New results from BLAST on the nucleon electromagnetic form factors

Haiyan Gao and the BLAST Collaboration

Department of Physics and the Triangle Universities Nuclear Laboratory, Duke University, Durham, NC 27708, U.S.A.

Abstract. Recently, a new experiment was carried out in the South Hall Ring at the MIT-Bates Accelerator Laboratory. This experiment utilized a polarized electron beam, a pure hydrogen (deuterium) internal polarized gas target, and the symmetric Bates Large Acceptance Spectrometer Toroid (BLAST) detector. The proton electric to magnetic form factor ratio, $\frac{G_E^p}{G_M^p}$ at Q^2= 0.15 - 0.65 (GeV/c)^2 has been determined from the experiment by measuring the spin-dependent ep elastic scattering asymmetry in both sectors simultaneously. This is the first experiment to measure $\frac{G_E^p}{G_M^p}$ using a polarized proton target, which is complementary to recoil polarimetry experiments. The neutron magnetic form factor G_M^n has been extracted from the measurement of the spin-dependent asymmetry from the inclusive $\vec{d}(\vec{e},e)$ process in a similar Q^2 with a vector polarized deuterium target, and the neutron electric form factor G_E^n has been extracted by measuring the spin-dependent asymmetry from the coincidence $\vec{d}(\vec{e},e'n)$ process simultaneously. Preliminary results on the nucleon form factors from the BLAST experiment are presented.

Keywords: electron scattering, polarization, nucleon form factors
PACS: 25.30.-c, 25.30.Rw, 29.25.-t, 29.30.-h

INTRODUCTION

The electromagnetic form factors of the nucleon are fundamental quantities describing the distribution of charge and magnetization within nucleons. Quantum Chromodynamics (QCD) is the theory of strong interaction in terms of quark and gluon degrees of freedom. While QCD has been extremely well tested in the high energy regime, where perturbative QCD is applicable, understanding confinement and hadron structure in the non-perturbative region of QCD remains challenging. Knowledge of the internal structure of protons and neutrons in terms of quark and gluon degrees of freedom is not only essential for testing QCD in the confinement regime, but it also provides a basis for understanding more complex, strongly interacting matter at the level of quarks and gluons.

The proton electric (G_E^p) and magnetic (G_M^p) form factors have been studied extensively in the past from unpolarized electron-proton (ep) elastic scattering using the Rosenbluth separation technique [1]. Recent advances in polarized beams, targets, and polarimetry have allowed for a new class of experiments extracting $\mu_p G_E^p/G_M^p$ from spin degrees of freedom. Recent data from polarization transfer experiments [2, 3, 4] measuring this ratio directly with unprecedented precision, show that $\frac{\mu_p G_E^p}{G_M^p}$ drops to approximately 0.3 at the highest measured Q^2 value ($\sim$ 5.5 (GeV/c)^2). This is very different from unity, as suggested by previous unpolarized cross section measurements [5, 6] and verified by recent experiments [7, 8].

While the intriguing Q^2 dependence of the proton form factor ratio can be described [9, 10, 11], it is important to understand the discrepancy between results obtained from recoil proton polarization measurements and those from the Rosenbluth method. Two-photon exchange contributions [12, 13, 14] are believed to contribute to the observed discrepancy between the polarization method and the Rosenbluth technique. Currently, there are intensive efforts both in theory [15, 16] and in experiment aiming at understanding the two-photon exchange contributions to electron scattering in general, particularly with respect to the aforementioned discrepancy in the proton form factor ratio.

As an independent extraction of the proton form factor ratio from polarized electron scattering, we recently completed a new experiment in which longitudinally polarized electrons were scattered from a polarized proton target at the MIT-Bates accelerator Laboratory. The proton electric to magnetic form factor ratio can be extracted from the spin-dependent asymmetry with high precision up to a Q^2 value of about 0.65 (GeV/c)^2. Such a double-polarization experiment is important because it employs a completely different experimental technique with different systematic uncertainties from recoil proton polarization measurements. The Q^2 region covered by the BLAST experiment also overlaps with the low Q^2 end of the Jefferson Lab recoil polarization measurement [2].

