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MEASUREMENTS OF THE ELECTRIC FORM FACTOR OF THE NEUTRON AT JLAB VIA RECOIL POLARIMETRY IN THE REACTION $\mathrm{d}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{n}})\mathrm{p}$

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Preliminary results are reported for measurements of the ratio of the electric form factor to the magnetic form factor of the neutron, $G_\mathrm{E}^\mathrm{n}/G_\mathrm{M}^\mathrm{n}$, obtained via recoil polarimetry from the quasielastic $^2\mathrm{H}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{n}})\,^1\mathrm{H}$ reaction at Q^2 values of 0.45, 1.13, and 1.45 $(\mathrm{GeV}/c)^2$. The measurements, conducted in Hall C of the Thomas Jefferson National Accelerator Facility, together with other recent polarization measurements, are the result of a decade long effort to establish a firm experimental database for the important, but elusive, electric form factor of the neutron.

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1. *Introduction*

Electromagnetic nucleon form factors provide vital input for nuclear structure calculations based on hadronic degrees of freedom. When combined with parity violation measurements of the weak neutral form factor and the assumption of charge symmetry, they also allow a flavor decomposition of the light quark flavor currents needed to test our understanding of QCD. However, although good measurements have been made of the electric form factor of the proton and of the magnetic form factors of both the proton and the neutron, the electric form factor of the neutron has proved to be a formidable experimental challenge. Unlike the case of the proton, free neutron targets don't exist, and the electric form factor of the neutron is small and dominated by the magnetic form factor. In the case of quasi-free scattering from deuterium using Rosenbluth separations, the electric and magnetic form factors enter quadratically. Together with proton subtraction and radiative corrections, this has led to results dominated by systematic errors. Elastic scattering from deuterium, once considered a promising technique, has proven to be dominated by significant theoretical uncertainties in choosing among various, otherwise-equivalent, effective nucleon-nucleon interactions.

Over the last decade, a number of promising new techniques, involving measurement of polarization degrees of freedom, have been developed to measure the electric form factor of the neutron, $G_{\mathrm{E}}^{\mathrm{n}}$. Experiments employing recoil polarimeters [1, 2], polarized ^{3}He targets [3 − 5] and polarized deuterium targets [6, 7] have yielded the first precision measurements of $G_{\mathrm{E}}^{\mathrm{n}}$. These first polarization measurements of $G_{\mathrm{E}}^{\mathrm{n}}$ are limited to $Q^2 \leq 0.67$ (GeV/c)^2 and are, within errors, consistent with the Galster parameterization [8]. (Here, $Q^2 = 4EE' \tan^2(\theta_{\mathrm{e}}/2)$ where $E(E')$ is the incident(scattered) electron energy and θ_{e} is the electron scattering angle.) In addition to polarization measurements, $G_{\mathrm{E}}^{\mathrm{n}}$ has been extracted from a theoretical analysis of the deuteron quadrupole form factor [9] for Q^2 values up to 1.6 (GeV/c)^2. What these techniques share in common is that the results are sensitive to the ratio $g = G_{\mathrm{E}}^{\mathrm{n}}/G_{\mathrm{M}}^{\mathrm{n}}$ in a linear manner, and that, for the most part, theoretical complications appear to be small and well understood.

Here a report is given on the results of experimental measurements of the ratio g of the electric form factor to the magnetic form factor of the neutron at three Q^2s ranging up to 1.47 (GeV/c)^2, obtained via recoil polarimetry by the Jefferson Laboratory (JLab) collaboration. Since $G_{\mathrm{M}}^{\mathrm{n}}$ is well known, this allows a clean extraction of $G_{\mathrm{E}}^{\mathrm{n}}$. In a separate contribution, Frank Wesselmann is presenting the results from a second deuterium experiment at JLab, using a polarized deuterium target at $Q^2 = 0.5$ and 1.0 (GeV/c)^2. Shortly after this talk was presented at the NAPP 2003 Conference, preprints of the final results from both experiments were submitted for publication, see references [10, 11]. These new results, together with other results using deuterium and ^{3}He targets at Bates, Mainz and JLab, provide a remarkably consistent set of polarization measurements on the neutron's electric form factor up to a four-momentum transfer squared (Q^2) of 1.47 (GeV/c)^2.

