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ELECTROMAGNETIC STRUCTURE OF NUCLEONS

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PREFACE

This monograph is intended to provide a critical review and analysis of recent studies of the electromagnetic structure of nucleons. The first chapter is devoted to a precise definition of what is meant by the electromagnetic form factors. The different types of experiments which have given information on these form factors are discussed in Chapter II with emphasis on the theoretical assumptions and approximations made in analysing the experimental numbers in terms of form factors. Chapter III is devoted to the recent dispersion theoretic analyses of the form factors. The theoretical development here has the two goals of serving as a first introduction to the dispersion methods for physicists at the graduate level and of indicating clearly the various approximations made at present in implementing the dispersion theory approach. In Chapter IV the validity of quantum electrodynamics is discussed and it is shown how possible deviations in this theory alter the nucleon form factor analyses. Two appendices are included with formal developments.

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S. D. D.

September 1960 F. Z.

CONTENTS

CHAPTER I

DEFINITION OF ELECTROMAGNETIC STRUCTURE OF NUCLEONS

The first step in any discussion of the electromagnetic structure of the nucleon is of necessity a precise definition of what is meant by such structure. For purposes of introducing and illustrating this definition, it will be convenient to fix attention, for the moment, on the scattering of electrons from protons; it is this experiment, after all, which has produced the present information on the proton's electromagnetic structure.

To lowest order in e, the electric charge, a single virtual

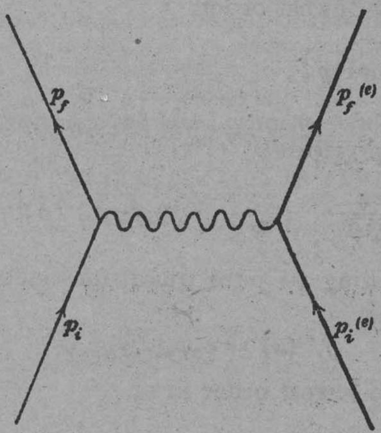

FIG. I.1. Feynman diagram for electron-proton scattering to order e^2. The proton is treated as a point Dirac particle. The line represents a proton, the heavy line, an electron, and the wavy line, a photon.

photon is exchanged between the electron and the proton. The Feynman diagram representing this process is illustrated in Fig. I.1.

The transition amplitude corresponding to this diagram may be written [1]

$$\int \frac{d^4q}{(2\pi)^4} \langle p_f | \int j_\mu^{(P)}(x) e^{-iq.x} \, d^4x | p_i \rangle \frac{1}{q^2} \langle p_f^{(e)} | \int j_\mu^{(e)}(x) e^{iq.x} \, d^4x | p_i^{(e)} \rangle \tag{1.1}$$

where p_f, p_i and $p_f^{(e)}$, $p_i^{(e)}$ are the final and initial 4-momenta of the proton and electron, respectively, $q_\mu = (p_f - p_i)_\mu = (p_i^{(e)} - p_f^{(e)})_\mu$ is the 4-momentum transferred from electron to proton, and $j_\mu^{(P)}(x)$, $j_\mu^{(e)}(x)$ are the electromagnetic current operators of the proton and electron. The factor q^{-2} is the propagator for the virtual photon which is exchanged [2]. According to quantum electrodynamics, the current operator for the electron is given by,

$$j_\mu^{(e)}(x) = e_0 \bar{\psi}_e(x) \gamma_\mu \psi_e(x)$$

where $\psi_e(x)$ is the electron field, and e_0 is the unrenormalized charge. Thus, to lowest order,

$$\langle p_f^{(e)} | \int j_\mu^{(e)}(x) e^{iq.x} \, d^4x | p_i^{(e)} \rangle$$

$$= \frac{e_0}{\sqrt{(4E_f^{(e)}E_i^{(e)})}} (\bar{u}_{p_f}^{(e)} | \gamma_\mu | u_{p_i}^{(e)}) \int d^4x e^{i(p_f(e) - p_i(e) + q).x}$$

$$= \frac{e_0}{\sqrt{(4E_f^{(e)}E_i^{(e)})}} (\bar{u}_{p_f}^{(e)} | \gamma_\mu | u_{p_i}^{(e)}) (2\pi)^4 \delta^4 (p_f^{(e)} - p_i^{(e)} + q). \tag{1.2}$$

