Ratio of the electric to magnetic form factors in nuclei

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Abstract. A long standing question in nuclear physics is the effect of the nuclear medium on the properties of the nucleon. In this paper, we present a review of past and present efforts in the search for evidence of possible modifications of the nucleon form factors inside the nuclear medium, using the $(e, e'p)$ reaction. Particularly, we discuss the E89-044 experiment, which studied the quasi-elastic $^3\mathrm{He}(e, e'p)^2\mathrm{H}$ reaction at a transfer momentum $Q^2 = 1.5$ (GeV/c)^2 and two different beam energies of 1255 and 4807 MeV in the Hall A of Jefferson Laboratory. The extraction of the $^3\mathrm{He}(e, e'p)^2\mathrm{H}$ cross section has been performed with a fitting procedure method, using the simulation program MCEEP (Monte Carlo for Electro-Nuclear Coincidence Experiments), taking into account the effects of internal and external radiation and spectrometer resolutions. Unpolarized nuclear response functions have been separated for two different values of the longitudinal polarization of the exchanged photon ϵ. Possible changes in the structure of nucleons embedded in a nucleus are studied indirectly, via the ratio of Longitudinal and Transverse nuclear response functions. A comparison of extracted data using the Polarization Technique in the $^4\mathrm{He}(\vec{e}, e'\vec{p})$ reaction, with the predictions of the Relativistic Distorted Wave Impulse Approximation Madrid code is also showed.

1 Introduction

Quasielastic $(e, e'p)$ reactions have provided over the years an enormous wealth of information on nuclear structure, particularly, on single particle degrees of freedom: energies, momentum distributions and spectroscopic factors of nucleons inside nuclei [1–3]. In recent years important efforts have been devoted to provide more realistic theoretical descriptions of these processes [4–16].

The quasielastic region defines the domain where the cross section is dominated by the elastic scattering of an electron from the beam on one of the nucleons. Detection of both the scattered electron and knockout nucleon allows reconstruction of the missing energy that is associated with the undetected recoil system.

There are several advantages that make an electromagnetic probe of interest. The exchange of a virtual photon associated with an electron-probe is very wel described by QED. Furthermore, the electron scattering process allows the energy and momentum transfers to the nucleus to be selected independently. We can vary, at constant q and ω, the polarization of the exchanged photon, thus probing different combination of the nuclear currents.

A very topical issue in nuclear physics at present is the search for evidence of possible modification of the nucleon form factors inside the nuclear medium. A number of double polarized $(\vec{e}, e'\vec{p})$ experiments have been carried out recently to measure polarization transfer asymmetries, motivated by the hope that such observables may provide valuable information that can shed some light on this issue. Importantly, transferred polarization observables have been identified as being ideally suited for such studies: they are believed to be the least sensitive to most standard nuclear structure uncertainties and accordingly to provide the best opportunities for studying the nucleon form factors in the nuclear medium. Other well known method to measure the ratio of electric to magnetic form factors of the nucleon is the Rosenbluth separation technique.

Unfortunately, distinguishing possible changes in the structure of nucleons embedded in a nucleus from more conventional many-body effects is only possible within the context of a model. Nucleon modifications can be described in terms of coupling to excited states, and such changes are intrinsically intertwined with many-body effects, such as meson-exchange currents (MEC) and isobar configurations (IC). Therefore, interpretation of an experimental signature as an indication of modifications of the nucleon form factors only makes sense if this results in a more economical effective description of the bound, quantum, nuclear many-body system.

