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ELECTROMAGNETIC INTERACTIONS

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During the last two years a large number of papers have been published on the subject of electromagnetic interactions. These were mainly devoted to clarifying and developing old ideas.

This period was marked by great experimental progress. I shall mention only the theoretical reports directly connected with experimental work, particularly in the fields which have been most fully represented at this conference.

Electromagnetic interactions are usually put under a separate heading, and, moreover, since the last conference there have been the Boston and Stanford conferences, which were entirely devoted to high energy electromagnetic interactions. There are important reasons for this separation. On the other hand, the relation between electromagnetic interactions and high energy physics as a whole should be borne in mind. The successes and errors of electromagnetic theory exactly reflect the developments taking place in the theory of elementary particles. Let us take as an example the method of complex angular momentum, which reached a climax at the time of the last conference. This was fairly clearly reflected in the theory of electromagnetic interactions.

At the last conference, a series of interesting experimental set-ups was formulated in connection with this method. One of the most pressing questions posed in this respect was that concerning the "Reggization" of the photon.

The experimental data from electron-proton scattering showed that the slope of the photon trajectory is in any case much smaller than that of the vacuum trajectory.

The fate of the other experimental proposals based on the complex angular momentum method in the theory of electromagnetism largely coincides with that of similar proposals in the strong interaction theory.

One of the most outstanding achievements of high energy physics is the successful classification of strong interactions on the basis of the SU_3 group. The extension of this symmetry to electromagnetic interactions leads to a series of interesting conclusions, which open the way to a reliable checking of its validity. This is one of the questions deserving the most attention.

Theoretical analysis of electromagnetic interactions continues to be based on: perturbation theory, dispersion relations, resonance and pole approximations. Moreover, it is very characteristic of electromagnetic interactions that the main source of information on isoscalar parts of the e - N and γ - N interaction amplitudes is the study of reactions on bound systems (mainly on deutons).

In this connection, work devoted to the improvement of the impulse approximation is very much in evidence.

In most cases, the aim of these investigations is to determine the interaction constants and other characteristics of particles and resonances. Data about these characteristics may create a link (if only in the resonance approximation for the present) between phenomena which have so far been regarded as separate. Classification of these data will help us to understand the symmetries existing in nature, and in particular to check SU_3 symmetry.

This aim constitutes a strong link between research on electron scattering and meson photoproduction and, to a certain extent, electrodynamics in the region of high momentum transfers. This report is devoted to these subjects.

1. Unitary Symmetry

The extension of unitary symmetry to electromagnetic interactions (Coleman-Glashow and Cabibbo-Gatto)[1/] is based on the fact that the electromagnetic current transforms in the same way as a tensor operator, associated with a regular representation of SU_3 groups. In other words, the electromagnetic interaction removes the degeneracy in SU_3 symmetry, In particular, it breaks isotopic symmetry, which is part of SU_3 symmetry.

However, the electromagnetic interaction does not break a certain SU_2 sub-group of the SU_3 group, which forms V-spin symmetry quite similar to isospin symmetry. The V-spin and the electric charge form a set which is exactly similar to the isospin-hypercharge set.

The two sub-groups are mathematically equivalent.

To the isospin multiplets for a given hypercharge in the second sub-group correspond V-spin multiplets for a given electric charge in the first sub-group.

Systematic study of this correspondence carried out by Levinson, Lipkin and Meshkov /2/ and also Macfarlane and Sudarshan /3/, showed a simple way of obtaining relations depending on the symmetry of the first sub-group from the relations of the second sub-group. The conservation of V-spin gives relations which are valid to any order in e^2/hC. Matrix elements, to first order in e^2/hC (one-photon vertices and processes), are governed by relations which are exactly similar to the Okubo Gell-Mann first order formula. Matrix elements of the second order (mass splitting, 2 -photon processes) are governed by the second order Okubo formula.

Examples of relations between matrix elements, neglecting "semi-strong" SU_3-breaking interactions :

a) Photoproduction [2]

$$\frac{\langle \gamma p | N^{*0} \pi^+ \rangle}{\langle \gamma p | Y^{*0} K^+ \rangle} = \frac{\langle \gamma p | N^{*0} \rho^+ \rangle}{\langle \gamma p | Y^{*0} K^{*+} \rangle} = -\sqrt{2}$$

$$\frac{\langle \gamma n | N^{*-} \pi^+ \rangle}{\langle \gamma n | Y^{*-} K^+ \rangle} = \frac{\langle \gamma n | N^{*-} \rho^+ \rangle}{\langle \gamma n | Y^{*-} K^{*+} \rangle} = -\sqrt{3}$$

$$|\langle \gamma p | \Sigma^0 K^+ \rangle| + \sqrt{3}\, |\langle \gamma p | \Lambda K^+ \rangle| \geq \sqrt{2}\, |\langle \gamma p | n \pi^+ \rangle| \geq \big|\, |\langle \gamma p | \Sigma^0 K^+ \rangle| - \sqrt{3}\, |\langle \gamma p | \Lambda K^+ \rangle| \,\big|$$

b) One-photon electromagnetic decay

$$\frac{1}{\sqrt{3}} \langle \varphi | \pi^0 \gamma \rangle = -\langle \varphi | \eta \gamma \rangle = \langle K^{*+} | K^+ \gamma \rangle = -\frac{1}{2} \langle K^{*0} | K^0 \gamma \rangle = \langle \rho^+ | \pi^+ \gamma \rangle \quad (d)$$

