

FROM THEORY TO EXPERIMENT: HADRON ELECTROMAGNETIC FORM FACTORS IN SPACE-LIKE AND TIME-LIKE REGIONS

E. Tomasi-Gustafsson¹, G.I. Gakh², and A.P. Rekalov²

¹*DAPNIA/SPhN, CEA/SACLAY, 91191 Gif-sur-Yvette Cedex, France;*

²*National Science Center “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine*

Hadron electromagnetic form factors contain information on the intrinsic structure of the hadrons. The pioneering work developed at the Kharkov Physical-Technical Institute in the 60's on the relation between the polarized cross section and the proton form factors triggered a number of experiments. Such experiments could be performed only recently, due to the progress in accelerator and polarimetry techniques. The principle of these measurements is recalled and surprise and very precise results obtained on proton are presented. The actual status of nucleon electromagnetic form factors is reviewed, with special attention to the basic work done in Kharkov Physical-Technical Institute. This paper is devoted to the memory of Prof. M.P. Rekalov.

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1. INTRODUCTION

Electromagnetic form factors (FFs) are fundamental quantities which describe the internal structure of composite particles. Hadron FFs contain dynamical information about charge and magnetic currents and are calculated in frame of hadron models. Elastic hadron FFs can be studied through elastic electron hadron scattering $e+h \rightarrow e+h$, or through annihilation reaction $\bar{p}+p \rightarrow e^+ + e^-$, where the momentum q is transferred by the exchange of one photon. Assuming this reaction mechanism, FFs enter in the expression of hadron electromagnetic vertex, and can be directly accessible from experiment, measuring the differential cross section and polarization observables.

Polarization observables, indeed, is the key word of this talk, which is dedicated to the fundamental contribution of the “Kharkov theoretical school”, led by Academician A. I. Akhiezer, whose memory we honour today. Basic papers, in collaboration with Prof. M. P. Rekalov [1-2], were written in the late 60's, which indicated the way to get precise data on FFs at large values of the four-momentum transfer squared, $-q_\mu^2$.

Such experiments have been realized only recently, due to the progress achieved in building high intensity polarized beams, spectrometers, hadron polarimeters in the GeV range. The model independent derivation of the necessary observables, the ideas and the suggestions made in Kharkov almost 40 years ago, represent a remarkable advance of the theory on experiment. At that time it was difficult to conceive that an intense high polarized beam could be accelerated, and the calculations were done for polarized target, which seemed more realistic.

Nowadays higher transfer momenta are reached with polarized beam and hadron polarimeters which can measure the polarization of the scattered hadron, proton [3-5] or deuteron [6-7], but polarized targets are also currently used.

In this presentation, we briefly present the main lines of the theoretical background, describe the experimental set up and focus on the results and their implications.

2. ELECTRON - HADRON ELASTIC SCATTERING-THEORETICAL FRAMEWORK

2.1. THEORETICAL FRAMEWORK

The Feynman diagram for elastic electron-nucleon scattering is shown in Fig. 1, assuming the one-photon exchange, together with the notations of the particle four-momenta.

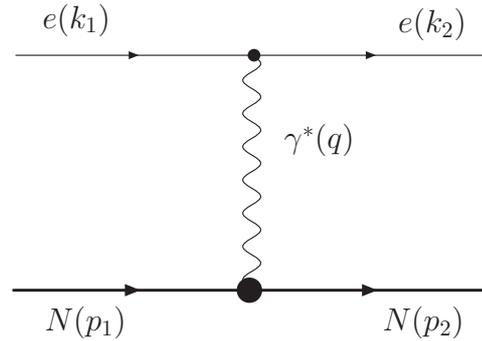


Fig. 1. Feynman diagram for elastic scattering $e^- + N \rightarrow e^- + N$

The most convenient frame for the analysis of elastic eN scattering is the Breit frame, which is defined as the system where the initial and final nucleon energies are the same. As a consequence, the energy of the virtual photon vanishes and its four-momentum square, coincides with its three-momentum square (in modulus). Therefore, the derivation of the formalism in Breit system is more simple and has some analogy with a non-relativistic description of the nucleon electromagnetic structure. We choose the z -axis parallel to the virtual photon three-momentum \vec{q} in the Breit frame and the xz -plane as the scattering plane. An useful kinematical relation can be derived between the electron scattering angle in the Lab system θ_e and in the Breit system θ_B :

$$\cot^2 \frac{\theta_B}{2} = \frac{\cot^2 \theta_e / 2}{1 + \tau}, \quad \tau = -\frac{q_\mu^2}{m^2}, \quad (1)$$

where m is the nucleon mass and $q = k_1 - k_2$.

