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HADRONS IN THE NUCLEAR MEDIUM

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Nucleon properties are modified in the nuclear medium. To understand these modifications and their origin is a central issue in nuclear physics. For example, a wide variety of QCD-based models, including quark-meson coupling and chiral-quark soliton models, predict that the nuclear constituents change properties with increasing density. These changes are predicted to lead to observable changes in the nucleon structure functions and electromagnetic form factors. We present results from a series of recent experiments at MAMI and Jefferson Lab, which measured the proton recoil polarization in the $^4\mathrm{He}(\vec{e}, e'\vec{p}\,)^3\mathrm{H}$ reaction to test these predictions. These results, with the most precise data at $Q^2 = 0.8$ (GeV/c)^2 and at 1.3 (GeV/c)^2 from E03-104, put strong constraints on available model calculations, such that below $Q^2 = 1.3$ (GeV/c)^2 the measured ratios of polarization-transfer are successfully described in a fully relativistic calculation when including a medium modification of the proton form factors or, alternatively, by strong charge-exchange final-state interactions. We also discuss possible extensions of these studies with measurements of the $^4\mathrm{He}(\vec{e}, e'\vec{p}\,)^3\mathrm{H}$ and $^2\mathrm{H}(\vec{e}, e'\vec{p}\,)n$ reactions as well as with the neutron knockout in $^4\mathrm{He}(\vec{e}, e'\vec{n}\,)^3\mathrm{He}$.

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1. Introduction

The underlying theory of strong interactions is quantum chromodynamics (QCD), yet there are no ab-initio calculations of nuclei available. Nuclei are effectively and well described as clusters of protons and neutrons held together by a strong, long-range force mediated by meson exchange, whereas the saturation properties of nuclear matter arise from the short-range, repulsive part of the strong interaction [1]. At nuclear densities of about 0.17 nucleons/fm^3, nucleon wave functions have significant overlap. In the chiral limit, one expects nucleons to lose their identity altogether and a transition to a quark-gluon plasma is expected in nuclei [2]. This phase transition is extensively being studied at the RHIC facility.

Within QCD, there is no known way to derive anything like an atomic nucleus in which the constituents do not change as the mean density (or temperature) increases [3]. The discovery of the nuclear EMC effect, the depletion of the deep inelastic structure function observed in the valence quark regime, almost twenty years ago, brought the subject of quarks into nuclear physics with great impact. However, the specific causes of the modifications observed in the nuclear structure functions have not yet been identified with certainty [4]. Miller and Smith [5] argue that the depletion is due to some interesting effect involving dynamics beyond the conventional nucleon-meson treatment of nuclear physics. One such explanation is a medium modification of bound nucleon structure. A variety of models predict deviations from the free-space nucleon form factors in the nuclear medium: A calculation by Lu et al. [6, 7], using a quark-meson coupling (QMC) model, suggests deviations from the free-space electromagnetic form factor which result in measurable effects on observables in model calculations over the four-momentum-transfer squared, Q^2, range $0.0 < Q^2 < 2.5$ (GeV/c)^2. Similar measurable effects have been calculated in a light-front-constituent quark model by Frank et al. [8], a modified Skyrme model by Yakshiev et al. [9], a chiral quark-soliton model (CQS) by Smith and Miller [10] and the Nambu-Jona-Lasinio model [11, 12]. These calculations are generally consistent with present constraints on possible medium modifications for both the electric form factor (from the coulomb sum rule, for $\mathrm{Q}^2 < 0.5$ (GeV/c)^2 [13−15]) and the magnetic form factor (from a y-scaling analysis [16] for $\mathrm{Q}^2 > 1$ (GeV/c)^2), and limits on the scaling of nucleon magnetic moments in nuclei [17].

Although models using free nucleons and mesons as quasi-particles are successful in the description of many aspects of nuclear physics, one may therefore expect that their use is under certain circumstances a highly uneconomical approach, especially given that these are not the fundamental entities of the underlying theory. The use of medium-modified nucleons as quasi-particles may be a better choice. To experimentally demonstrate any modification of the nucleon form factors, one is required to have excellent control over the reaction mechanism effects [18]. The nucleus, as a bound many-body quantum system, has inherent many-body effects, such as meson-exchange currents (MEC) and isobar configurations (IC). In addition, when probing nuclear structure one has to deal with final-state interactions (FSI). Thus, distinguishing possible changes in the spatial structure of nucleons embedded in a nucleus from more conventional many-body effects is only possible within the context of a model.