THE $\vec{p}(\vec{e},e'p)$ PROCESS AND THE PROTON ELECTRIC TO MAGNETIC FORM FACTOR RATIO

The spin-dependent asymmetry for elastic e-p scattering has the following form [17]:

$$A = \frac{\Delta}{\Sigma} = -\frac{2\tau v_{T'} \cos\theta^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}\,, \tag{1}$$

where θ^*, ϕ^* are the target spin polar and azimuthal angles defined relative to the three-momentum transfer vector of the virtual photon. The experimental asymmetry A_{exp}, is related to the spin-dependent asymmetry of Eqn. 1 by the relation

$$A_{exp} = P_b P_t A\,, \tag{2}$$

where P_b and P_t are the beam and target polarizations, respectively. A determination of the ratio $\frac{G_E^p}{G_M^p}$, independent of the knowledge of the beam and target polarization, can be precisely obtained by forming the so-called super ratio [18, 19]:

$$R = \frac{A_1}{A_2} = \frac{2\tau v_{T'} \cos\theta_1^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_1^* \cos\phi_1^* G_M^p G_E^p}{2\tau v_{T'} \cos\theta_2^* {G_M^p}^2 - 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta_2^* \cos\phi_2^* G_M^p G_E^p}\,, \tag{3}$$

where A_1 and A_2 are elastic electron-proton scattering asymmetries measured at the same Q^2 value, but with two different proton spin orientations relative to the corresponding three-momentum transfer vector, i.e., (θ_1^*, ϕ_1^*) and (θ_2^*, ϕ_2^*), respectively. For a detector configuration that is symmetric with respect to the incident electron momentum direction, and a polarized target with the spin vector aligned at an angle with respect to the beam line, A_1 and A_2 can be measured simultaneously by forming two independent asymmetries with respect to either the electron beam helicity or the target spin orientation in the beam-left and beam-right sector of the detector system, respectively. For the BLAST experiment, the target spin angle was aligned around 45° relative to the incident electron momentum direction.

THE QUASIELASTIC $\vec{d}(\vec{e},e')$, $\vec{d}(\vec{e},e'n)$ PROCESSES AND THE NEUTRON ELECTROMAGNETIC FORM FACTORS

Measurements of the neutron electric form factor are extremely challenging because of the lack of free neutron targets, the smallness of the G_E^n, and the dominance of the magnetic contribution to the unpolarized differential cross-section. A promising approach to measure G_E^n is to use polarization degrees of freedom. One can employ a vector polarized deuteron target and a longitudinally polarized electron beam to probe the neutron magnetic and the electric form factors by measuring the spin-dependent asymmetry from the following two processes: $\vec{d}(\vec{e},e')$ and $\vec{d}(\vec{e},e'n)$.

The spin-dependent contribution to the inclusive $\vec{d}(\vec{e},e')$ cross section is completely contained in two spin-dependent nuclear response functions, a transverse response $R_{T'}$ and a longitudinal-transverse response $R_{TL'}$ [17]. These appear in addition to the spin-independent longitudinal and transverse responses R_L and R_T. These spin-dependent response functions $R_{T'}$ and $R_{TL'}$ can be isolated experimentally by forming the spin-dependent asymmetry A defined with respect to the electron beam helicity. In terms of the nuclear response functions, A can be written [17]:

$$A = \frac{-\cos\theta^* v_{T'} R_{T'} + 2\sin\theta^* \cos\phi^* v_{TL'} R_{TL'}}{v_L R_L + v_T R_T} \tag{4}$$

where the v_k are kinematic factors, and θ^* and ϕ^* are the target spin angles defined previously. The response functions R_k depend on Q^2 and the electron energy transfer ω. By choosing $\theta^* = 0$, *i.e.* by orienting the target spin parallel to the momentum transfer $\vec{q}$, one selects the transverse asymmetry $A_{T'}$ (proportional to $R_{T'}$); by orienting the target spin perpendicular to the momentum transfer $\vec{q}$ ($\theta^* = 90°$, $\phi^* = 0°$), one selects the transverse-longitudinal asymmetry $A_{TL'}$ (proportional to $R_{TL'}$). $R_{T'}$ at quasi-elastic kinematics contains a dominant magnetic contribution and is essentially proportional to $(G_M^n)^2 + (G_M^p)^2$ in the plane-wave-impulse approximation picture. One can determine the neutron magnetic form factor from the inclusive asymmetry measurement using the state-of-the-art calculations of the asymmetry once the proton magnetic form factor has been determined. Such an experimental technique has been used successfully in experiments [20, 21, 22] with a polarized ^{3}He target where the magnetic contribution of the protons is minimal because of the unique spin structure of the ^{3}He nuclear ground state.

