E12-11-002: PAC49 Jeopardy Update

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Jefferson Lab PAC37 approved experiment E12-11-002, "Proton Recoil Polarization in the ^{4}He$(e, e'p)^3$H, ^{2}H$(e, e'p)n$, and ^{1}H$(e, e'p)$ Reactions", in 2011. In this brief overview, we give an update on relevant new experiments, new theoretical developments, and progress in instrumentation over the past ten years.

I. INTRODUCTION

In continuation of the series of our earlier experiments at MAMI [1] and JLab Hall A (E93-049 and E03-104) [2, 3], Jefferson Lab experiment E11-002 [4] will measure the proton recoil polarization in the ^{4}He$(\vec{e}, e'\vec{p})^3$H, ^{2}H$(\vec{e}, e'\vec{p})n$, and ^{1}H$(\vec{e}, e'\vec{p})$ reactions in Hall C. It will be able to fully reconstruct the final state in the reactions and reap the same benefits as a tagged experiment [5]. First, the measurements will include two new high-precision data points of the polarization-transfer double ratio at $Q^2 = 1.0$ and 1.8 (GeV/c)^2 to thoroughly study the Q^2 dependence of possible modifications of in-medium proton form factors; Fig. 1. Particularly the expected data at $Q^2 = 1.8$ (GeV/c)^2 are decidedly valuable to discriminate between various models that attempted to describe existing data. Second, E12-11-002 will measure not only at small values of missing momentum, where models can be calibrated, and reaction-mechanism effects are shown to be small, but also at larger missing momenta, where the off-shellness, or virtuality, of the bound proton, is large. The data will provide a significantly improved proton virtuality coverage at $Q^2 = 1.0$ (GeV/c)^2 to study the expected strong dependence of medium effects on the momentum of the bound nucleon; Fig. 2. The data will cover a range from about $p_m = -200$ MeV/c to $+300$ MeV/c in parallel kinematics, with special emphasis on the $x > 1$ region. We will also take data from ^{4}He$(\vec{e}, e'\vec{p})^3$H and ^{2}H$(\vec{e}, e'\vec{p})n$ to compare knockout data of tightly and weakly bound protons to further probe the bound nucleon electromagnetic current including possible medium modifications of the proton electromagnetic form factor. Modern calculations are readily available for both reactions; *e.g.* [6–10, 14, 15].

A variety of topical review articles have been published since the approval of E12-11-002 in-

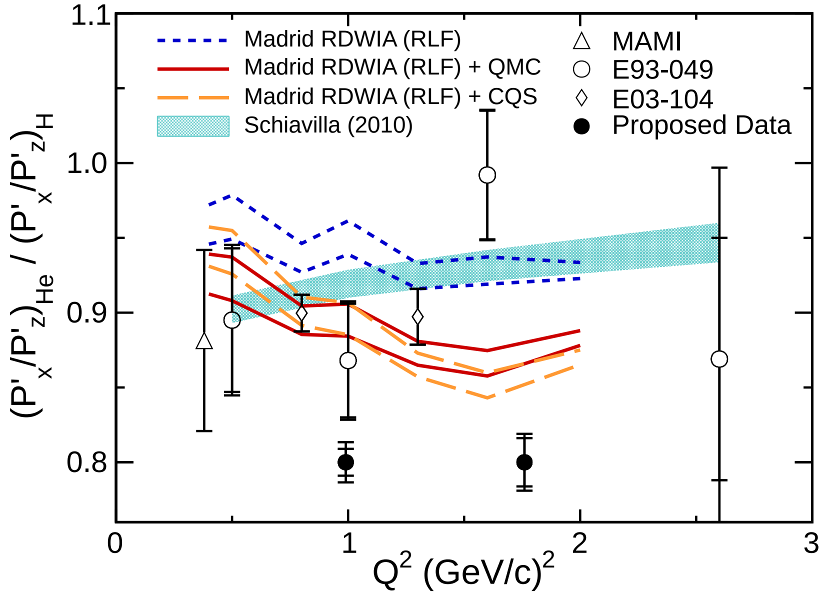

FIG. 1. Previous polarization-transfer double ratios for $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ (open symbols) [1–3] along with arbitrarily placed proposed data (solid points). The proposed data are integrated over a missing momentum range of $|p_m| < 100$ MeV/c for 1.0 (GeV/c)^2 and over $|p_m| < 175$ MeV/c for 1.8 (GeV/c)^2. The data are compared to calculations from Schiavilla *et al.* [6] (updated in [7]) and the Madrid group [8–10] using the *cc1* (lower set of curves) and *cc2* (upper set of curves) current operators. In-medium form factors from the QMC [11] (solid curve) and CQS [12] (dashed curve) models were used in two of the Madrid calculations. The inner error bar reflects statistical uncertainties only, while the outer bar includes the effect of projected experimental systematic uncertainties.