One of the basic results which has made $(e, e'p)$ reactions so appealing for investigations of single particle properties is the factorized approach [1, 17–19]. Within this approximation, the $(e, e'p)$ differential cross section factorizes into a single-nucleon cross section, describing electron proton scattering, and a spectral function which gives the probability to find a proton in the target nucleus with selected values of energy and momentum compatible with the kinematics of the process. The simplicity of the factorized result makes it possible to get a clear image of the physics contained in the problem. Even being known that factorization does not hold in general, it is often assumed that the breakdown of factorization is not too severe, and then it is still commonplace to use factorized calculations for few body systems or for inclusive scattering. The importance of factorization lies on the fact that the interpretation of experimental data is still usually based on this property by defining an *effective* spectral function that is extracted from experiment in the form of a reduced cross section. Assuming that factorization holds at least approximately, reduced cross section would yield information on momentum distributions of the nucleons inside the nucleus. On the other hand, these momentum distributions would cancel when taking ratios of cross sections and consequently these ratios might give information on the electromagnetic form factors of the nucleons [20, 21].

2 The Relativistic Distorted Wave Impulse Approximation (RDWIA)

In this section we briefly review the general formalism needed to describe coincidence $(\vec{e}, e'\vec{p})$ reactions.

In RDWIA, the nucleon current

$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\,\hat{J}_N^\mu(\omega,\vec{q})\,\psi_B(\vec{p}) \tag{1}$$

is calculated with relativistic ψ_B and ψ_F wave functions for initial bound and final outgoing nucleons, respectively. $\hat{J}_N^\mu$ is the relativistic nucleon current operator of $cc1$ or $cc2$ forms [22]. As bound state wave function, Dirac-Hartree solutions from relativistic Lagrangian with scalar and vector (S-V) meson terms [23] or solutions of Dirac equation with phenomenological Woods-Saxon wells are customarily used. The wave function with asymptotic momentum $\vec{p}'$ for the outgoing proton is a solution of the Dirac equation containing S-V optical potentials.

Assuming plane waves for the electron (treated in the extreme relativistic limit), the differential cross section for outgoing nucleon polarized $A(\vec{e},e'\vec{p})B$ reactions can be written in the laboratory system in the general form

$$\frac{d\sigma}{d\varepsilon_f d\,\Omega_f d\,\Omega_F} = \frac{E_F p_F}{(2\pi)^3}\sigma_M f_{rec}\,\omega_{\mu\nu}W^{\mu\nu}\ , \tag{2}$$

where σ_M is the Mott cross section, $\{\varepsilon_f, \Omega_f\}$ are the energy and solid angle corresponding to the scattered electron and $\Omega_F = (\theta_F, \phi_F)$ the solid angle for the outgoing proton. The factor f_{rec} is the usual recoil factor, $\omega_{\mu\nu}$ is the familiar leptonic tensor that can be decomposed into its symmetric (helicity independent) and antisymmetric (helicity dependent) parts and $W^{\mu\nu}$ is the hadronic tensor which contains all of the hadronic dynamics of the process. The latter is defined from bilinear combinations of the one body nucleon current matrix elements given in Eq. (1).

The cross section can be also written in terms of hadronic responses by making use of the general properties of the leptonic tensor. For $(\vec{e},e'\vec{p})$ reactions with the incoming electron polarized and the final nucleon polarization also measured, a total set of eighteen response functions contribute to the cross section. For an unpolarized cross section and if an average on azimuthal angle is done, only two responses, R_L and R_T, contribute.

3 Rosenbluth separation and polarization ratio technique

Free proton form factors can be determined experimentally by measuring the unpolarized cross section as a function of the scattered electron angle θ_e and transfer momentum Q^2. This is named the Rosenbluth separation technique.

$$\frac{G_E^2}{G_M^2} = 2\tau(1+\tau)v_L\frac{\mathcal{R}^L}{\mathcal{R}^T}\ . \tag{3}$$

They can also be determined using a polarized electron beam and measuring the longitudinal and transverse polarization components of the final proton. This is the polarization ratio technique.

$$\frac{P_s'}{P_l'} = -\frac{G_E}{G_M}\left[\tau\left(1+(1+\tau)\tan^2\frac{\theta_e}{2}\right)\right]^{\frac{1}{2}} \tag{4}$$

where $\tau = \frac{Q^2}{4M_N^2}$ and v_L is a kinematical factor included in the leptonic tensor $\omega_{\mu\nu}$.

