the final state, and by its peculiar (electromagnetic) decay modes, for instance $\eta \rightarrow \gamma + \gamma$. The corresponding simpler π channel for eta production is $\pi^- + p \rightarrow \eta + n$ (5). The proton instead than the neutron in the final state may be an advantage, particularly in identifiying neutral decays.

Respect to question A. This is less trivial. The angular distribution of the η near threshold is isotropic, and with relatively high cross section, in the channel $\pi^- + p \rightarrow \eta + n$. Notwithstanding the system n η could break in S-wave as well as in some mixed S + D or P + D wave state, whose interference results in an isotropical distribution. The question is of relevant importance, and connected to the existence, or not, of a new η Barion octed, in $S_{1/2}$ state, which finds its place in the SU6 Symmetry (6). An observed isotropy in the photoproduction channel (7) can *convalid* the S wave hypothesis, considering that the interferences between states are in general very different in the channels γ → nucleon and π + nucleon.

A further method to check the existence of a pure S wave is to measure the polarization of the recoil proton in the photoproduction. This is much easier that to measure the polarization of the final neutron in pion-production.

d) Photoproduction of vector bosons

Let me now spend a few minutes over some experimental results which seem to me of high theoretical interest and adequate to indicate the needs of the experimentalists in terms of beams. This is the photoproduction of the ρ, and in particular the diffraction production.

The ρ (rho) is an old friend of the physics with photons: its first evidence came out at Cornell, in photoproduction (8). The rho has mass 750 MeV, with a width ~ 100 MeV, and isotopic spin I = 1. It mostly decays into 2 pions. It is important to know that the rho is a vector boson, with the same quantum numbers than a photon: J = 1, parity = — 1, charge conjugation C = — 1.

In a sense it could be said that when a photon travels in space it is confined to be a gamma in the real space by the conservation of energy and momentum. Apart from this, it could spontaneously indulge at other states, like a pair of

close electrons, or a rho or some other vector boson (v. b.), as represented on top of Fig. 2.

To make any transformation $\gamma \leftrightarrow \rho$ real, one must supply something to recoil, usually some collision with a particle. Considering the nuclear properties of the rho, a nuclear interaction with small momentum transfer can become an interesting way to study the probability of the $\gamma \leftrightarrow \rho$ transformation.

In more practical terms, we must expect, with Berman and Drell (9), a relevant diffraction production of the rho in the process:

$$\gamma + p \rightarrow \rho_o + p \rightarrow \pi^+ + \pi^- + p, \qquad [1]$$

as well as, more in general in the process:

$$\gamma + \text{nucleus} \rightarrow \rho_o + \text{nucleus} \rightarrow \pi^+ + \pi^- + \text{nucleus} \qquad [2]$$

In these processes a photon materializes, via interaction with the field around a nuclear target, as a spin one resonance with the same quantum numbers than a gamma.

The target nucleus does not change its quantum numbers, and its internal energy has a good probability to remain unchanged (no excitation), when the recoil momentum is small: a condition well realized by photons of high energy ($\geqslant 4$ GeV) when the ρ_o is produced forward.

One can express these interactions by some definite formalism. One could be a diagram as given in Fig. 2a) which is a particular case of the general diagram 2b).

The diagram a) is similar to the Amati Fubini Stanghellini models (9) of diffraction scattering (diagram 2c, relative in this case to the pion-nucleon scattering).

The diffraction process should exhibit a differential cross section proportional to the differential cross section for elastic pion-nucleon scattering of the same total energy.

When comparing the diagrams (a) and (c) of Fig. 2 we see the similarity of the structures: in (c) we must introduce a $\rho\pi\pi$ copling at two vertices; in (a) we must introduce the $\gamma\pi\omega$ and the $\rho\pi\omega$ vertices.

Of course, the rho diffraction could be considered one part of a general program: which are the vector resonances coupled to the photon? i.e., which "bumps" are found in the created mass in addition to the rho and ω at 750 and 780 MeV, respectively? This program is beginning now, but already the photoproduction of the ρ has been substantiated by experiment.

One of the Cambridge groups (10) has recently given experimental evidence of rho diffraction production. They have studied high energy photoproduction of neutral rho mesons at small angles of the rho. The typical disposition is sketched in Fig. 3.

The experiment was based on the detection of the two pions, π^+, π^-, from the decay of the neutral rho. The processes were those listed in [1] and [2]. The typical results are shown in Fig. 4.

In Fig. 4b is reported the mass spectrum for dipions from hydrogen target, at $\xi = 0°$, ξ being the angle the total momentum of the dipion system makes with the direction of the incident gamma ray. α is the opening angle between the two pions. The same situation in Fig. 4a refers to the dipions from a carbon target.

As we see, a bump corresponding to the mass of the rho (M_ϱ = 750 MeV; ΔM = 100 MeV) is rather evident, very evident in the more copious events from carbon. Please, notice how nice the results in C are. We'll come back to this point.

The measurements were subdivided into small quadrimomentum transfers, and were taken at different energies of the gamma's. In this way the diffraction mechanism of the production has been confirmed.