2-photon electromagnetic decay

$$\langle \eta | 2\gamma \rangle = -\frac{1}{\sqrt{3}} \langle \pi^0 | 2\gamma \rangle$$

c) Relations between form factors (Coleman-Glashow, Cabibbo-Gatto)

$$\left.\begin{aligned} &\mu(\Sigma^+) = \mu(p)\,; \quad \mu(\Lambda) = \tfrac{1}{2}\mu(n)\,; \quad \mu(\Xi^0) = \mu(n) \\ &\mu(\Xi^-) = \mu(\Sigma^-) = -[\mu(p) + \mu(n)]\,; \quad \mu(\Sigma^0) = -\tfrac{1}{2}\mu(n) \end{aligned}\right\} (m)$$

$$\mu(\Sigma^0, \Lambda) = -\frac{\sqrt{3}}{2}\mu(n)$$

d) Relations between electromagnetic splittings of baryon multiplets

$$\delta M(\Xi^-) - \delta M(\Xi^0) = \delta M(\Sigma^-) - \delta M(\Sigma^+) + \delta M(p) - \delta M(n)$$

The forbiddenness of certain electromagnetic processes is of particular interest, for instance

$$Y_1^{*-} \to \Sigma^- + \gamma \,, \qquad \Xi^{*-} \to \Xi^- + \gamma$$

or the $V \to \gamma$ transition, where V is a unitary-singlet vector meson; the latter forbiddenness is particularly interesting from the point of view of the study of the $\varphi - \omega$ mixing.

Great possibilities for studying unitary symmetry on the basis of its extension to magnetic interactions were pointed out yesterday in the excellent report by Professor Salam, especially in connection with the "triality" quantum number.

However, the real relations are greatly complicated by the "semi-strong" interaction which breaks the V-spin symmetry and in particular the above-mentioned relations.

Thus, when calculating the width of $\eta \to 2\gamma$, the considerable difference between the mass of the π^0 and η-meson should be taken into account:

$$W(\eta \to 2\gamma) = \frac{1}{3}\left(\frac{m_\eta}{m_\pi}\right)^3 W(\pi^0 \to 2\gamma).$$

As a result, the lifetime of the η -meson is found to be 2.4×10^{-18} sec, i.e. two orders of magnitude less than the lifetime of the π^0 meson.

Calculations of η -meson photoproduction in the nucleon field of nuclei (Belletini et al.)/4/ and in the reaction $e^+ + e^- \to \eta + \gamma$ (Celeghini and Gatto)/5/ show that these effects are very difficult to measure, but it is interesting to evaluate even a lower limit on the lifetime. Multiplet mass corrections will also affect the relation between the form factors.

In addition to the mass corrections, it should also be taken into account that the physical particle states include a mixture of pure states (due to the symmetry breaking interaction) and that the relations may take a more complex form.

Okubo has shown that, even if the symmetry breaking interaction is taken into account, certain relations still persist, for example instead of (d) we have:

$$\frac{1}{\sqrt{3}}\left[\langle\varphi|\pi^0\gamma\rangle + \langle\rho^0|\eta\gamma\rangle\right] = \langle\varphi|\eta\gamma\rangle - \frac{4}{3}\langle K^{*0}|K^0\gamma\rangle + \frac{1}{3}\langle\rho^0|\pi^0\gamma\rangle$$

and instead of (m):

$$\mu(\Sigma^0,\Lambda) = \frac{\sqrt{3}}{6}\left[\mu(\Sigma^0) + 3\mu(\Lambda) - 2\mu(\Xi^0) - 2\mu(n)\right]$$

The successful use of these formulae for electromagnetic mass splitting has led many physicists to endeavour to estimate the separate mass differences from dynamic approaches.

2. Interaction of electrons with nucleons

As is known, the electron-nucleon interaction is satisfactorily described by the diagram given below more accurately than it is at present possible to test by experiment.

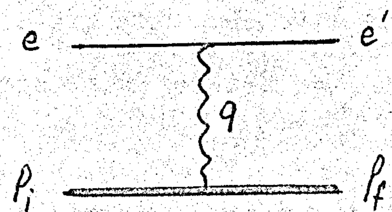


Fig. 1

The transition amplitude is then expressed by two relativistically invariant parameters, the Dirac form factor $F_i(q^2)$ and the Pauli form factor $F_2(q^2)$ (q^2 is the square of the four-dimensional momentum transfer):

$$\left.\begin{aligned} F_1(0) &= e \\ F_2(0) &= eg_p \end{aligned}\right\} \text{ for protons} \qquad \left.\begin{aligned} F_i(0) &= 0 \\ F_2(0) &= eg_n \end{aligned}\right\} \text{ for neutrons}$$

Linear combinations F_1 and F_2 are more convenient for the analysis of cross-sections:

$$G_E(q^2) = F_1(q^2) - \frac{q^2}{4M^2} F_2(q^2)$$
$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

M is the nucleon mass

In the Breit system, these form factors ~~are made to~~ may represent the space distributions of the charge and the magnetic moment. This interpretation, however, meets with some opposition [6].

The space-like region of q^2 $(q^2 > 0)$ corresponds to the scattering of electrons on nucleons, which is described by the well-known Rosenbluth formula:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \left\{ \frac{G_E^2 + \frac{q^2}{4M^2} G_M^2}{1 + q^2/4M^2} + 2\frac{q^2}{4M^2} G_M^2 \, tg^2 \frac{\theta}{2} \right\} \tag{1}$$

The region $q^2 < -4\,M^2$ corresponds to the annihilation channel $\bar{p} + p \rightarrow e^+ + e^-$; the cross section is described by the formula[7]:

$$\frac{d\sigma}{d\cos\theta_c} = \frac{\pi}{8} \frac{e^2}{(4\pi)^2} \cdot \frac{1}{E\sqrt{E^2 - M^2}} \cdot \left[|G_M|^2 (1 + \cos^2\theta_c) - \frac{4M^2}{q^2} |G_E|^2 \sin^2\theta_c \right] \tag{2}$$

where θ_c is the angle in the centre of mass system and E the total energy of the proton

$$q^2 = -4\,E^2 < -4\,M^2.$$

The form factors are real functions for $q^2 > -4\mu^2$ (where μ is the mass of the meson) and are complex for $q^2 < -4\mu^2$. Thus in the region $q^2 > 0$, the measurement of the differential cross section for e - p scattering gives complete information concerning G_E^p and G_M^p, whereas in the region $q^2 < -4M^2$, polarisation experiments are necessary in order to determine completely the complex form factors G_E and G_M. The polarisation experiments were discussed by Zichichi et al.[7]

At this conference, Bilenkij and Ryndin[9] presented a fairly full analysis of possible polarisation experiments for $\bar{p} + p \rightarrow e^+ + e^-$.