2. The experiment

In the quasi-free approximation, the polarization transfer by a longitudinally polarized electron beam to the recoiling neutron produced in quasielastic electron-neutron scattering is restricted to the (n·p) scattering plane [12, 13], where the longitudinal component D_{LL}, and the transverse (sideways) component, D_{LS}, are parallel and perpendicular, respectively, to the neutron's momentum vector,

$$P_{\mathrm{S}} = D_{\mathrm{LS}} = \frac{-2}{I_0}\sqrt{\tau(1+\tau)}\ \tan(\theta_{\mathrm{e}}/2) G_{\mathrm{E}} G_{\mathrm{M}} \tag{1}$$

$$P_{\mathrm{L}} = D_{\mathrm{LL}} = \frac{1}{I_0}\frac{E+E'}{M_{\mathrm{n}}} \tan^2(\theta_{\mathrm{e}}/2) G_{\mathrm{M}}^2 \tag{2}$$

and

$$\frac{P_{\mathrm{S}}}{P_{\mathrm{L}}} = \frac{-2M_{\mathrm{n}}\sqrt{\tau(1+\tau)}}{(E+E')\tan(\theta_{\mathrm{e}}/2)}\frac{G_{\mathrm{E}}}{G_{\mathrm{M}}}\,. \tag{3}$$

In the above equations, $I_0 = G_{\rm E}^2 + G_{\rm M}^2\tau(1 + 2(1 + \tau)\tan^2(\theta_{\rm e}/2))$, $\tau = Q^2/4M_{\rm n}^2$, and $M_{\rm n}$ is the neutron mass. Measurements of $D_{\rm LS}$ and $D_{\rm LL}$ via a secondary analyzing reaction permit an extraction of the ratio g. A significant advantage of this ratio technique is that the beam helicity and the analyzing power of the secondary reaction cancel in the polarization transfer ratio $D_{\rm LS}/D_{\rm LL}$. Also, for quasifree emission, Arenhovel [14] demonstrated that $D_{\rm LS}$ and $D_{\rm LL}$ are insensitive to final state interactions (FSI), meson exchange currents (MEC), isobar configurations (IC), and to theoretical models of deuteron structure. This is illustrated in the top half of Fig. 1 where the polarization ratio is plotted versus np scattering angle. The bottom half of the figure shows a simulation of our finite acceptance for one of our three kinematics.

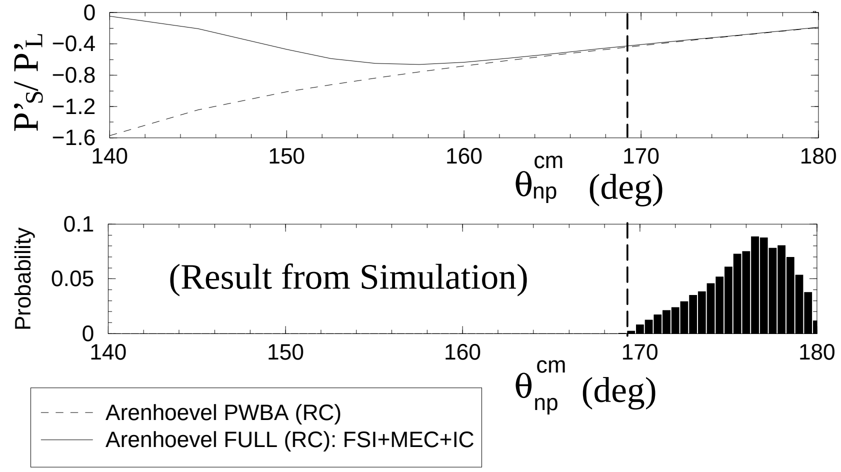

Fig. 1. The top figure shows that the ratio of polarizations is insensitive to a multitude of nuclear physics effects for forward neutron knockout (180° center-of-mass np angle). The bottom figure shows the finite acceptance of the E93038 neutron polarimeter (NPOL) after kinematic cuts.