If we assume a diffraction mechanism, the differential cross section around 0° (in agreement with the optical theorem) is written:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma+p \rightarrow \varrho+p} = \text{const}\left(\frac{k\sigma_{\pi N}}{4\pi}\right)^2 e^{Bt}$$

where $\sigma_{\pi N}$ is the total cross section for pion nucleon scattering, and t is the square of the invariant momentum transfer; k is the laboratory energy of the γ ray, and B is a constant taken from the elastic π–N scattering; its value is (9.5 ± 2) $(\text{BeV/c})^{-2}$.

The experimental results do not disagree with this prevision, still within rather large errors.

Moreover, photoproduction from carbon, aluminium and copper gave additional evidence for

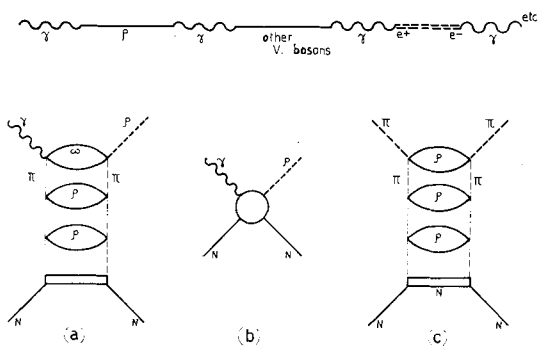

Fig. 2 - On top: the possible states of a photon, when some adequate recoil is supplied. Fig. 2a): a specific schema for the photoproduction of the ρ, according to the Amati Fubini Stanghellini model. Fig. 2b): a general representation of the ρ photoproduction. Fig. 2c): the Amati Fubini Stanghellini model for diffraction scattering of the pion.

a diffraction mechanism, as the curve of Fig. 5 indicate. In this curve the authors give a plot, versus the atomic number A, of the production cross section of the ρ_o at 4.4 GeV of the photons, when the ρ is emitted at 0°. Then results are compared with the 0° cross section for pion scattering. The plot shows that there is coherent production, and it suggests that there is a simple relationship between the rho photoproduction and the pion nucleus scattering.

I am insisting a moment on the rho as a good example of the future trends of the physics with high energy photons. At least in three respects.

One is the interest of studying these diffraction processes at the highest energies (4 GeV is still low) and to compare them more strictly with the corresponding π N and NN processes.

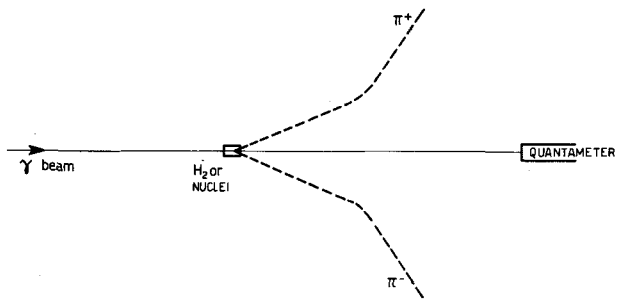

Fig. 3 - A sketch of the experimental disposition of the Cambridge group (10) for the process $\gamma + p \rightarrow \rho_o + p$.

The second: the ρ can decay in $e^+ e^-$ and $\mu^+ \mu^-$ pairs; for instance in diagrams of the type of Fig. 6. This strictly simulates the creation of electron pairs in a pure electrodynamic process, and could induce someone to believe that electrodynamic theories are wrong.

Of course this word, simulation, may be wrong: we simply are insisting in defining pure electrodynamics which only exist, so pure, in our provisional mathematical methods.

Anyway, the problem is fundamental, due also to the importance of knowing these photoproduction processes (and another one, the production of the ρ through one pion exchange) for giving a sense to the verification of electrodynamics.

A third point refers to the results in carbon, which look so nice: the background is low, and the width of the ρ is not enlarged: rather it seems to be reduced, if this has any sense. Perhaps we should take this result as an invitation from nature to study the nucleon (its peripheral atmosphere in this case) not only when the nucleon is alone in empty space, like the hydrogen, but also when it is immersed in its natural environment, the complex nucleus. Let's remember that electrons and photons are the right probes to go and see how a nucleon behaves inside the nuclear matter. Much better than pions.

I referred to the ρ as to the best example, but of course other bosons can be created like the rho, and the nuclear diffraction could be a good way to evidentiate them. Let's use now what we said on the ρ from our point of view, by going back to our Table I.

All the strong and diffraction interactions we said, which we will call for brevity s.d., have something in common:

— they are at least three body processes and are relatively rare,

— they are critical in the angles,

— the interest of the measurement increases with the energy of the producing photon.

— they do not have an easy equivalent in the proton machines. This is a reply to the question A) we put at the beginning.

The first of these points means the need of coincidences between the triggering counters: that is a good duty cycle. Let's put this important request in Table I, column 3.

We must remind that in coincidence experiments the maximum useful yeld per second (that is, the number of good events G) you can collect per unit time is fixed by the percentage c of accidentals you can accept in your experiment. If this is true, one finds that G is proportional to the duty cycle (11) D:

$$G \sim D$$

in coincidence experiments.

This relation is valid for beams already beyond a given limit of intensity: it is my opinion that all γ ray beams of high energy are today beyond this limit or close to it.

The other requests, on the γ beam raw, are:

— energy (we will wellcome for these experiments the highest energies);

— emittance (should present emittances, better say collimations, be improved, this improvement will be very wellcome for this diffraction physics). Let's put these requests on the Table I.