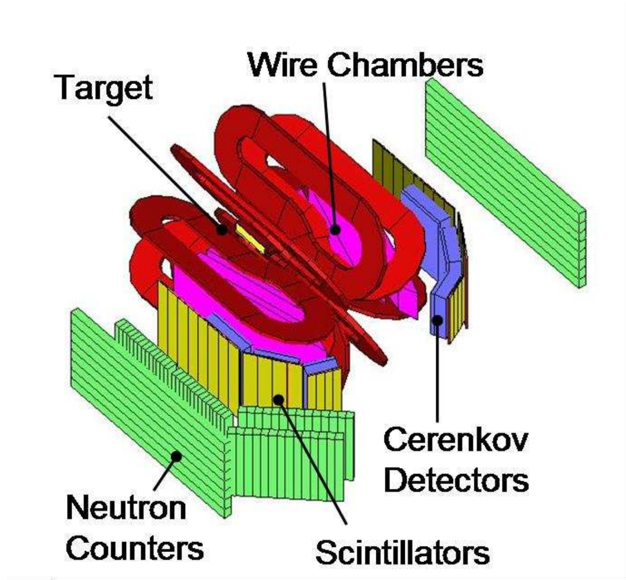

FIGURE 1. The schematics of the BLAST detector setup.

The scattering cross-section for longitudinally polarized electrons from a polarized deuteron target for the $\vec{d}(\vec{e},e'n)$ reaction can be written as [23, 24]:

$$S = S_0 \left\{ 1 + P_1^d A_d^V + P_2^d A_d^T + h(A_e + P_1^d A_{ed}^V + P_2^d A_{ed}^T) \right\}, \tag{5}$$

where S_0 is the unpolarized differential cross section, h the polarization of the electrons, and P_1^d (P_2^d) the vector (tensor) polarization of the deuteron. A_e is the beam analyzing power, $A_d^{V/T}$ the vector and tensor analyzing powers, and $A_{ed}^{V/T}$ the vector and tensor spin-correlation parameters. The polarization direction of the deuteron is defined with respect to the three-momentum transfer vector, $\vec{q}$. The vector spin-correlation parameter A_{ed}^V contains a term representing the interference between the small neutron electric form factor and the dominant neutron magnetic form factor, when the target spin is perpendicular to the $\vec{q}$ vector direction. Thus, the spin-dependent asymmetry (defined with respect to the electron beam helicity) from the $\vec{d}(\vec{e},e'n)$ reaction for vector polarized deuteron gives access to the quantity $\frac{G_E^n}{G_M^n}$ to first order when the target spin direction is aligned perpendicular to $\vec{q}$. One can determine G_E^n from this ratio once the neutron magnetic form factor has been determined. Such experiments are extremely challenging since they involve both neutron detection and a vector polarized deuteron target and have been carried out previously at NIKHEF [25], and Jefferson Lab [26, 27].

THE BLAST EXPERIMENT

The experiment was carried out in the South Hall Ring of the MIT Bates Linear Accelerator Center, which stored an intense polarized beam with a beam current of up to 225 mA and longitudinal electron polarization of 0.65 at an incident beam energy of

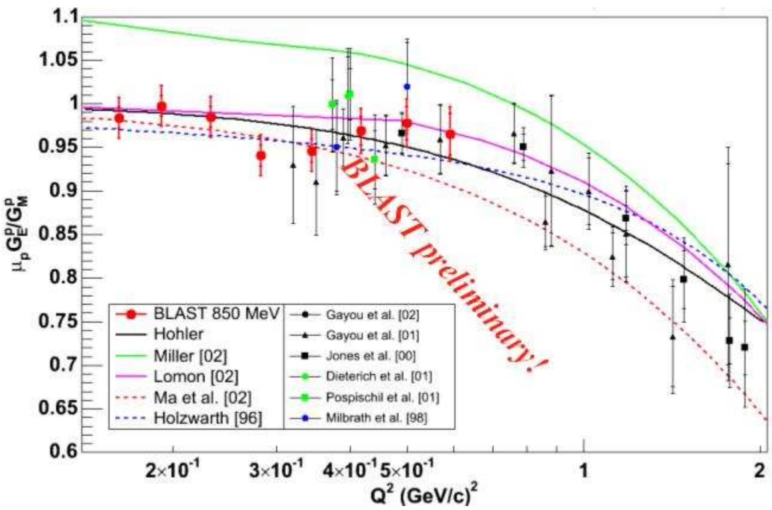

FIGURE 2. The preliminary BLAST results on the extracted proton electric to magnetic form factor ratio as a function of Q^2 together with world data from recoil polarization measurements (see text).

