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POLARIZATION PHENOMENA IN THE SCATTERING OF ELECTRONS BY PROTONS IN THE HIGH-ENERGY REGION

1. It is known (1) that the study of elastic $(e+p)$-scattering with unpolarized particles makes it possible to determine two combinations of electromagnetic form factors:

$$G_M^2, \qquad G_E^2 + \tau G_M^2, \qquad \tau = q^2/4m^2,$$

where q^2 is the square of the transferred four-momentum and m is the nucleon mass. At large transferred momenta ($\tau \gg 1$), separating the charge form factor from these combinations is difficult for the following reasons:

a) Higher symmetries predict $G_{Mp}^2/G_{Ep}^2 = 9$, independently of the value of q^2 (2), which is confirmed by experimental data (3) over the entire currently investigated region of transferred momenta.

b) The factor τ in the combination $G_E^2 + \tau G_M^2$ enhances, for $\tau > 1$, the contribution of the magnetic form factor; moreover, at high electron energies the enhancement is such that it becomes practically impossible to isolate the charge form factor of the proton. Thus, in the scattering of electrons with energy 20 BeV, $\tau_{\max} = 10$, and the contribution of the charge form factor is 1%; for electrons with energy 40 BeV, $\tau_{\max} = 20$.

In this connection the question arises: might polarization experiments be useful for determining the proton charge form factor at large q^2?

Various polarization characteristics of the process of electron scattering by protons were calculated in the works of A. I. Akhiezer, L. N. Rosenzweig, I. M. Shmushkevich (4), and Frolov (5). In papers (4,5), however, the question of using polarization experiments to determine the charge form factor at high energies was not considered. In the present note we analyze the polarization characteristics of (ep)-scattering in order to elucidate the possibilities of measuring the proton charge form factor at large transferred momenta.

2. The simplest of the possible polarization experiments in elastic (ep)-scattering are measurements of the polarization of one of the final particles, if the initial particles are unpolarized, or measurement of the azimuthal asymmetry of the angular distribution in the case in which one of the initial particles is polarized. It turns out ([4]), however, that in the Born approximation no polarization arises in either the final electron or the proton if the initial particles are unpolarized, and likewise no asymmetry of the angular distribution arises in the scattering of polarized electrons on an unpolarized target or in the scattering of unpolarized electrons on a polarized target. Azimuthal asymmetry arises only in the scattering of polarized electrons on polarized protons, while the polarization of recoil protons differs from zero in the case in which the initial particles are polarized. The most general formulas describing these polarization characteristics were obtained in works ([4,5]).

Below we show that measurement of the polarization of the recoil proton or of the asymmetry of the angular distribution, with a definite choice of the directions of the polarization vectors of the initial particles, makes it possible to determine the char-

proton charge form factor at large transferred momenta. The formulas arising in this case can be obtained from the corresponding general formulas ([4,5]), if in the latter one uses the form factors G_M and G_E instead of the Dirac F_1 and Pauli F_2 form factors.

3. Let us first discuss possible experiments on measuring the polarization of recoil protons arising in the scattering of unpolarized electrons by polarized target protons. The following measurements prove to be the most sensitive to the charge form factor.

a) The longitudinal polarization of recoil protons arising in the scattering of electrons by protons whose polarization vector $\mathbf{s}_1$ is orthogonal to the momentum $\mathbf{p}_2$ of the scattered proton ($\mathbf{s}_1 \cdot \mathbf{p}_2 = 0$) is determined by the following expression (laboratory frame):

$$\mathbf{s}_2 \frac{d\sigma}{d\Omega_R} = \mathbf{p}_2(\mathbf{s}_1 \cdot \mathbf{q}_1)\Gamma(\theta, \varepsilon_1)\frac{\tau - \varepsilon_1}{\tau + 1}\, G_{EG}M, \tag{1}$$

where

$$\frac{d\sigma}{d\Omega_R} = \left(\frac{\alpha}{2\varepsilon_1}\right)^2 \frac{\cos^2\theta/2}{\sin^4(\theta/2)[1+\varepsilon_1(1-\cos\theta)]}\left[2\,\mathrm{tg}^2\,\frac{\theta}{2}\,\tau G_M^2 + \frac{G_E^2 + \tau G_M^2}{1+\tau}\right];$$

$\mathbf{s}_2$ is the polarization vector of the final proton; $q_1 = (\varepsilon_1, \mathbf{q}_1)$ is the 4-momentum of the initial electron; $q_2 = (\varepsilon_2, \mathbf{q}_2)$ is the 4-momentum of the final electron; θ is the electron scattering angle, $\alpha = 1/137$, $q = q_2 - q_1$; $\Gamma(\theta, \varepsilon_1) = \alpha^2/2\tau[1 + \varepsilon_1(1 - \cos\theta)]^2$.

We use the system of units $h = c = m = 1$.