3. THE PHYSICS OF FORM FACTORS

a) Some general remarks

We saw before that one can study the fundamental state and the possible excited states of a distribution of charges and currents by absorption and emission of photons.

But suppose now you wish to know the structure of your system in its fundamental state, when unexcited.

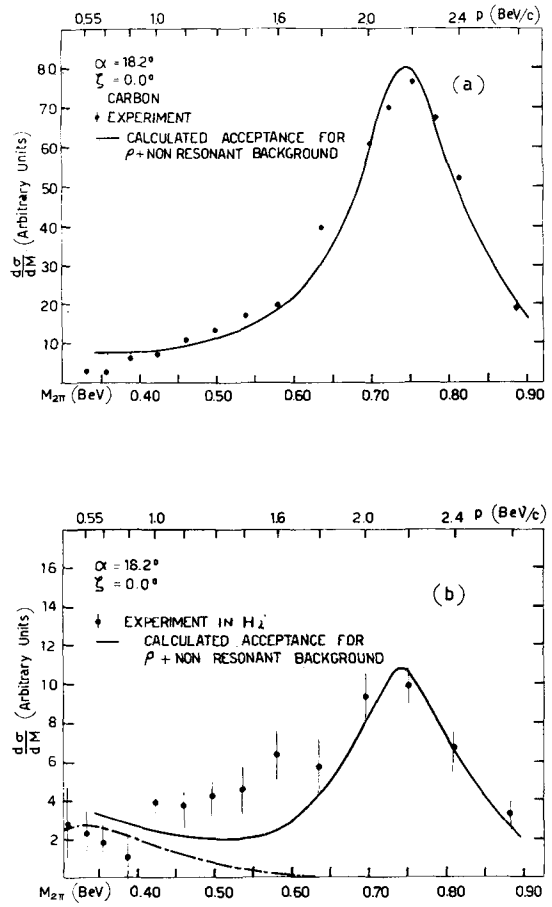

Fig. 4 - Results at Cambridge on the photoproduction of the meson: a) results in carbon, b) results in H_2.

In this case a convenient thing to do is to use a probe and an experimental disposition that excite the system as little as possible, and which gives detailed information on the structure of the fundamental state through the measurement of some clearly defined dynamical parameters.

For instance, in order to study the fundamental structure of an electric cloud A, that is a system of charges and currents, one could suggest to send electrons or muons as exploring missiles, and to try to induce tre strcuture of A from the elastic or quasi-elastic scattering of these charged particles. He would not suggest the use of photons, that is to send electromagnetic waves and to study their Thompson or Compton scattering: in this case you will excite the structure A, and at the end you will learn what A can do when it is excited; and it will be more difficult to extract the structure of its fundamental state.

The use of electrons or muons, therefore, tells you of the form (charges and currents) of the system A. You can measure the probability of a given momentum transfer q in the collision e + A, and deduce a function $G = G(q^2)$, the form factor, which is related to the basic structure of A. When the impact parameter is large, and therefore q is rather small, and therefore the system A is point-like respect to the wave-lengths associated with the collisions, $G(q^2)$ is equal to unity or to a constant, depending on its normalization; in this case, for a charged A, we meet something similar to the known Rutherford formula. If A is a proton or a neutron, or a nucleus, $G(q^2)$ is the function that has a fundamental role in knowing the electromagnetic structure of these particles. The theory (12) predicts under rather satisfactory hypothesis the relation between the angular distribution of the scattered particles and $G(q^2)$.

In these years the elastic collisions:

$$\begin{aligned} e + p &\rightarrow e + p \\ e + n &\rightarrow e + n \\ e + \text{nucleus} &\rightarrow e + \text{nucleus} \end{aligned} \qquad [3]$$

have been studied rather deeply, and the equivalent ones for the muons are now in progress.

The calculation of these processes follows in its first approximation the schemes represented in Fig. 7a.

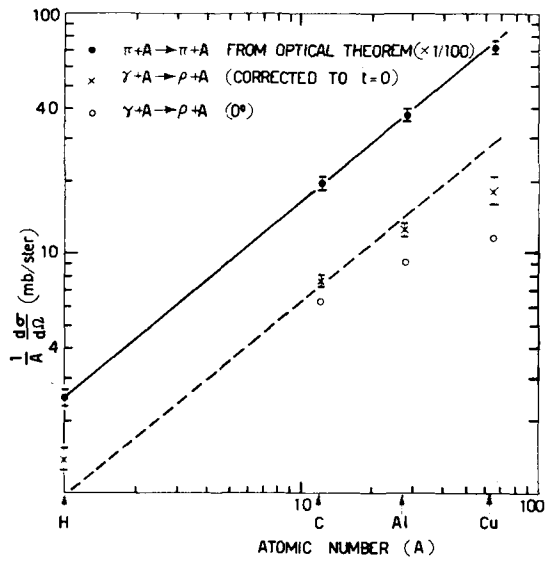

Fig. 5 - Photoproduction of the ρ_o, Cambridge. A plot versus the atomic number, A, of the 0° 4.40-BeV rho photoproduction cross sections and the 0° cross sections for pion scattering. The optical theorem was used to calculate the pion-nucleus cross sections from measurements of the total cross sections. In order to compare the A dependence of the two cross sections, the rho cross sections were extrapolated to momentum transfer $t = 0$. The line drawn through the rho data has the same slope as the fit to the pion cross sections. This plot shows that there is coherent production, and it suggests that there is a simple relationship between the rho photoproduction and pion-nucleus scattering.