850 MeV. A Siberian Snake in the ring opposite of the interaction point preserved the electron polarization, which was continuously monitored with a Compton polarimeter installed upstream of the internal target region. The background was minimized with a tungsten collimator in front of the target cell.

The polarized protons (vector polarized deuterium) were feed into an open-ended, cylindrical target cell 60 cm long by 15 mm in diameter from an Atomic Beam Source (ABS). The ABS provided a highly polarized ($P_t \sim 0.8$ for proton and $P_t \sim 0.9$ for deuteron vector polarization) isotopically pure target without windows in the beam line, and with fast spin reversal to reduce systematic errors. The ABS was operated in single state mode in order to avoid depolarization due to hyperfine interactions in the case of hydrogen. The ABS switched between states every five minutes and the ring was filled with alternating electron polarizations every half hour.

The relatively low luminosity $L = 1.6 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ of the internal gas target was compensated by the large acceptance spectrometer. The symmetric detector package was built around eight copper coils which provided the 0.4 Tesla BLAST toroidal magnetic field. Two of the sectors were instrumented with three drift chambers each for momentum, angular, and positional resolution, scintillators for triggering and time-of-flight, and Čerenkov detectors for pion rejection. Additional scintillators at backward angles beyond the drift chambers extended the acceptance to $Q^2 = 0.85(\mathrm{GeV/c})^2$. The neutron detectors were enhanced in the right sector with a detection efficiency of $\sim 30\%$ as compared to $\sim 10\%$ in the left sector due to the choice of the target spin angle. The setup allowed simultaneous measurements of the $\vec{d}(\vec{e},e'p)$, $\vec{d}(\vec{e},e'd)$ in addition to the $\vec{d}(\vec{e},e')$ and the $\vec{d}(\vec{e},e'n)$ processes. The schematics of the BLAST detector is shown in Fig. 1.

The elastic events for *ep* elastic scattering were selected with a cut on the invariant mass of the scattered electron, and a vertex cut, and fiducial cuts on the acceptance. These cuts were also consistent with kinematic cuts on the 3-momentum of the recoil

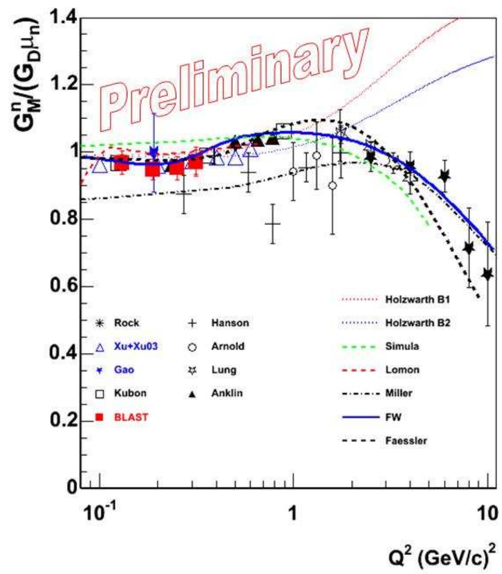

FIGURE 3. Preliminary BLAST results on G_M^n from the $\vec{d}(\vec{e},e')$ process together with world data and a few selected theoretical curves (see text).

proton, and timing and co-planarity cuts on the scintillators. These cuts were sufficient to reduce the background to less than 1%. The background was measured with 14.9 kC of integrated beam charge on the same target cell without hydrogen gas flowing in the target cell. The beam blowup effect was shown to be negligible by measuring the H(e,e′n) rates between hydrogen and the empty target with no hydrogen gas flowing. There were two data collection periods for the deuterium running: 320 kC of accumulated charge in 2004 with the target spin angle of 32° and 550 kC in 2005 with a target spin angle of 47°.

PRELIMINARY BLAST RESULTS

Fig. 2 shows the preliminary BLAST results on the extracted proton form factor ratio together with the world data from recoil polarization measurements [2, 3, 28, 29, 30, 31]. The inner error bars are the statistical errors, while the outer error bars are the quadrature sum of the statistical and systematic errors. Also shown are a few selected models: the soliton model [32], the extended vector meson dominance model [33], the relativistic constituent quark model (CQM) [34], and the relativistic quark spectator-diquark model calculation by Ma *et al.* [35, 36]. We also show the Höhler [37] parameterization.