2. *Recoil polarization in quasi-elastic electron scattering*

The charge and magnetic responses of a single nucleon are quite well studied from elastic scattering experiments. Measuring the same response from quasi-elastic scattering off nuclei and comparing with a single nucleon is thus an intuitive method to investigate the properties of nucleons inside nuclei. In free electron-nucleon scattering, the ratio of the electric to magnetic Sachs form factors, G_E and G_M, is given by [19, 20]

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z} \cdot \frac{E_e + E_{e'}}{2m_p} \tan(\theta_e/2), \tag{1}$$

where P'_x and P'_z are the transverse and longitudinal transferred polarizations (see Fig. 1). The beam energy is E_e, the energy (angle) of the scattered electron is $E_{e'}$ (θ_e) and m_p is the proton mass. This relation was extensively used to extract G_E/G_M for the proton, see e.g. [21−25] for measurements at JLab.

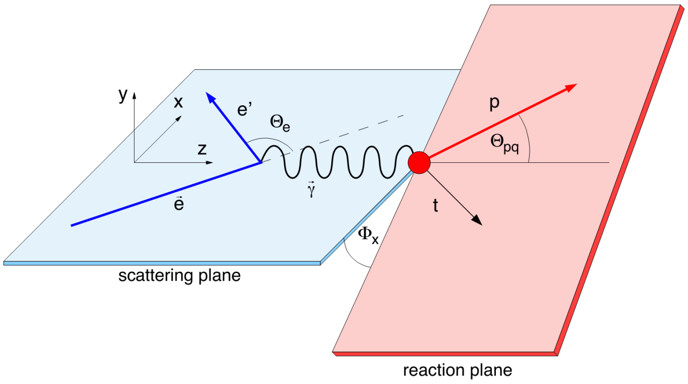

Fig. 1. Coordinate system used to define the components of the recoil proton polarization in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ *reaction. The* z *axis is along the momentum transfer, the* x *axis is in the scattering plane perpendicular to the momentum transfer* $\vec{q}$ *and the* y *axis is perpendicular to the scattering plane, forming a right-handed system.*

When such measurements are performed on a nuclear target in quasi-elastic kinematics, the experimental results for the polarization-transfer ratio are conveniently expressed in terms of the polarization double ratio

$$R = \frac{(P'_x/P'_z)_A}{(P'_x/P'_z)_{^1\mathrm{H}}}, \tag{2}$$

where the polarization-transfer ratio for the quasi-elastic proton knockout $A(\vec{e}, e'\vec{p})$ reaction is normalized to the polarization-transfer ratio measured in elastic $^1\mathrm{H}(\vec{e}, e'\vec{p})$ scattering in the identical setting in order to emphasize differences between the in-medium and free values. Such a double ratio cancels also nearly all experimental systematic uncertainties. A proper interpretation of the results requires accounting for such effects as FSI and MEC. At high momentum transfer, however, the contribution of many-body and rescattering mechanisms are strongly suppressed [26]. Polarization-transfer observables provide us with a way to study the behavior of the nucleon form factors in the nuclear medium.

3. *Present experimental results*

JLab experiment E89-033 was the first to measure the polarization transfer in a complex nucleus, ^{16}O [27]. The results are consistent with predictions of relativistic calculations based on the free-proton form factor with an experimental uncertainty of about 18%. Polarization transfer has been used previously to study nuclear medium effects in deuterium [28 – 30] Within statistical uncertainties, no evidence of medium modifications was found. More recently, polarization-transfer data on ^{2}H were measured in JLab experiment E89-028 [31], under conditions very similar to those for experiment E93-049 [32] on ^{4}He. Realistic calculations to describe this reaction were performed by Arenhövel. Experimental results (open triangles) for the ^{2}H-to-^{1}H polarization-transfer double ratio, along with the results of a calculation by Arenhövel (dashed curve), are shown in Fig. 2. Arenhövel's full calculation describes the ^{2}H data well. As the sampled density is small and the bound proton in ^{2}H is nearly on mass-shell, it is not surprising that there are no indications for medium modifications of the proton electromagnetic form factors in the ^{2}H data.