This is a diagram where the proton remains in its fundamental state (diagram a) and those scattered electrons are measured which do not loose too much energy in bremsstrahlung in some moment of the collision.

When the energy increases, other modes can appear (12), as expressed in Fig. 7b (the exchange of 2 photons, resulting in a virtual Compton effect from the N33 resonance) or Fig. 7c (the exchange with the intermediate of some x_o meson).

All this is in part an evolution of the Rutherford elastic scattering. The photon (in the first diagram of Fig. 7) only carries momentum, not energy. It is a momentum carrier, it is a « spacelike » photon.

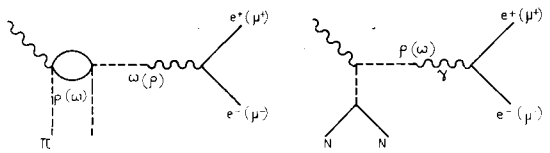

Fig. 6 - (After Bermann and Drell): Production of a lepton pair in the decay of a vector boson, through diffraction and one pion exchange.

b) Form factors from electron beams

It is evident that the physics of the form factors is not going to an end at any energy, considering that the potential possibility to find out fine details in the structure of the proton is obviously increasing with the momentum transfer in the collision. This physics has been in the most recent years the best glory of the electron beams.

It is impossible to summarize here the situation. Who wishes informations, can go to the papers and summaries presented at the Hamburg Conference (13), and also to the recent results from Cambridge (14). The efforts of Stanford, Cornell, Cambridge, Orsay and other places have brought to the knowledge of the form factor of the neutron and of the proton in the range of four-momentum transfers, from very low up to 7 $(BeV/c)^2$, that is up to 175 F^{-2}. To the eyes of the physicist a rather soft nucleon appears, may be with no hard core, even when one goes below 3×10^{-14} cm of distance from its center. The structure of the nucleon is still uncertain: when one admits that the distributed charges and currents are due to resonant states of mesons with $J = 1$ and $I = 0$ or $I = 1$, one discovers that the existing known states, ρ, ω, φ are hardly enough, as if the vector bosons of the cloud were not all known yet; a conclusion not disconnected from what we said on the research of vector bosons in diffraction experiments with photons (§ 2, d).

The developments of the form factor physics are obvious, but very interesting. One is to go ahead with $G(q^2)$ to see if we continue to sink in the soft cloud. These are difficult experiments: the cross section decreases very fast, and this justifies the high intensities of some recent machines, SLAC first of all.

Another is the study of the form factor of the nuclei: the recent results of Stanford (15) in the e-nuclei scattering for H^3 and He^3 are perhaps indicative of a new trend, which could establish further cultural links between the physics of the nuclei and the physics of elementary particles. Another could be the form factor of the nucleon inside the nucleus: the elastic electron-nucleon collision (corrected of the Fermi motion) with one nucleon of a complex nucleus. One should be perhaps careful before being sure that there is nothing fundamental to learn respect to the collision with isolated protons.

But something more is coming out in this period in form factors, which is as interesting from a theoretical than an instrumental point of view. And a little educational, to distinguish between the reality and our schematic divisions.

I said that the electron probe may be a nice visitor, who does not excite the nucleon. This is less and less true when energy or momentum transfers increase: other diagrams are present, beyond the simple elastic scattering. For instan-

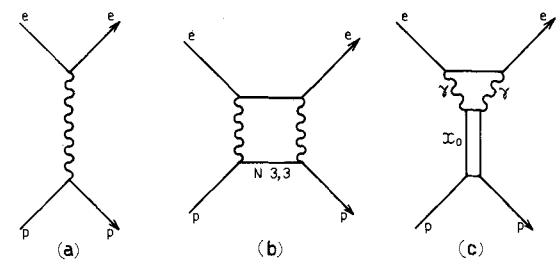

Fig. 7 - Scattering of electrons and muons. Fig. 7a): Elastic scattering through one photon exchange. Fig. 7b): Elastic scattering through two photon exchange, resulting in a virtual Compton effect from the N_{33} resonance. Fig. 7c): Exchange with the intermediate of some x_o meson.

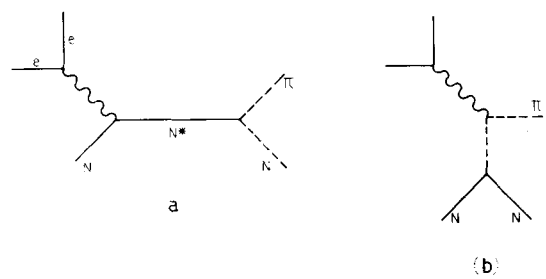

Fig. 8 - Some possible diagrams for the pion electroproduction. See text.

ce (16) the diagrams of Fig. 8. The final result is in both cases the electroproduction of a pion

$$e + p \rightarrow e + p + \pi; \qquad [4]$$

but in our classification they are somewhat different things: the first results in a method for determining the spin and parity of the e.m. transformation form factors of nucleon isobars N*; the second in a method for determining the form factor of the pion. Well, everything is theoretically rather in order, and already these different diagrams are being studied. But the point is that to separate the elastic electron-nucleon collisions from the electroproduction expressed in diagrams a) and b) of Fig. 8 is going to be more and more difficult with the increasing energy of the electron projectiles. We already had an idea of these difficulties in listening in Hamburg (17) to the delicate magnet that SLAC (Stanford) is preparing for the e-p and e-n scattering. To fix order of magnitudes, we can say that the momentum resolution in measuring the scattered particle shall be better (with an obvious reduction of the dimensions of the physical quantities) than the ratio of the pion mass to the total energies. This means that in the 10-40 GeV region, we need momentum resolutions of a few per thousand (apart the limits for the radiative corrections to the electrons).