For the sake of simplicity, we have only mentioned the $\bar{p} + p \rightarrow e^+ + e^-$ process but the $\bar{p} + p \rightarrow \mu^+ + \mu^-$ process will also take place and the ratio of the cross section for these processes will be:

$$\sigma_T(\bar{p}p \rightarrow \mu^+\mu^-) \,/\, \sigma_T(\bar{p}p \rightarrow e^+e^-) \approx 1 + 0\,\left(\frac{m_\mu}{E}\right)^4 \approx 1 \,.$$

The measurement of this ratio is a way of checking the electrodynamics of the μ-meson.

What conclusions can be drawn from experimental data on the differential cross sections of e - p scattering ?

The validity of formula (1) can be checked, namely a dependence of the cross section of the form $\frac{1}{\sigma_0}\frac{d\sigma}{d\Omega} = A + B\,tg^2\,\frac{\theta}{2}$.

Within the limits of existing experimental accuracy this checking would not yield much information. Firstly, these results are only the consequence of the smallness of $e^2/\hbar c$ and of the corresponding smallness of radiative corrections. Secondly, the dependence having the form $A + B\,tg^2\frac{\Theta}{2}$ arises not only as the result of the diagram shown in Fig. 1. Corrections of ~~the~~ second order are rather difficult to evaluate, due to strong interaction effects. Particular attention should be paid to "two-photon terms", namely those of the type shown in Fig. 2.

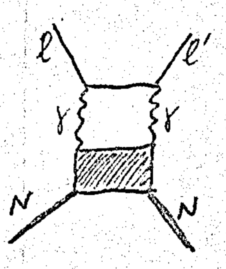


Fig. 2

The shaded section may include meson-nucleon and meson-meson resonances, increasing the part played by two-photon terms. After having taken into account the effects of the πN system resonances, it was found /10/ that the corrections to the formula were within $\sim 1\%$, and that the polarisation of the recoil protons was $< 0.3\%$.

The effect of meson resonances may be considered in the light of the paper by Gourdin and Martin /11/.

Let us consider the origin of the dependence $A + B\,tg^2\Theta/2$. Accordingly let us note the relation between the angles Θ_c

(reaction angle for the annihilation channel in the centre of mass system) and θ (e-p scattering angle in the laboratory system).

$$\cos\theta_c = \left(1 + \frac{1}{1+q^2/4M^2}\,\mathrm{ctg}^2\frac{\theta}{2}\right)^{\frac{1}{2}} \qquad (3)$$

The angular distribution in the annihilation channel for one-photon exchange is:

$$a(q^2) + b(q^2)\,\mathrm{Cos}^2\,\theta_c \qquad (4)$$

which, by the use of (3), leads to the form

$$\mathrm{ctg}^2\frac{\theta}{2}\left[A(q^2) + B(q^2)\,\mathrm{tg}^2\frac{\theta}{2}\right]$$ for the scattering reaction.

The explicit form (4) is due only to the fact that the reaction in the annihilation channel occurs through the state $J = 1$, $P = -1$. Thus the dependence $(A + B\,\mathrm{tg}^2\frac{\theta}{2})$ is the result of more general assumptions than those made when deriving formula (1). This dependence is not violated by any radiative corrections which do not modify the one-photon nature of the exchange. The dependence $A + B\,\mathrm{tg}^2\frac{\theta}{2}$ is also valid for scattering on a system with any spin and even for inelastic processes, for instance the process $e + d \rightarrow p + n + e'$. If the two-photon terms are due to a pion resonance with other values of J and P, the Rosenbluth formula may need correction.

Analysis will show that only resonances with J^P equal to 1^+ and 2^+ (excluding spins above 2) can give an appreciable deviation from the Rosenbluth formula. The deviation will be mainly observed at small ϕ. If the resonance has a mass of 1 BeV and a coupling constant of ~ 1, then for $q^2 = 30\ f^{-2}$ the deviation will be of the order of 10 % (evaluated by Flamm and Kummer[12]).

Thus, the verification of formula (1) for small angles and high energies may reveal the two-photon contribution, although this verification is not effective for certain types of two-photon contributions.

The most effective methods of evaluating two-photon contributions are:

(a) Measurement of the difference between $(e^- - p)$ and $(e^+ - p)$ scattering cross sections - the interference of the one-photon and two-photon terms in these cases is of the opposite sign. This measurement will give an estimate of the real part of two-photon amplitude.

(b) The measurement of the polarisation of recoil nucleons will make it possible to evaluate the imaginary part of two-photon amplitude. Two-photon amplitude has a complex spin structure and, of course, is no longer described by two relativistic invariant parameters.

Form Factors

So far there has been no reason to doubt that radiative corrections fall outside the limits of accuracy of the experiment and that the measurement of $\frac{d\sigma}{d\Omega}$ gives information concerning G_E and G_M. What does this information tell us ?