cluding Arrington *al.*, "Hard probes of short-range nucleon–nucleon correlations" [16]; Hen *et al.*, "The EMC Effect and High Momentum Nucleons in Nuclei" [17]; Malace *et al.*, "The Challenge of the EMC Effect: existing data and future directions" [18]; degli Atti *et al.*, "In-medium short-range dynamics of nucleons: Recent theoretical and experimental advances" [19]; Hen *et al.*, "Nucleon-nucleon correlations, short-lived excitations, and the quarks within" [20]; Guichon *et al.*, "Quark–Meson-Coupling (QMC) model for finite nuclei, nuclear matter and beyond" [21]; and Cloët *et al.*, "Exposing novel quark and gluon effects in nuclei" [22]. Malace *et al.* [18] and, in particular, Hen *et al.* [20] stress the relevance of E12-11-002. Discussing our previous results [1–3], the review of Hen *et al.* concludes: "Thus our view is that the results of the nuclear polarization experiments strongly indicate that medium effects do influence electro-magnetic form factors. We eagerly await new experiments with improved precision and at larger values of p_{miss} which would confirm or rule out this interpretation" [20].

In 2020, A.W. Thomas published a review article in Oxford Research Encyclopedias, Physics, with the title "Role of Quarks in Nuclear Structure" [23]. It is this question that is at the core of

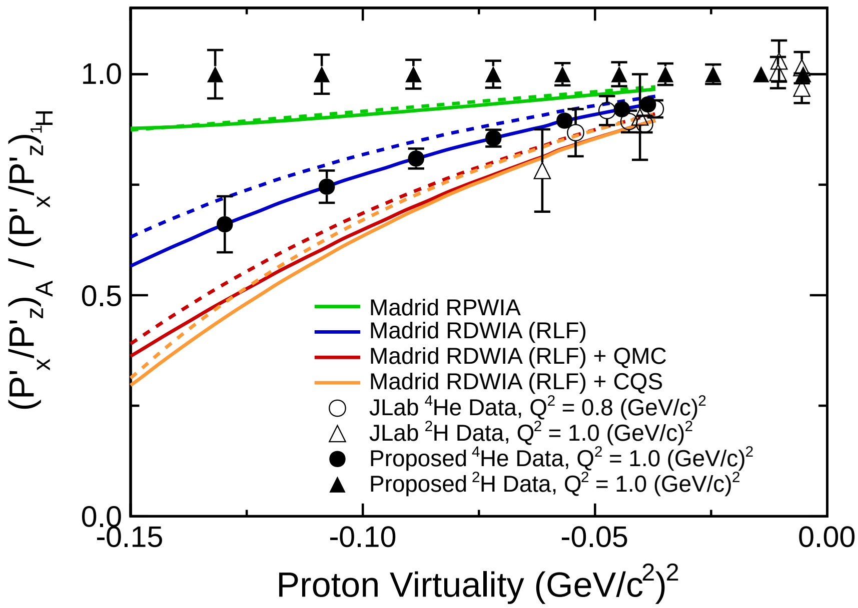

FIG. 2. Polarization-transfer ratio P'_x/P'_z from bound nucleon knockout off ^{4}He (solid circles) and ^{2}H (open triangles) compared to P'_x/P'_z from elastic ep scattering as a function of proton virtuality. The curves are various calculations using the model of Udias *et al.* for the reaction on ^{4}He and current operators $cc1$ (solid curves) and $cc2$ (dotted curves). The points indicate previous data [3, 13] 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.

the motivation of E12-11-002.