Our measurements were carried out in Hall C of the Thomas Jefferson National Accelerator Facility. A beam of longitudinally polarized electrons scattered quasielastically from a neutron in a 15-cm liquid deuterium target. We measured the beam polarization with a Møller polarimeter [15], and changes in beam polarization were typically on the order of one to two percent. The helicity of the beam was reversed at a frequency of 30 Hz to eliminate instrumental asymmetries. The scattered electron was detected in the High Momentum Spectrometer (HMS) in coincidence with the recoil neutron. The neutron polarimeter (NPOL) designed specifically for E93-038 [16] was used to measure the up-down scattering asymmetry from the transverse component of the recoil neutron polarization presented to the polarimeter. To permit measurements of the scattering asymmetry from different combinations of $P_{\rm S}$ and $P_{\rm L}$, a dipole magnet (Charybdis) located in front of the polarimeter precessed the recoil neutrons polarization vector through an angle

χ.

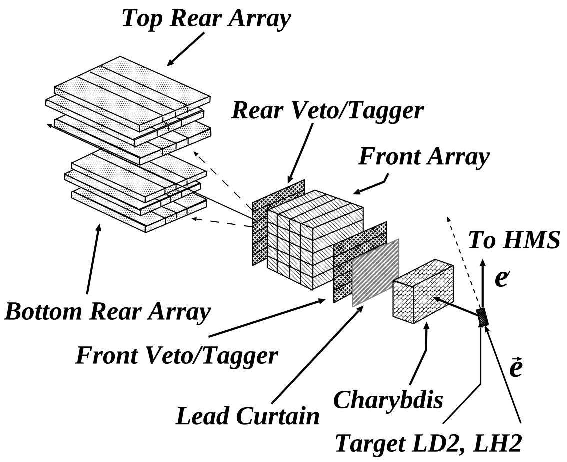

Fig. 2. Schematic diagram of the neutron polarimeter.

The experimental arrangement of the neutron arm is shown in Fig. 2. Not shown is the massive shield hut surrounding the device. A 10-cm front lead curtain attenuated the flux of electromagnetic radiation and charged particles incident on the polarimeter. To achieve an overall luminosity of 3×10^{38} cm^{-2}s^{-1}, the polarimeter was segmented into a total of 44 plastic scintillation detectors, in two arrays. The front array played the role of an active analyzer. The flight path from the center of the target to the center of the front array was 7.0 m, and the mean flight path from the front array to the rear array was 2.5 m. For a fixed neutron scattering angle of 46.0°, central Q^2 values of 0.45, 1.15, and 1.47 (GeV/c)^2 were achieved by tuning the beam energy. We compared the measured time-of-flight with the time-of-flight calculated from electron kinematics and offsets determined by a calibration procedure; the result is centered on zero with a FWHM of approximately 1.5 ns. Quasi-elastic events are selected with tight cuts on the time-of-flight, spectrometer momentum, and missing momentum spectra. Figure 3 shows a typical invariant missing mass spectrum, before and after these cuts.

We conducted asymmetry measurements with the polarization vector precessed through $\chi = \pm 40°$ at each of our Q^2 points; in addition, at $Q^2 = 1.15$ and 1.47 (GeV/c)^2, we conducted asymmetry measurements with the polarization vector precessed through $\chi = 0°$ and $\pm 90°$. The acceptance-averaged values of Q^2 are 0.45, 1.13, and 1.45 (GeV/c)^2. To extract the physical scattering asymmetry, we calculated the cross ratio, r, which is defined to be the ratio of two geometric means, $(N_\mathrm{u}^+ \ N_\mathrm{d}^-)^{1/2}$ and $(N_\mathrm{u}^- \ N_\mathrm{d}^+)^{1/2}$ where N_u^+ (N_d^-) is the yield for neutrons scattered up(down) when the beam helicity was positive(negative); The physical scattering asymmetry is then given by $(r-1)/(r+1)$. The merit of this cross ratio technique [17] is that the neutron polarimeter results are independent of the luminosities for positive and negative helicities, and the efficiencies and acceptances of the top and bottom halves of the polarimeter. Beam charge asymmetries (of typically 0.1%) and detector threshold differences cancel in the cross ratio. Figure 4 shows the $Q^2 = 1.15$ (GeV/c)^2 asymmetry data as a function of the spin precession angle χ. Excellent agreement was obtained for the p(n,n)p and p(n,p)n scattering asymmetries.

