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Spokesperson: H. Merkel

Title: Study of the nuclear density dependence of medium correction via polarization transfer measurement of protons removed from s- and p- shell in ^{12}C

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Abstract of physics: In ^{12}C the effective nuclear density for s-shell knockout is about twice as high as for p-shell knockout. Polarization transfer measurements ^{12}C($\vec{e}$, e'$\vec{p}$), knocking out proton from the s- or p- shell, can provide constraints on the ratio of the in-medium electric to magnetic form factor as a function of the local nuclear density. Using two model predictions for the in-medium form factors, we show that a measurable modifications in the ratios of the double polarization observables between those single-particle levels (nuclear densities) can be observed or a meaningful upper limit for such can be set.

We propose a polarization transfer measurement with $E = 600\,\mathrm{MeV}$ and $I = 20\,\mu\mathrm{A}$ MAMI/A1 electron beam line and a solid thin carbon target. The protons will be detected with spectrometer A in coincidence with the scattered electron in spectrometer B or C. This is a standard setup for A1. For Q^2=0.4 (GeV/c)^2 the spectrometer acceptance can cover a missing momentum range of approximately 0$\pm$100 MeV/c. Within 10 days of beam we can achieve the required statistics. The expected results are presented in the proposal.

Abstract of equipment: Standard A1 equipment with solid state target and Focal Plane Polarimeter.

MAMI specifications :

beam energy:	600 MeV
beam current:	20 μA
time structure:	continuous beam
polarization:	yes

Experiment specifications:

targets and chamber:	solid state target $45\,\mathrm{mg/cm^2}$, LH_2 target for calibration
hall:	spectrometer hall
beam line:	standard to spectrometer hall

spectrometer:	particles:	range of angles:	out of plane:
SpekA	p	34.7°	—
SpekB	e	82.4°	—

Beam time request :

set-up without beam:	2 days
set-up with beam:	4 h
data taking:	144 h

1 Scientific background and motivation

Nuclei are well described as ensembles of protons and neutrons held together by a strong mutual force. The nucleons are complex entities and the question of whether their internal structure is changed while they are embedded in nuclei has been a long-standing question in nuclear physics which remains unsettled [1].
The polarization transfer measured in the p(e, e'p) reaction is a direct measure of the ratio of the proton elastic electric to magnetic form factor (FF) ratio at some value of the four- momentum transfer Q^2:

$$\frac{P_x}{P_z} = -\frac{2M_p}{(E+E')\tan(\theta/2)}\frac{G_E^P(Q^2)}{G_M^P(Q^2)} \tag{1}$$

where $P_x(P_z)$ is the transverse (longitudinal) polarization transfer, E (E') is the incident (scattered) electron energy, θ is the electron scattering angle, and M_p is the proton mass (see [2] for details).
When exclusive (e,e'p) measurements are performed on a nuclear target, the polarization transfer observables are sensitive to the modifications of the form factors of the embedded nucleons, which we denote by $\frac{G_E^*}{G_M^*}$ [3-5]. The double polarizations

$$\left(\frac{(P_x/P_z)_A}{(P_x/P_z)_H}\right), \tag{2}$$

taken between a knockout nucleon from a nucleus A and a free nucleon, are only moderately sensitive to many-body effects like meson-exchange currents (MEC), isobar currents (IC), and final-state interactions (FSI) [6-8]. Small changes to the measured observables in nuclei due to these many-body effects are possible. Distinguishing between the latter and the in-medium nucleon structure modification is possible only using theoretical calculations.
The challenge is to observe (or, exclude) deviations which are outside the theoretical and experimental uncertainties that can be used as evidence for changes in the bound nucleon form factor compared to that of a free one.
The combination of high intensity, high polarization, continuous electron beams, and high precision spectrometers with focal plane polarimeters at MAMI/A1 allows a measurement of the ratio of polarization observables to a level of 1-2% [5, 9]. With such measurements the theoretical uncertainties are the limit factor.
High-precision experiments and calculations, designed to look for differences between the in-medium polarizations and the free values, compared polarization observables measured in quasi-elastic scattering off nuclear targets to these obtained for hydrogen [5]. We discuss here the possibility to identify in-medium effects and study their local nuclear density dependence by comparing quasi-elastic proton removal from the s- shell and p-shell in ^{12}C. As we show below, in these cases the local nuclear density is dramatically different.
Obtaining consistent results for medium modification if one compares s-shell and p-shell knockout protons in the ^{12}C(e, e'p)^{11}B reaction, or if one compares the quasi-elastic scattering to that off a free proton, is a strong support that can reduce the theoretical uncertainty of the magnitude of the medium modifications. Moreover, one expects the medium modification to depend on the local nuclear density and/or the bound nucleon momentum/virtuality. Measurements that can map the effects as a function of these two variables may reveal the nature of the medium modifications.