4 E89-044 Hall A Jefferson laboratory experiment

The E89-044 experiment [24–28] took place in experimental Hall A of Jefferson Laboratory (Jlab) in Newport News, USA. The ^{3}He$(e,e'p)$ cross section was measured at different beam energies and spectrometers angles. In this analysis of the E89-044 data we have focused our atention on the $Q^2 = 1.5$ (GeV/c)^2 at two different beam energies. In Table 1 an overview of the studied kinematics are showed.

The one photon exchange is not the only process taking place in the $(e,e'p)$ reaction. The incoming and outgoing particles can radiate real and virtual photons in the presence of the Coulomb field of the target nucleus or other nuclei. These internal radiaton effects influence the number of counts per bin in the missing energy spectrum by shifting events from one bin to another. In order to extract the unradiated cross section and compare the experimental results to existing theories, one has to correct the measured cross section for these radiative losses. Because we are interested in the ^{3}He$(e,e'p)^2$H cross section, there is also the need to substract the ^{3}He$(e,e'p)pn$ contribution from the missing energy spectrum. To correct for radiative losses and substract the 3-bbu contribution, the ^{3}He$(e,e'p)$ experiment is simulated with the Monte Carlo for electro-nuclear coincidence experiments (MCEEP) program. MCEEP simulates coincidence $(e,e'X)$ experiments by averaging theoretical models over an experimental acceptance. A fitting procedure allows the adjustement of the experimental number of counts with the simulated before radiation until the experimental missing energy spectrum is reproduced by the simulated data. Figure 1 and Figure 2 show the cross section results for kinematics 01 and kinematics 03 respectively.

The ^{3}He$(e,e'p)^2$H cross sections are extracted at fixed Q^2 and ω at beam energies of 4.807 GeV (kinematics 01) and 1.2504 GeV (kinematics 03) in parallel kinematics. These measurements allow to separate the R_T and R_L response functions and the preliminary results are showed in Figure 3 and Figure 4.

Table 1. Overview of studied kinematics in E89-044 Hall A Jlab experiment, at constant $q = 1.5$ GeV/c and $\omega = 837$ MeV.

Kinematics	E$_i$ (GeV)	ϵ	E$_f$ (GeV)	θ_e (deg)	θ_p (deg)
01	4.803	0.943	3.966	16.40	48.30
03	1.254	0.108	0.417	118.72	14.13

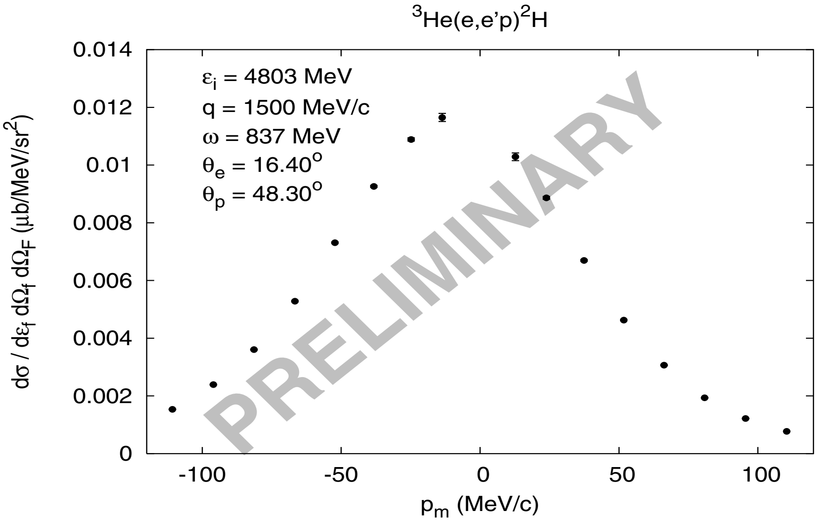

Figure 1. Experimental cross section for the ${}^3\mathrm{He}(e,e'p){}^2\mathrm{H}$ reaction at kinematics 01.