The values $G_E(q^2)$ and $G_M(q^2)$ found in the experiment on e-p scattering are rapidly decreasing functions of q^2 : of special interest in this connection are the recent experiments involving the maximum values of q^2 so far obtained, which show that when $q^2 \sim 100\ f^{-2}$ the form factors fall as $\frac{1}{q^2}$ and that the relation $\lim_{q^2 \to \infty} G_E/G_M = 1$ is not contradictory to experimental data. These results were predicted by Sachs /13/ on the basis of the conditions

$$\lim_{q^2 \to \infty} G_E(q^2) = Z_2^{(s)} Q, \quad \lim_{q^2 \to \infty} G_M(q^2) = Z_2^{(s)} Q \tag{5}$$

where $Z_2^{(s)} = Z_1^{(s)}$ are renormalization constants of the wave function and the vertex part. Index s refers to strong interactions. Q is the physical charge of the nucleon.

The relations (5) may be obtained as a result of the asymptotic conditions of Källen, /14/ who discussed quantum electrodynamics. The validity of the asymptotic conditions (5) for

Dirac and Pauli form factors means that:

$$\lim_{q^2 \to \infty} F_1(q^2) = Z_2^{(s)}\, Q\ , \qquad \lim_{q^2 \to \infty} q^2 F_2(q^2) = 0 \qquad (6)$$

Logunov et al./15/ on the basis of the general principles of quantum field theory and also the analyticity of the $G(q^2)$, which has been proved in perturbation theory, showed that the limiting values of the form factors when $q^2 \to \infty$ and $q^2 \to -\infty$ must coincide. Since, when $q^2 > 0$, $G(q^2)$ are real, then when $q^2 \to -\infty$ the imaginary part of the form factor must vanish.

Comparison of form factors obtained in reactions $\bar{p} + p \to e^+ + e^-$ and $e + p \to e' + p'$ for high values of q^2 may be used to check field theory and, in a similar way, Pomeranchuk's theorem on the equality of total cross sections of particle and antiparticle interaction.

Apparently, it will soon/16/ be possible to compare $G(q^2)$ with $G(-q^2)$ at high values of q^2 and to know to what extent the values of q^2 reached can be considered asymptotic.

Thus the investigation of form factors at high values of q^2 is of primary importance, going far beyond the aim mentioned at the beginning of the report. With this in view, many attempts have been made to determine the interaction constants $g_{v\gamma}$ and

$g_{V_{NN}}$ of vector particles on the basis of form factor data.

After the pioneering work of Frazer and Fulco, who proposed an explanation of the iso-vector nucleon form factor by the resonant $\pi\pi$-interaction in a P-state, it became a tradition to analyse experimental data on form factors on the basis of resonance formulae. A simple approximation of form factors based on Clementel and Villi does not satisfy the condition that form factors should fall as $\frac{1}{q^2}$ at high values of q^2. Moreover, the conditions (6) together with the requirement for the analyticity of form factors leads to the sum rule

$$\int_{4\mu^2}^{\infty} I_m F_{2p}(t')dt' = 0 \qquad (7)$$

The assumption that form factors are described by pion resonances means that:

$$I_m F_{2i}(t) = \pi \sum_{j=1}^{N_i} E_{ij}\, m_{ij}^2\, \delta(t-m_{ij}^2) \qquad (8)$$

where $i = s, v$, represent isoscalar and isovector form factors respectively.

By incorporating (8) in (7), we find that $N_i \geqslant 2$, i.e. at least 2 resonances are necessary for each form factor with opposite signs for E_{ij}. Even before these considerations arose

Balachandran et al.[17] and several other authors considered it necessary to introduce an additional pole with the sign E_{ij}, and E_{ij} of opposite sign for the ρ-meson pole with a mass in the 1200 MeV region. The combination of these two poles imitates the expression of Clementel and Villi with $m_{\rho\varepsilon\varphi} < m_{\rho}$. This difference in the masses gives rise to certain difficulties.

The two-pole model is unsatisfactory for various reasons. In particular this model implies an explicit form for the spectral function in the dispersion relation:

$$G_i(t) = \frac{1}{\pi}\int_{t_0}^{\infty} \frac{g(t)}{t'-t}\, dt' + G(-\infty).$$

However, following the example of Levinger and Peierls[18] it is possible to attempt to construct g(t) from the value of G(t) found by experiment, or at least to come to certain conclusions about g(t) without using definite models. The idea of this method is not new and consists of transforming the t-plane into a circle of unit radius. The function of the new variable is expanded in a power series and the expansion coefficients are used for extrapolation into the time-like region. A series of additional conditions may be used. The result of this work shows that the spectral function for the proton form factor has a maximum when t is near m_{ρ}^2 and becomes negative for high values of t. This work also shows that it is necessary to introduce complementary poles.

The concrete results on the $g_{V\gamma}$ and g_{VNN} coupling constants extracted from the data on form factors should be considered as preliminary, since all these results are based on particular models. Moreover it is not at present known how many vector mesons exist and how many of them can take part in the process.

Furthermore, as shown by Ball and Wang[19], the approximation (8), which of course does not take into account the width of the resonances, may lead to considerable errors.

Scattering of electrons on deuterons

In order to obtain a complete picture of the e-N interaction, it is necessary to investigate the electromagnetic interactions of the simplest two-nucleon and three-nucleon bound systems. The study of such interactions encounters difficulties of principle, due to the absence of a solution of the relativistic bound state problem. The best that can be done is to examine the "few-nucleon" system in the non-relativistic approximation and on the basis of approximations whose consistency and accuracy are difficult to establish. Recently, attention has been centred on the elastic scattering of electrons on deuterons. // It is fairly simple to establish relativistic parameters describing the amplitude for the elastic scattering of electrons on d[20].