The matrix element corresponding to the diagram of Fig. 1 is:

$$M = \frac{e^2}{q_\mu^2} l_\alpha J_\alpha, \quad l_\alpha = \bar{u}(k_2) \gamma_\alpha u(k_1), \quad (2)$$

where l_α is the electromagnetic current of electron, J_α is the nucleon electromagnetic current, e is the proton charge.

The nucleon electromagnetic current can be written in terms of Pauli and Dirac nucleon FFs $F_1(q^2)$ and $F_2(q^2)$:

$$J_\mu = \bar{u}(p_2) \left(F_1(q^2) \gamma_\mu - \frac{F_2(q^2)}{2m} \sigma_{\mu\nu} q_\nu \right) u(p_1), \quad (3)$$

where $\sigma_{\mu\nu} = \frac{1}{2}(\gamma_\mu \gamma_\nu - \gamma_\nu \gamma_\mu)$.

Note that $q_\mu J_\mu = 0$ for any values of $F_1(q^2)$ and $F_2(q^2)$, i.e. the current J_μ is conserved.

The expressions for the different components of the current J_α in the Breit frame are:

$$J_0 = 2m(F_1 - \tau F_2) \chi_2^+ \chi_1;$$

$$\vec{J} = (F_1 + F_2) \chi_2^+ i\vec{\sigma} \times \vec{q}_B \chi_1,$$

and allow to introduce in a straightforward way the Sachs nucleon electromagnetic FFs, electric and magnetic, which are written as:

$$G_E(q^2) = F_1(q^2) - \tau F_2(q^2);$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2). \quad (4)$$

Such identification can be easily understood, if one takes into account that the time component of the current J_0 , describes the interaction of the nucleon with Coulomb potential. Correspondingly, the space component \vec{J} describes the interaction with the magnetic field.

The differential cross section in the Lab system is written as

$$\frac{d\sigma}{d\Omega_e} = \frac{|M|^2}{64\pi^2 m^2} \left(\frac{\varepsilon_2}{\varepsilon_1} \right)^2, \quad (5)$$

where $\varepsilon_1(\varepsilon_2)$ is the energy of initial (final) electron, $d\Omega_e$ is the element of the final electron solid angle in the Lab frame.

From Eq. (2) we can obtain the following representation for $|M|^2$

$$|M|^2 = \left(\frac{e^2}{q^2} \right)^2 L_{\mu\nu} W_{\mu\nu};$$

$$L_{\mu\nu} = l_\mu l_\nu^*, \quad W_{\mu\nu} = J_\mu J_\nu^*,$$

where $L_{\mu\nu}$ is the lepton tensor and $W_{\mu\nu}$ is the nucleon tensor.

The product of the tensors $L_{\mu\nu}$ and $W_{\mu\nu}$ is a relativistic invariant, therefore it can be calculated in any reference system. For comparison with experiment it is more convenient to use the differential cross section in Lab system (the Rosenbluth formula [8])

$$\frac{d\sigma}{d\Omega_e} = \sigma_M \left[2\tau G_M^2 \tan^2 \frac{\theta_e}{2} + \frac{G_E^2 + \tau G_M^2}{1 + \tau} \right] \quad (6)$$

with

$$\sigma_M = \frac{4\alpha^2}{(-q^2)^2} \frac{\varepsilon_2^3}{\varepsilon_1} \cos^2 \frac{\theta_e}{2} =$$

$$= \frac{4\alpha^2}{(-q^2)^2} \frac{\varepsilon_2^2 \cos^2(\theta_e/2)}{1 + (2\varepsilon_1/m) \sin^2(\theta_e/2)},$$

where $\alpha = e^2/4\pi \approx 1/137$, σ_M is the Mott cross-section, describing a scattering of relativistic electrons by a point particle (with charge e and spin $1/2$).