Similarly, according to pure quantum electrodynamics, the proton current is

$$j_\mu^{(P)}(x) = e_0 \bar{\psi}_p(x) \gamma_\mu \psi_p(x) \tag{1.3}$$

so that, again to lowest order in e_0,

$$\langle p_f | \int j_\mu^{(P)}(x) \, e^{-iq.x} \, d^4x | p_i \rangle$$

$$= \frac{e_0}{\sqrt{(4E_f E_i)}} (\bar{u}_{p_f} | \gamma_\mu | u_{p_i}) \int d^4x e^{i(p_f - p_i - q).x}. \tag{1.4}$$

The lowest order Feynman amplitude is then obtained by combining equations (1.1), (1.2), and (1.4). Now the basic assumption involved in deducing equation (1.4) is that the coupling of the proton to the virtual photon is described simply by quantum electrodynamics, in which the proton is a point particle of unit charge and the usual Dirac magnetic moment. It is clear, however, that this assumption is not at all valid—in particular the proton couples strongly to mesons and other particles, so that equation (1.3) for the electrodynamic current of the proton is certainly not correct. For example, since there is presumably a cloud of virtual mesons around the proton, one should add the meson current to $j_\mu^{(P)}$, i.e. one should write [3]

$$j_\mu^{(P)}(x) = e_0\bar{\psi}_p(x)\gamma_\mu\psi_p(x)+ie_0(\varphi(x)\nabla_\mu\varphi(x)^*-\varphi(x)^*\nabla_\mu\varphi(x)),$$

where $\varphi(x)$ is the meson field. Similarly more terms should be added corresponding to other particles which can appear virtually. All these virtual particles, then, produce effects which change the structure of the vertex at which the photon is absorbed by the proton; that is they change the form of equation (1.4). That such effects are not negligible is illustrated, for example, by observing that the proton's magnetic moment, $2.79e/2M$, differs greatly from the Dirac moment, $e/2M$.

One must therefore expect deviations from the result of equation (1.4). These deviations will, in general, be of two kinds. First, the fact that the proton's moment is not equal to the Dirac moment means that there will be a Pauli term of the form $\sigma_{\mu\nu}F_{\mu\nu}^{(e)}$ in addition to the simple $\gamma_\mu A_\mu^{(e)}$ term already included [4]. Second, because of the cloud of virtual mesons about the proton, the coupling of the photon to the proton may take place over an extended region in space—thus one should replace

$$\int d^4x e^{i(p_f-p_i)\cdot x}e^{-iq\cdot x}$$

in which the photon is absorbed on a point proton, by something like

$$\int d^4x' \int d^4x e^{i(p_f-p_i)\cdot x}F(x'-x)e^{-iq\cdot x'}.$$

This may be conveniently rewritten as

$$\int d^4x e^{i(p_f-p_i-q)\cdot x}F(q^2)$$

where

$$F(q^2) = \int d^4y e^{-iq\cdot y} F(y),$$

$$F(y) = \int \frac{d^4q}{(2\pi)^4} e^{iq\cdot y} F(q^2). \tag{1.5}$$

Physically, one might interpret this by saying that if the spatial extension of the proton is, for example, due to a virtual meson cloud, then the photon could be absorbed at x' by a virtual meson emitted from the proton at x. $F(x-x')$ might therefore be expected to have the 'size' of the meson cloud around the proton. If these alterations are incorporated into equation (1.4), it becomes

$$\langle p_f | \int j_\mu^{(P)}(x) e^{-iq.x} d^4x | p_i \rangle$$
$$= \frac{1}{\sqrt{(4E_f E_i)}} (\bar{u}_{p_f} | \gamma_\mu F_1(q^2) + i\sigma_{\mu\nu} q_\nu F_2(q^2) | u_{p_i})$$
$$\times \int d^4x e^{i(p_f - p_i - q).x}. \tag{1.6}$$

Here a different spatial extent is associated with the original convection current coupling $\gamma_\mu A_\mu^{(e)}$, and with the subsequently introduced Pauli term $\sigma_{\mu\nu} F_{\mu\nu}^{(e)}$. Note that the charge e_0 has been included in F_1.

