ELECTROMAGNETIC INTERACTION AND NUCLEON STRUCTURE

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1. Experiments on High Energy Electrodynamics

Last year at the CERN conference it appeared suitable to discuss questions of high energy electrodynamics and of nucleon structure at the same session. The reason is that most of our knowledge of nucleon structure rests on elastic and inelastic scattering of electrons in hydrogen and deuterium; in interpeting these results it has to be assumed that quantum electrodynamics (QED) remains valid at all momentum transfers used. Conversely the nucleon structure experiments can also give limits on the range of validity of QED.

In this talk I will include miscellaneous topics in electrodynamics both at high and low momentum transfers; in addition I will give some data on neutral pion decay. Professor Hofstadter will report separately on his experiments dealing with nucleon structure. I will also include some new material on nucleon structure from several other sources.

The general picture either in nucleon structure or 3176
on the limits of QED has not changed greatly during the

last year although the accuracy of much of the data is improved, and many new ideas have been introduced.

No newer results can be reported on the experiment on electron pair production at very large angles. An experiment is in progress by Richter[1] for the observation of the coincidences between the two electrons produced symmetrically relative to the incident photon.

A proposal has been made by Petukhov and collaborators[2] to use the electron Compton effect for $\sim$600 Mev photons as the means of studying the limits of QED. At that energy the invariant momentum transfer is only 25 Mev but they hope to compensate for this by an attampted accuracy of 0.2%, which allows to approach the $\sim 3.10^{-14}$ cm cut-off distance. Petukhov and collaborators are proposing to put the recoil electrons in the forward direction in coincidence with the photons scattered at 45^{0} and 135^{0}. In working to an accuracy of 0.2% it is of course essential that all the theoretical corrections be known to a comparable accuracy. Radiative corrections and some others have been evaluated to fourth order by Brown and Feynman.[3] These calculations were extended by evaluation of the cross section of the double Compton scattering (i.e. Compton scattering in which an additional γ-ray will be emitted) to larger energies of the additional quantum. Different uncertainties were estimated and appear to be reasonable[4] although I believe this to be an exceedingly difficult experiment. A proposal to use the annihilation of fast
3176 positrons in flight to study the limits of QED has been made by Andreani, Budini and Reina[5].

I would like to give a brief progress report on the design of the experiment on electron scattering by the method of colliding electron beams, from two separate storage rings. This experiment is now under construction at Stanford University [6]. The electron beam from the Stanford linear accelerator is injected into two magnetic storage rings as shown in Fig. 1. Both magnets operate as weak focusing synchrotrons although the "n" value alternates between 0 and 1.1. Injection is accomplished

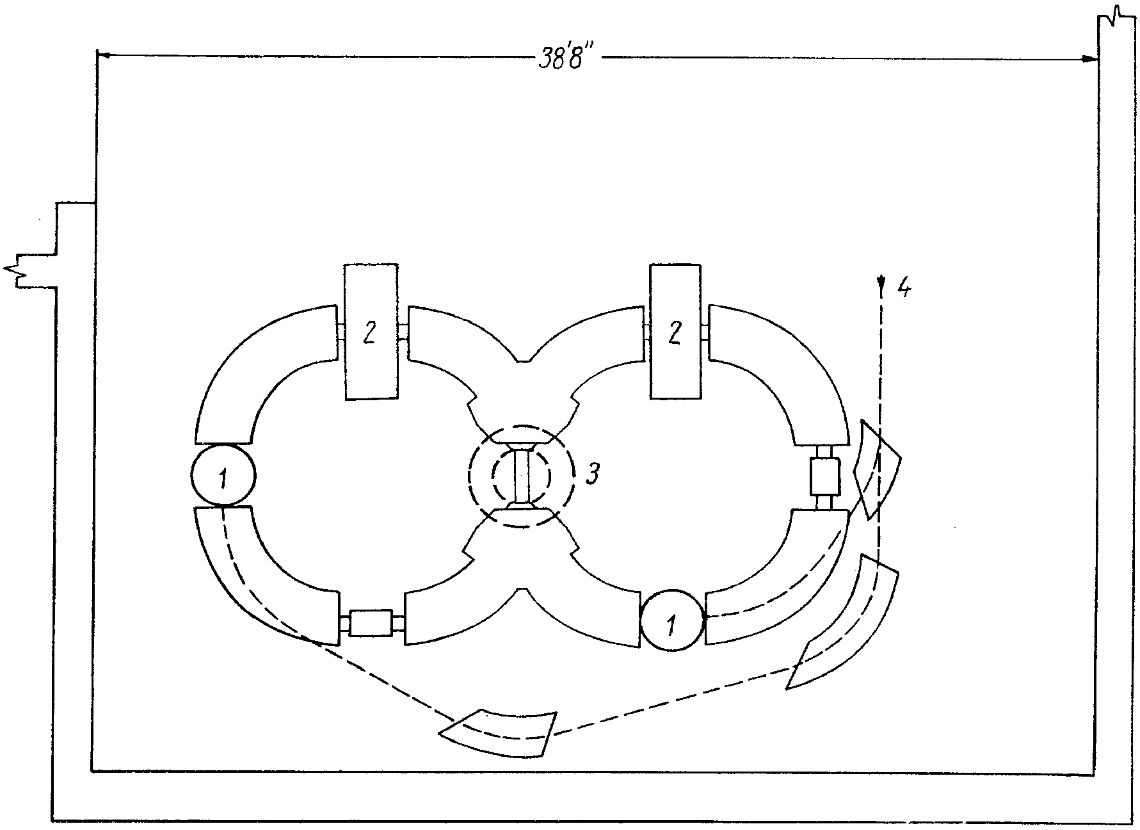

Fig.1. Diagram of electron-electron colliding beam experiment at Stanford University. 1 - the pulsed, inflector; 2 - R.F. cavities; 3 - interaction region; 4 - the incident beam.

by a pulse deflector which discontinuously decreases the amplitude of the betatron oscillations in such a way that the orbits remain radially contained. The

3176

equilibrium orbit is smaller than the orbit at injection; therefore the classical radiation loss of the circulating electron beam will pull the orbits out of the field of the pulse deflector. It is thus possible to stack many pulses into the orbit. The circulating current requirements are moderate; a current of one ampere is entirely sufficient. A radio frequency cavity in each ring compensates for the radiation loss.

The mean life of the electrons in each ring is estimated as several hours. The main sources of beam-loss are the following:

a) Quantum fluctuation in radiation emission; such fluctuations will excite synchrotron oscillations which may exceed the limit of stability. The effect of this phenomenon on the life-time can be made small by a sufficiently high radio frequency voltage applied to the cavities. For the radiation loss of 4.1 kev per turn and a cavity voltage of 20 kv the lifetime due to this effect is many years.

b) Losses due to energy loss by emission of large single quanta in collisions of the electrons with the nuclei in the residual gas. At the design pressure of 10^{-9} mm of Hg this phenomenon gives a thirty year beam life.

c) Losses due to multiple coulomb scattering in the residual gas and losses due to nuclear interactions are negligible.

Positive ions are swept out to avoid instabilities due to the focusing effects of the ions. Interaction
3176 region forces perturb the betatron oscillations but do not appear to lead to instabilities.

Detection will make use of the 180° coincidences between the final electrons. Background rates have been evaluated on the basis of a mock-up experiment carried out using the present Stanford accelerator. The expected counting rate at 1 Bev centre of mass energy is 1.3 counts/second at 35 degree scattering angle and 0,32 counts/second at 90 degree scattering angle. This means that a 3% accuracy giving a cut-off distance of 3×10^{-15} cm appears feasible.

The magnets, radio frequency systems and vacuum systems are under construction and the actual experiment can be attempted in 1960.

I should like to report on an experiment on the scattering of positrons by electrons carried out by Poirier, Bernstein and Pine[7] at a laboratory positron energy of 200 Mev. This experiment has of course no relation to the high momentum questions regarding QED since the invariant moment transfer is only 10 Mev.