Of course, there are severe requirements on the momentum definition and the emittance of the impinging beam. Let's put these requirements of emittance and energy in our Table I, for the form factor (≡ f.f.) physics.

But in general, to separate the elastic processes from reactions like [4], one must control more than one particle among the final states. This means that coincidence techniques are important or necessary, and again we need beams with high duty cycle. Let's put immediately an f.f. mark in the duty cycle column on Table I. This is one of the most conflicting points. In fact, to go to the highest energies and intensities, f.i. 40 GeV, the linac seems more adequate that the electrosynchrotron, but the duty cycle is bad. I hope this conference will discuss these points: if it is possible and to which extent to go through stretching rings which dilute in time the sharp pulses of the linear accelerator; and to which energy the electronsynchrotrons are still convenient.

c) Form factors from muon beams

Now let's go to the beams of μ mesons, which is the other alternative for studying the form factor. The muons are interesting at least in two respects. One is immediate: an intense well collimated muon beam can make more easy the physics of form factors, when you substitute e by μ, for in this case one avoids some of the uncertainties connected to the radiation losses: the μ is heavy enough, at least for our time.

The second reason is more refined: the form factor $G(q^2)$ from e and μ should be the same apart from the possible differences in structure among e and μ. Let's stop a moment on this, by looking to the results on μ -p elastic scattering which came recently from the Brookhaven AGS (18), and to the interpretation given from these same authors.

The $G(q^2)$ form factor has been measured, and is shown in Fig. 9.

In this figure we compare the results on the form factors (19) for electrons and muons. Please notice that the errors on the muons are large, but not much more than the errors with the electrons.

The form factors from e and μ substantially agree, and the authors invite us not to take for granted the fact that the μ point stay below the e points.

Anyway, they try to get a quantitative limit from this situation, which is interesting here.

Following Barnes (20) and Drell (21), they attribute to the leptons a form factor,

$$f = (1 + q^2/\Lambda^2)^{-1}$$

where, however, Λ may be different for the electron and the muon. Let's define a quantity

$$D^2 = \frac{1}{\Lambda_\mu^{-2} - \Lambda_e^{-2}} = \frac{\Lambda_\mu^2 \Lambda_e^2}{\Lambda_e^2 - \Lambda_\mu^2}$$

Then, to first order,

$$\frac{f_\mu}{fe} = (1 + \frac{q^2}{D^2})^{-1}$$

and the ratios of muon and electron scattering cross sections (evaluated at the same values of q^2 and of the incident momentum p_0), give a measure of D^2. From their experiment they find $D^2 = 187\ F^{-2}$ ($D \rightarrow \infty$ if $\Lambda_\mu = \Lambda_e$), but they warn us not to believe yet. They prefer to interpret their results as giving a lower limit on the size of any deviation:

$$D^2 > 95\ F^{-2}$$

which corresponds to $(1.9\ BeV/c)^2$ with 95% confidence. This limit could be higher ($D^2 > 220\ F^{-2}$) in case the comparison among e and μ were only based on the shape of the cross section versus q^2; perhaps it is better to stick to the first value. The value of D is a nice contribute to the

study of the possible anomalies in the e.m. properties of the muon respect to the electron; it is different in nature but strongly cooperative with the limits given by pair production of the muons (22) and by the (g-2) measurement on the muon (23).

Just to express in an improper but intuitive way the meaning of D, we can add that by introducing $d_\mu = \Lambda_\mu^{-1}$ and $d_e = \Lambda_e^{-1}$ (the physical « dimensions » of the μ and the e) the length: $D^{-1} = d = \sqrt{d_\mu^2 - d_e^2}$ is less than ~ .1 Fermi. This limit, is already meaningful.

When we look to the experiment of Brookhaven (again in Fig. 9) we would have more intense muon beams (for a factor 20 or 100, for instance), and more energetic, and still with a duty cycle which allows coincidences. This will push the limit of d much further, and will allow a further exploration in the form factors of nucleons and nuclei. Let's put these requests in our Table I, for this is a very interesting physics.

On this point SLAC has some good proposals. You take the muons of a given sign produced by pair production:

$$\gamma + \text{nucleus} \rightarrow \mu^+ + \mu^- + \text{nucleus};$$

with the convenient optic you can store at least a part of them (together with some contaminating pions and antiprotons) in a storage ring. In the laboratory system these muons, in case they have an energy of ~ 5 – 10 GeV, will have a lifetime of the order of

$$\tau \times \frac{E_\mu}{m_\mu c^2} = (2.212) \times 10^{-6} \frac{E_\mu}{m_\mu c^2} \approx (1 - 2) \times 10^{-4} \text{ sec}$$

By keeping the muon beam circulating in the storage ring for a time of this order, it will be cleaned of all the contaminating pions, whose proper lifetime is 2.56×10^{-8} sec. Then you can use the muon beam in some straight section of the storage ring, or you can spill out the beam from the storage: in any case you have enlarged the duty cycle, respect to the duty cycle in the linac, by a factor around 100, and still with high intensity and good momentum definition.