The missing momentum p_m corresponds to the initial momentum of the struck nucleon in plane-wave kinematics. In the deuteron, due to the low nuclear density, the expected effect of medium modifications at low missing momenta is too small to be detected unambiguously [10-13]. New measurements for high missing momentum are still unpublished [14]. Several polarization-transfer proton-knockout experiments have been performed on ^{4}He, both at the MAMI facility [15] and at Jefferson Lab (JLab) [5, 16]. The double-ratio of the in-plane polarization components in ^{4}He and a free proton,

$$\left(\frac{(P_x/P_z)_{He}}{(P_x/P_z)_H}\right), \tag{3}$$

which reflects the changes in the corresponding ratio of the electric and magnetic form factors, does not agree with state- of-the-art Distorted Wave Impulse Approximation (DWIA) calculations [5] using free nucleon form factors, but can be well described by including effects of medium modified form factors [17-22]. However, it has recently been shown [23] that including strong effects from charge-exchange FSI can also explain the observed double-ratio of Eq. 3.

The induced proton polarization in the ^{12}C(e,e'p) reaction has been reported by Woo [24] at quasi-elastic kinematics and MAMI energies, covering a missing momentum range of 0- 250 MeV/c. Polarization transfer measurements on ^{16}O were carried out at JLab [25]. Transverse and longitudinal polarization components were measured in quasi-elastic perpendicular kinematics at Q^2=0.8 (GeV/c)^2. The relatively large uncertainties on both the measurements and the calculations did not allow identification of deviations due to medium effects.

In this work we propose that the current state-of-the-art of calculations and measurements allows observing possible medium effects that are associated with local nuclear density. This can be done by comparing quasi-elastic s-shell and p-shell removal of protons from ^{12}C rather than comparing quasi-elastic to elastic scattering off Hydrogen.

We start by briefly presenting the Relativistic Multiple Scattering Glauber Approximation (RMSGA). We then discuss the local nuclear density difference between s- and p-shell protons in and present a few model calculations that estimate the magnitude of the expected effect of medium modifications on double polarization observables.

The Relativistic Multiple-Scattering Glauber Approximation (RMSGA) [28] is the theoretical framework used in this work. It is a parameter-free model that was used to describe well cross sections, nuclear transparencies and other observables in a large variety of electron and hadron induced exclusive reactions in kinematical conditions close to the case we discuss here [21, 29, 30]. The RMSGA provides an unfactorized approach to the (e,e'p) reaction. In contrast to factorized models which write the cross section in an electron- proton part times a FSI-corrected nuclear-structure part, the RMSGA computes the cross sections starting from the amplitudes. In the RMSGA the reaction amplitudes can be factorized in a part that describes the wave function of the proton in the nuclear ground state, times an off-shell current operator for the electron-proton scattering, times an attenuation factor that accounts for the FSI of the emerging proton. The eikonal Glauber FSI phase is a scalar in spin-space, hence the FSI do not contain any spin effects. The proton in the nuclear ground state is described by a single-particle bound state wave function obtained from the Serot-Walecka model [31]. To describe the polarization observable in the polarized electron scattering off the bound proton, the off-shell cross section CC2 was used [32]. FSI were calculated using a relativistic extension of the Glauber approximation. In the computation of the FSI, the local nuclear density obtained from the independent-particle wave function was corrected for the short-range

correlations (SRC) assuming Jastrow correlation function [33].
The effective density (ρ(r)) for both the s-shell and the p-shell proton in quasi-elastic proton knockout from ^{12}C are shown in Fig. 1 as a function of missing momentum. These densities are obtained with mean-field single-particle wave functions. We observe the effective density probed in proton knockout from the s-shell is about 0.1 fm^3 and rises slightly with increasing missing momentum p$_m$. This is more than double the density probed in knockout from the p-shell, which is around 0.04 fm^3. Also shown in the figure is δ(r) which is the calculated