It is seen from formula (1) that, for determining the charge form factor, one measurement of the longitudinal polarization is sufficient for each value of τ. The disadvantages of this method are the necessity of measuring the longitudinal polarization of the recoil proton, and also the necessity of changing the direction of the initial-polarization vector as the proton scattering angle changes. One may fix the proton scattering angle, thereby fixing the direction of the vector $\mathbf{s}_1$; the square of the transferred momentum τ can then be varied by changing the energy of the primary electron beam.

b) The longitudinal polarization of recoil protons arising in the scattering of electrons by protons whose polarization vector is orthogonal to the momentum of the incident electron ($(\mathbf{s}_1 \cdot \mathbf{q}_1) = 0$) is determined by the expression:

$$\mathbf{s}_2 d\sigma/d\Omega_R = \mathbf{p}_2(\mathbf{s}_1 \cdot \mathbf{q})\Gamma(\theta, \varepsilon_1)\{\tau^2 G_M(G_M + 2G_E) + \tau G_E^2 \tag{2}$$

$$-2\varepsilon_1\tau[\tau G_M(G_M - 2G_E) - G_E(G_E - 2G_M)] + \varepsilon_1^2[\tau G_M(G_M - 2G_E) - G_E^2]\}.$$

For a fixed value of τ, the expression in braces is a polynomial of second degree in the energy ε_1. Therefore, measuring the longitudinal polarization of recoil protons at three different values of the initial-electron energy corresponding to a fixed value of τ will make it possible to separate out three combinations of form factors:

$$G_1 = \tau^2 G_M(G_M + 2G_E) + \tau G_E^2,$$

$$G_2 = \tau G_M(G_M - 2G_E) - G_E(G_E - 2G_M),$$

$$G_3 = \tau G_M(G_M - 2G_E) - G_E^2.$$

If $\tau \simeq 1$, then $G_2 = G_M^2 - G_E^2$; for $\tau \gg 1$, $G_1 = \tau^2 G_M(G_M + 2G_E)$, $G_2 = G_3 = \tau G_M(G_M - 2G_E)$.

In contrast to a), here there is no need to change the direction of the vector $\mathbf{s}_1$; however, in order to isolate the charge form factor, for $\tau \gg 1$ it is necessary to carry out at least two measurements of the polarization of recoil protons for each value of τ.

c) If the vector $\mathbf{s}_1$ lies in the scattering plane, with $(\mathbf{s}_1 \cdot \mathbf{q}_1) = 0$, then the transverse polarization of recoil protons is determined by the expres-

by

$$\mathbf{s}_2 \frac{d\sigma}{d\Omega_R} = \left(\mathbf{q}_1 - \mathbf{p}_2 \frac{\mathbf{q}_1 \cdot \mathbf{p}_2}{\mathbf{p}_2^2}\right) \Gamma(\theta, \varepsilon_1) \frac{\mathbf{s}_1 \cdot \mathbf{q}}{1+\tau} \left[\tau G_M (G_M - G_E) + \varepsilon_1 G_M (G_E + \tau G_M)\right] + \mathbf{s}_1 \Gamma(\theta, \varepsilon_1) \frac{\varepsilon_1^2 - 2\varepsilon_1 \tau - \tau}{1+\tau} (G \tag{3}$$

It follows from this formula that measurement of the transverse polarization at different ε_1, corresponding to a fixed τ, makes it possible to isolate the combination $G_M(G_M - G_E)$, which is sensitive to the charge form factor of the proton.

4. In the scattering of polarized electrons by unpolarized target protons, longitudinally polarized protons arise (if the electron mass is neglected). In this case the polarization vector is determined by the expression

$$\mathbf{s}_2 \frac{d\sigma}{d\Omega_R} = 4\mathbf{p}_2 \frac{(\mathbf{s} \cdot \mathbf{q})}{1+\tau} \Gamma(\theta, \varepsilon_1) \left[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M)\right], \tag{4}$$

where $\mathbf{s}$ is the polarization vector of the initial electron. By measuring the polarization of the scattered proton at two different values of ε_1, corresponding to one value of τ, one can isolate the combination of form factors $G_M(G_M + G_E)$.

5. The differential cross section for scattering of polarized electrons, whose polarization vector satisfies the condition $(\mathbf{s} \cdot \mathbf{q}_1) = 0$, by polarized target protons is determined by the expression

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_R} \left[1 + A(\mathbf{s}, \mathbf{s}_1)\right], \tag{5a}$$

$$\frac{d\sigma}{d\Omega_R} A(\mathbf{s}, \mathbf{s}_1) = -(\mathbf{s} \cdot \mathbf{s}_1) \Gamma(\theta, \varepsilon_1) m_e G_{EG} M, \tag{5b}$$

where m_e is the electron mass. Hence it is clear that the addition to the differential cross section due to the polarizations of the initial particles is determined by the product of the form factors $G_{MG} E$.

Thus, there exists a series of polarization experiments that are more effective for determining the charge form factor of the proton than measurement of the differential cross section for unpolarized particles.

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Note: Figure translations are in progress. See original paper for figures.