This form has been obtained on the basis of physical ideas about what effects could be produced by the presence of a meson cloud around the proton. It is in addition, however, the most general form which is allowed for the coupling of a photon to a physical proton by the requirements of gauge invariance and Lorentz invariance. This can be seen as follows. Consider the matrix element

$$\langle p_f | \int j_\mu^{(P)}(x) e^{-iq.x} d^4x | p_i \rangle. \tag{1.7}$$

The translational invariance of the theorists' world implies

$$j_\mu^{(P)}(x) = e^{iP.x} j_\mu^{(P)}(0) e^{-iP.x}$$

where P is the total energy momentum operator; thus equation (1.7) becomes

$$\int d^4x e^{i(p_f - p_i - q).x} \langle p_f | j_\mu^{(P)}(0) | p_i \rangle.$$

Now the matrix element $\langle p_f|j_\mu^{(P)}(0)|p_i\rangle$ must be of the form

$$\langle p_f|j_\mu^{(P)}(0)|p_i\rangle = \frac{1}{\sqrt{(4E_f E_i)}}(\bar{u}_{p_f}|O_\mu|u_{p_i}),$$

where O_μ is a Lorentz 4-vector, and is also a 4×4 matrix in the spinor space of the proton. The factor $\sqrt{(4E_f E_i)}$ appears here, incidentally, only for normalization purposes.

The matrix element is a function only of the 4-vectors p_f and p_i, which are subject to the restrictions $p_f^2 = p_i^2 = M^2$; from these one can construct only one scalar variable, which is chosen to be $(p_f - p_i)^2 = q^2$. The operator O_μ, then, must be constructed from the scalar q^2, the vectors $p_{f\mu}$ and $p_{i\mu}$, or equivalently the vectors q_μ and $P_\mu = (p_f + p_i)_\mu$, and the Dirac γ matrices. Since O_μ is a 4×4 matrix, it can always be written as a linear contribution of the 16 matrices

$$1, \quad \gamma_\mu, \quad \sigma_{\mu\nu}, \quad \gamma_5\gamma_\mu, \quad \gamma_5;$$

since, in addition, it is not a pseudovector, the two γ_5 terms cannot appear.

The coefficients of the remaining terms are functions of whatever scalars can be formed; that is, of q^2, $\not{p}_f$ and $\not{p}_i$. By use of the commutation rules of the Dirac matrices, $\not{p}_f$ and $\not{p}_i$ can be moved to the left and right of the expression, respectively. But $\bar{u}_{p_f}\not{p}_f = \bar{u}_{p_f}M$, and $\not{p}_i u_{p_i} = M u_{p_i}$; thus the $\not{p}_f$ and $\not{p}_i$ scalars can be eliminated and the most general form for O_μ is

$$O_\mu = a(q^2)q_\mu + b(q^2)P_\mu + c(q^2)\gamma_\mu + d(q^2)\sigma_{\mu\nu}q_\nu + e(q^2)\sigma_{\mu\nu}P_\nu.$$

Now the following identities are easily verified:

$$(\bar{u}_{p_f}|i\sigma_{\mu\nu}P_\nu|u_{p_i}) = (\bar{u}_{p_f}|-q_\mu|u_{p_i}),$$
$$(\bar{u}_{p_f}|i\sigma_{\mu\nu}q_\nu|u_{p_i}) = (\bar{u}_{p_f}|2M\gamma_\mu - P_\mu|u_{p_i}),$$

for free physical proton states which satisfy the Dirac equation $(\not{p} - M)u_p = 0$. Hence O_μ can be reduced to the form

$$O_\mu = a'(q^2)q_\mu + c'(q^2)\gamma_\mu + d'(q^2)\sigma_{\mu\nu}q_\nu,$$

where a', c', and d' are certain linear combinations of a, b, c, d, and e.