Fig. 3 shows the preliminary results on G_M^n as a function of Q^2 extracted from the inclusive asymmetry measured from the $\vec{d}(\vec{e},e')$ process [38]. The BLAST data are shown with the statistical and systematic errors added in quadrature. Also shown are the world data on G_M^n from different experiments [39, 40, 41, 42, 43, 44, 45, 20, 46, 21, 22]. Previously, G_M^n has been extracted from inclusive asymmetry measurements from the $^3\vec{H}e(\vec{e},e')$ process at the MIT-Bates Laboratory [20, 46] and the Jefferson Laboratory [21, 22]. In addition to the theory curves shown in Fig. 1, the relativistic

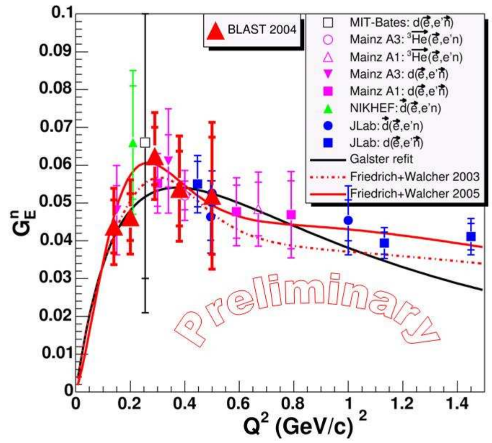

FIGURE 4. Preliminary BLAST results on G_E^n from the $\vec{d}(\vec{e},e')$ process together with world data from polarization experiments, the Friedrich and Walcher [49] parameterization and a Galster [57] fit of the recent G_E^n data [50].

constituent quark model (CQM) with SU(6) symmetry breaking and a constituent quark form factor [47], and a Lorentz covariant chiral quark model [48] are also shown. Also shown is a parametrization by Friedrich and Walcher [49] which explicitly takes into account the pion cloud effect.

Fig. 4 shows the preliminary BLAST results on G_E^n extracted from $\vec{d}(\vec{e},e'n)$ as a function of Q^2 [50]. The state-of-the-art calculation by Arenhövel *et al.* [51] was used in the Monte Carlo simulation of the BLAST measurement in extracting the G_E^n values. Also shown are the world data on G_E^n from various double polarization measurements [26, 27, 25, 52, 53, 54, 55, 56]. The preliminary BLAST results are from the 2004 BLAST deuterium data set only, and are shown with the statistical errors as the inner error bars and outer error bars being the quadrature sum of the statistical and systematic errors. The final error bars will be significantly reduced both in the statistical and systematic uncertainties. The preliminary BLAST results on G_E^n have been used already to make new, precise determinations of strange form factors of G_M^s and G_E^s by the Jefferson Lab HAPPEX collaboration from parity-violating electron scattering.

ACKNOWLEDGMENT

We thank the staff at the MIT-Bates Linear Accelerator Center for the delivering of high quality electron beam and for their technical support which made this experiment a success. We thank T.W. Donnelly and H. Arenhövel for stimulating discussions. This work is supported in part by the U.S. Department of Energy under contract number DE-FC02-94ER40818 and DE-FG02-03ER41231.