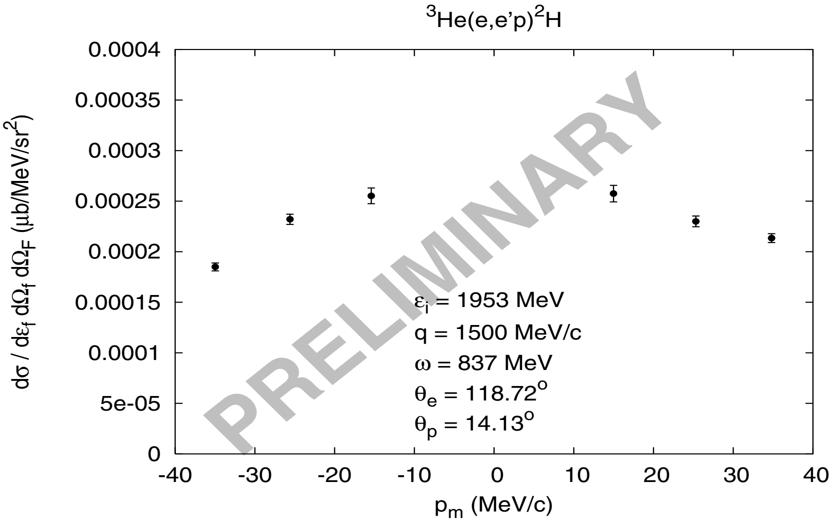

Figure 2. Experimental cross section for the ${}^3\mathrm{He}(e,e'p){}^2\mathrm{H}$ reaction at kinematics 03.

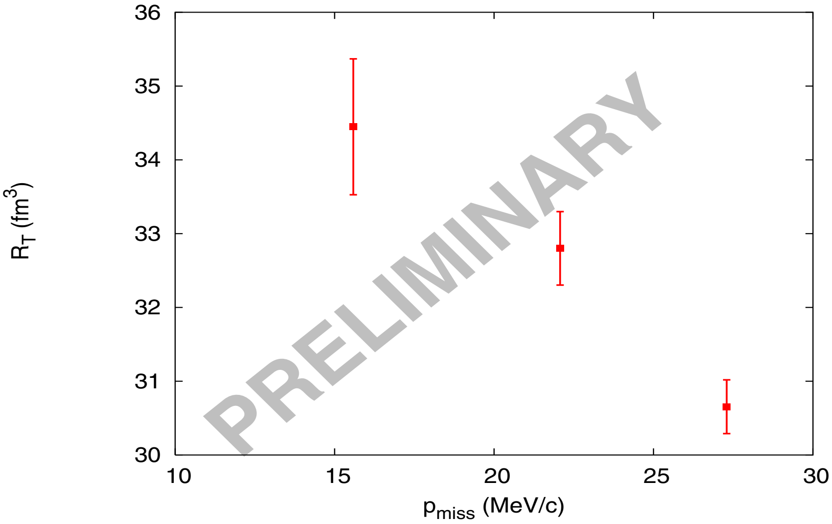

Figure 3. Transverse response function for the $^3\mathrm{He}(e,e'p)^2\mathrm{H}$ reaction at kinematics 01 and 03 (preliminary).