It is expressed in terms of three relativistically invariant functions of momentum transfer: $F_c(q^2)$, the charge form factor, $F_Q(q^2)$, the quadrupole electric factor and $F_M(q^2)$ the magnetic dipole factor. The cross section for the reaction $e + d \rightarrow e' + d'$ has the form[20]:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[A(q^2) + B(q^2)\, tg^2 \frac{\theta}{2} \right] \quad ;$$

$$A = F_c^2(q^2) + \frac{8}{9}\eta\, F_Q^2(q^2) + \frac{2}{3}\eta(1+\eta)\, F_M^2(q^2); \quad B = \frac{4}{3}\eta(1+\eta)\, F_M^2(q^2),$$

where $\eta = q^2/4M_d^2$.

So far the approach has been as strict as in the case of e-p scattering. In order to establish the connection between deuteron and nucleon form factors, recourse must be taken to the impulse approximation characterized by the following diagram:

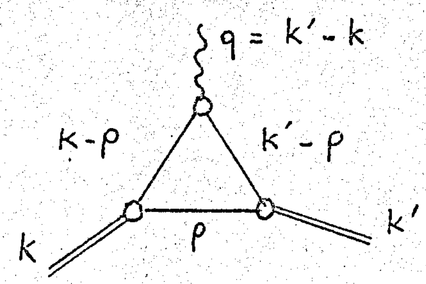


Fig. 3

The deuteron form factors are expressed by nucleon form factors multiplied by functions of the following type:

$$U(q) = \int_0^\infty U_n^2(\tau) j_\ell \left(\frac{q\tau}{2}\right) d\tau ,$$

where U_n is the deuteron wave function and

j_ℓ the spherical Bessel function.

When using form factors found in this way, the assumptions on which the impulse approximation is based must be borne in mind:

(a) the nucleon current in the diagram in Fig. 3 is replaced by its value on the mass shell.

(b) only the first order of the expansion of the current dependence on p momentum is taken into account.

(c) the "observer" nucleon propagator is replaced by its value for $p = 0$.

(d) the non-relativistic wave-function of the deuteron is used.

Only when $q \ll M$ can these approximations be expected not to give rise to considerable error.

In addition, the impulse approximation does not take into account the interaction of the virtual photon with exchange meson currents. Attempts were made[22] to study the $e + d \rightarrow e' + d'$ reaction on the basis of one-dimensional dispersion relations. On account of the existence of a very low anomalous threshold, only a few diagrams can be studied. The study includes intermediate pion states and shows that the S-matrix theory makes it possible in principle to take into account corrections to the impulse approximation; however, for the time being, this theory is not yet comparable to the more advanced non-relativistic theory, since it has not yet reached the quantitative stage.

Adler and Drell[23] presented at this conference an evaluation of the exchange meson currents. Since the isospin of the deuteron is equal to 0, the contribution to the interaction can only come from isoscalar meson currents, due to an odd number of pions at the electromagnetic vertex. It is to be expected that the most important contribution will be that of the diagram:

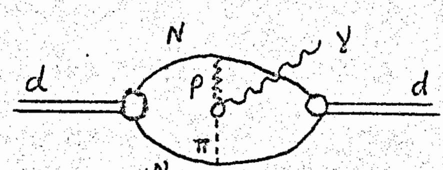


Fig. 4

A well-known calculation, assuming a 7 % contribution from the D-state in the deuteron, gives the following value for the anomalous magnetic moment of the deuteron:

$$\mu_D = \mu_p + \mu_n - \frac{3}{2} P_D(\mu_p + \mu_n - \tfrac{1}{2}) = 0.840$$

$$P_D = 0.07,$$

which differs from the observed value $u_D = 0.857$ beyond the limits of error. Taking into account the exchange current of the Fig. 4 type gives a contribution $\Delta\mu_D = (1\bar{\text{-}}2)\cdot 10^{-2}$ nuclear magnetons and explains the difference observed, if a coupling constant $g_{\gamma\pi\rho}$ corresponding to a width $\Gamma_{\rho\to\pi\gamma} = 0.5$ MeV is assumed.

The contribution to the electric and quadrupole form factors exceeds the limits of error only at high values of q^2. The correction to the magnetic form factor of the deuteron improves the agreement between theory and recent experimental data.

The study of e d -scattering encounters serious difficulties due to the vanishing of the charge form factor of the neutron: $F_n \propto q^2$ and is very small, so one has the choice of using high values of q^2 or developing a more accurate theory for low values of q^2.

In the region of small q^2 it is difficult to correlate G_{En} data obtained on the basis of e d scattering,

$$G_{En}(q^2) = 0.00 \pm 0.01 \quad \text{for} \quad 0.3 \leqslant q^2 \leqslant 2.2 \ F^{-2} ,$$

with data from neutron-electron scattering.

$$\frac{d}{dq^2} G_{En} \bigg|_{q^2=0} = - (0.021 \pm 0.001) \ F^2$$

It is not yet very clear whether this is a real difficulty or the consequence of the over-estimation of the accuracy of the study of ed-scattering. Kaiser[24] suggests that this difficulty can be explained by the effects of the polarizability of the neutron.

H^3 and He^3 Form Factors

Experiments by the Hofstadter Group[25] on the scattering of electrons by H^3 and He^3 and the theoretical analysis of these experiments by Schiff[26] showed that the study of these effects can give valuable information about the electric form factor of the neutron and the ground state of the three-nucleon system. The formulae for (eH^3) and (eHe^3) scattering cross-sections coincide with equation (1).

Each cross-section includes two relativistically invariant form factors $F_{ch}(He^3)$ and $F_{mag}(He^3)$, and $F_{ch}(H^3)$ and $F_{mag}(H^3)$. As in the case of ed-scattering, in the impulse approximation, these form factors are expressed as linear combinations of nucleon form factors. Three structure functions F_L, F_o and F_x serve as coefficients in these combinations.

Four form factors are found in the experiment and the three structure functions and the charge form factor are determined from four equations, the other nucleon form factors being considered as known from experiments on ep and ed-scattering.