REFERENCES

1. M. Rosenbluth, *Phys. Rev.* **79**, 615 (1950).

2. M. Jones *et al.*, *Phys. Rev. Lett.* **84**, 1398 (2000).
3. O. Gayou *et al.*, *Phys. Rev. Lett.* **88**, 092301 (2002).
4. V. Punjabi *et al.*, *Phys. Rev. C* **71**, 055202 (2005).
5. R. Walker *et al.*, *Phys. Rev. D* **49**, 5671 (1994).
6. L. Andivahis *et al.*, *Phys. Rev. D* **50**, 5491 (1994).
7. M. Christy *et al.*, *Phys. Rev. C* **70**, 015206 (2004).
8. I. Qattan *et al.*, *Phys. Rev. Lett.* **94**, 142301 (2005).
9. A. Belisky, X. Ji, and F. Yuan, *Phys. Rev. Lett.* **91**, 092002 (2003).
10. G. Miller, and M. Frank, *Phys. Rev. C* **65**, 065205 (2002).
11. S. Brodsky *et al.*, *Phys. Rev. D* **69**, 076001 (2004).
12. P. Guichon, and M. Vanderhaeghen, *Phys. Rev. Lett.* **91**, 142303 (2003).
13. P. B. W. Melnitchouk, and J. Tjon, *Phys. Rev. Lett.* **91**, 142304 (2003).
14. M. Rekalo, and E. Tomasi-Gustafsson, *Eur. Phys. J. A* **22**, 331 (2004).
15. Y. Chen *et al.*, *Phys. Rev. Lett.* **93**, 122301 (2004).
16. A. Afanasev, and N. Merenkov, *Phys. Rev. D* **70**, 073002 (2004).
17. T. Donnelly, and A. Raskin, *Ann. Phys* **169**, 247 (1986).
18. H. Gao, *Int. J. Mod. Phys. E* **12**, 1 (2003).
19. H. Gao, *Int. J. Mod. Phys. E* **12**, 567 (2003).
20. H. Gao *et al.*, *Phys. Rev. C* **50**, R546 (1998).
21. W. Xu *et al.*, *Phys. Rev. Lett.* **85**, 2900 (2000).
22. W. Xu *et al.*, *Phys. Rev. C* **67**, 012201 (2002).
23. H. Arenhoevel, *Phys. Lett. B* **199**, 13 (1987).
24. H. Arenhoevel, *Z. Phys. A* **331**, 123 (1988).
25. I. Passchier *et al.*, *Phys. Rev. Lett.* **82**, 4988 (1999).
26. H. Zhu *et al.*, *Phys. Rev. Lett.* **87**, 081801 (2001).
27. G. Warren *et al.*, *Phys. Rev. Lett.* **92**, 042301 (2004).
28. O. Gayou *et al.*, *Phys. Rev. C* **64**, 038202 (2001).
29. S. Dieterich *et al.*, *Phys. Lett.* **B500**, 47 (2001).
30. T. Pospischil *et al.*, *Eur. Phys. J* **A12**, 125 (2001).
31. B. Milbrath *et al.*, *Phys. Rev. Lett.* **80**, 452 (1998).
32. G. Holzwarth, *Z. Phys.* **A356**, 339 (1996).
33. E. Lomon, *Phys. Rev. C* **66**, 045501 (2002).
34. G. Miller, *Phys. Rev. C* **66**, 032201 (2002).
35. B. Ma *et al.*, *Phys. Rev. C.* **65**, 035205 (2002).
36. B. Ma *et al.*, *Phys. Rev. C.* **66**, 048201 (2002).
37. G. Höhler *et al.*, *Nucl. Phys.* **B114**, 505 (1976).
38. N. Meitanis, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA 02139 (2006).
39. R. Arnold *et al.*, *Phys. Rev. Lett.* **61**, 806 (1988).
40. S. Rock *et al.*, *Phys. Rev. Lett.* **49**, 1139 (1982).
41. A. lung *et al.*, *Phys. Rev. Lett.* **70**, 718 (1993).
42. K. Hanson *et al.*, *Phys. Rev. D* **8**, 753 (1973).
43. H. Anklin *et al.*, *Phys. Rev. B* **336**, 313 (1994).
44. H. Anklin *et al.*, *Phys. Rev. B* **428**, 248 (1998).
45. G. Kubon *et al.*, *Phys. Rev. B* **524**, 26 (2002).
46. H. Gao, *Nucl. Phys. A* **631**, 170 (1998).
47. F. Cardarelli, and S. Simula, *Phys. Rev. C* **62**, 065201 (2000).
48. A. Faessler *et al.*, *Phys. Rev. D* **73**, 114021 (2006).
49. J. Friedrich, and T. Walcher, *Eur. Phys. J. A* **17**, 607 (2003).
50. V. Ziskin, Ph.D. thesis, Massachusetts Institute of Technology, Cambridge, MA 02139 (2005).
51. H. Arenhoevel *et al.*, *Eur. Phys. J. A* **23**, 147 (2005).
52. T. Eden *et al.*, *Phys. Rev. C* **50**, 1749R (1994).
53. M. Ostrick *et al.*, *Phys. Rev. Lett.* **83**, 276 (1999).
54. C. Herberg *et al.*, *Eur. Phys. Jour. A* **5**, 131 (1999).
55. J. Becker *et al.*, *Eur. Phys. Jour. A* **6**, 329 (1999).
56. D. Rohe *et al.*, *Phys. Rev. Lett.* **83**, 4257 (1999).
57. S. Galster, *Nucl. Phys. B.* **32**, 221 (1971).