A positron beam is formed as shown in Fig. 2. A copper converter is placed approximately half way in the electron linear accelerator at Stanford to produce

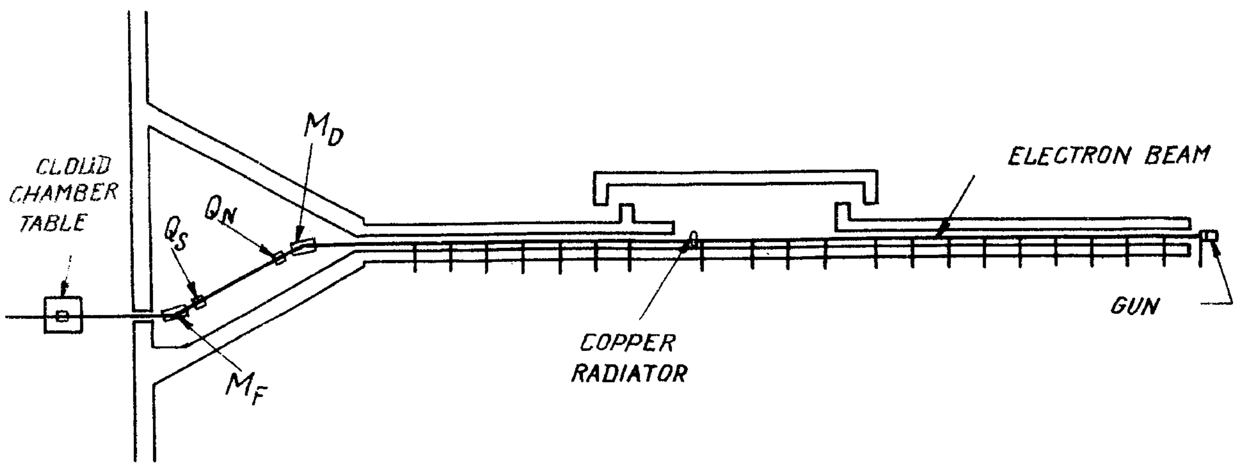

Fig.2. Diagram of formation of positron beam from the linear accelerator.

a photon-electron-positron cascade. The positrons are accelerated by reverse phasing of the remainder of the accelerator. The positron beam is then focussed into a flat ribbon and passed into a beryllium scatterer; the scattered positrons and recoil electrons entering a diffusion cloud chamber. Electron-positron scattering events are identified from the kinematics; rather complex analysis is necessary to discriminate against background events.

The theoretical cross section differes from the Rutherford cross section by the addition of a term corresponding to the magnetic scattering due to the Dirac moment and a term due to the presence of virtual annihilation. This term was originally added by Bhaba. Fig. 3 shows the cross section as given by the various theories plotted against the fraction of the incident

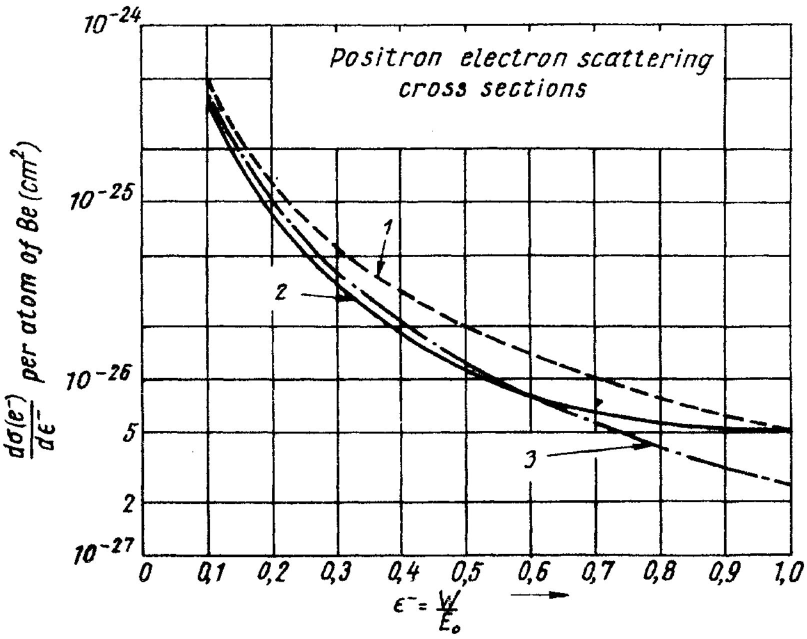

Fig.3. Positron-electron scattering cross-sections.

Theoretical curves shown are:

1- Rutherford scattering; 2-Bhaba formula;

3 Bhaba formula without annihilation term.

energy received by the recoil electron. A rather odd theoretical result is the fact that the particle-antiparticle cross section for a spin 0 particle is the same as that of a Dirac paticle in the relativistic limit. Fig. 4 shows the final data, in good agreement with the Bhaba theory. If the virtual annihilation diagram is omitted, seriously disagreement with the data results in

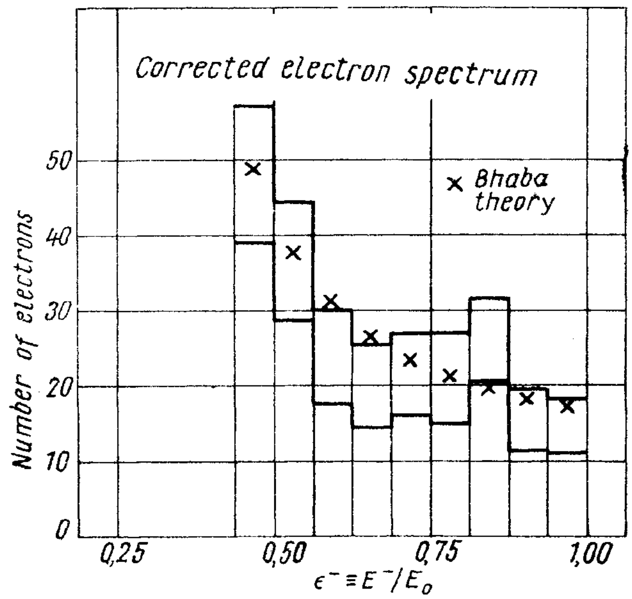

Fig.4. Experimental results of Poirier, Bernstein and Pine on electron-positron scattering at 200 Mev. Lower and upper experimental limits are shown as well as the values calculated from Bhaba theory.

the region of high momentum transfer. (Similar conclusions can be drawn from positronium energy levels). The absolute cross section is slightly lower than the theoretical value; this is probably due to the radiative corrections which have not been fully computed.

I now turn to the work of Varfolomeyev[8] and others dealing with the Bremsstrahlung of electrons in the energy range from 10^{11} to 10^{13}ev. As you recall at these energies modifications of the Bethe-Heitler formula 3176 are expected due to multiple scattering of the primary electron during the radiation process the Landau-Pomeranchuk effect and also due to the "density effect" of the medium (Ter-Michaeljan). It has been shown that these effects should be particularly noticeable in terms of the frequency of occurence of softer photons. Hence the authors made an analysis of the frequency distribution of positron-electron pairs at lower energies under more than a radiation length in an emulsion stack.

The authors analysed 15 such showers; the primary energy was determined by the number of particles in the shower at greater depth and the "cancellation" effect of the positive and negative electrons on the density of ionisation. Fig 5 shows typical experimental data of the frequency distribution of pairs of electrons of energy greater than 1.5 Mev compared with either the calculations according to Bethe-Heitler Bremstrahlung spectra or the curve calculated according to the formula of Migdal which takes into account both of the effects of the medium mentioned above. A test greatly favours the second type curves.

Perkins and collaborators repeated similar experiments using, however, different data handling methods; their data also confirm the Migdal calculations (see Proceed. of the 1959 Cosmic Ray Conference in Moscow).