Note that the very specific $\cot^2(\theta_e/2)$ dependence of the reduced cross-section $\sigma_M^{-1} d\sigma/d\Omega_e$ for elastic eN scattering ($N = p, n$) results from the assumption of one-photon-exchange mechanism for the considered reaction. This can be easily proved, by cross-symmetry considerations, looking to the annihilation channel, $e^+ + e^- \rightarrow \bar{p} + p$ [9-10]. In the CMS of such reaction, the one-photon-exchange mechanism induces a simple and evident $\cos^2 \theta$ -dependence of the corresponding differential cross section (θ is the angle of the emitted nucleon in center of mass system), due to the C-invariance of the hadron electromagnetic interaction, and unit value of the photon spin. The particular $\cot^2(\theta_e/2)$ -dependence of the differential cross section (6) is at the basis of the method to determine both nucleon electromagnetic FFs, G_E and G_M , using the ε linearity of the *reduced* cross section:

$$\sigma_{red}^{Born}(\theta_e, \tau) =$$

$$= \varepsilon(1 + \tau) \left[1 + \frac{2\varepsilon_1}{m} \sin^2(\theta_e/2) \right] \frac{4\varepsilon_1^2}{\alpha^2} \frac{\sin^4(\theta_e/2)}{\cos^2(\theta_e/2)} \frac{d\sigma}{d\Omega_e} =$$

$$= \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2), \quad (7)$$

$$\varepsilon = \left[1 + 2(1 + \tau) \tan^2(\theta_e/2) \right]^{-1},$$

where ε is polarization parameter of the virtual photon (we use the common notation Q^2 for the value of the four-momentum transfer squared, $Q^2 = -q_\mu^2$).

Measurements of the elastic differential cross-section as a function of ε , at different angles θ_e for a fixed value of Q^2 allow G_E^2 and τG_M^2 to be determined as the slope and the intercept, respectively, from the linear ε dependence (7) (Rosenbluth fit) [6].

One can see that the backward eN scattering ($\theta_e = \pi$) is determined by the magnetic FF only, and that the slope for σ_{red} is sensitive to $G_E(Q^2)$. At large Q^2 , (such that $\tau \gg 1$), the differential cross section $d\sigma/d\Omega_e$ (with nonpolarized particles) is insensitive to G_E : the corresponding combination of the nucleon FFs, $(\varepsilon G_E^2 + \tau G_M^2)$ is dominated by the G_M^2 contribution, due to the following reasons:

1) $R_\mu = G_{Mp}(Q^2)/G_{Ep}(Q^2) \geq \mu_p$, where μ_p is the proton magnetic moment, so $R_\mu^2 \approx 8$;

2) The factor τ increases the G_M^2 contribution at large momentum transfer, where $\tau \gg 1$.

Therefore electron-proton scattering (with unpolarized particles) is dominated by the magnetic FF, at large values of momentum transfer. The same holds for electron-neutron scattering, even at relatively small values of Q^2 , due to the smaller values of the neutron electric FF.

As a result, for the exact determination of the proton electric FF, in the region of large momentum transfer, and for the neutron electric FF — at any value of Q^2 , polarization measurements are strongly required and in particular those polarization observables which are determined by the product $G_E(Q^2)G_M(Q^2)$, and are, therefore, more sensitive to G_E [1]. Both experiments (with polarized electron beam) have been realized: $p(\vec{e}, \vec{p})e$ for the determination of the proton FF G_{Ep} [3-5] and, for the determination of the neutron FF G_{En} , $\vec{d}(\vec{e}, e'n)p$ [11] and $d(\vec{e}, e'\vec{n})p$ [12].

In general the hadronic tensor $W_{\mu\nu}$ for elastic ep (en) scattering, contains four terms, related to the 4 possibilities of polarizing the initial and final protons (neutrons):

$$W_{\mu\nu} = W_{\mu\nu}(0) + W_{\mu\nu}(\vec{P}_1) + W_{\mu\nu}(\vec{P}_2) + W_{\mu\nu}(\vec{P}_1, \vec{P}_2),$$

where \vec{P}_1 and \vec{P}_2 are the polarization vectors of the initial and final protons (neutrons).

The first term corresponds to the unpolarized case, the second (third) term corresponds to the case when the initial (final) nucleon is polarized, and the last term describes the reaction when both nucleons (initial and final) are polarized.

One can show that the polarization of the final proton (neutron) vanishes, if the electrons are unpolarized: unpolarized electrons can not induce polarization of the scattered proton (neutron). This is a property of the one-photon mechanism for elastic eN scattering ($N = p, n$) and of the hermiticity of the Hamiltonian for the hadron electromagnetic interaction. Namely the hermiticity condition allows to prove that the hadron electromagnetic FFs are real functions of the momentum transfer squared in the space-like region $q^2 < 0$. On the other

hand, in the time-like region, which is scanned by the annihilation process $e^+ + e^- \rightarrow \bar{p} + p$, the nucleon FFs are complex functions of q^2 if $q^2 \geq 4m_\pi^2$, where m_π is the pion mass.