The comparison of the values of F_L and F_o found, with those calculated on the basis of ground state models of the three partial system, makes it possible to reach important conclusions concerning the characteristics of this state. The adjustable parameter F_x takes exchange currents into account.

The considerable part played by the exchange currents and the relativistic corrections means that the processes of electron-scattering on "few-nucleon" systems should be considered of great intrinsic interest, apart from the possibility of measuring the neutron form factor.

III. Photoproduction

During the period under review, a considerable amount of experimental information on meson photoproduction was obtained.

The thooretical approach to these phenomena is based on dispersion relations, resonance and pole approximations. Furthermore, an approach which is in many ways similar should be noted. This is based on considering the pion and pion-nucleon resonances as higher spin particles. A considerable programme of calculations of electromagnetic photon-nucleon interaction based on this approach was carried out by Gourdin, Salin et al.[27].

The results which they obtained give a satisfactory quantitative description of photoproduction and of the available data on meson electroproduction in the energy region below 1 BeV.

The relativistic approach makes it possible to predict certain effedts, for instance the electric quadrupole photoproduction amplitude in the region of the first resonance $\frac{E_{1+}}{M_{1+}} \approx - 4.5\%$ and also the magnetic quadrupole amplitude in the region of the second resonance $\frac{M_{2-}}{E_{2-}} \approx 2.5\ \%$, etc.

With respect to meson electro-production, Salin[28] showed, on the basis of this model, that the neutron Dirac form factor is apparently negative and indicated experimental conditions under which neutron form factors can be determined solely from electro-production data. At the same time, it follows from theory that the determination of the pion form factor is practically impossible with the present experimental data.

The approach under consideration is no doubt useful for evaluating the effect of the main factors in the processes and for orienting experiments. However, it includes a considerable number of parameters which have to be determined from experimental data. Moreover, this approach does not pretend to represent a detailed theory of the phenomenon - considerable divergences between experimental data and theoretical predictions are possible, owing to non-resonant contributions. As was pointed out by Althoff[29], new accurate data from the Bonn group on charged meson photoproduction do not agree with this theory.

The investigation of the photoproduction of vector particles at high energies deserves particular attention. A detailed study of these processes was made by Berman and Drell[30].

The introduction of vector resonances in diagrams with elementary constants was analysed by Gell-Mann and Zachariazen[31] on the basis of the dispersion approach, as early as 1961.

By measuring the contribution of "peripheral" diagrams, Figs. 5 and 6, it is possible to determine important properties concerning unstable vector particles.

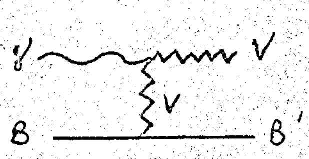


Fig. 5

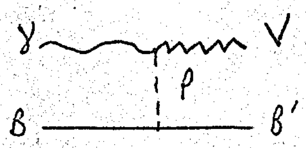


Fig. 6

Here γ is the photon, V the vector particle (ρ, K*·etc.), P the pseudoscalar particle (π, K) and B and B' the initial and final baryons.

The diagram in Fig. 5 gives a contribution to the cross-section which is proportional to the square of the magnetic moment and when $\Theta = 0^o$ this contribution does not vanish, which makes it possible to determine the magnetic moments of unstable vector particles by extrapolating the cross section to the corresponding pole. For neutral particles (for instance ρ^o, φ, ω) the diagram in Fig. 5 naturally disappears, and the mechanism can consequently be checked. Numerical evaluation of these cross sections is at present difficult because the corresponding constants are unknown.

Attempts are being made on the basis of the diagram in Fig. 6 to determine the width of the radiative decay of the ρ-meson. According to new Harvard data $\Gamma(\rho \to \pi\gamma) = 1.3$ MeV /33/. This value is very important for electromagnetic physics and its determination is one of the problems of the day.

In addition to the peripheral diagram in Fig. 6, effects described by the following diagrams are often discussed with a view to determining (γ - 3π) interaction:

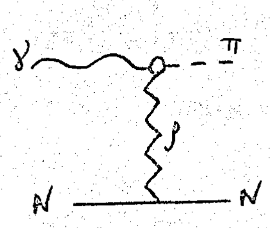


Fig. 7

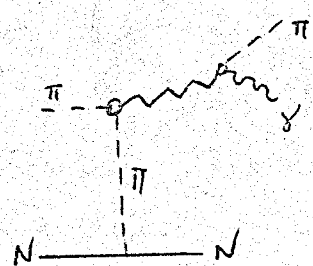


Fig. 8

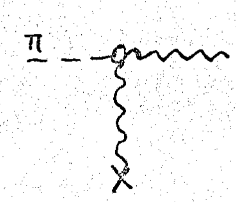


Fig. 9

These determinations are discussed below.

1) A rather old problem is the determination of from data on the photoproduction of single π-mesons, based on the study of the contribution of the diagram in Fig. 7.

If this diagram predominated in the high energy region, the photoproduction cross sections of π^0 and π^+ mesons would be equal. Recent measurements by Osborne et al. /34/ show that $d\sigma^0$ is greater than $d\sigma^+$ by about an order of magnitude in a fairly wide energy range. In the opinion of the authors, this means that the constant $g_{\gamma\pi\rho}$ is much smaller than $g_{\gamma\pi\omega}$ and testifies in favour of the selection rule introduced by Bronzan and Low[35], according to which $g_{\gamma\pi\rho}$ should be equal to zero. However, this relation between $d\sigma^{o}$ and $d\sigma^{+}$ may also mean that $g_{\rho NN} \ll g_{\omega NN}$.

A large number of papers were devoted to the determination of the $(\gamma\pi\rho)$ coupling constant based on the application of dispersion relations to the analysis of photoproduction near threshold.