And now I would like to report two papers of the research group at the synchrocyclotron at Dubna on positron electron pairs from neutral pion decays; this subject is of course only remotely connected with our main topic.

Budagov[9] and others have tabulated the angular and energy distributions of 27 Dalitz pairs resulting from the decay of neutral pions generated by charge exchange scattering of negative pions in a hydrogen diffusion chamber. 90.000 pictures were scanned. The fraction

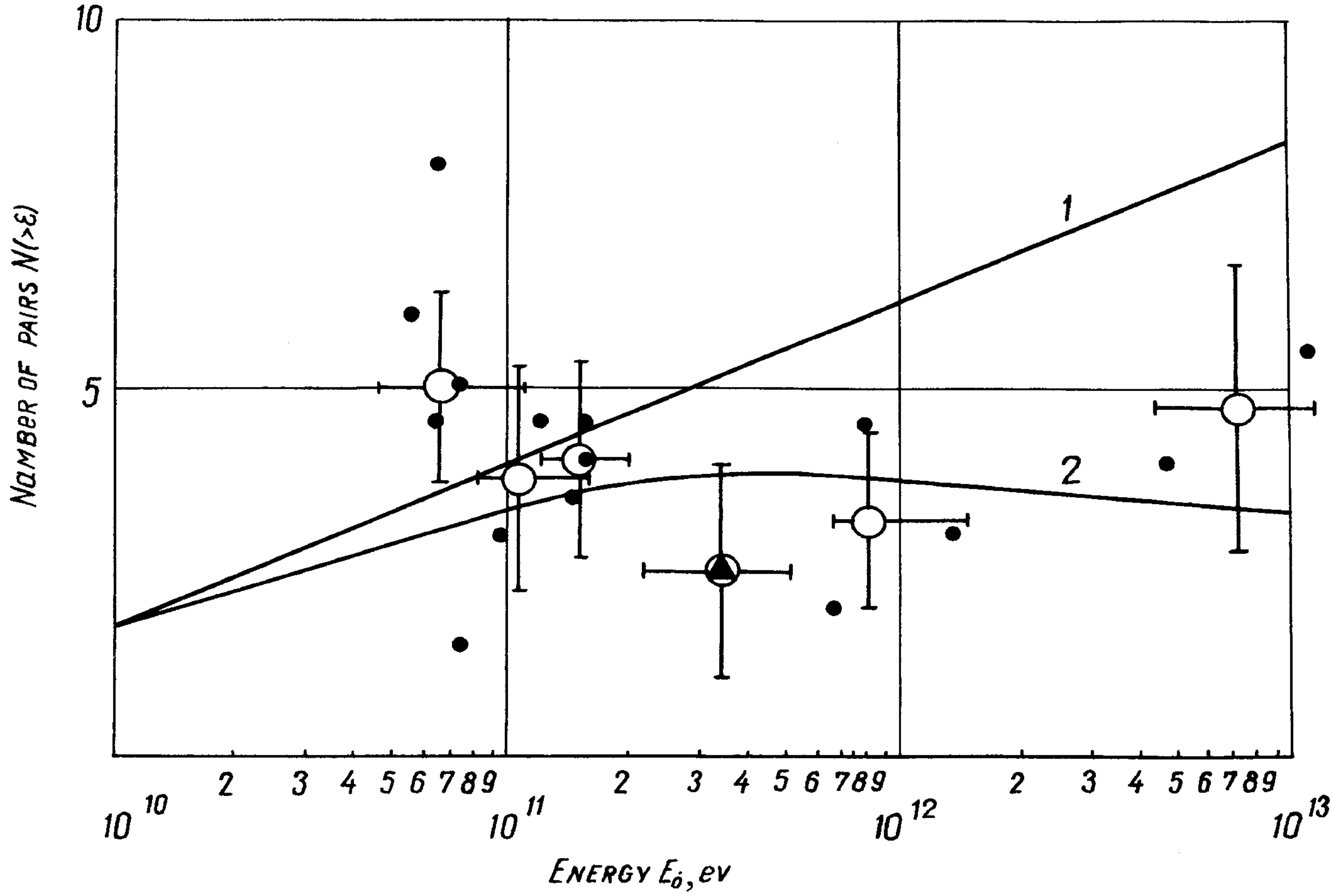

Fig.5. Plot of number of cascade pairs of energy above 1.5 Mev created at the depth up to 1 c.u. as a function of the energy of the primary electrons E_0 of 15 soft showers according to Varfolomeyev and others. The Bethe-Heitler Bremsstrahlung spectra were used in calculation of the curve 1; the curve 2 is calculated according to Migdal's formula. • - the experimental results of separate shower, ⊢○⊣ the same experimental results averaged according to several schowers.

3176

of Dalitz pairs as compared to ordinary two photon decays was found to be

$$\frac{\pi^0 \rightarrow e^+ + e^- + \gamma}{\pi^0 \rightarrow 2\gamma} = 0{,}0117 \pm 0{,}015$$

in agreement with the theoretical value of 0.0118. The energy and angular distributions are also in good agreement. Fig. 6. shows an histogram of the distribution in

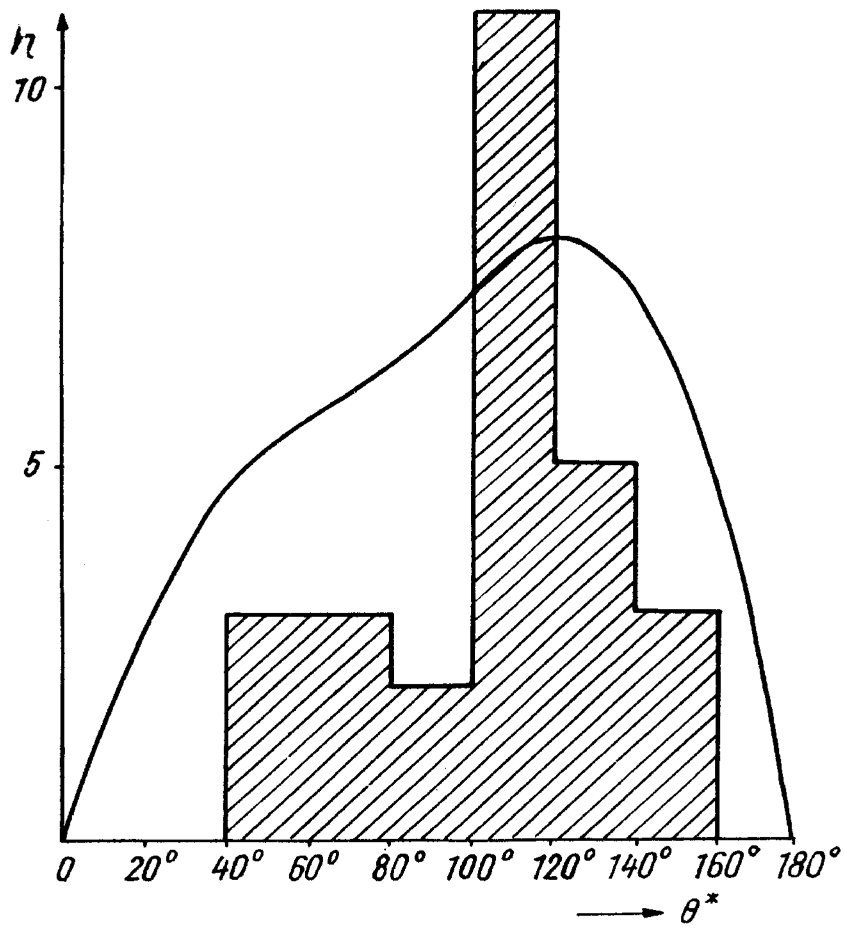

Fig.6. Histogram of angle between electron ~~and positron~~ for 27 Dalitz pairs ~~from~~ neutral pion decay. Solid curve ~~is~~ the theoretical curve of ~~Dalitz.~~

angle between the positive and negative electrons and Fig. 7 shows the distribution in the momentum transfer

3176

$$q^2 = (E^+ + E^-)^2 - (p^+ + p^-)^2$$

Theoretical curves are given for comparison.