The complexity of nucleon FF's (in the time-like region) results in specific polarization phenomena, for the annihilation process $e^+ + e^- \rightarrow \bar{p} + p$, which are different from the case of elastic electron - proton scattering. For example, the polarization of the final proton (or antiproton) is different from zero, even in the case of annihilation of unpolarized leptons: this polarization is determined by the product $\text{Im}(G_E G_M^*)$ (and, therefore, vanishes in the case of elastic electron - proton scattering, where FFs are real functions).

Note that the two-photon exchange in elastic ep scattering is also generating complex amplitudes. So the interference between one and two-photon amplitudes induces nonzero proton polarization, but small in absolute value, as it is proportional to α .

Numerous experiments have been done with the aim to detect such polarization at the momentum transfers $Q^2 \leq 1 \text{ GeV}^2$, but with negative result, at a percent level.

Only recently the above mentioned interference was experimentally detected, measuring the asymmetry in the scattering of transversally polarized electrons by an unpolarized proton target [13], which contains information on the imaginary part of the two-photon contribution.

Note that at very large momentum transfer, the relative role of two-photon exchange amplitudes may be increased (violating the counting in α), due to the steep Q^2 decreasing of hadronic electromagnetic FFs.

Note also that the analytical properties of the nucleon FFs, considered as functions of the complex variable $z = q^2$, result in a specific asymptotic behavior, as they obey to the Phragmen-Lindelof theorem:

$$\lim_{q^2 \rightarrow -\infty} F^{(SL)}(q^2) = \lim_{q^2 \rightarrow +\infty} F^{(TL)}(q^2) \quad (8)$$

The existing experimental data about the proton FFs in time-like region up to 15 GeV^2 , seem to contradict this theorem [14], showing that the asymptotic region is more far than expected.

Let us define a coordinate system where z -axis is parallel to the virtual photon three-momentum and xz is the scattering plane. One can find the following expressions for the components P_{2x} and P_{2z} of the proton polarization vector (in the scattering plane) - in terms of the proton electromagnetic FFs [1-2]:

$$\begin{aligned} DP_{2x} &= -2\lambda \cot \frac{\theta_e}{2} \sqrt{\frac{\tau}{1+\tau}} G_E G_M, \\ DP_{2z} &= \lambda \frac{\varepsilon_1 + \varepsilon_2}{m} \sqrt{\frac{\tau}{1+\tau}} (G_M)^2, \end{aligned} \quad (9)$$

where λ is the electron helicity, which takes values ± 1 , corresponding to the direction of spin parallel or antiparallel to the electron three-momentum, and D is

proportional to the differential cross section with unpolarized particles:

$$D = 2\tau G_M^2 + \frac{G_E^2 + \tau G_M^2}{1 + \tau} \cot^2 \frac{\theta_e}{2}. \quad (10)$$

So, for the ratio of these components one can find the following formula:

$$\frac{P_{2x}}{P_{2z}} = \frac{P_t}{P_l} = -2 \cot \frac{\theta_e}{2} \frac{m}{\varepsilon_1 + \varepsilon_2} \frac{G_E(q^2)}{G_M(q^2)}. \quad (11)$$

A measurement of the ratio of the transverse and the longitudinal polarization of the recoil proton is directly related to the ratio (11) of electric and magnetic FFs, $G_E(q^2)/G_M(q^2)$.

In the same way it is possible to calculate the dependence of the differential cross section for the elastic scattering of the longitudinally polarized electrons by a polarized proton target, with polarization P_1 :

$$\frac{d\sigma}{d\Omega_e}(P_1) = \left(\frac{d\sigma}{d\Omega_e} \right)_0 (1 + \lambda P_{1z} A_z + \lambda P_{1x} A_x), \quad (12)$$

where the asymmetries A_x and A_z (or the corresponding analyzing powers) are related in a simple and direct way, to the components of the final proton polarization:

$$A_x = P_{2x}, \quad A_z = -P_{2z} \quad (13)$$

This holds in the framework of the one-photon-exchange mechanism for elastic ep scattering. Note that the quantities A_x and P_{2x} have the same sign and absolute value, but the components A_z and P_{2z} being equal in absolute value, have opposite sign.

In the framework of the one-photon-exchange mechanism, there are at least two different sources of corrections to these relations:

- the standard radiative corrections;
- the electroweak corrections.