Up to this point only Lorentz invariance and the fact that the initial and final protons satisfy the free particle Dirac equation have been used. It is still necessary to impose the requirement of gauge invariance. This implies the continuity equation $\nabla_\mu j_\mu = 0$. Translating this into a condition on O_μ,

$$0 = \langle p_f|(\nabla_\mu j_\mu)_{x=0}|p_i\rangle = \frac{1}{\sqrt{(4E_f E_i)}}(\bar{u}_{p_f}|q_\mu O_\mu|u_{p_i});$$

therefore

$$0 = \frac{1}{\sqrt{(4E_f E_i)}}(\bar{u}_{p_f}|a'(q^2)q^2 + c'(q^2)\not{q} + d'(q^2)\sigma_{\mu\nu}q_\mu q_\nu|u_{p_i}).$$

The last term here is directly zero; the second vanishes because

$$(\bar{u}_{p_f}|\not{q}|u_{p_i}) = (\bar{u}_{p_f}|\not{p}_f - \not{p}_i|u_{p_i}) = (M-M)(\bar{u}_{p_f}|u_{p_i}) = 0.$$

Thus gauge invariance requires

$$q^2 a'(q^2) = 0.$$

Since in general, for virtual photons, $q^2 \neq 0$, it follows that $a'(q^2) = 0$. It is possible to show that $a'(0) = 0$ as well, by observing that the matrix element must be invariant under the transformation of interchanging p_f and p_i, and reversing the order of all γ matrices. This is most easily seen by an inspection of the relevant Feynman diagrams. The terms γ_μ and $\sigma_{\mu\nu}q_\nu$ are invariant to this, but the term q_μ changes sign.

The conclusion is that the most general form consistent with Lorentz invariance and gauge invariance, and with the fact that the two protons p_f and p_i satisfy the free Dirac equation, is

$$\langle p_f|j_\mu(0)|p_i\rangle = \frac{1}{\sqrt{(4E_f E_i)}}(\bar{u}_{p_f}|F_1(q^2)\gamma_\mu + iF_2(q^2)\sigma_{\mu\nu}q_\nu|u_{p_i}), \quad (1.8)$$

with the scalars c' and d' denoted here as F_1 and iF_2. Purely from these invariance arguments, then, it is clear that the form given in equation (1.6), on the basis of physical arguments is, in fact, the most general one possible. It is easy to see, in addition, from the fact that j_μ is a Hermitian operator, that the F's are real: explicitly,

$$\begin{aligned}(\bar{u}_{p_i}|F_1{}^*\gamma_\mu - iF_2{}^*\sigma_{\mu\nu}q_\nu|u_{p_f})\\ &= (\bar{u}_{p_f}|F_1\gamma_\mu + iF_2\sigma_{\mu\nu}q_\nu|u_{p_i})^*\\ &= \sqrt{(4E_fE_i)}\langle p_f|j_\mu(0)|p_i\rangle^* = \sqrt{(4E_fE_i)}\langle p_i|j_\mu(0)|p_f\rangle\\ &= (\bar{u}_{p_i}|F_1\gamma_\mu + iF_2\sigma_{\mu\nu}q'_\nu|u_{p_f})\end{aligned}$$

where $q' = p_i - p_f = -q$, so that $q'^2 = q^2$.

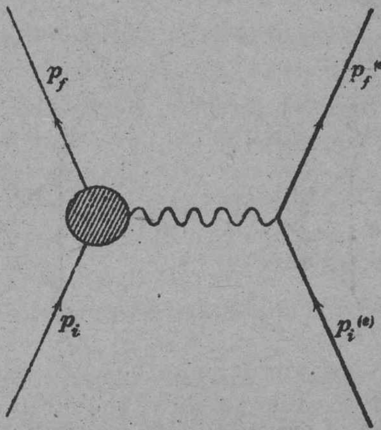

FIG. I.2. Diagram for electron-proton scattering to order e^2. The blob includes effects of all strongly interacting virtual particles.

The electron–proton scattering amplitude, to lowest order in the electric charge, is then given by

$$(\bar{u}_{p_f}|\gamma_\mu F_1(q^2) + i\sigma_{\mu\nu}q_\nu F_2(q^2)|u_{p_i}) \times \frac{1}{q^2}(\bar{u}^{(e)}_{p_f}|e_0\gamma_\mu|u^{(e)}_{p_i})$$
$$\times \frac{1}{\sqrt{(16E_fE_iE^{(e)}_fE^{(e)}_i)}}(2\pi)^4\delta^4(p_f - p_i + p^{(e)}_f - p^{(e)}_i). \quad (1.9)$$

This includes all possible effects due to clouds of virtual particles around the proton, and in fact, due to any contribution to the proton vertex which does not violate Lorentz invariance and gauge invariance.