None of the pictures are kinematically non-consistent with a $\pi^0 \rightarrow e^+ + e^-$ decay. One example of a double Dalitz pair $\pi^0 \rightarrow (e^+ + e^-) + (e^+ + e^-)$ was seen. As you will recall such an event was seen

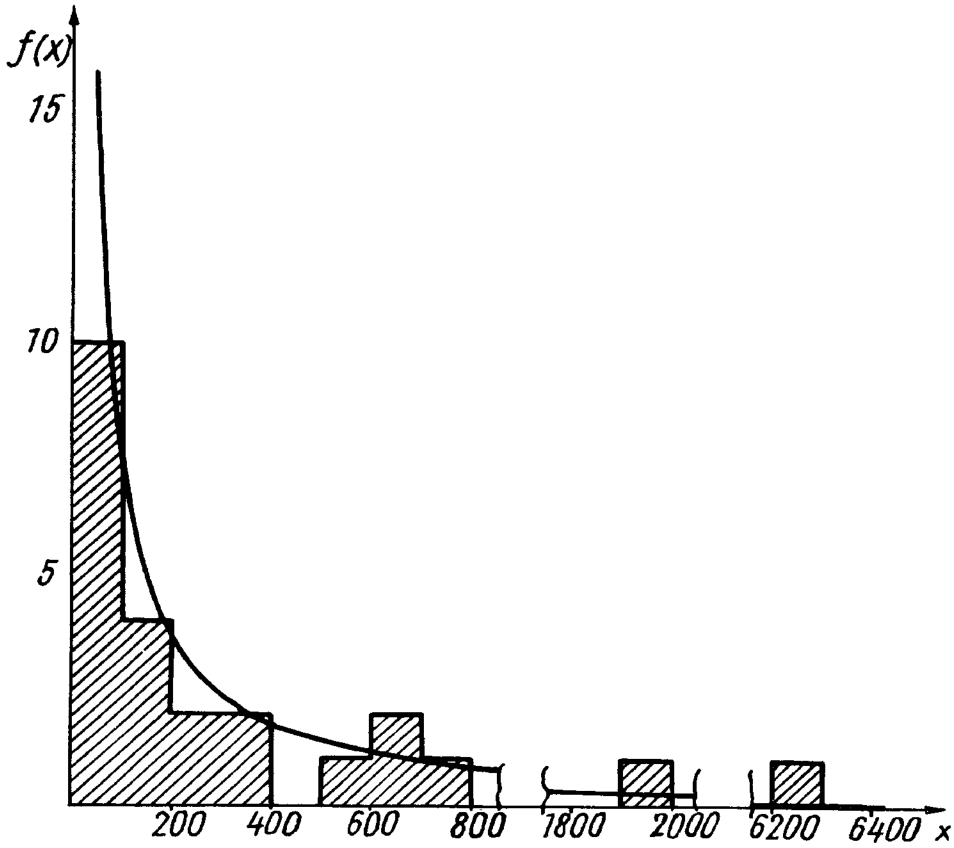

__Fig.7.__ Histogram of frequency of occurance of total four-momentum of Dalitz pairs from neutral pion decay. Solid curve is theoretical curve of Dalitz.

earlier by the Princeton cloud chamber group as a product of K_{π_2} event. It is of course of interest to search for a larger number of events in order to determine the correlation between the planes of decay of the two pairs.

Similar work is under way by Steinberger and collaborators at Columbia University. They have obtained 3176 a large number of double-Dalitz pairs in a bubble-chamber, sufficient to determine the parity of the neutral pion. The work is still in progress.*

2. Experiments on Nucleon Structure

I shall now describe the new material bearing on the nucleon structure problem, in particular on the electromagnetic structure of the neutron. The following methods are available for this purpose:

1) $e + D \rightarrow e' + p + n$ (quasi-elastic scattering on the deuterium)

2) $e + p \begin{cases} \nearrow \pi^{0} + p + e' \\ \searrow \pi^{+} + n + e' \end{cases}$ (inelastic electron scattering in hydrogen)

3) $e + D \rightarrow e' + D$ (elastic electron scattering in deuterium)

The new work using process (1) will be described by Prof. Hofstadter in a separate report. No progress on method (2) can be reported here although work is in progress. I will therefore turn to method (3), which has led to fruitful results during the last year due to the work of J. Friedman and H. Kendall.

Friedman and Kendall [10] have completed two experiment of a program to determine the charge and magnetic properties of the deuteron and the magnetic structure of the neutron. The two relevant reactions are process (3) above and the process of "elastic"

3176 * See: Samios, Schwartz, Steinberger. Phys. Rev. Letters, 3, 525, 1960.

photoproduction of neutral pions from the deuteron near resonance:

$$4)\quad \gamma + D \longrightarrow \pi^0 + D\,.$$

It can easily be shown that, if the elastic scattering is predominantly electric, the cross section of reaction (3) is of the general form

$$\frac{d\sigma}{d\Omega} = \sigma_R \left|F_{1D}\right|^2 \times \left|F_{1p} + F_{1n}\right|^2$$

where F_{1D} is the deuteron form factor for the electric charge distribution, F_{1p} and F_{1n} are the corresponding neutron and proton charge form-factors and σ_R is the scattering cross section for a point charge. You will recall that the form-factors are defined such that the nucleon current is given by

$$e\left\{F_1(q^2)\,\gamma_\mu + \frac{K}{2M}\,F_2(q^2)\,\gamma_\mu\left(\gamma_\gamma q_\gamma\right)\right\}$$

where K is the anamolous part of the nucleon magnetic moment; $F_1\ (q^2)$ thus includes scattering from the charge and the Dirac moment. If the scattering is both magnetic and electric then the corresponding terms in the Rosenbluth scattering formula have to be multiplied by the above factors or the corresponding maghetic terms.

To resolve the magnetic from the electric scattering, large scattering angles must be chosen where, however, the cross sections are small. Measurements were carried out by Friedman, Kendall and Gram at a laboratory angle of 145° with an incident electron energy of 260 Mev, corresponding to a four-momentum transfer of 2.24 fermi^{-1}.

The measured value of the cross section per unit solid angle was 1.91×10^{-34} cm^2/ster. The experiment was run at an over-all momentum resolution of 0.6% which is sufficient to resolve clearly the elastic peak from the inelastic events of the type (1), that is

$$e + D \longrightarrow e' + n + p$$

Fig. 8 shows a typical curve. At the values of angle and energy chosen about 45% of the scattering is magnetic.