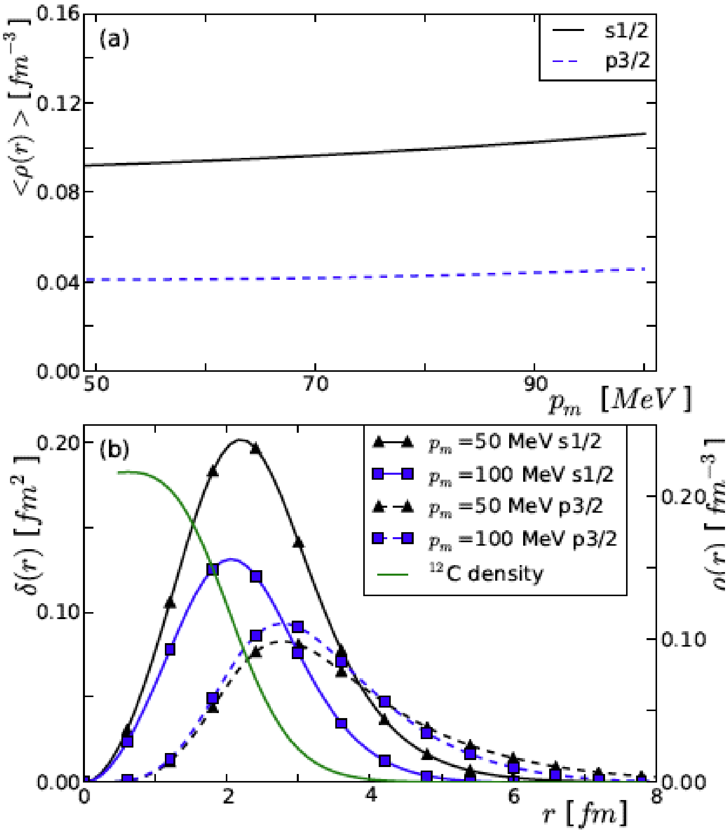

Figure 1: (a) Effective densities for protons removed from the s-shell and p-shell at Q^2 = 0.4 (GeV/c)^2 as a function of missing momentum. (b) δ(r) for s-shell (full) and p-shell (dashed) removal for a missing momentum of 50 (black curves) and 100 (blue curves) MeV. The ^{12}C density is also plotted (green curve) as a reference (scale on the right-side y-axis).

contribution from an infinitesimal density interval [r, r + dr] to the cross section for a quasifree ^{12}C(e, e'p) process and accounts for the effect of FSI and SRC therein. For a more detailed introduction on the quantity δ(r) we refer to Refs. [29, 34]. The FSI cause the largest contributions to the cross section to stem from the peripheral regions of the proton densities. These FSI effects are strongest for the high- density regions of the nucleus and thus affect the s-shell more than the p-shell.
To estimate the size of the in-medium modification we use two models with density-dependent medium-modified elastic form factors for the description of a bound proton. Fig. 2 shows the nuclear density dependence of the proton EM form factors at Q^2 = 0.4 (GeV/c)^2 described by the two models.
In the Chiral Quark Soliton (CQS) model [19, 35] the sea quarks are almost completely