II. THE EMC EFFECT AND SHORT-RANGE CORRELATIONS

The observation of the EMC effect in deep inelastic scattering, caused by the nucleus and a function of the local density, showed that the valence quarks of a bound nucleon carry less momentum than those of free nucleons. Conventional (nonquark) nuclear physics cannot account for it, and models that include nucleon modification are needed to describe the data [20]. The underlying origin of those modifications is still unclear. Do small modifications in a mean field primarily cause the changes? Are they momentum (virtuality) dependent? The phenomenological connection between the EMC effect and short-range correlations (SRC) hints at the EMC effect being caused by high-momentum nucleons in an SRC pair.

Over the last years, a vital program has been developed at JLab to study the unpolarized, polarized, and isovector EMC effects and probe SRC in inclusive and semi-inclusive reactions. These experiments provide crucial tests of models. For example, early predictions of the polarized EMC effect using the Nambu-Jona-Lasinio (NJL) model found considerably larger effects than for the unpolarized case [24], a more recent calculation using the QMC model found a less dramatic effect [25]. If the EMC effect arises only from highly correlated nucleons, there will be no polarized EMC effect [26]. In this vivid program, E12-11-002 is the only experiment that focuses on the elastic form factors.

III. RECENT EXPERIMENTAL SEARCHES FOR MEDIUM MODIFICATIONS OF FORM FACTORS

A. Recoil polarization

The most relevant new experiments since the approval of E12-11-002 are measurements from MAMI that studied the polarization transfer to bound protons in ^{2}H and ^{12}C over a large missing momentum region but with relatively low momentum transfer (Q^2) [27–32]. Together with prior results from JLab, the new data show a fairly similar distribution of the polarization-transfer double ratio from ^{2}H, ^{4}He, and ^{12}C compared to ^{1}H as a function of the proton virtuality. The distribution seems largely independent of the nucleus or the momentum transfer as long as the comparison is made at the same value of virtuality. The measured polarization-transfer components and their ratios were compared to state-of-the-art calculations to study the effects of final-state interactions on the individual components and the sensitivity of the calculated ratios to medium modifications of the form factor ratio [27–32]. Overall, the new data on P'_x/P'_z are well described by calculations using free form factors. This is not surprising, given the large statistical uncertainties of the new data and the smallness of the predicted medium effects. E12-11-002 remains unique as it will probe with high precision the modifications of the proton form-factor ratio at values of Q^2 where the expected effects are more pronounced while, at the same time, reaction-mechanism effects are predicted to be smaller.

An additional MAMI measurement compared the polarization-transfer ratio for protons knocked out of the s and p shells from ^{12}C at $Q^2 = 0.175$ (GeV/c)^2 [34]. The nuclear density in these shells differs by about a factor of 2, and calculations [35] suggest nuclear-density effects due to this difference. This measurement was carried out in a kinematic region where the s and p protons have the same missing momentum and about the same virtuality. The measured double ratio $R_{s\text{-shell}}/R_{p\text{-shell}}$ is in good agreement with PWIA and RDWIA calculations which used free proton form factor ratios. The uncertainty of the result is about 5% and similar to the size of the predicted medium effect [35]. Higher-precision data are needed for a definitive assessment.