4. VERIFICATION OF ELECTRODYNAMIC

a) Some general remarks

It seems that time is ripe for an experimental verification of the e.d. formulas at high momentum transfer; that is for a search of a possible breakdown of e.d. It is difficult to find a single meaning to this overfamous « breakdown » word. The fact in itself is simple: the physicists must verify the validity of the only microscopic theory they have developed in a satisfactory way, at least from a phenomenological point of view. (From as assiomatic and rigorous point of view they seem to be unhappy anyway of course). In fact it appears until now, with one possible exception we shall see in a moment, that the e.d. handbook works, in the sense that there are not contraddictions between the theory and the experimental facts: for instance e-e scattering (24), g-2 of the muon (23), etc.

This breakdown has popularity in high energy also due to some picturesque contained in the problem.

In fact, by verifying e.d. one verifies the geometry of our space at small distances: the quantitative formulas of e.d. are constructed on the very assumption that our space in Euclidian even down to the smallest distances, and that the concepts used in quantum mechanics, measurements of positions, momentum, etc. are the same concepts in terms of which the special relativistic postulate is formulated. If e.d. does not break down at small distances at a given momentum transfer, this assumption holds and we are rather ensured that our coordinates do not degenerate at small distances in some mollus-like system, like for instance they tend to do, with general relativity, at the greatest distances (25). Of course the contrary is not true:

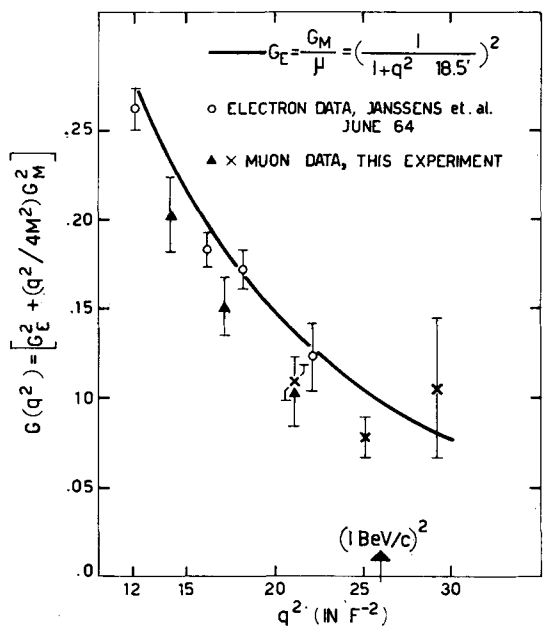

Fig. 9 - Comparison of $G(q^2)$ as measured in μ -p and e-p scattering. The smooth curve is the phenomenological fit used to compute the cross section. Data from ref. (18).

a breakdown could appear, because of some other and less fundamental reason.

The laws of e.d. have a unique role in physics, for, as we know we do not have at disposal any other precise theory. This allows to consider the problem from a somewhat different point of view: a good theory is in a sense a frame of reference. The theory of e.d. is in fact our frame of reference for measuring and defining the nature of the nuclear particles; the form factor of the proton, and its interpretation in terms of boson clouds or resonances, has a meaning as far as the electron does not have an unknown structure itselg. Of course this brings to the risk of tautology, and physicists escape it by making internal checks: e-e scattering, e-μ scattering, e-p scattering (26), etc.

Of course, this risk never stops. We are dipped in e.d., and we are spectators of the nuclear phenomena in an e.m. world: when we check e.d. we in reality compare high momentum transfers (that is the output from the target we chose) with the laws of e.d. at small momentum transfer, ionization, electron cascade, etc.: that is the output from the quantameter or the monitor on the beam.

This immediately reminds us of the importance of quantametry, and we must put a mark (≡ e.d.) in our Table I, column 8, for this point: the experimentalists are going to demand further progresses in precision quantametry and monitoring.

In the case of the photons it may be that accurate calorimetric measurements can help to break the close circle of electrodynamic, by giving some independent occasion for an absolute calibration.

b) Pair production at large angles

The experiment of one Cambridge group is the most recent and definite indication of a breakdown of e.d. (27). The experiment was done with the Cambridge Electron Accelerator (CEA).

These authors have measured the photoproduction of wide angle electron positron pairs in the energy range from 1 to 6 BeV, of the photon; the target was carbon. This experiment is therefore a new test of quantum electrodynamics at high energies and small distance.

The object of the experiment was the behaviour of the electron propagator for large space like virtual momenta. The experimental disposition is given in Fig. 10.

The measured cross sections were compared with the theory, starting from the Bethe-Heitler formula and introducing the possible radiative corrections; these corrections being specifically evaluated by a Montecarlo integration over the acceptance of the system. The carbon form factor was introduced as well as possible, taking it from the elastic electron scattering on carbon nuclei.

I don't have the most recent results here, but we can see in Fig. 11 the results, as given in (27); they are equally indicative in our considerations.

One can see that the experimental results do not stay on the horizontal line at level one; therefore they do not agree with the previsions of quantum electrodynamics for pair productions, and they rather suggest a breakdown of the theory, or the presence of other processes.