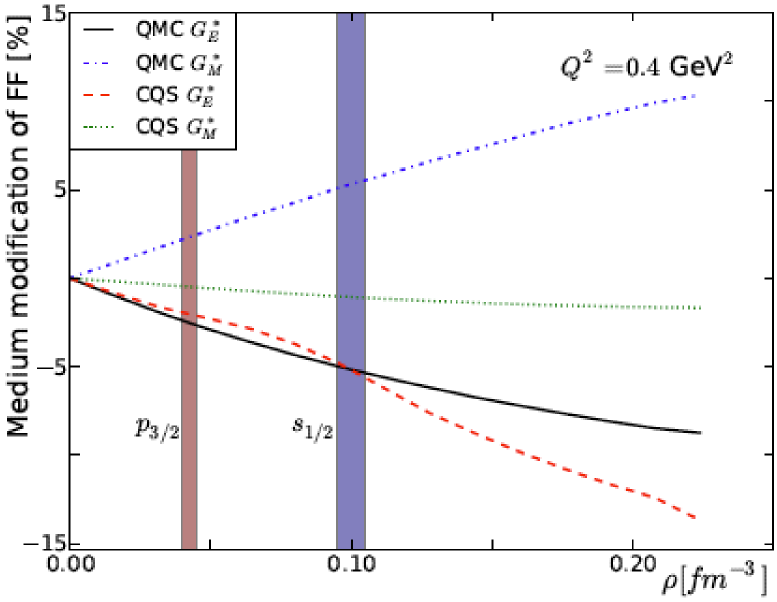

Figure 2: The nuclear density dependence of the proton EM form factors from the QMC and CQS models as a function of nuclear density at $Q^2 = 0.4$ (GeV/c)^2. The shaded bands show the effective nuclear densities for the two proton shells probed in the ^{12}C(e,e'p) reaction at these kinematics.

unaffected, whereas the valence quarks yield significant modifications of the form factors in the nuclear environment. The model yields a decrease of the electric form factor of about 5% at nuclear saturation density ($\sim$ 0.16 fm^3), while the modification of the magnetic form factor is smaller, around 1-2%. In the Quark Meson Coupling (QMC) model [17, 36] the form factors are found to be in- creasingly modified as the nuclear density increases. For ex- ample, at saturation nuclear density, the nucleon electric form factor is, reduced by approximately 7%, similar to the CQS model. The magnetic form factor increases by about the same amount, which is quite different from the CQS value.
These QMC and CQS model calculations contained in Fig. 2 do not intend to yield precise predictions for the proposed ^{12}C($\vec{e}$, e'$\vec{p}$) measurement, neither to test/select the most appropriate model. These calculations point to the possible size of the effect we expect to see from scattering off the tightly bound s-shell proton relative to the less bound p-shell proton. See Fig. 3 for an estimate of the difference between the two shell removals for realistic measurement conditions discussed below. The physics motivation for this experiment was also published as a Phys. Rev paper [39].

2 The proposed measurement

We propose to perform the measurements with the MAMI/A1 beam line and spectrometers [26, 27]. A 20 A, 600 MeV, electron beam can be used to bombard a solid thin carbon target. Spectrometer A with the FPP can be used to detect the proton and spectrometers B or C will be used to detect the scattered electron in coincidence with the proton.
The MAMI/A1 spectrometers have a scattering angle acceptance of approximately 4 degrees, and a momentum acceptance of 20-25%. The momentum resolution achievable by this setup allow reconstructing the missing mass and clearly identifying the s- and p-removal protons, which are separated by more than 2 MeV. The proposed kinematics are,

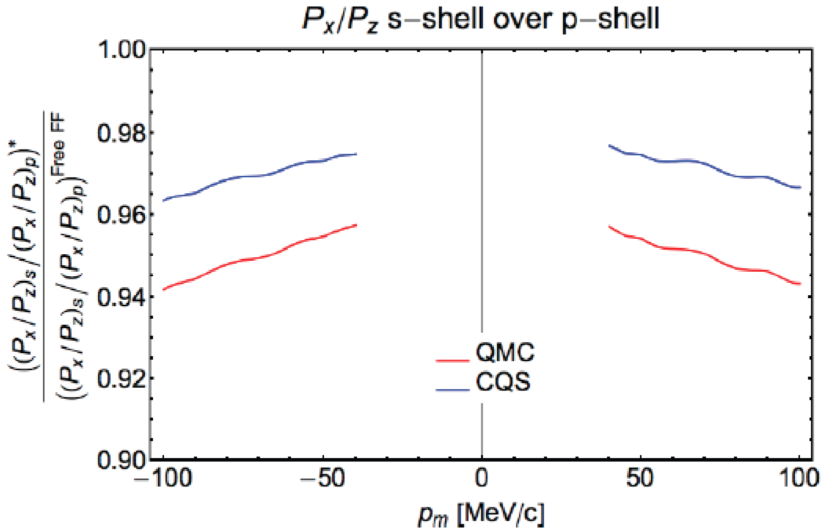

Figure 3: The ratio of the expected in-medium modification effect in the s- and p-shell removals.