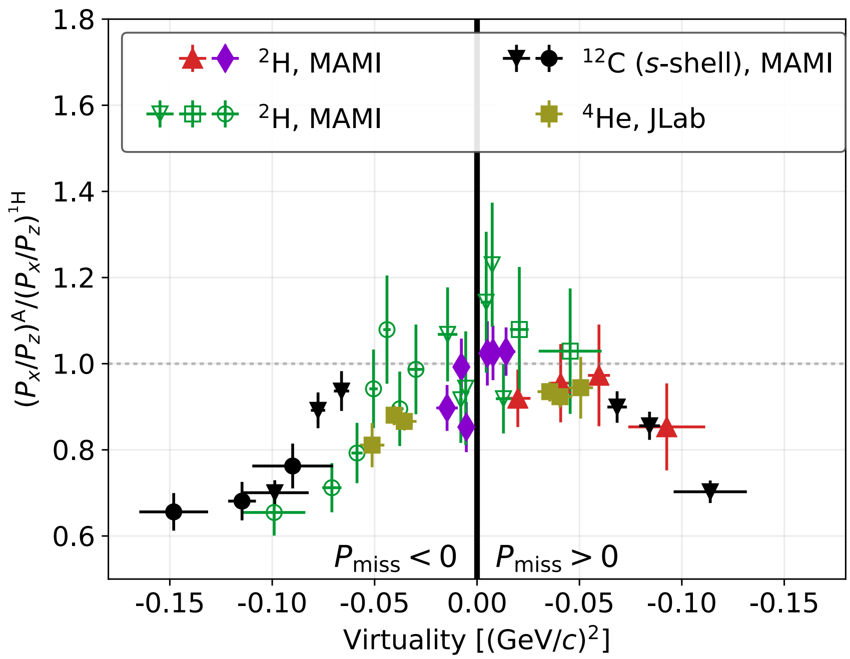

FIG. 3. Data of the double-ratios $\frac{(P_x/P_z)^A}{(P_x/P_z)^{^1\mathrm{H}}}$ from ^{2}H [31] (red and purple filled symbols) and [27, 29] (green, open symbols), from s-shell knockout in ^{12}C [28] (black filled symbols), and ^{4}He [3] (yellow filled squares). In each of these ratios, the denominator is calculated using the "moving-proton" prescription [30, 33]. The ^{4}He data shown were taken at Q^2= 0.8 (GeV/c)^2, the MAMI data at Q^2= 0.18, 0.40, and 0.65 (GeV/c)^2. Figure adapted from [31].

B. Coulomb sum

While the polarization-transfer measurements are sensitive to the ratio of the electromagnetic form factors, measurements of the longitudinal response function in the quasielastic $A(e,e')$ reaction and the associated Coulomb sum rule [36] are mainly sensitive to the electric form factor. Morgenstern and Meziani report in [37] that the longitudinal response function for a variety of nuclei from ^{40}Ca to ^{238}U is "quenched" and that the Coulomb sum rule is not saturated. The interpretation of these experimental findings is controversial: Cloët, Bentz, and Thomas successfully describe this quenching in their approach based on the NJL model and find it as the main driver of the effect changes of the proton Dirac form factor in the nuclear medium [36]. Lovato *et al.* [38] describe the present ^{12}C data with their Green's function Monte Carlo calculation. They state that the so-called quenching emerges as a result of initial-state correlations and final-state interactions. Additional data at larger values of the three-momentum transfer are needed. The JLab experiment E05-110 analysis is still preliminary, but the latest results show agreement within uncertainties with prior measurements of the Coulomb sum at a momentum transfer of $q = 550$ MeV/c by Barreau

[39] and Meziani [40] for ^{12}C and ^{56}Fe targets, respectively [41]. While those measurements at Saclay indicated quenching, the JLab E05-110 experiment aimed at producing Coulomb sum measurements for the first time at larger momentum transfer up to $q = 1000$ MeV/c for ^{4}He, ^{12}C, ^{56}Fe, and ^{208}Pb targets. Results at larger momentum transfer are expected soon and will shed more light on the question of Coulomb-sum-rule quenching and the validity of the disparate model approaches of Refs. [36] and [38].

IV. UPDATES ON MODEL CALCULATIONS

A. Reaction model

A calculation by Schiavilla and collaborators [6] based on variational wave functions for the bound three- and four-nucleon systems has described the polarization-transfer ratio in $^{4}\mathrm{He}(\vec{e}, e'\vec{p})^{3}\mathrm{H}$ with free-nucleon electromagnetic form factors. The excellent description required an unusually large polarized charge exchange correction [42]. This challenged the interpretation of the experimental data in terms of medium-modified form factors. The calculation [6] has now been expanded and updated with NN amplitudes, which describe FSI within a Glauber approximation, to include more realistic parameterizations available from SAID, valid over the entire angular region [7]. The calculation is better constrained, but the data description is now only fair and underestimates the observed effect for all but one data point. It is important to note that the impact of the FSI is decreasing with Q^2, making the push of E12-11-002 to the highest reasonably achievable momentum transfer particularly valuable.