Our interest is obviously high on the experiment of Cambridge, for the discrepancy is a big

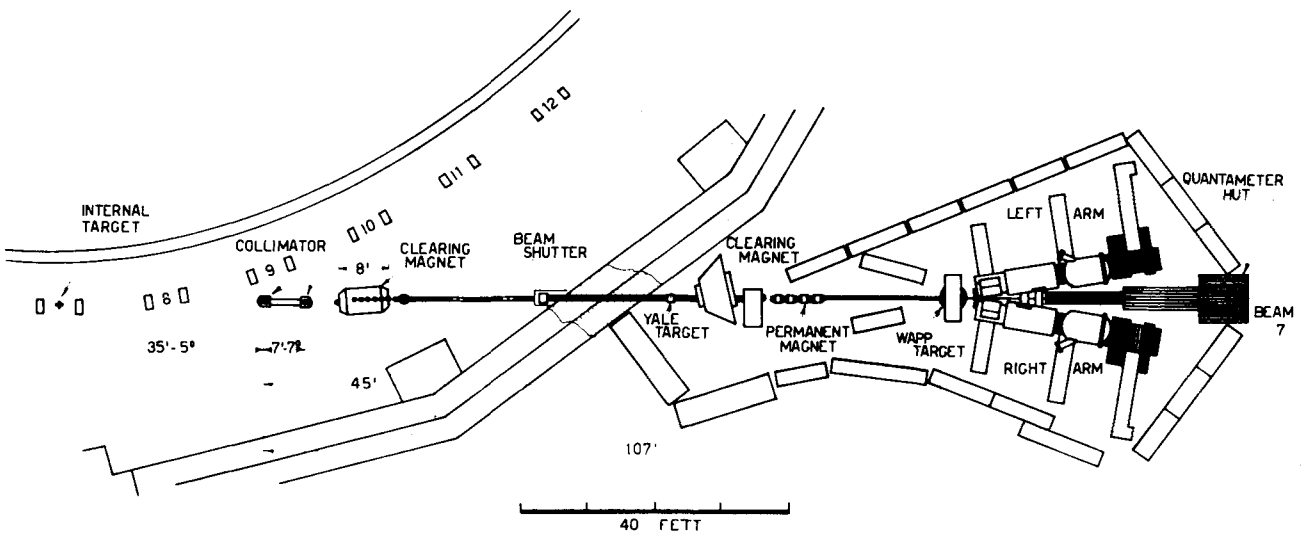

Fig. 10 - A drawing showing the general layout of the apparatus in the experiment of CEA on the $e^+ e^-$ pair production.

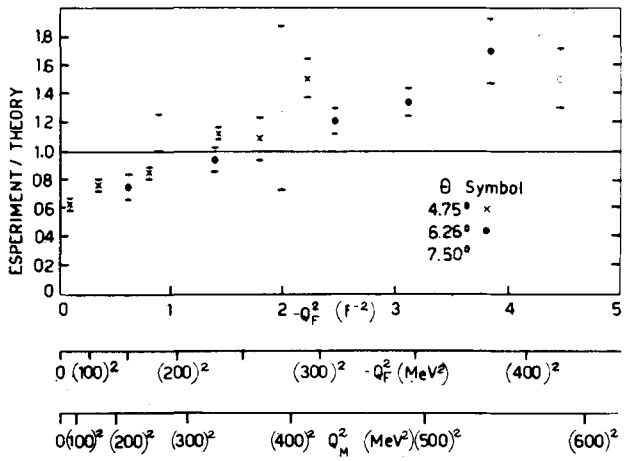

Fig. 11 - Results on electron pair production of CEA. In the ordinates: the ratio R of the experimental yields to the calculated yields. R is given as a function of the mass of the virtual fermion ($-Q_F^2$) and the mass of the outgoing electron positron system (Q_M^2).

one, and in case it is maintained some of our faith in the « stability » of e.d. is weakened; also considering, after Drell (28), that the discrepancy can not be adjusted enough by the effect of the vector bosons.

We need confirmation of these results, not for overskepticism, but in view of the huge revolutionary size of the discrepancy. Anyway this experiment may stimulate new researches in more directions:

— One is again the photoproduction of strong particles at different momentum transfer: it is important for instance to know the coupling between the gamma the pion and the vector bosons, those bosons which can decay into pairs, and simulate « pure » electromagnetic processes.

— Another may be to continue the pair production of muon pairs, which is being explored at Cambridge up to $8F^{-2}$ of the muon propagator. Very interesting confirmations already came out in these last years, in carbon (29), at Frascati and Cambridge. The comparison between electron and muons can indicate, in case of « breakdown », where we can look to find the reason of it. No breakdown yet.

— Another may be the Compton effect to the highest energies (30).

— Another is to repeat the experiments of pair production with hydrogen, to avoid the possible complications of the carbon form factor and its excitation levels. This is an hard request, the difficulties being much more that in carbon. But the effort could repay. Perhaps even in some unexpected way. We could discover that e.d. at high momenta still holds very well: so well that we have in our hands, with pair production of electron and (even more) of muon pairs, a good tool for studying form factors of the baryons.

Let's try now to put these perspectives in Table I with a mark e.d. We have to make requests of high energy, considering that we need high momentum transfers; good emittance and momentum definition, particularly when we'll need electron beams to verify bremsstrahlung processes; very precise quantametry, for the reasons we already said.