Q^2=0.4 (GeV/c)^2, a beam energy of 600 MeV, which gives a scattered electron energy of E'=384 MeV, and a scattering angle of 82.4 (34.7) degree for the electron (proton). This setup covers a missing momentum range of approximately 0100 MeV/c. At these kinematics the cross section is large enough so that the data rate is limited by the Data Acquisition System. The analyzing power of the FPP, and the spin precession angle of the proton in the spectrometer magnetic field are such that within a reasonable amount of beam time (see below) enough statistics can be collected to ensure that the statistical uncertainties are smaller than both the systematic and theoretical uncertainties. The expected systematic uncertainties are dominated by the spin precession of the proton in the magnetic field of the spectrometer, requiring an accurate reconstruction of the proton trajectory in the magnetic field, as well as knowledge of the field map. Comparison of the measured polarization components with the well known results for a free proton at the same Q^2 can be used to test the systematic uncertain- ties. The false asymmetries are removed by using straight- through runs, where the carbon analyzer is removed, resulting in straight tracks throughout the polarimeter chambers. We estimate based on previous results [5, 9, 15], a conservative systematic uncertainty of 2% in the polarization ratio. Note, however, that this estimate is for the full acceptance of the spectrometer. The comparison of the polarization ratios for s- shell and p-shell protons can be performed for individual parts of the focal plane and then combined. This procedure reduces the variation of the trajectories through the magnetic field, and its contribution to the systematic uncertainty.

2.1 Beam Time Request

The beam request is based on our experience with the last measurements at MAMI/A1. For hydrogen 12 M events yield 156,000 events that passed all the software cuts and yield a Pz/Px ratio with statistical uncertainty of 2%. With data collection at a rate of 400 Hz to obtain this statistical uncertainty requires 1 shift of beam on target.
For this experiment we wish the statistical uncertainty to be at the level of 1%. For hydrogen we therefore request 2 days Only 1/3 of the carbon event will be from s-shell

removal. To obtain 1% uncertainty for these 6 more days of beam are required.
The total beam request is therefore:

- Set up, calibration, checks with beam - 2 days
- Hydrogen measurement (one setup) - 2 days
- Carbon measurement (one kinematics) - 6 days
- Total - 10 days

Fig. 4 shows the predicted ratio of s and pshell removal calculations with in-medium modification. The faked data were simulated

3 Expected results

Fig. 4 shows the predicted ratio of s and pshell removal calculations with in-medium modification to the free ratio. The CQS and QMC models discussed above were used to describe the in-medium case, the modification- free ratio was calculated with free proton form factors (i.e., no medium modification). All predictions use the RMSGA framework. The ratio is shown as a function of the (e,e'p) missing momentum p_m and integrated over the acceptance of the MAMI/A1 spectrometers as listed above. So Fig. 4 is our estimate of the result of the proposed measurement.
In Fig. 4 super double ratios substantially different from unity are an indication of in-medium modification. As can be deduced from Fig.4 the expected effect is about 5%. With four p_m bins (measured simultaneously) each measured with 2% uncertainty, the deviation from unity can be determined with very high certainty. The points shown on the figure are at values between the calculations and reflect the expected uncertainties. they show clearly that an effect at this level can be either confirm of excluded with the proposed measurement.