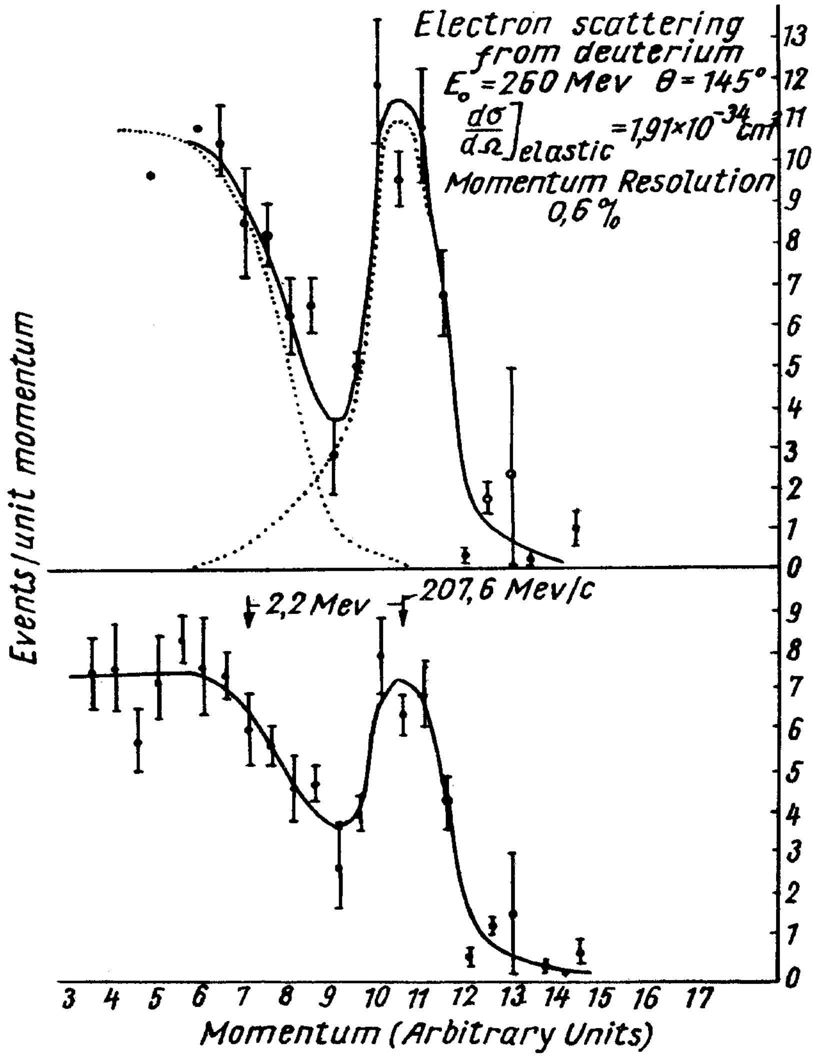

Fig. 8. Elastic peak of 260 Mev electrons scattered in deuteron at 145° according to Friedman and Kendall. The momentum, resolution is 0.6%. Note the beginning of the inelastic peak

$$\frac{d\sigma}{d\Omega}_{elastic} = 1{,}91 \cdot 10^{-34}\ \text{cm}^2.$$

The cross section for the inelastic reaction (1) is sensitive to the interaction between the neutron and proton in the final state, since it is essentially a low energy photo-disintegration process. No satisfactory theoretical fit of the curve corresponding to reaction (1) has been made in the region where the final state interaction is dominant. It is hoped that this will be possible and give additional information concerning nucleon-nucleon interaction.

At the particular setting of angles and energy the scattering is very sensitive to the magnetic radius of the neutron since the proton and neutron magnetic scattering amplitudes almost cancel. Fig. 9 shows the measured ratio

$$R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} \Big/ \left[F^2(q^2)\,\sigma_{Mott}\right]$$

plotted against an assumed neutron magnetic radius based on an exponential model. F_{1n} is assumed zero and the experiment is used to determine an RMS radius of the neutron based on an exponential model. Friedman and Kendall using repulsive core wave functions, find that the fit of figure 9 corresponds to the following value of the RMS radius of the magnetic form factor of the neutron, based on exponential model:

$$a_n = \left[0{,}76 \begin{smallmatrix} +\,0{,}030 \\ -\,0{,}025 \end{smallmatrix}\right] \text{ fermi}$$

The errors shown are statistical. Systematic errors are estimated at $\pm$ 0.05f. As is shown in Fig. 10, the result is less sensitive to the assumption that the electric form factor of the neutron should be exactly zero than are the measurements of Hofstadter and Sobottka on the magnetic radius of the neutron based on a direct sub-

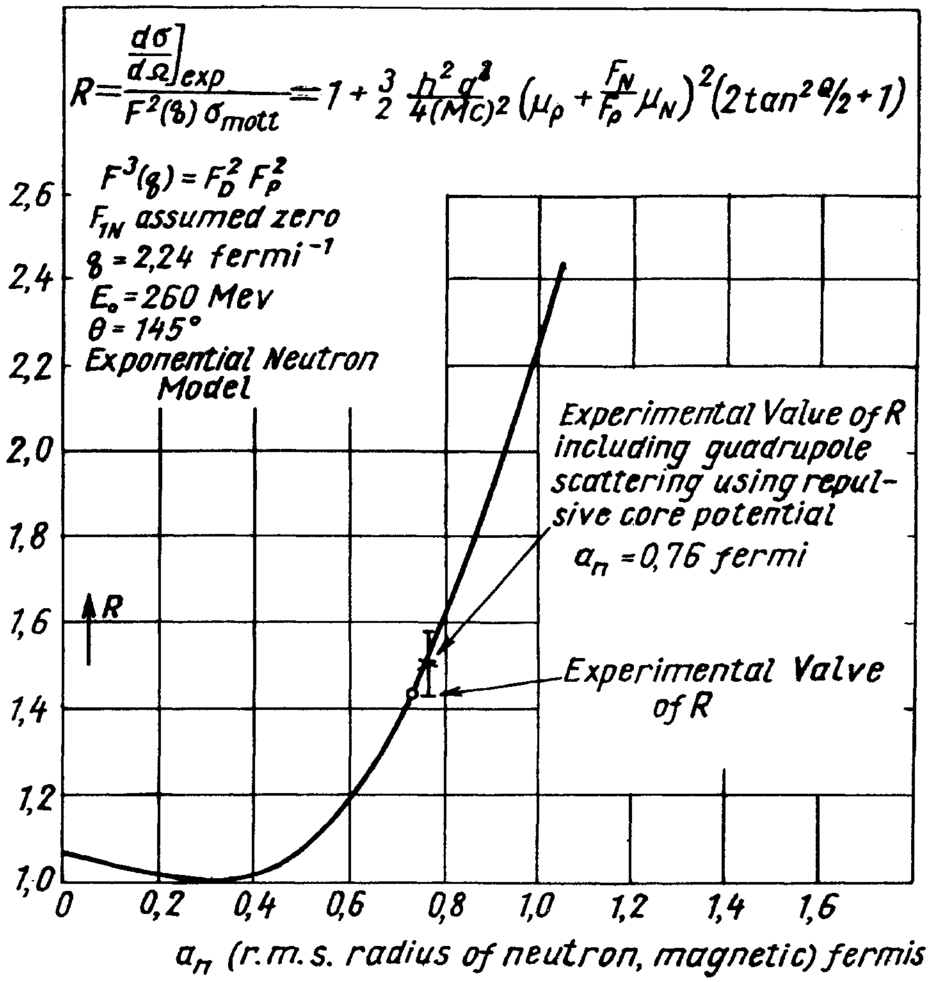

Fig.9. The differential elastic cross section for electrons on the deutron,normalized to the Mott cross section times the product of squares of the deutron and proton form factors

$$R=\left\{\frac{d\sigma}{d\Omega}_{exp}\right\}\Big/\left\{F^2(q^2)\sigma_{Mott}\right\}$$

plotted as a function of an assumed neutron magnetic radius (in exponential neutron model)

$$R=1+\frac{3}{2}\frac{\hbar^2 q^2}{4(Mc)^2}\left(\mu_p+\frac{F_N}{F_p}\mu_n\right)^2\left(2\tan^2\theta/2+1\right)$$

$$F^2(q)=F_D^2\,F_P^2,\quad F_{1N}=0,\quad q=2{,}24\ \text{fermi}^{-1},$$

$$E_0=260\ \text{Mev},\quad \theta=145°$$

traction method between the deuteron quasi-elastic scattering and proton-elastic scattering. There is, however, an uncertainty due to the contribution of scattering from the electric quadrupole moment of the deuteron.