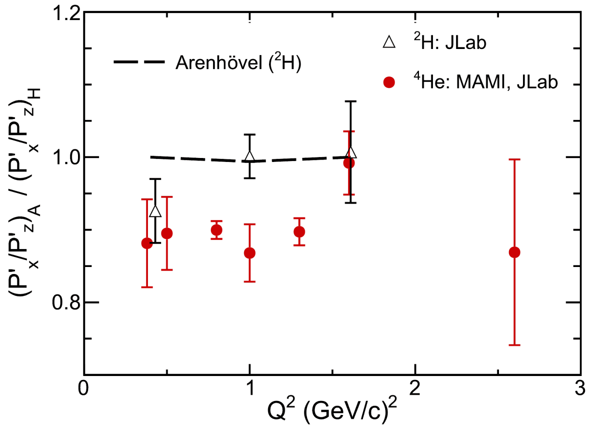

Fig. 2. Bound-to-free polarization-transfer double ratio R at low missing momenta for $^2\mathrm{H}(\vec{e},e'\vec{p})n$ *(open triangles) from Ref. [31] and for* $^4\mathrm{He}(\vec{e},e'\vec{p})^3\mathrm{H}$ *(closed circles) from Refs. [32 – 34] as a function of* Q^2*. The curve shows a results of a calculation by Arenhövel (dashed line) for deuterium.*

One might expect to find larger medium effects in ^{4}He, with its significantly higher density. Indeed, recent Jefferson Lab Experiment E03-103 has measured the EMC effect for various nuclei and results indicate that the nuclear dependence of the cross section is nearly identical for ^{4}He and ^{12}C [35]. Although estimates of the many-body effects in ^{4}He may be more difficult than in ^{2}H, calculations for ^{4}He indicate they are small [26]. The first $^4\mathrm{He}(\vec{e},e'\vec{p})^3\mathrm{H}$ proton recoil-polarization measurements were performed at MAMI at $Q^2 = 0.4$ (GeV/c)^2 [33] and at Jefferson Lab Hall A at $Q^2 = 0.5$, 1.0, 1.6, and 2.6 (GeV/c)^2, E93-049 [32]. Experiment E03-104 added two high-precision points at $Q^2 = 0.8$ and 1.3 (GeV/c)^2 [34]. The results are shown in Fig. 2 (solid points). The missing-mass technique was used to identify ^{3}H in the final state. For a reliable interpretation of the experimental data, it is imperative to have good control over conventional many-body effects in the reaction. All these data were thus taken in quasi-elastic kinematics at low missing momentum with symmetry about the three-momentum-transfer direction to minimize these effects. Furthermore, they can be studied with the induced polarization, P_y, which is a direct measure of final-state interactions. Induced-polarization data were taken simultaneously to the polarization-transfer data.

Figure 3 shows the results for P_y. The induced polarization is small at the low missing momenta in this measurement. The sizable systematic uncertainties are due to possible instrumental asymmetries. Dedicated data were taken during E03-104 to study these and help significantly reduce systematic uncertainties in the extraction of P_y. The data are compared with results of a relativistic distorted-wave impulse approximation (RDWIA) calculation by the Madrid group [38 – 40]. In this model, FSI are incorporated using an updated version of the RLF relativistic optical potentials [42, 43] that distort the final nucleon wave function; the MRW optical potential of [44], used in Ref. [34], does not yield an as good description of P_y as the modified RLF potential shown here. Charge-exchange terms are not taken into account in the Madrid RDWIA calculation; preliminary studies show, however, that they are of small effect in this model [45]. Calculations are shown for choices of *cc1* and *cc2* current operators as defined in Ref. [46]. The choice