B. In-medium form factors

An impressive body of theoretical work on in-medium modifications of electromagnetic form factors has been published since the approval of E12-11-002. Calculations were based on the QMC model [43, 44], the in-medium modified π-ρ-ω soliton model [45], the Friedberg-Lee model [46], and the AdS/QDC model [47]. All these calculations predict a decreased in-medium to free form-factor ratio of the proton, $(G_E^*/G_M^*)/(G_E/G_M)$. Tentative evidence for such a reduction has been seen in the existing ^{4}He polarization-transfer data [1–3]. In fact, in very recent work, Miller [48] studied various Poincaré-invariant, composite-proton models that respect the Ward-Takahashi identity and in which quarks are confined and showed generally that medium modification of the proton structure must occur and that the bound proton must be larger than a free one.

Coulomb-sum-rule and recoil-polarization experiments are most sensitive to those in-medium form factors. However, the effects of density-dependent form factors have also significant impact on cross sections and must be carefully understood. Those effects were studied in the $A(\nu,\mu)$ [49], $A(e,e')$, $A(\nu,\nu')$ [50], and $A(e,e'p)$ [51] reactions within the framework of a relativistic single-particle model and density-dependent in-medium nucleon form factors from the QMC model. Effects of medium modifications of nucleon form factors on neutrino scattering were also reported in, *e.g.*, Refs. [52, 53].

The presence of the nuclear medium is excepted to influence hadron properties with impact in various reactions. While previous data in the $^4\text{He}(\vec{e},e'\vec{p})^3\text{H}$ reaction have been critical, E12-11-002 remains that approved experiment that directly aims to study in-medium electromagnetic form factors in the relevant kinematic regime, with low systematic uncertainties and sufficient statistical precision. It is an indispensable experiment.

V. UPDATES ON INSTRUMENTATION FOR E12-11-002

E12-11-002 was approved prior to the completion of the 12 GeV energy upgrade of CEBAF and the commissioning of the new SHMS spectrometer in Hall C. The SHMS has been installed and commissioned over the last several years, and the required performance characteristics of the SHMS that were speculative in the original proposal have now been realized. We note again that our requirements for the Hall C beam line and for the SHMS and HMS maximum momentum and momentum resolutions are quite modest, and have already been demonstrated in Hall C in the 12 GeV era.

The polarization of the recoil proton will be measured in the Focal Plane Polarimeter (FPP), which has been previously installed in the detector shield house of the HMS in Hall C for the GEp-III and GEp-2γ experiments. For those experiments, the FPP consisted of two (passive) CH_2 analyzer blocks in series, with each one followed by two drift multiwire chambers. Analysis of the GEp-III and GEp-2γ data indicated that instrumental asymmetries in the FPP, while in general manageable, can be significantly reduced by adding extra tracking planes (through the efficient redistribution of planes from a spare chamber that has already been constructed). In addition to enhancing the overall tracking efficiency of the FPP, it is expected that this will also significantly reduce instrumental uncertainties in the device, which is of benefit in the extraction of the induced polarization, P_y.

Prior to the onset of the COVID-19 global pandemic, we had initiated a plan to move the

FPP tracking chambers, along with a significant portion of the associated electronics, to CNU for refurbishment. Obviously, this effort has been delayed, but we are hopeful that it can be reinitiated this fall. Appropriate laboratory space has been identified at CNU that will allow for effective cosmic ray testing following the plane redistribution process.

There has also been important new knowledge gained over the past decade related to the optimization of the FPP analyzer design. At the time of our original proposal, our plan was to replace the original analyzer system with a new arrangement of variable thickness CH_2 blocks and active scintillator layers. Recent experiments at Dubna ([54–57]) have measured effective proton and neutron analyzing powers for C,CH,CH_2, and Cu) at large incident momenta. Through these efforts, we have learned that with an optimized analyzer design and by using calorimetry, it may be possible to increase the effective analyzing power by making use of charge exchange reactions; these reactions have a larger analyzing power than previous thought, especially for larger atomic number. We are currently in the process of developing a full GEANT-4 simulation of the FPP analyzer (and wire chambers) to better understand how our original proposal design may be improved upon.

VI. SUMMARY

The observation of the EMC effect points to the modification of the bound nucleon in the nuclear medium. As parton distributions are modified in the medium, so are, arguably, also electromagnetic form factors. Such modifications have consistently been predicted. With 37 days of approved beam time, E12-11-002 is set to find evidence at high Q^2 (15 days) and over a wide range of proton virtuality (25 days).

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