The usual approach, based on dispersion relations, gives the following structure for the photoproduction amplitudes in the near-threshold region:

for the isovector amplitude parts $ReF_i^v(s_1 t) = P_i^v(s_1 t) + I_i^v(s_1 t)$

and ~~for~~ isoscalar parts

$$ReF_i^s(s_1 t) = P_i^s(s_1 t) + I_i^s(s_1 t) + A(t) \tag{9}$$

Here P_i are pole (Born) terms, I_i are dispersion integrals and $A(t)$ is the contribution from the diagram in Fig. 7.

Lebedev and Kharlamov[36] calculated the dispersion integrals from the imaginary parts of the amplitudes, which were taken from experiment, and obtained an upper limit for A(t). Even if all this contribution is attributed to diagram 5, an upper limit $\Gamma_{\gamma\pi\rho} \lesssim 0.1$ MeV is obtained for the width, which strongly disagrees with $\Gamma_{\gamma\pi\rho}$ found from the reactions $\gamma + p \rightarrow p + \rho^{o}$.

The determination of the $\gamma\pi\rho$ coupling constant from near-threshold photoproduction leads to a wide range of values. However, it should be pointed out that all these values are situated within the $\Gamma_{\gamma\pi\rho} \leqslant 0.1$ MeV.region.

The differences between the data of different authors, as shown by Lebedev and Kharlamov, are due to the fact that the contribution of A(t) is of the same order as the inaccuracy in the calculation of the dispersion integrals I(t). Particular concern is caused by the contribution of the second resonance and particularly by the question as to whether the contribution of the $\gamma\pi\rho$ interaction will not be counted twice: the first time as the A(t) term and the second time as the contribution of the second resonance. Considerable light may be thrown on this question, since if the second resonance is found in the reaction

$$\gamma + d \rightarrow d + \pi^{o} \qquad (d\pi^{o}),$$

due solely to the isovector part of the amplitude, there is no direct connection between the contribution of the second resonance and $A(t)$.

It seems advisable on the basis of the reaction $(d\pi^o)$ at small angles to make a distinction between isoscalar and isovector as well as other resonances.

The main source of uncertainty in finding $\Gamma_{\gamma\pi\rho}$ are errors in the calculation of I; these can be eliminated/37/ by measuring the D-wave amplitude of the photoproduction. The contribution of I_i to the D-wave amplitude is small because of the centrifugal barrier, and the need for accurately evaluating it no longer arises (for instance, there is no need to take into account the integration range above the first resonance).

The determination of $A(t)$ by measuring the D-wave in the $\gamma + p \rightarrow p + \pi^o$ and $\gamma + p \rightarrow n + \pi^+$ reactions in the low energy region appears to be the most reliable. However, there are not yet sufficient experimental data for this method.

The measurement of the isoscalar amplitudes is of great interest, since the $I_i^{(s)}$ values are small and the main contribution comes from $P_i^{(s)}$ and $A(t)$. Such measurement has so far mainly been carried out on the basis of the study of reactions involving photoproduction of charged mesons on deuterons. The theory of these reactions is given in /38/.

Among the work on near-threshold photoproduction on deuterons should be mentioned that of the Moscow Group [39] devoted to detailed theoretical and experimental investigation of the processes

$$\gamma + d \longrightarrow d + \pi^o \qquad (d\pi^o)$$
$$\gamma + d \longrightarrow p + n + \pi^o \qquad (np\pi^o).$$

The authors show that in the relation $\frac{d\sigma\,(\gamma d \longrightarrow d(pn) + \pi^o)}{d\sigma\,(\gamma + p \longrightarrow p + \pi^o)}$ in the small angle region of the process, the contribution of $(np\pi^o)$ is less than 5 %. $\frac{d\sigma}{d\Omega}(d\pi^o)$ in this region is very critical for the isotopic structure of the amplitude, for small amplitudes, and uncritical for the deuteron wave function.

The drawback of extracting the isoscalar amplitude from the data on elastic photoproduction of π^o and on σ^- / σ^+ is that the contribution of the isoscalar amplitude only slightly exceeds the uncertainty arising from the use of the impulse approximation. However, the experiment can also be carried out so that the relative contribution of the isoscalar part is greatly increased by the singlet interaction in the final state of the neutron and the proton in the inelastic π^o meson production reaction. In that case, it is necessary to record p and n with a very small relative angle of divergence.

The investigation of the threshold region is of interest apart from the determination of the $\gamma\pi\rho$ interaction constant. The relative simplicity of this phenomenon gives reason to believe that accurate quantitative information in this region will be particularly useful for future checking of the theory.

2) The Dubna Group[40] attempted to determine the coupling constant $(\gamma-3\pi)$ from the reaction $\pi^- + p \rightarrow p + \pi^- + \gamma$. The authors succeeded in showing that the diagram in Fig. 10 makes the main contribution to the rigid part of the γ-quanta spectrum. The other diagrams give a contribution which decreases sharply when the energy of the photon increases. By selecting the rigid part of the photon spectrum from the experimental data, the authors estimate the $g_{\gamma\pi\rho}$, which is about one order of magnitude greater than the $g_{\gamma\pi\rho}$ obtained from photoproduction data, but agrees with data on the peripheral production of ρ-mesons[33].

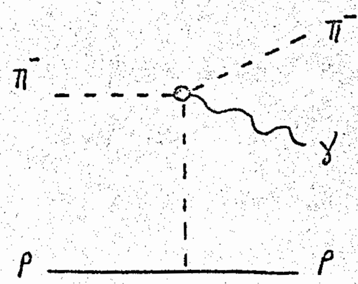


Fig. 10

3) In order to give the full picture, it should be mentioned that the $(\gamma-3\pi)$ interaction can be studied by investigating the conversion of π into ρ in the Coulomb field of the nucleus $\pi^{\pm} + Z \rightarrow \rho^{\pm} + Z$ (see Fig. 9). This possibility has already been discussed[41].