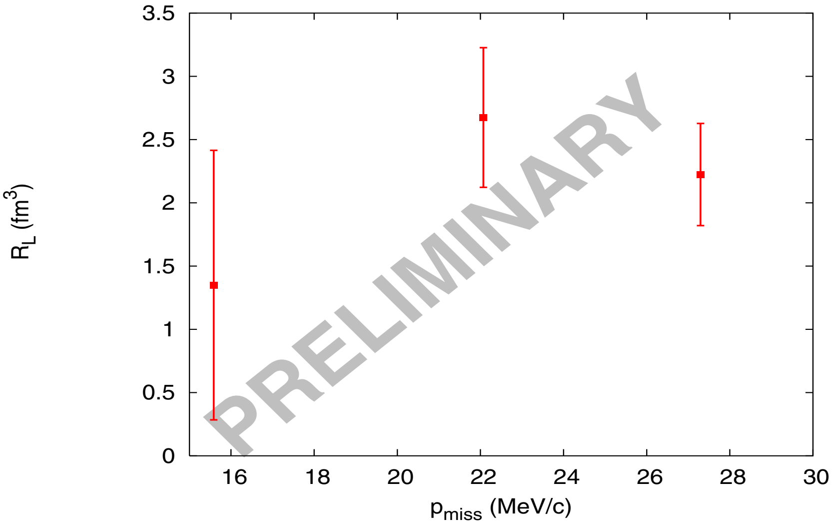

Figure 4. Longitudinal response function for the $^3\mathrm{He}(e,e'p)^2\mathrm{H}$ reaction at kinematics 01 and 03 (preliminary).

5 Polarization transfer ratio in ^{4}He($\vec{e}, e'\vec{p}$) reaction

Experiment E93-049 performed at Jlab Hall A measured the proton recoil polarization in the ^{4}He$(\vec{e}, e'\vec{p})^3$H reaction at Q^2 = 0.5, 1.0, 1.6, and 2.6 (GeV/c)^2 [21]. Data extracted were compared with the RDWIA Madrid code including density dependent nucleon form factors. The density dependent form factors were taken from the quark-meson coupling model (QMC) [29], computed for a bag radius of 0.8 fm. In order to get well behaved modified form factors in the free case, we scaled the ones parametrized by Gari and Krumplemann [30] (labelled as GK) with the ratio between the QMC form factors at a given density and those predicted for free conditions,

$$G_{E,M}(Q^2, \rho(\vec{r})) = G_{E,M}^{GK}(Q^2) \frac{G_{E,M}^{QMC}(Q^2, \rho(\vec{r}))}{G_{E,M}^{QMC}(Q^2, 0)}, \tag{5}$$

where $G_{E,M}^{QMC}(Q^2, \rho(\vec{r}))$ are the density-dependent Sachs form factors of the proton immersed in nuclear matter with local baryon density $\rho(\vec{r})$.