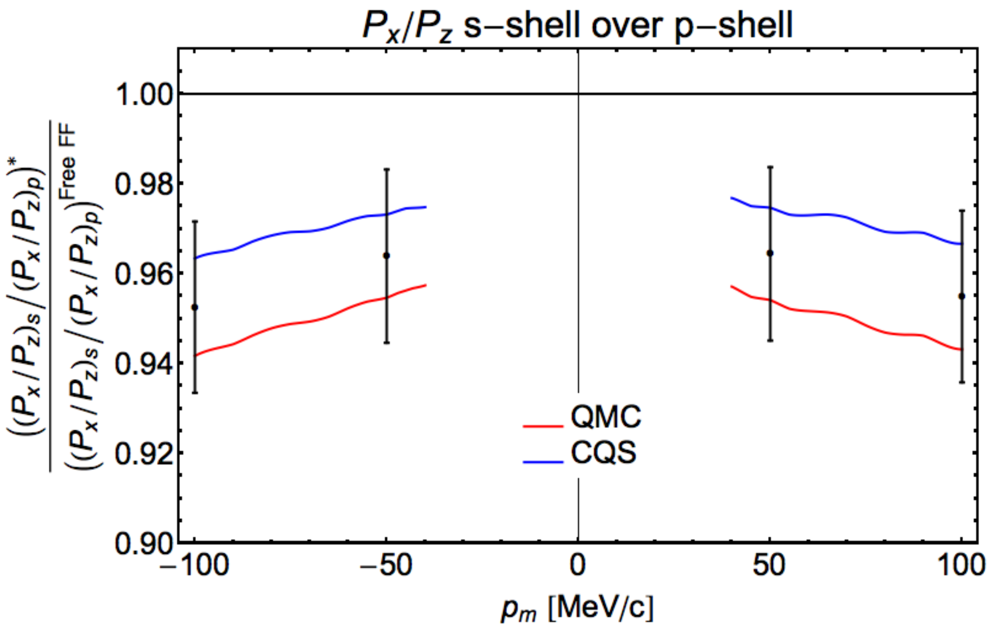

Figure 4: Same as Fig. 3 with faked data. See text for details.

References

[1] A. Bracco, P. Chomaz, J. Gaardhje, P.-H. Heenen, G. Ros- ner, E. Widmann, and G.-E. Korner, NuPECC Long Range Plan 2010: Perspectives of Nuclear Physics in Europe (2010), URL http://www.nupecc.org/.

[2] A. I. Akhiezer and M. P. Rekalo, Sov. J. Part. Nucl. 4, 277 (1974).

[3] I. Cloet, G. A. Miller, E. Piasetzky, and G. Ron, Phys. Rev. Lett. 103,082301 (2009).

[4] S. Strauch, S. Malace, and M. Paolone (2009).

[5] M. Paolone, S. P. Malace, S. Strauch, I. Albayrak, J. Arrington, B. L. Berman, E. J. Brash, B. Briscoe, A. Camsonne, J.-P. Chen, et al. (E03-104 Collaboration), Phys. Rev. Lett. 105, 072001 (2010).

[6] J.-M. Laget, Nucl. Phys. A579, 333 (1994).

[7] J. J. Kelly, Phys. Rev. C59, 3256 (1999).

[8] J. Ryckebusch, D. Debruyne, W. Van Nespen, and S. Janssen, Phys. Rev. C60, 034604 (1999).

[9] X. Zhan, K. Allada, D. Armstrong, J. Arrington, W. Bertozzi,W. Boeglin, J.-P. Chen, K. Chirapatpimol, S. Choi, E. Chu- dakov, et al., Phys. Lett. B705, 59 (2011).

[10] D. Eyl, A. Frey, H. Andresen, J. Annand, K. Aulenbacher, J. Becker, J. Blume-Werry, T. Dombo, P. Drescher, H. Fischer, et al., Z. Phys. A352, 211 (1995).

[11] B. D. Milbrath, J. I. McIntyre, C. S. Armstrong, D. H. Barkhuff, W. Bertozzi, J. P. Chen, D. Dale, G. Dodson, K. A. Dow, M. B. Epstein, et al. (Bates FPP Collaboration), Phys. Rev. Lett. 80, 452 (1998).

[12] D. Barkhuff, C. Armstrong, W. Bertozzi, J. Chen, D. Dale, G. Dodson, K. Dow, M. Epstein, M. Farkhondeh, J. Finn, et al., Phys. Lett. B470, 39 (1999).

[13] B. Hu, M. K. Jones, P. E. Ulmer, H. Arenhovel, O. K. Baker, W. Bertozzi, E. J. Brash, J. Calarco, J.-P. Chen, E. Chudakov, et al., Phys. Rev. C 73, 064004 (2006).