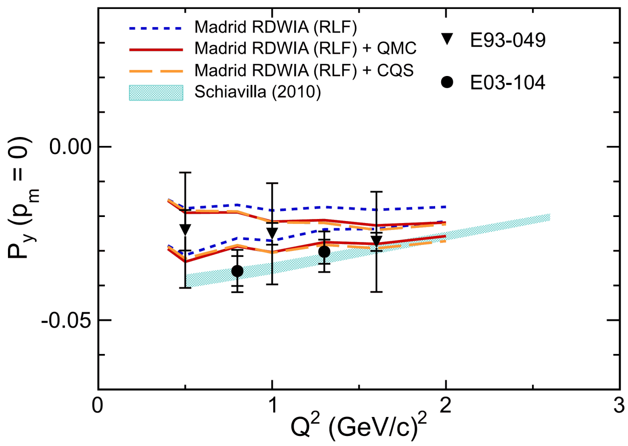

Fig. 3. $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ *induced polarization data from Jefferson Lab experiment E93-049 [32] along with results from experiment E03-104 [36]. The data are compared to calculations from Schiavilla et al. [37] and the Madrid group [38 – 40] using the cc1 (lower set of curves) and cc2 (upper set of curves) current operators. In-medium form factors from the QMC [6] (solid curve) and CQS [10] (dashed curve) models were used in two of the Madrid calculations. Note that the comparison is made for missing momentum* $p_m \approx 0$ *and that the experimental data have been corrected for the spectrometer acceptance for this comparison.*

cc1 yields the largest prediction for P_y in absolute value and describes the data well; possibly hinting at the importance of the lower spinor components in this relativistic calculation; see [40]. We note that these RDWIA calculations provide also good descriptions of, e.g., the induced polarizations as measured at Bates in the ^{12}C(e,e'$\vec{p}$) reaction [47, 40] and of A_{TL} in $^{16}O(e, e'p)$ as previously measured at JLab [48]. While the polarization-transfer observables are expected to be sensitive to possible nucleon medium modifications, results of the RDWIA calculation including medium-modified form factors show only some small effect on the induced polarization. The data are also compared with the results of a calculation from Schiavilla et al. [37] (shaded band). That model uses variational wave functions for the bound three- and four-nucleon systems, non-relativistic MEC and free nucleon form factors. The FSIs are treated within the optical potential framework and include both spin-independent and spin-dependent charge-exchange terms which play a crucial role in the prediction of P_y. Note that the charge-exchange term gives the largest contribution to Schiavilla's calculation of P$_y$. This model describes the data well after being constrained to the new data from E03-104.

The ^{4}He polarization-transfer double ratio is shown in Fig. 4. The recent data from E03-104 (filled circles) [34] are consistent with the previous data from E93-049 [32] and MAMI [33] (open symbols). The polarization-transfer ratio (P'_x/P'_z) in the ($\vec{e}, e'\vec{p}$) reaction on ^{4}He is significantly different from those on hydrogen. The data are compared with results of the same RDWIA calculations by the Madrid group [38 – 40] (dotted curves) as in Fig. 3. MEC are not explicitly included in the Madrid

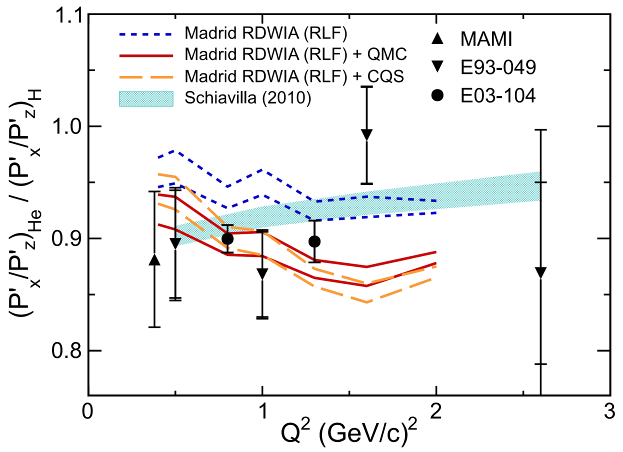

Fig. 4. $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ *polarization-transfer double ratio* R *as a function of* Q^2 *from Mainz [33] and Jefferson Lab experiments E93-049 [32] (open symbols) and E03-104 [34] (filled circles). The data are compared to calculations from the Madrid group [38 – 40], using the cc1 (lower set of curves) and cc2 (upper set of curves) current operators, and Schiavilla et al. [37] as in Fig. 3. Not shown are a relativistic Glauber model calculation by the Ghent group [41] and results from Laget [26] which give both a value of* $R \approx 1$.