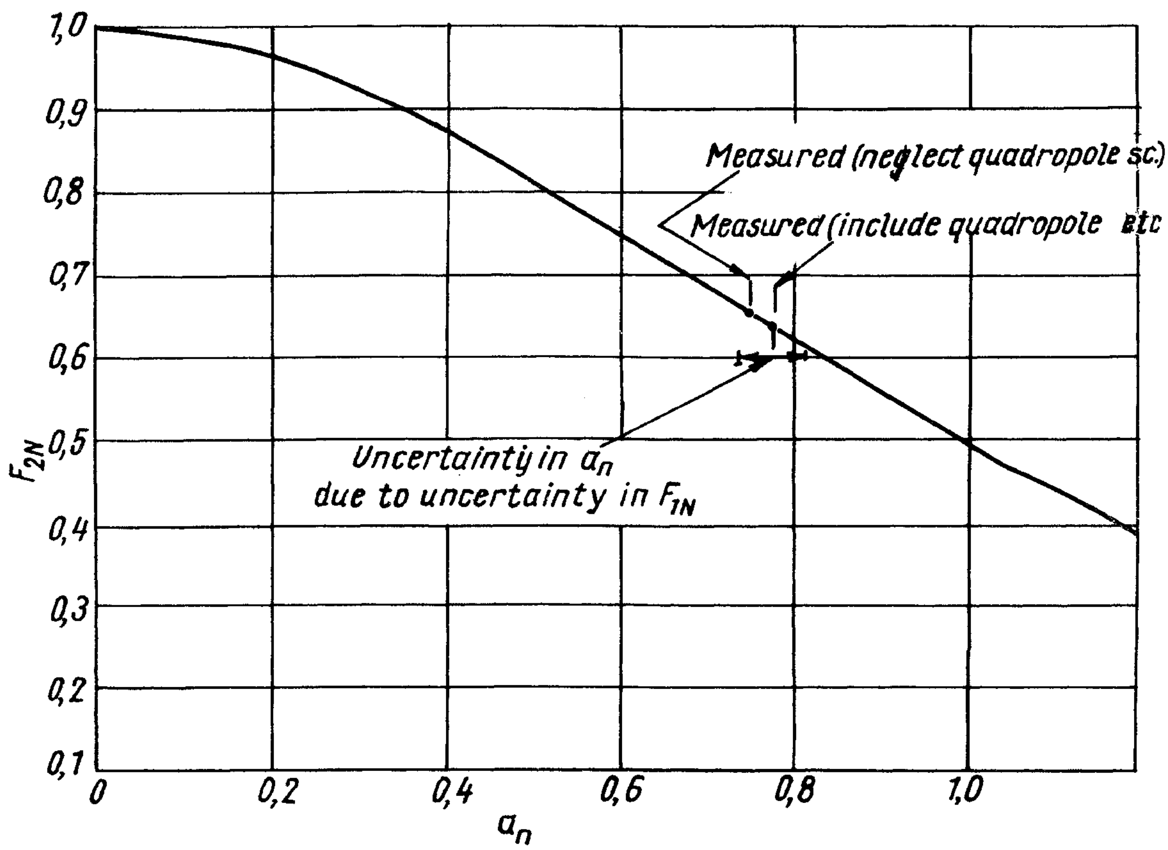

Fig. 10. The form factor curve of the magnetic moment distribution of the neutron as determined by elastic electron scattering E_o=260 Mev θ =145°. Contributions from quadrupole scattering and an assumed neutron charge distribution are indicated:

1-measured point (neglecting quadrupole scattering); 2- including quadrupole scattering; 3 - uncertainty in a_n due to uncertainty in F_{in}.

The "elastic" neutral pion production depends on the quantity:

$$|f_n + f_p|^2 |F_D|^2 .$$

Here f_n and f_p are the production amplitudes of neutral pion photo-production and F_D is the magnetic form factor of the deuteron.

3176

The amplitudes f_n and f_p depend on the energy given to the pion-deuteron system while $(F_D)^2$ depends on the momentum transfer to the system. The momentum transfer and the energy can be independently controlled by appropriate choice of the deuteron angle and energy. We are making here use of the fact that neutral photo pion production proceeds almost 100% via magnetic dipole absorbtion. By detecting momentum analyzed deuterons in an energy sensitive detector the form factor of the deuterons has been found as a function of momentum transfer for a center of mass photon energy of 450 Mev. Preliminary results for momentum transfers from 1.7 to 2.7 fermi^{-1} show only a qualitative agreement between the magnetic moment and electric charge form factors of the deuteron, (see Fig. 11). Specifically the analysis indicates a less steep momentum dependence of the form factor than it is expected from the repulsive core deuteron wave functions which give agreement with the elastic scattering at small angles as measured by McIntyre. The disagreement may possibly be due to a larger contribution of the D-state to the magnetic form factor than to the electric form factor.

The experiment can be programmed to keep the γ-ray energy constant and vary the form factor curve by varying the momentum transfer, or, alternatively, to keep the form factor constant and measure the photoproduction resonance by varying the energy. As is shown in Fig. 12, the resonance is wider than that observed from the free proton; this is presumably a consequence of the internal momentum of the deuteron.

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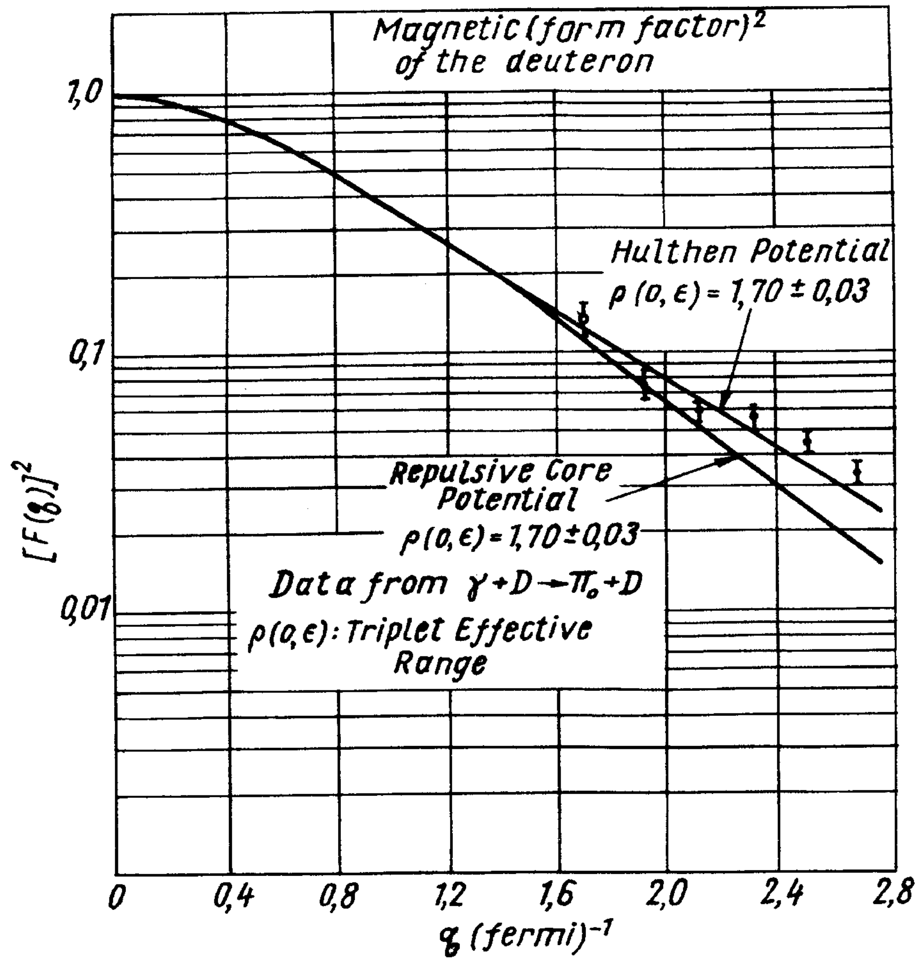

Fig.11. The square of the magnetic form factor of the deuteron as determined from coherent neutral photomeson production. The data have been normalized to the predicted curves at the low - q points: 1 - Hulthen potential, $\rho(0,\epsilon)=1,70\pm0,03$; 2 - repulsive core potential $\rho(0,\epsilon)=1,70\pm0,03$, where $\rho(0,\epsilon)$ is the triplet effective range.