[14] I. Yaron et al., To be submitted (2013).

[15] S. Dieterich, P. Bartsch, D. Baumann, J. Bermuth, K. Bohinc, R. Bhm, D. Bosnar, S. Derber, M. Ding, M. Distler, et al., Phys. Lett. B500, 47 (2001).

[16] S. Strauch, S. Dieterich, K. A. Aniol, J. R. M. Annand, O. K. Baker, W. Bertozzi, M. Boswell, E. J. Brash, Z. Chai, J.-P. Chen, et al., Phys. Rev. Lett. 91, 052301 (2003).

[17] D.-H. Lu, A. W. Thomas, K. Tsushima, A. G. Williams, and K. Saito, Phys. Lett. B417, 217 (1998).

[18] J. R. Smith and G. A. Miller, Phys. Rev. Lett. 91, 212301 (2003).

[19] J. R. Smith and G. A. Miller, Phys. Rev. C70, 065205 (2004).

[20] T. Horikawa and W. Bentz, Nucl. Phys. A762, 102 (2005).

[21] P. Lava, J. Ryckebusch, and B. Van Overmeire, Prog. Part. Nucl. Phys. 55,437 (2005).

[22] I. Cloet, W. Bentz, and A. W. Thomas, Phys. Lett. B621, 246 (2005).

[23] R. Schiavilla, O. Benhar, A. Kievsky, L. E. Marcucci, and M. Viviani, Phys. Rev. Lett. 94, 072303 (2005).

[24] R. J. Woo, D. H. Barkhuff, W. Bertozzi, J. P. Chen, D. Dale, G. Dodson, K. A. Dow, M. B. Epstein, M. Farkhondeh, J. M. Finn, et al. (Bates FPP Collaboration), Phys. Rev. Lett. 80, 456 (1998).

[25] S. Malov, K. Wijesooriya, F. T. Baker, L. Bimbot, E. J. Brash,C. C. Chang, J. M. Finn, K. G. Fissum, J. Gao, R. Gilman, et al., Phys. Rev. C 62, 057302 (2000).

[26] K. Blomqvist, W. Boeglin, R. Bhm, M. Distler, R. Edelhoff, J. Friedrich, R. Geiges, P. Jennewein, M. Kahrau, M. Korn, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 403, 263 (1998).

[27] T. Pospischil, P. Bartsch, D. Baumann, R. Bhm, K. Bohinc,N. Clawiter, M. Ding, S. Derber, M. Distler, D. Elsner, et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **483**, 713 (2002).
[28] J. Ryckebusch, D. Debruyne, P. Lava, S. Janssen, B. Van Over- meire, and T. Van Cauteren, Nucl. Phys. A728, 226 (2003).
[29] J. Ryckebusch, W. Cosyn, and M. Vanhalst, Phys. Rev. C 83, 054601 (2011).
[30] W. Cosyn and J. Ryckebusch, Few Body Syst. 49, 77 (2011). [31] R. Furnstahl, B. D. Serot, and H.-B. Tang, Nucl. Phys. A615,441 (1997).
[32] T. De Forest, Nucl. Phys. A392, 232 (1983).
[33] W. Cosyn, M. C. Martinez, and J. Ryckebusch, Phys. Rev. C 77, 034602 (2008)
[34] W. Cosyn and J. Ryckebusch, Phys. Rev. C80, 011602 (2009). [35] C. Christov, A. Gorski, K. Goeke, and P. Pobylitsa, Nucl. Phys. A592, 513 (1995).
[36] D.-H. Lu, K. Tsushima, A. W. Thomas, A. G. Williams, and K. Saito, Phys. Rev. C60, 068201 (1999).
[37] C. Ciofi degli Atti, L. Frankfurt, L. Kaptari, and M. Strikman, Phys. Rev. C76, 055206 (2007).
[38] L. B. Weinstein, E. Piasetzky, D. W. Higinbotham, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. 106, 052301 (2011).
[39] G. Ron, W. Cosyn, E. Piasetzky, J. Ryckebusch, and J. Lichtenstat, Phys Rev. C **87**, 028208 (2013).