calculation. Predictions by Meucci et al. [49] show that the two-body current (the seagull diagram) effects on the polarization-transfer ratio are generally small; less than 3% at low missing momenta and visible only at high missing momenta. It can be seen that the Madrid RDWIA calculation (dotted curves) overpredicts the data. The agreement of the Madrid model with the polarization-transfer data is improved after including the density-dependent medium-modified form factors from the QMC [6] or CQS [10] models in the RDWIA calculation (solid and dashed curves). This agreement has been interpreted as possible evidence of proton medium modifications [32]. An alternative interpretation of the observed suppression of the polarization-transfer ratio is offered within the more traditional calculation by Schiavilla et al. [37] (shaded band). Schiavilla's calculation uses free nucleon form factors and explicitly includes MEC effects which are suppressing R by almost 4%.

Currently, the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ polarization-transfer data can be well described by either the inclusion of medium-modified form factors or strong charge-exchange FSI in the models. The difference in the modeling of final-state interactions is the origin of the major part of the difference between the results of the calculations by Madrid et al. [38 – 40] and Schiavilla et al. [37] for the polarization observables. Optical potentials in these models have now been constrained to the new induced polarization data from E03-104.

4. *Possible future experiments*

Current quite different, state of the art, models which employ free nucleon form factors (Madrid RDWIA and Schiavilla) agree in their predictions above $Q^2 = 1.3$ (GeV/c)^2 where ambiguities in the choice of the current operator become smaller. Including medium modifications of the proton form factors in the Madrid calculations, on the other hand, results in an easily observable reduction of the polarization-transfer double ratio of at least 5%. A recent experiment proposal, PR12-11-002 [50], to Jefferson Lab PAC 37 therefore proposed to measure one new high-precision data point of the ^{4}He polarization-transfer double ratio at $Q^2 = 1.8$ (GeV/c)^2. Such a data point will be decidedly valuable to refute either of these approaches: If a new result agrees with that set of calculations without the need of medium modified form factors, it will seriously challenge the present models of in-medium effects. If, on the other hand, the new data will agree with those predictions which include the QMC or CQS form factors, it is very hard to see how this observation can be reconciled in the other models given the already tight constraints from E03-104.

As second part of PR12-11-002 is an extensive study of the proton recoil-polarization observables as a function of missing momentum or proton virtuality in both the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ and $^2\mathrm{H}(\vec{e}, e'\vec{p})n$ reactions at $Q^2 = 1.0$ (GeV/c)^2. Ciofi degli Atti et al. [51] argue that the modification of the wave function of the bound nucleon in a nucleus should strongly depend on the momentum of the nucleon. The data on deuterium will provide a link between free ep scattering and quasi-elastic proton knockout in ^{4}He. The ^{2}H and ^{4}He data have in common that in both cases the reaction takes place on a bound, off-shell nucleus. While the proton in helium is tightly bound in a nuclear medium which is much denser than that in deuterium, similar proton virtualities can be reached in both, the ^{2}H$(e, e'p)n$ and ^{4}He$(e, e'p)^3$H reactions at larger missing momenta; $\approx$ 300 MeV/c in the proposed experiment. Here, the proton virtuality is defined as $v = p^2 - m_p^2$, where p is the four-momentum of the bound proton. In the impulse approximation $p^2 = (m_A - E_m)^2 - p_m^2$, where E_m and p_m are respectively the missing energy and momentum in the $A(e, e'p)$ reaction. The origin of medium effects, as density dependent or bound-nucleon-momentum dependent, could thus be studied in the comparison between both of these data. Figure 5 shows R for previous and for the proposed data as a function of the proton virtuality.