I wish to add polarization, of the photon beam at least: this could perhaps help to separate the strong diagrams bringing to pair production, considering that the effect of the polarization in pure e.d. should be known.

5. CONCLUSIONS

Now, let's stop here, and let's look to Table I. And let's resist the temptation to conclude that we just wish everything on the table.

In fact our demands may be rather specific. Should we start from the more important, we, the users, would insist first for high energy and for an high duty cycle.

These two demands, as we saw, come from many experiments on form factors, electrodynamics, photoproduction; and they regard both the electron and the photon beams. Unfortunately these are two conflicting requests for the electron machines, as we said. In fact the radiation losses of the electrons may compell us to use the linear accelerators, when we go to energies beyond 30 or 50 GeV. But the duty cycle of the linear accelerator at room temperature is low. And the cryogenics is not ready yet to help us with cavities of low losses, which may allow a good duty cycle at least at low intensity of the beam.

I would hesitate to consider the request of beams of higher intensity as a top one, considering the values already achieved to day. The fluxes indicated in Table I are already tremendous and already the quantity of information that an extended detection can give is very large; let's notice that in many experiments with electrons and photons the main errors do not come from the statistics, but are rather systematic in nature.

It is evident that there is very great demand for the qualities connected to precision and stability: stability of the beam during time; good emittance, good monitoring. These demands are of the highest importance for research in electrodinamics and for the study of the rare events. They are severe demands, as we are learning the hard way: many systematic errors come from instability of the beam.

Another point (in column 5 of Table I). We wish to have, as we said, monochromatic and polarized photons: the goal is important, and it pays to make any progress in that direction. Even if the intensity will be 10^{-6} or 10^{-7} of the original beam. We have detectors who cannot anyway stand more intensity that that: the bubble chambers.

As we saw, energy is of great importance, also if we'll pass on the colliding electron beams a given fraction of the problems we considered here. In this respect the coming electron machines, the 40 GeV linear accelerator at Stanford (SLAC) and the 15 GeV electronsynchrotron at Cornell University are extremely wellcome.

Let me make a final remark.

When we consider the physics of today with electrons, muons and photons, its natural development in future and its continuous progressing in the last five years, I have the feeling that there are within this branch of our science, even more definite and compelling reasons to go towards the highest energies than in the physics with π and proton beams (31).

Acknowledgement

I am grateful to the physicists of Cambridge, Slac, Stanford, Nina, Hamburg and Frascati for the informations and discussions I could have with them.

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(11) Let's define:
n = average number of incident particles per second (average intensity);
n_0 = actual, instanteneous intensity, when the beam is on.
$n/n_0 = D$ = duty cycle of the beam.
N_1, N_2, rate of the pulses in counters 1, 2, when the machine is on (this is the instantaneous rate: in average counter 1 receives $N_1 D$ pulses per second).
G = number of good events per second (average).
k_1, k_2, k_3, constants of proportionality, so that:
$G = k_3 n$; $N_1 = k_1 n_0$; $N_2 = k_2 n_0$
A = accidentals per second between the counters 1, 2 (average);
τ = resolving time of the basic double coincidence;
$c \equiv A/G$ = maximum percentage of accidentals the user is ready to accept in his experiment.
Then we have:

$$A = 2\tau k_1 k_2 n_0^2 D$$

$$c = \frac{2\tau k_1 k_2 n}{k_3 D}; \qquad k_3 n = \frac{c k_3^2 D}{2\tau k_1 k_2}$$

This means that

$$(*) \qquad G \leqslant \frac{c k_3^2 D}{2\tau k_1 k_2}$$

that is, once c is fixed, the yield is limited by the value of D. Formula (*) includes the assumption that n is not the limiting parameter, for it is high enough to allow too many accidentals. This is certainly true in case of the linear accelerators.

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(19) The form factor $G(q^2)$ we are considering here is related to the cross section (differential versus the momentum transfer square) by (18):

$$\frac{d\sigma}{dq^2} = \frac{4\pi\alpha^2}{q^2} \frac{G(q^2)}{1 + q^2/4M^2} (1 - q^2/2Mp_o + ...)$$

and $G(q^2) = G^2_E + (q^2/4M^2) G^2_M$; α is the fine structure constant; G_E, G_M are the two known proton form factors; M the proton mass; p_o is the momentum of the incident muon.

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(30) I am grateful to R. Gatto for reminding this point. Of course the Compton effect at the smallest angles (which is the more interesting region) is either difficult or impossible.

(31) I don't intend here, of course, to discuss a choice between the proton and the electron machines, which is a much broader and difficult question. Consider for instance that the Protonsynchrotron can give a generous supply of photons through the π° decay. It is pleasent in itself to contemplate the internal consistency in the growth and advance of a research field.

STATUS OF DESIGN, CONSTRUCTION, AND RESEARCH PROGRAMS AT SLAC *

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(Presented by R. B. Neal)

1. INTRODUCTION

Earlier planning and progress related to the Stanford Twomile Linear Accelerator were reported at previous conferences (1, 2, 3, 4). This report can be more definitive since it occurs at a time when the design of the accelerator and its auxiliary components and systems has been essentially completed and construction is well advanced. Completion of the accelerator will oc-

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