2.2. EXPERIMENTAL RESULTS

Highly polarized electron beams are available at different accelerators, MAMI (Mainz), MIT (Bates), JLab (Virginia). At JLab, where the G_{Ep} experiment was done [3-5], electron energies are available up to 6 GeV, the typical intensity about 30 μA and the polarization from 60 to 80%. The (longitudinal) electron polarization is obtained by photoemission from a semiconductor cathode using polarized laser light from a pulsed diode laser. Beam polarimeters based on Mott, Moeller or Compton scattering measure the electron beam polarization with an error of the order of percent.

Measurements of elastic ep scattering require coincidence experiments in order to eliminate the background, even if in a binary process, in principle, the detection of one particle allows to reconstruct fully the kinematics.

The momentum of the scattered proton is analyzed by a high resolution spectrometer which focal plane detection constitutes also the front detection of the focal polarimeter.

Proton polarimeters in the GeV range are based on inclusive scattering on a graphite or polyethylene target, where one charged particle is detected. The azimuthal

asymmetry of the scattered particle contains the information on the polarization of the proton at the focal plane.

The optimization of the figure of merit (efficiency and analyzing powers) in the GeV range was carefully studied at Saturne accelerator [15] and at JINR-LHE accelerator complex in Dubna, where polarized proton beams are available in the GeV range [16]. In particular it has been shown that the thickness of the target is a very important parameter, and depends on the proton energy. For proton momenta over 3 GeV/c, very thick targets (larger than the collision length) do not improve the polarimeter performances.

After that a good elastic ep event is identified by energy and angular correlation of the two outgoing particles, and its polarization measured, the ratio of the longitudinal and transverse polarization is directly related to the ratio $R = \mu G_E/G_M$ (μ is the proton magnetic moment), by Eq. (11).

The ratio R is shown in Fig. 2. These data show two remarkable features: high precision of the polarization data, compared to the Rosenbluth data, and monotonical decrease with Q^2 which can be parametrized as:

$$R(Q^2) = 1 - (0.130 \pm 0.005) \left(Q^2 / \text{GeV}^2 - (0.04 \pm 0.09) \right) \quad (14)$$

2.3. IMPLICATIONS

This means that the charge and magnetic currents in the nucleon are different, contrary to what had been previously assumed. Indeed, a commonly used parametrization was a dipole approximation for both FFs, which was compatible with an exponential distribution of the charge, in non-relativistic approximation, and agreed with predictions from quark counting rules [22-23].

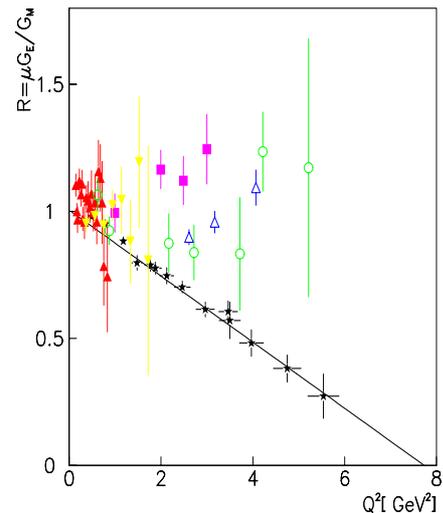


Fig. 2. Q^2 -dependence for the proton form factor ratio. Selected data from Rosenbluth measurements are plotted: from [17] (solid triangles); from [18] (solid circles); from [19] (open circles); from [20] (solid squares); from [21] (open triangles). Polarization data (solid stars) are shown together with the fit from Eq. (14)

QCD predicts a $q^2 F_2(q^2)/F_1(q^2)$ scaling, because $F_2(q^2)$ carries an extra factor $1/q^2$ as it requires a spin flip. Such scaling was approximately in agreement with the previous data, and it was argued that asymptotic predictions were reached already at $Q^2 \approx 2 \dots 5 \text{ GeV}^2$.

When logarithmic corrections are added, pQCD parametrizations may reproduce the polarization data (which scale as $\sqrt{-q^2} F_2(q^2)/F_1(q^2)$). However analytical properties of FFs, which should satisfy Phragmen-Lindeloff theorem, are fulfilled by such parametrizations only at much larger value of Q^2 [24].