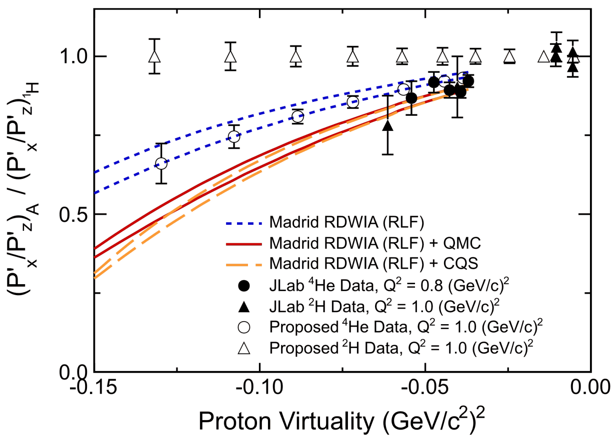

Fig. 5. Polarization-transfer ratio P'_x/P'_z from bound nucleon knockout off ^{4}He and ^{2}H compared to P'_x/P'_z from elastic ep scattering as a function of proton virtuality. The curves are various calculations using the model of Udias et al. for the reaction on ^{4}He and current operators cc1 (lower set of curves) and cc2 (upper set of curves). The points indicate previous data [31, 34] (solid symbols) and the statistical uncertainties of the proposed data and which are arbitrarily placed on the RDWIA (cc1) curve for ^{4}He and at $R = 1$ for ^{2}H.

A complementary and very important experiment would be the measurement of the nucleon knockout in quasielastic scattering in the ^{4}He$(\vec{e}, e'\vec{n}\,)^3$He reaction. Cloët et al. [12] have studied possible in-medium changes of the bound neutron electromagnetic form-factor ratio with respect to the free ratio, the superratio $(G_E^*/G_M^*)\,/\,(G_E/G_M)$. At small values of Q^2 this superratio depends on the in-medium modifications of the nucleon magnetic moment and the effective electric and magnetic radii. The superratio of the neutron is dominated by the expected increase of the electric charge radius in the nuclear medium and is found to be greater than one. In contrast, the proton superratio is predicted to be smaller than one. A comparison of high-precision measurements of the reactions ^{2}H$(\vec{e}, e'\vec{n})p$ and ^{4}He$(\vec{e}, e'\vec{n}\,)^3$He would allow to test these predictions.

5. *Summary*

Polarization transfer in the quasi-elastic proton-knockout reaction is arguably one of the most direct experimental methods to identify nuclear-medium changes to nucleon properties, which are predicted by QCD-based models, as other conventional medium effects, such as many-body currents and final state interactions, are suppressed. Furthermore, the possible role of FSI in the interpretation of these data can be constrained by the induced polarization P_y. After such constraints, present $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ polarization-transfer data can be well described by either the inclusion of medium-modified form factors or strong charge-exchange FSI in the models.

Possible future measurements of the quasielastic $(\vec{e}, e'\vec{p})$ and $(\vec{e}, e'\vec{n})$ reactions in both ^{4}He and ^{2}H targets would allow to further probe the bound nucleon electromagnetic current, including possible medium modifications of the proton electromagnetic form factor.

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SVOJSTVA HADRONA U JEZGRAMA

Svojstva nukleona mijenjaju se u jezgrama. Razumijevanje tih promjena i njihovih uzroka je središnje pitanje nuklearne fizike. Na primjer, niz modela zasnovanih na QCD, uključivši vezanje kvark-mezon i solitonske modele kiralnih kvarkova, predviđaju da sastavnice jezgri mijenjaju svojstva s povećanjem gustoće. Predviđa se da te promjene vode na promjene nukleonskih strukturnih funkcija i elektromagnetskih faktora oblika koji se mogu opažati. Opisujemo ishode niza nedavnih mjerenja u MAMI i Jefferson Lab-u u kojima se mjerila odbojna polarizacija protona u reakciji $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ radi provjera navedenih predviđanja. Ti ishodi, zajedno s najtočnijim podacima na $Q^2 = 0.8$ (GeV$/c)^2$ i na 1.3 (GeV$/c)^2$ iz mjerenja E03-104, postavljaju jaka ograničenja na modelske račune. Tako ispod $Q^2 = 1.3$ (GeV$/c)^2$, izmjereni omjeri prijenosa polarizacije uspješno opisuju relativistički računi kada se uključe promjene protonskih faktora oblika u jezgri, ili, kao inačica, snažna izmjena naboja u međudjelovanju u konačnom stanju. Raspravljamo također proširenje tih studija na mjerenja $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ i $^2\mathrm{H}(\vec{e}, e'\vec{p})n$ reakcija te na izbijanje neutrona u $^4\mathrm{He}(\vec{e}, e'\vec{n})^3\mathrm{He}$ reakciji.