The amplitude (1.9) may be interpreted as corresponding to a diagram like Fig. I.2 instead of Fig. I.1. The blob around the proton–photon vertex is supposed to indicate that no attempt is made to specify in detail how the interaction occurs—that is, the blob is meant to summarize all effects of any number of virtual particles as indicated in Fig. I.3.

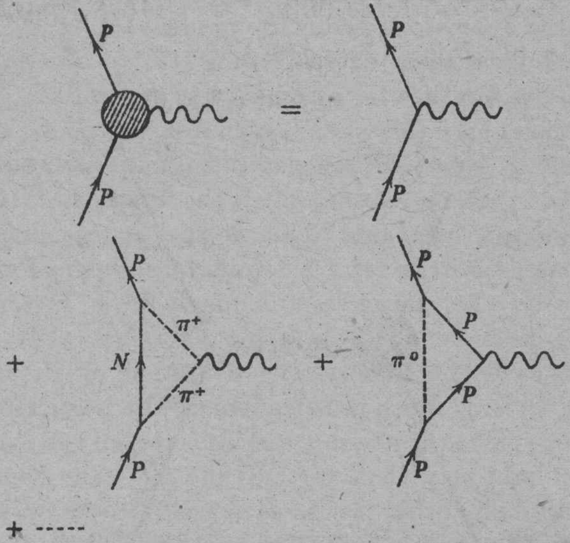

FIG. I.3. Examples of diagrams which contribute to the blob of Fig. I.2. The dashed lines represent pions.

The cross-section resulting from the amplitude of equation (1.9) is the Rosenbluth cross-section [5],

$$\frac{d\sigma}{d\Omega} = \frac{e^2}{4(4\pi)^2 E_0^2} \frac{\cos^2(\frac{1}{2}\theta)}{\sin^4(\frac{1}{2}\theta)} \frac{1}{1+\frac{2E_0}{M}\sin^2(\frac{1}{2}\theta)}$$

$$\left\{F_1^2 - \frac{q^2}{4M^2}(2(F_1+2MF_2)^2\tan^2(\tfrac{1}{2}\theta)+\{2MF_2\}^2)\right\}$$

where

$$q^2 = -\frac{(2E_0\sin(\frac{1}{2}\theta))^2}{1+\frac{2E_0}{M}\sin^2(\frac{1}{2}\theta)}; \qquad (1.10)$$

and E_0 denotes the incident energy and θ the scattering angle of the electron in the laboratory system.

If this formula is used to interpret the experimental results for electron–proton scattering, then F_1 and F_2 may be measured as functions of the invariant momentum transfer of the scattering. By definition, $F_1(0) = e$, the renormalized physically observed charge, and $F_2(0) = \mu_a = g(e/2M) = 1{\cdot}79\mu_B$, the anomalous magnetic moment [6].

A point particle of charge e and total magnetic moment $(g+1)\mu_B$ is a particle for which $F_1(q^2) = e$ and $F_2(q^2) = g\mu_B$ for *all* values of q^2; this is easily seen from equation (1.5). Thus by definition, a particle has electromagnetic structure—i.e. is not a point particle—if and only if the functions $F_1(q^2)$ and/or $F_2(q^2)$ are not constant. This is the precise definition of electromagnetic structure. The functions F_1 and F_2 are called respectively, the charge and moment form factors of the proton.

It should be noted that the definition of F_1 and F_2 in equation (1.8), is quite independent of the particular process of electron–proton scattering, but involves only the interaction of a real proton with a virtual photon. The same vertex appears in many other processes as well; it was only to make the physical meaning of the form factors a little clearer that their definition was introduced through the discussion of electron–proton scattering.

The functions $F_1(q^2)$ and $F_2(q^2)$ as defined in equation (1.8) from consideration of electron–proton scattering, are defined only for negative—i.e. spacelike—values of q^2, because $q^2 = (p_f-p_i)^2 = 2M^2-2p_f \, . \, p_i \leqslant 0$. The definitions of F_1 and F_2 may be extended to include positive—i.e. timelike—values of q^2 by writing

$$\langle \bar{p}p'^{(-)}|j_\mu(0)|0\rangle = \frac{1}{\sqrt{(4\bar{E}E)}}\,(\bar{u}_{p'}|F_1(q^2)\gamma_\mu + iF_2(q^2)\sigma_{\mu\nu}q_\nu|v_{\bar{p}})$$

where $\langle \bar{p}p'^{(-)}|j_\mu(0)|0\rangle$ is the amplitude to create a proton–antiproton pair from a virtual photon. Here p' is the proton 4-momentum, $\bar{p}$ is the antiproton 4-momentum, $q = p'+\bar{p}$, and $\langle \bar{p}p'^{(-)}|$ is a proton–antiproton state with ingoing boundary conditions [7]. This definition gives F_1 and F_2 for $q^2 \geqslant 4M^2$.