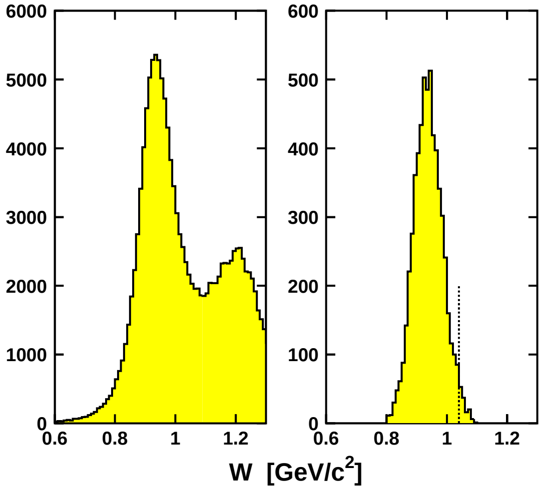

Fig. 3. The yield (in arbitrary units) verses missing invariant mass in GeV/c^2 *for the* $Q^2 = 1.47\,(\mathrm{GeV}/c)^2$ *kinematics, before (left) and after (right) kinematic cuts.*

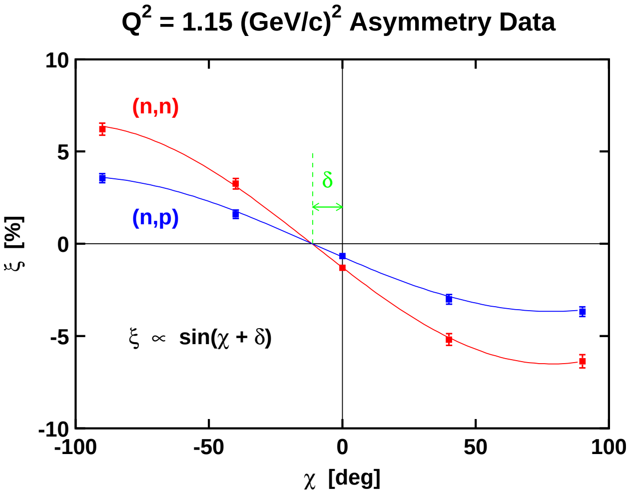

Fig. 4. $Q^2 = 1.15$ (GeV/c)^2 *asymmetry data as a function of the spin precession angle* χ.

To account for the finite experimental acceptance and nuclear physics effects such as FSI, MEC, and IC, we averaged Arenhovel's theoretical calculations [18] over the experimental acceptance. These calculations include leading-order relativistic contributions to a non-relativistic model of the deuteron as an n-p system, employ the Bonn R-space NN potential [19] for the inclusion of FSI, and include MEC and IC. Other realistic potentials (e.g., the Argonne V18 [20]) give essentially the same results. The theoretical values of the recoil polarization were calculated over a kinematic grid; during the averaging procedure, the recoil polarization was computed via multidimensional interpolation between the grid elements.

A false asymmetry or a dilution of the asymmetry can arise from the two-step process $^2\mathrm{H(e,e'p)n} + \mathrm{Pb(p,n)}$; the contamination from this process was assessed by running with a liquid hydrogen target. The contamination levels are negligible ($<$ 0.2%) for $\chi = \pm 40°$, and $\pm 90°$ at all of our Q^2 points; for $\chi = 0°$, the contamination levels are approximately 0.2% and 3% at $Q^2 = 1.13$ and 1.45 $(\mathrm{GeV}/c)^2$, respectively; Afanasev et al. [21] have calculated radiative corrections to the polarization-transfer coefficients. The primary effect is depolarization of the electron such that both polarization-transfer coefficients should be increased by 1.9%, 3.7%, and 4.4% at $Q^2 = 0.45$, 1.13, and 1.45 $(\mathrm{GeV}/c)^2$, respectively; however, these effects nearly cancel in the polarization ratio such that the net effect upon g is small at $Q^2 = 0.45$ $(\mathrm{GeV}/c)^2$ and negligible at the two higher Q^2 points.