For high energy π-mesons, the momentum transfer can be very small:

$$\left| t_{min} \right|^{\frac{1}{2}} = \left| m_\rho^2 / 2E_\pi \right| < R_Z^{-1}$$

where R_Z is the radius of the nucleus. Under these circumstances a coherent process is possible. The differential cross-section greatly depends on the angle:

$$\frac{d\sigma}{d\Omega} = Z^2 \alpha F(\psi) \frac{2\pi \Gamma_{\gamma\pi\rho}}{m_\rho} \frac{\theta^2}{\left[\theta^2 + m_\rho^4 / 4E_\pi^4\right]^2}$$

and assumes a very high value. At its maximum when $\theta = m_\rho^2 / 2E_\pi^2$ (assuming that $\Gamma_{\gamma\pi\rho} = 0.5$ MeV and that the nuclear form factor $F(\psi) = 1$) the cross section reaches 0.4 barn/ster.

Coulomb and nuclear processes can be separated by measuring the angular distribution.

These considerations /30/ also apply to the conversion of K-mesons into K*-mesons in the Coulomb field. Owing to the small difference between the masses, $M_{K*} - M_x = 390$ MeV, the minimum momentum transfer is approximately the same as in the $\pi \rightarrow \rho$ conversion.

The comparison of $\Gamma_{\gamma\pi\rho}$ and $\Gamma_{\gamma K K^*}$ is of interest for checking unitary symmetry.

As has been seen, the width of the ρ-meson into π and γ is a very important feature. However, data concerning this width are contradictory although very plentiful. This is probably due to the fact that at the present stage there is no reliable way of isolating the contributions of peripheral diagrams. It is also interesting to note that the value of $\Gamma(\rho \rightarrow \pi + \gamma)$ was found to be the same in the effects described by one-meson exchange diagrams (see figures 8, 9 and 10).

The smaller order of magnitude of the upper limit for $\Gamma(\rho \rightarrow \pi + \gamma)$ obtained from near-threshold photoproduction may mean that A(t) in formula (9) includes not only the contribution from diagram 7, but also a contribution which counterbalances it. For instance, this could be the contribution of the ρ'-meson which was introduced in the isovector nucleon form factor models.

The data mentioned shows that the determination of resonance interaction constants both for e - p scattering and meson photoproduction is still at a preliminary stage. At the same time it is clear that the study of these effects is very promising.

IV. Electrodynamics

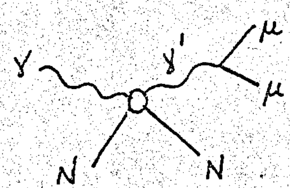
Electrodynamic calculations relating to experimental work mainly concern the discussion of the possible divergence of experimental data from the predictions of electrodynamics. For a more accurate definition of "divergence" it is necessary to pay due attention to radiative corrections of a higher degree of accuracy than the experiment (this is the most usual kind of calculation).

Another kind of calculation investigates which experiments for checking electrodynamics are the most critical for possible divergences.

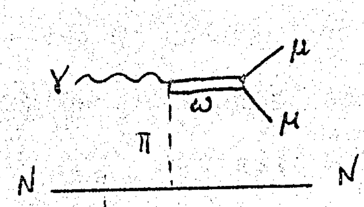
A third kind of calculation concerns the discussion of evident divergences from electrodynamics connected with taking strong interactions into account.

Drell[/42/] presented at this conference a study of sharply asymmetric photoproduction of μ-pairs, where nearly all the energy of the photon is transmitted to one meson, which is recorded, the other meson emitted being almost at rest. The Bethe-Heitler cross-section is found to be $\sigma \approx 10^{-34}/K$ (GeV) cm^2. The main feature in this case is that the cross section is sensitive to modification of the muon propagator, shifted a long distance - 2 km - from the mass shell.

Experimental arrangements which do not call for coincidence diagrams are convenient for experiments on linear accelerators. The production of pairs on protons will receive a considerable contribution from strong interactions due to virtual Compton effect diagrams:



and to diagrams of the type



These processes are also of intrinsic interest. They can be isolated by means of the sharp angle dependence of Bethe-Heitler cross-section.

A large programme of calculation of electrodynamic corrections[43] and evaluation of the effect of strong interactions was carried out by Gatto et al. in connection with colliding beam projects. Similar calculations were also carried out in part by other authors (see for example [44]).

Corrections were obtained by combining renormalization group methods for the totalisation of the final (not infra-red) part and a well-known formula which totalises the infra-red part.

Corrections to the cross sections of reactions $\bar{p} + p \rightleftarrows e^+ + e^-$ and $\bar{p} + p \rightleftarrows \mu^+ + \mu^-$ are of interest in connection with the problems under discussion.

The relation obtained for the total cross sections is as follows:

$$\frac{\sigma_T(\bar{p}p \to \mu^+\mu^-)}{\sigma_T(\bar{p}p \to e^+e^-)} \cong \left[1 - 6\left(\frac{m_\mu}{E}\right)^4\right]\left[1 + \frac{\alpha}{\pi}\, \ln \frac{m_e}{m_\mu}\left(\frac{13}{3} + 4\,\ln 2 + 4\,\ln \frac{\varepsilon}{E}\right)\right]$$

Evaluations of the effects of electromagnetic interactions on regularities established for strong interactions are also of considerable interest.

The generalization of Low's formula for the emission of soft photons and also of the dispersion relations for elastic processes when electromagnetic interactions are taken into account /45/ were discussed in the report by L.D. Soloviev /46/. This approach, in particular, makes it possible to generalize asymptotic relations at high energies also when electromagnetic interactions are taken into account.

The author wishes to take this opportunity of expressing his thanks to A.A. Komar and S. Berman for useful discussions and to E. Lebedev for his great help in preparing this report.

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