It is possible to show that this definition of F_1 and F_2 in the region $q^2 \geqslant 4M^2$ coincides with the analytic continuation of the form factors defined in equation (1.8), treated as functions of the complex variable q^2. It will turn out that it is for many purposes more convenient to think of F_1 and F_2 in terms of this pair production process.

For spacelike q, where F_1 and F_2 may be thought of as related to the absorption of a virtual photon on a proton, it is possible to choose a co-ordinate system in which q has no time component. This is the barycentric system in which the incident (or outgoing) electron and proton have equal and opposite momenta. In this system, it is conventional to define spatial charge and moment densities by

$$e_1(r) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} F_1(-\mathbf{q}^2) e^{-i\mathbf{q}\cdot\mathbf{r}}$$

$$e_2(r) = \int \frac{d^3\mathbf{q}}{(2\pi)^3} F_2(-\mathbf{q}^2) e^{-i\mathbf{q}\cdot\mathbf{r}}. \qquad (1.11)$$

It should be emphasized that this definition depends on a particular choice of Lorentz frame, in which the proton is not stationary, and therefore the relation of these densities to any real physical extension of the proton is quite unclear.

Note that

$$\int e_{1,2}(r)\, d^3\mathbf{r} = F_{1,2}(0).$$

The mean square radii of the spatial distributions are defined by

$$\langle r^2\rangle_{1,2} = \int r^2 e_{1,2}(r)\, d^3\mathbf{r} \Big/ \int e_{1,2}(r)\, d^3\mathbf{r}$$

$$= 6F'_{1,2}(-\mathbf{q}^2)|_{\mathbf{q}^2=0}/F_{1,2}(0).$$

Therefore, for small q^2, one gets, in the special co-ordinate system:

$$F_{1,2}(-\mathbf{q}^2) = F_{1,2}(0) - \mathbf{q}^2 F'_{1,2}(-\mathbf{q}^2)|_{\mathbf{q}^2=0} + \cdots$$

$$= F_{1,2}(0)(1 - \tfrac{1}{6}\mathbf{q}^2\langle r^2\rangle_{1,2} + \ldots).$$

This may clearly also be written covariantly in any co-ordinate system: thus

$$F_{1,2}(q^2) = F_{1,2}(0)(1 + \tfrac{1}{6}q^2\langle r^2\rangle_{1,2} + \ldots).$$

The mean square radius, then, just measures the slope of the form factor as $q^2 \to 0$; if the form factor is a very smooth function of q^2, this slope may give a way of simply summarizing its properties. If, however, the form factor does not have a fairly constant slope, the value of the rms radius is quite independent of its overall behaviour and therefore may in general not be a very useful concept.

Up to this point the discussion has been limited to the form factors and electromagnetic structure of the proton. It must now be expanded to recognize the existence of neutrons as well. The first step in accomplishing this is to affix an index P, for proton, onto all the form factors, densities, and radii so far defined.

The same considerations given above for the proton may also be made for the neutron; explicitly, define

$$\langle n_f|j_\mu(0)|n_i\rangle = \frac{1}{\sqrt{(4E_fE_i)}}(\bar{u}_{n_f}|F_1^N(q^2)\gamma_\mu + iF_2^N(q^2)\sigma_{\mu\nu}q_\nu|u_{n_i})$$

where $q = n_f - n_i$, and n_f, n_i are the 4-momenta of the neutron after and before absorbing the virtual photon. Equivalently, for timelike $q^2 \geqslant 4M^2$, the pair production amplitude is