It has recently been possible to use the Cornell 1.2 Bev/c electron synchrotron [11] to conduct elastic electron scattering experiments from the proton. A target of polyethylene is placed in one of the straight sections and either the scattered electrons or recoil protons are

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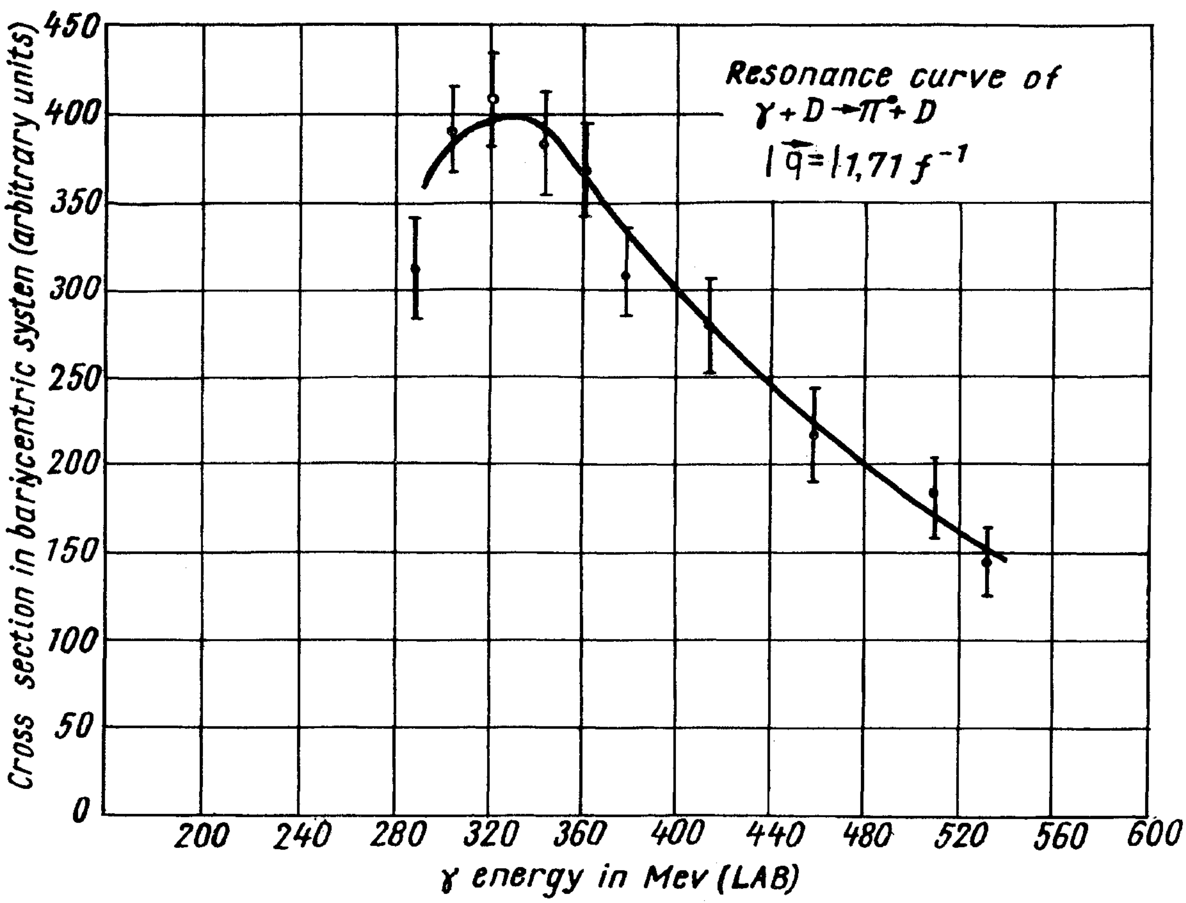

Fig.12. Photoproduction resonance from reaction $\gamma + D \rightarrow \pi^0 + D$ The momentum transfer of 1.71 $(\text{fermi})^{-1}$ is constant for these data.

detected with a simple quadrupole lens spectrometer. The observed cross sections are made absolute by monitoring the external X-ray beam. Absolute monitoring is good to about 10%; in the data given in Fig. 13 the 600 Mev point has been normalized to the data of Hofstadter and collaborators. The resultant cross sections can be expressed as a proton form factor (if we assume that the electric and magnetic form factors are the same).

Fig. 13 shows the form factor plotted against the square of the momentum transfer. The theoretical curve is the usual exponential model corresponding to the
3176 RMS radius of 0.8 fermi. Note that the data are fully

consistent with the results of Hofstadter and collaborators. The present experimental arrangement permits measurements to be carried out to values of 40 for the square of the momentum transfer in fermi^{-2}.

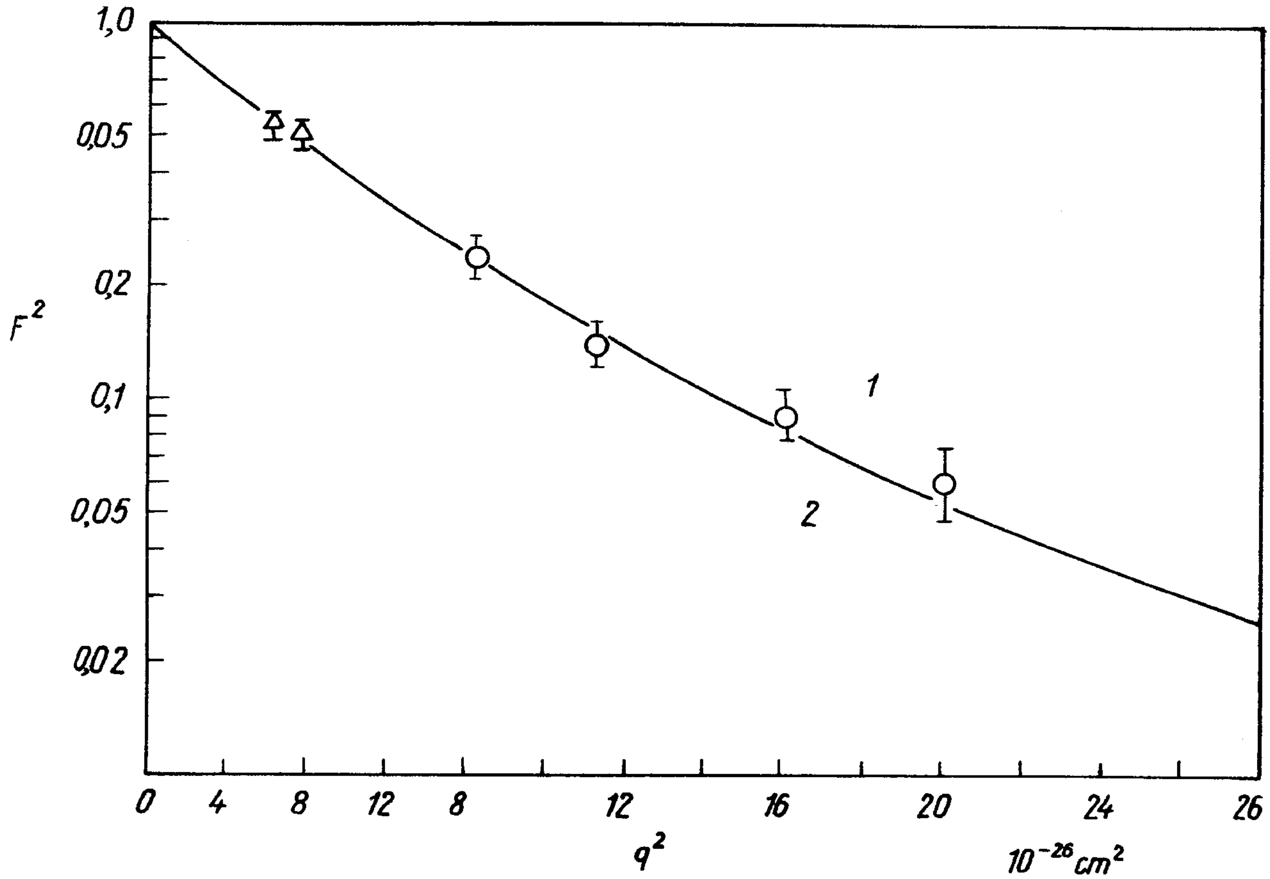

Fig.13. The square of the proton form factor (electric and magnetic assumed equal) as obtained from electron scattering from the internal beam of the 1.2 Bev Cornell synchrotron. The solid curve corresponds to an exponential model of 0.8 fermi RMS radius, 1 corresponds to a = 0.7 fermi, 2 corresponds to a= 0.9 fermi.