Another important issue concerns the light nuclei structure, ^2H , ^3He . A good description of the electromagnetic properties of these nuclei requires the knowledge of nucleon FFs. A modification of the proton FFs requires either another prescription for the neutron FFs, or a revision of other ingredients of the models, such as wave functions or meson exchange currents, relativistic effects etc [25].

Data in time-like region are also necessary for a complete understanding of the nucleon structure. The separation of individual electromagnetic FFs has not been done, yet. As electromagnetic FFs are complex functions of q^2 in time-like region, polarization experiments are necessary. The present understanding is poor, and few phenomenological models can describe all data in the full kinematical region [26]. Experiments are planned in future, at Novosibirsk, Frascati, FAIR.

Reasons of the discrepancy between the two methods have been indicated in the two-photon exchange [27]. However this is incompatible with model independent considerations, which require non-linearity of the Rosenbluth fit as a function of ε and the experiments do not give evidence for the presence of such mechanism [28-31].

Recent calculations of the box diagram prove that this contribution is small [32-33]. A more realistic explanation relies on the method used to calculate and to apply standard radiative corrections, as a multiplicative factor to the measured cross section. Such factor contains a large ε and Q^2 dependence, which are the relevant variables. Therefore, this procedure induces large correlations between the parameters of the Rosenbluth fit [34]. A recent suggestion to apply higher order corrections, through the structure function method, proves to be successful in bringing into agreement the two sets of data [35].

3. CONCLUSIONS

The pioneering work [1] is at the origin of a series of experiments and programs at different world accelerators. The unexpected results which were obtained changed our view on the nucleon structure.

Although an English translation of the original papers [1-2] was soon available, these papers did not receive the consideration they deserve and are not properly quoted. Only recently these papers have been added

to the High-Energy Physics Literature Database [37] and appear very little quoted in comparison with later works. From this database, it appears today that works, which essentially reproduce the same result are more widely quoted, as for example Ref. [38] which appeared at least one year later and Ref. [39] published in 1981.

This situation is not new, and unfortunately not adequate citation of appropriate references is a current problem. Efforts and concernment of scientific authorities at the level of Editorial board of journals, Conference Committees, representatives and individuals are necessary in order to have a proper appreciation of these achievements.

We would like to conclude with a citation from [1]: “Thus, there exist a number of polarization experiments which are more effective for determining the proton charge FF than is the measurement of the differential cross section for unpolarized particles”.

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ОТ ТЕОРИИ К ЭКСПЕРИМЕНТУ: ЭЛЕКТРОМАГНИТНЫЕ ФОРМФАКТОРЫ АДРОНОВ В ПРОСТРАНСТВЕННО- И ВРЕМЕНИПОДОБНЫХ ОБЛАСТЯХ

Е. Томаси-Густафссон, Г.И. Гах, А.П. Рекало

Электромагнитные формфакторы адронов содержат информацию о внутренней структуре адронов. Пионерская работа, выполненная в 60-е годы в Харьковском физико-техническом институте, посвященная связи протонных формфакторов с сечением рассеяния поляризованных частиц, инициировала ряд экспериментов. Такие эксперименты стали возможны совсем недавно благодаря прогрессу в конструировании ускорителей и поляриметров. Приведены условия этих измерений и прецизионные результаты опытов с протонами. Представлен современный статус электромагнитных формфакторов нуклонов, особое внимание уделено основополагающей работе, выполненной в Харьковском физико-техническом институте. Статья посвящена памяти профессора М.П. Рекало.

ВІД ТЕОРІЇ ДО ЕКСПЕРИМЕНТУ: ЕЛЕКТРОМАГНІТНІ ФОРМФАКТОРИ АДРОНІВ У ПРОСТОРОВО- ТА ЧАСОПОДІБНИХ ОБЛАСТЯХ

Е. Томасі-Густафссон, Г.І. Гах, О.П. Рекало

Електромагнітні формфактори адронів містять інформацію про внутрішню структуру адронів. Піонерська робота, виконана у 60-ті роки у Харківському фізико-технічному інституті, яка була присвячена зв'язку протонних формфакторів з перерізом розсіювання поляризованих частинок, ініціювала низку експериментів. Такі експерименти стали можливими зовсім недавно завдяки прогресу у конструюванні прискорювачів та поляриметрів. Наведені умови цих вимірювань та прецизійні результати дослідів з протонами. Представлений сучасний стан електромагнітних формфакторів нуклонів, особлива увага приділена основоположній роботі, яка була виконана у Харківському фізико-технічному інституті. Стаття присвячена пам'яті професора М.П. Рекала.