$$\langle \bar{n}, n'^{(-)}|j_\mu(0)|0\rangle = \frac{1}{\sqrt{(4E'\bar{E})}}(\bar{u}_{n'}|F_1^N(q^2)\gamma_\mu + iF_2^N(q^2)\sigma_{\mu\nu}q_\nu|v_{\bar{n}})$$

where $q = n' + \bar{n}$, and n', $\bar{n}$ are the 4-momenta of the neutron and antineutron produced by the photon. Then the static limits for the neutron fix [8]

$$F_1^N(0) = 0$$
$$F_2^N(0) = \mu_N = -1{\cdot}91\,\frac{e}{2M}.$$

These equations, together with the analogous ones for protons, may be combined into one as follows: write

$$\langle p_f|j_\mu(0)|p_i\rangle = \frac{1}{\sqrt{(4E_fE_i)}}(\bar{u}_{p_f}|(F_1^s(q^2) + \tau_3F_1^v(q^2))\gamma_\mu + i(F_2^s(q^2) + \tau_3F_2^v(q^2))\sigma_{\mu\nu}q_\nu|u_{p_i}) \quad (1.11)$$

where p_f and p_i now refer to the 4-momenta of the final and initial nucleons, τ_3 is the z-component of the isotopic spin operator for the nucleon, and has the value $+1$ if p_f, p_i refer to a proton, and -1 if p_f, p_i represent a neutron. F_1^s and F_2^s are called the isotopic scalar charge and moment form factors, F_1^v and F_2^v are called the isotopic vector charge and moment form factors.

Evidently the following correspondence obtains:

$$\begin{aligned} F_1^P &= F_1^s + F_1^v \\ F_2^P &= F_2^s + F_2^v \\ F_1^N &= F_1^s - F_1^v \\ F_2^N &= F_2^s - F_2^v. \end{aligned} \tag{1.12}$$

Therefore

$$F_1^s(0) = F_1^v(0) = e/2$$

$$F_2^s(0) = \frac{\mu_P + \mu_N}{2} = -0{\cdot}06\,\frac{e}{2M}$$

$$F_2^v(0) = \frac{\mu_P - \mu_N}{2} = 1{\cdot}85\,\frac{e}{2M}.$$

This decomposition into isotopic scalar and vector form factors is useful in the theoretical discussions which are based on the assumption of charge independence in the strong couplings between mesons and nucleons [7]. In all theoretical analyses presented in the succeeding chapters, charge independence, i.e. conservation of isotopic spin, will be assumed.

CHAPTER II

THEORETICAL APPROXIMATIONS AND ASSUMPTIONS IN OBTAINING NUCLEON FORM FACTORS FROM EXPERIMENT

It was remarked in Chapter I that the definition of the form factors F_1 and F_2 involves only the interaction of a real nucleon with a virtual photon. Thus any experimental arrangement which replaces the 'question box' of Fig. II.1 by a known interaction probes electromagnetic structure of the nucleon. Five types of experiments which have been carried out to determine the nucleon form factors are discussed in this chapter. These are:

1. Elastic electron–proton scattering for information on proton structure.

$$e + P \rightarrow e + P$$

2. Neutron–electron interaction for information on neutron structure.

$$N + e \rightarrow N + e$$

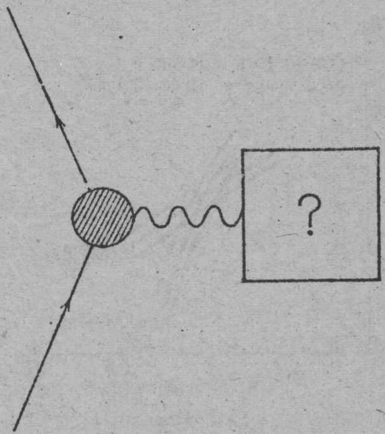

Fig. II.1. General process for measuring nucleon form factors.

3. Inelastic electron–deuteron scattering for information on neutron structure.

$$e + D \rightarrow e' + N + P$$

4. Elastic electron–deuteron scattering for information on neutron structure.

$$e + D \rightarrow e + D$$

5. Electron production of pions from protons primarily for information on neutron structure.

$$e + P \rightarrow \begin{cases} N + \pi^{+} \\ P + \pi^{0} \end{cases}$$

Theoretical assumptions and approximations which are required in order to extract values for $F_1(q^2)$ and $F_2(q^2)$ from these experiments are analysed in what follows.