Some additional information on the proton structure has been obtained by study of the proton-Compton effect at the effective energy about 56 Mev by Goldansky[12] and collaborators. Their work is in good agreement with the extensive earlier work on the subject. The experiments on photon scattering are in general more complicated to interpret than electron scattering experiments since two photon lines rather than one line connect to the nucleon structure. It is customary to express the effect of the two photon diagrams by a "polarizability". This quantity introduces correction factors proportional to the square of the photon energy into the usual formulae for the proton-Compton effect. Specifically the cross sections for the proton-Compton effect becomes

$$\sigma(\theta)=\frac{1}{2}r_0^2\left(\frac{\gamma'}{\gamma}\right)^2\Big\{\left[(1-A_E\gamma^2)^2+(A_M\gamma^2)^2\right](1+\cos^2\theta)-$$
$$-4A_M\gamma^2(1-A_E\gamma^2)\cos\theta+\gamma\gamma'(1-\cos\theta)^2+\gamma\gamma' f(\theta)\Big\}$$

where the Powell formula, which includes the Compton scattering by the anomalous magnetic moment of the proton, has been corrected by the magnetic and electric polarizabilities A_M and A_E (in units $\frac{e^2}{\hbar c}\left(\frac{\hbar}{Mc}\right)^3=6{,}8\cdot10^{-44}\,cm^3$).

$$f(\theta)=42{,}88-34{,}63\cos\theta-3{,}12\cos^2\theta$$

Examination of the equation shows

that the scattering in the forward direction is sensitive to the sum of the polarizabilities while the measurement in the backward direction is sensitive to the difference. The experimental conditions did not permit measurements in the forward direction and therefore the corresponding values had to be taken from the dispersion theoretical calculations of Cini and Stroffolini. Data at angles from 45° to 150° were taken using a customary anti-

3176

coincidence, converter and coincidence telescope arrangement. The results are shown in Fig. 14. A least square fit of this curve gave a value of A_E equal to

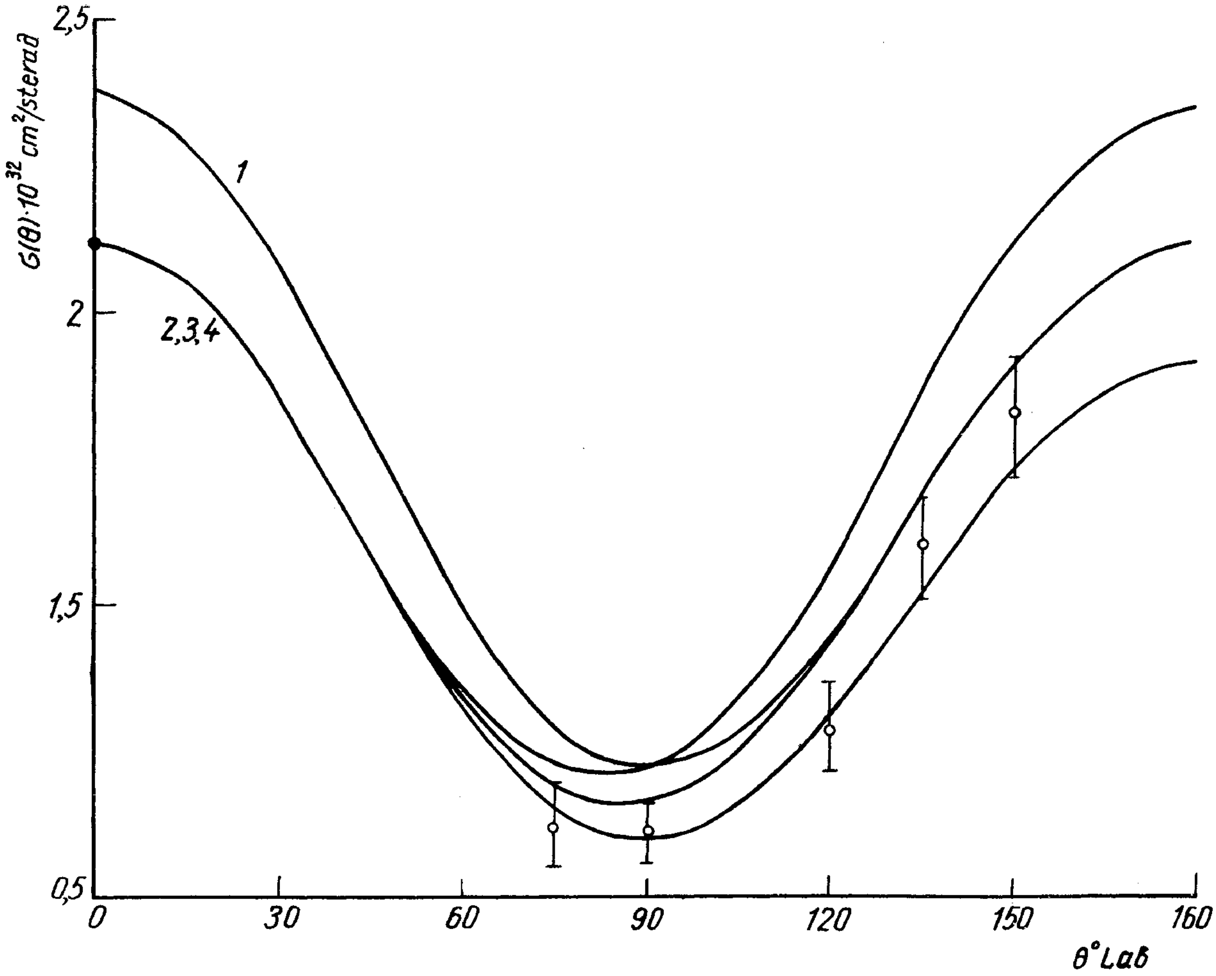

Fig.14. Experimental cross section of proton Compton scattering at about 56 Mev according to Goldanskii and others.

Curve 1 $A_E = A_M = 0$

Curve 2 $A_E = 0, \quad A_M = 16$

Curve 3 $A_E = A_M = 8$

Curve 4 $A_E = 16, \quad A_M = 0$

$(9 \pm 2) \times 10^{-43}$ cm^3 and a value for the magnetic polarizability several times less and compatible within the experimental errors with zero. The experimental value 3176 of the electric polarizability corresponds to the RMS unit charge dipole moment fluctuation equal to $\sim 2.10^{-14}$ cm.

To summarize the present situation, we can state:

1). No new data on large momentum transfer QED have been introduced and thus no experiments disagreeing with QED are in existence.

2). Several new experiments in agreement with theory in low momentum transfer QED have been performed.

3). The general experimental picture in nucleon structure remains unchanged; our knowledge on the magnetic structure of the neutron has gained in accuracy.

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3176