3. *Results and conclusions*

Our values for G_E^n are plotted in Fig. 5 together with the current world data [1, 2, 4−7, 9] extracted from polarization measurements and an analysis of deuteron quadrupole form factor. We fitted these data and the G_E^n slope at the origin as measured via low-energy neutron scattering from electrons in heavy atoms [22] to

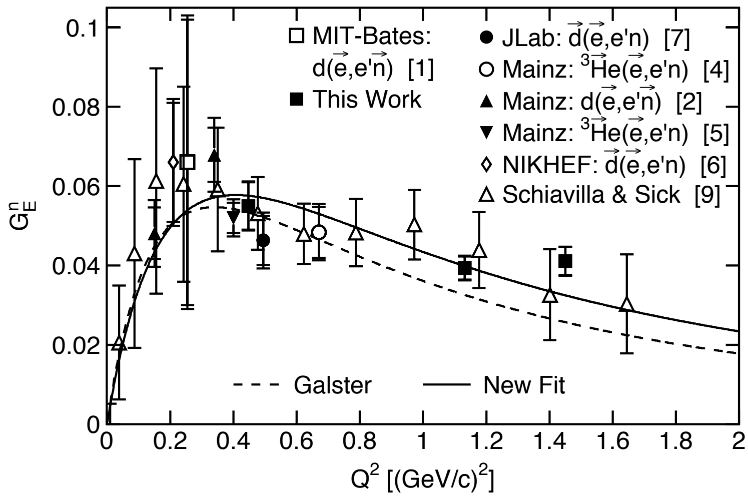

Fig. 5. Our preliminary data from E93039 with the current world data on G_E^n versus Q^2 extracted from polarization measurements and an analysis of deuteron

quadrupole form factor and t20 data [1, 2, 4-7, 9]. The Galster parameterization [8] is the dashed line, and our two-parameter Galster fit [10] is the solid line.

a Galster-type parameterization. Details can be found in a paper accepted for publication [10]. Preliminary results from E93026, which used a polarized deuterium target, appear to be in good agreement with our results and the Galster parameterization [23]. Tremendous progress has been made in measuring and understanding nucleon form factors in the last decade. Excellent work has been carried out by many laboratories and groups. A reliable data base for $G_{\rm E}^{\rm n}$ is now available, with good consistency between laboratories and techniques. An approved JLab experiment [24] to extend $G_{\rm E}^{\rm n}$ to $Q^2 = 3.4$ GeV^2 will improve spatial resolution and challenge models. However, we will need $Q^2 > 20$ GeV^2 to reach the scaling regime. Meanwhile lattice QCD calculations are eagerly awaited.

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MJERENJE ELEKTRIČNOG FAKTORA OBLIKA NEUTRONA U JLABU ODBOJNOM POLARIMETRIJOM U REAKCIJI $\mathrm{d}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{n}})\mathrm{p}$

Opisujemo početne ishode mjerenja omjera električnog i magnetskog faktora oblika neutrona, $G_\mathrm{E}^\mathrm{n}/G_\mathrm{M}^\mathrm{n}$, putem odbojne polarimetrije u kvazielastičnoj reakciji ${}^2\mathrm{H}(\vec{\mathrm{e}},\mathrm{e}'\vec{\mathrm{n}})\,{}^1\mathrm{H}$, za vrijednosti Q^2 od 0.45, 1.13 i 1.45 $(\mathrm{GeV}/c)^2$. Ta smo mjerenja izveli u Halli C JLaba, i ona, zajedno s drugim nedavnim polarizacijskim mjerenjima, predstavljaju desetgodišnji napor da se utvrdi pouzdana baza podataka o važnom, ali varljivom, električnom faktoru oblika neutrona.