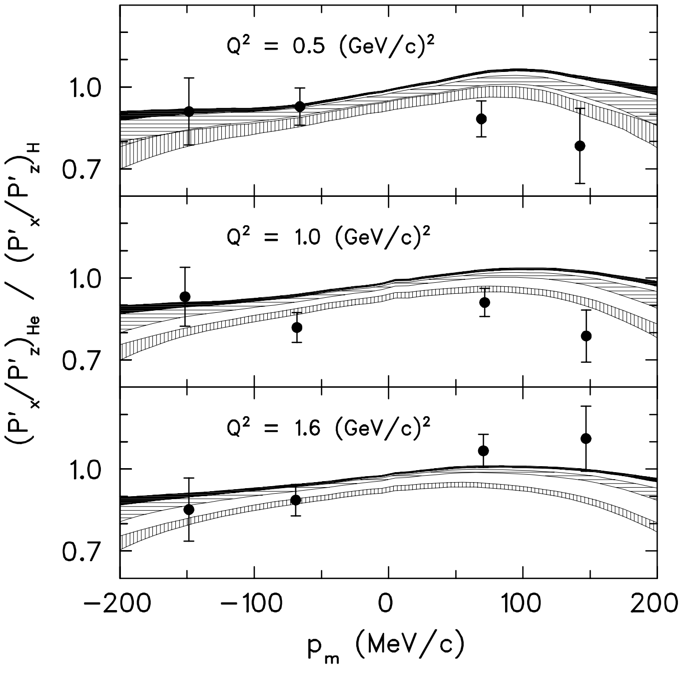

Figure 5. Measured values of the polarization double ratio R for ^{4}He$(\vec{e}, e'\vec{p})^3$H at Q^2 = 0.5 (GeV/c)^2 (top), Q^2 = 1.0 (GeV/c)^2 (middle), and Q^2 = 1.6 (GeV/c)^2 (bottom). The shaded bands represent RPWIA calculations (solid), relativistic DWIA calculations (horizontal dashes) and relativistic DWIA calculations including QMC medium–modified form factors [29] by Udias *et al.* [9, 10] (vertical dashes). The bands reflect variations due to choice of current operator, optical potential, and bound-state wave function (see also Ref. [20]).

Results are showed in Figure 5. Both the RPWIA and the RDWIA give a reasonable, but not perfect, description of the missing momentum dependence of the data. The difference in magnitude between the RDWIA calculation and the data at Q^2 = 0.5 and 1.0 (GeV/c)^2 can be largely eliminated by including the QMC medium modifications, whereas at Q^2 = 1.6 (GeV/c)^2 the calculation without QMC medium modifications already gives a satisfactory description. More precise data could unambiguously settle whether this is just a statistical fluctuation, and would constitute a demanding test of modern nucleon-meson descriptions of nuclear physics.

Finally, in Figure 6 we compare the ratio of form factors, extracted using the two techniques described before, for the ^{3}He$(e, e'p)$ and ^{4}He$(\vec{e}, e'\vec{p})$ reactions. In Figure 6 we can see the results where we have divided the corresponding ratio by the equivalent ratio in the free electron proton scattering.

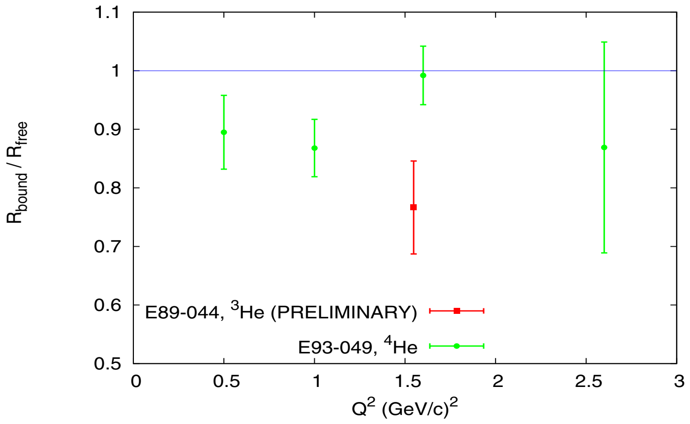

Figure 6. Bound Nucleon Form Factors *vs* Free. Beware that the value using the Rosenbluth technique in experiment E89-044 (red point) is still PRELIMINARY.

6 Summary and conclusions

A review of past and present efforts in the search for evidence of possible modifications of the nucleon form factors inside the nuclear medium using the $(e, e'p)$ reaction has been done. Special attention has been paid on the analysis of the ^{3}He$(e, e'p)^2$H reaction and results have been shown for the Cross Section and the Longitudinal and Transverse Response Functions.

Actually, a new ^{3}He$(e, e'p)^2$H analysis, extracting a new point in the L/T separation at $Q^2 = 4$ (GeV/c)^2 is being performed. New results of a recent experiment performed at Jlab: E03-104, “Probing the Limits of the Standard Model of Nuclear Physics with the ^{4}He$(\vec{e}, e'\vec{p})$ reaction” will provide a more accurate measure of Polarization transfer Ratio. Until the extraction of this new point in the L/T separation at $Q^2 = 4$ (GeV/c)^2 in the $^3\mathrm{He}(e, e'p)^2\mathrm{H}$ reaction and the analysis of the Jefferson Laboratory E03-104 experiment, no definitive conclusion can be established about modifications of the nucleon form factors inside the nuclear medium.

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