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Charge Form Factor of the Neutron from the Reaction $^2\vec{\mathrm{H}}(\vec{e},e'n)p$

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We report on the first measurement of spin-correlation parameters in quasifree electron scattering from vector-polarized deuterium. Polarized electrons were injected into an electron storage ring at a beam energy of 720 MeV. A Siberian snake was employed to preserve longitudinal polarization at the interaction point. Vector-polarized deuterium was produced by an atomic beam source and injected into an open-ended cylindrical cell, internal to the electron storage ring. The spin correlation parameter A_{ed}^V was measured for the reaction $^2\vec{\mathrm{H}}(\vec{e},e'n)p$ at a four-momentum transfer squared of 0.21 $(\mathrm{GeV}/c)^2$ from which a value for the charge form factor of the neutron was extracted. [S0031-9007(99)09392-8]

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Although the neutron has no net electric charge, it does have a charge distribution. Precise measurements [1] where thermal neutrons from a nuclear reactor are scattered from atomic electrons indicate that the neutron has a positive core surrounded by a region of negative charge. The actual distribution is described by the charge form factor G_E^n, which enters the cross section for elastic electron scattering. It is related to the Fourier transform of the charge distribution and is generally expressed as a function of Q^2, the square of the four-momentum transfer. Data on G_E^n are important for our understanding of the nucleon and are essential for the interpretation of electromagnetic multipoles of nuclei, e.g., the deuteron.

Since a practical target of free neutrons is not available, experimentalists mostly resorted to (quasi)elastic scattering of electrons from unpolarized deuterium [2,3] to determine this form factor. The shape of G_E^n as a function of Q^2 is relatively well known from high precision elastic electron-deuteron scattering [3]. However, in this case the cross section is dominated by scattering from the proton and, moreover, is sensitive to nuclear-structure uncertainties and reaction-mechanism effects. Consequently, the absolute scale of G_E^n still contains a systematic uncertainty of about 50%.

Many of the aforementioned uncertainties can be significantly reduced through the measurement of electronuclear spin observables. The scattering cross section with both longitudinal polarized electrons and a polarized target for the $^2\vec{\mathrm{H}}(\vec{e},e'N)$ reaction, can be written as [4]

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

where S_0 is the unpolarized cross section, h the polarization of the electrons, and P_1^d (P_2^d) the vector (tensor) polarization of the target. 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 target analyzing powers and spin-correlation parameters depend on the orientation of the target spin. The polarization direction of the deuteron is defined by the angles Θ_d and Φ_d in the frame where the z axis is along the direction of the three-momentum transfer ($\mathbf{q}$) and the y axis is defined by the vector product of the incoming and outgoing electron momenta. $A_{ed}^V(\Theta_d = 90°, \Phi_d = 0°)$ contains an interference term, where the effect of the small charge form factor is amplified by the dominant magnetic form factor [4–6]. At present, there is a worldwide effort to measure the neutron charge form factor by scattering polarized electrons from neutrons bound in deuterium and ^{3}He nuclei, where either the target is polarized or the polarization of the ejected neutron is measured. Experiments with external beams have been carried out at Mainz [7] and MIT [8–10]. In the present paper we describe a measurement performed at NIKHEF (Amsterdam), which uses a stored polarized electron beam and a vector-polarized deuterium target.

The experiment was performed with a polarized gas target internal to the AmPS electron storage ring [11].

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An atomic beam source (ABS) was used to inject a flux of 3×10^{16} deuterium atoms/s (in two hyperfine states) into the feed tube of a cylindrical storage cell cooled to 75 K. The cell had a diameter of 15 mm and was 60 cm long. An electromagnet was used to provide a guide field of 40 mT over the storage cell which oriented the deuteron polarization axis perpendicular to **q** in the scattering plane. A doublet of steering magnets around the target region compensated for the deflection of the electron beam by the guide field. In addition, two sets of four beam scrapers preceding the internal target were used to reduce events that originated from beam halo scattering from the cell. By alternating two high-frequency transitions [12] in the ABS, the vector polarization of the target [$P_1^d = \sqrt{3/2}\,(n_+ - n_-)$], with $n_\pm$ the fraction of deuterons with spin projection ± 1), was varied every 10 s. Compared to our previous experiments with tensor-polarized deuterium [13–15], this target setup resulted in an increase of the figure of merit by more than 1 order of magnitude, with a typical target thickness of 1×10^{14} deuterons/cm^2.

Polarized electrons were produced by photoemission from a strained-layer semiconductor cathode (InGaAsP) prepared to the negative electron affinity surface state with cesium and oxygen [16]. The transverse polarization of the electrons was measured by Mott scattering at 100 keV. After linear acceleration to 720 MeV the electrons were injected and stacked in the AmPS storage ring. In this way, beam currents of more than 100 mA could be stored, with a lifetime in excess of 15 min. Every 5 min, the remaining electrons were dumped, and the ring was refilled, after reversal of the electron polarization at the source. The polarization of the stored electrons was maintained by setting the spin tune to 0.5 with a strong solenoidal field (using the well-known Siberian snake principle [17]). Optimization of the longitudinal polarization at the interaction point was achieved by varying the orientation of the spin axis at the source and by measuring the polarization of the stored electrons with a polarimeter based on spin-dependent Compton backscattering [18].

Scattered electrons were detected in the large-acceptance magnetic spectrometer Bigbite [19,20] with a momentum acceptance from 250 to 720 MeV/c and a solid angle of 96 msr (see Fig. 1). Kinematics were chosen such that G_E^n was probed near its maximum (as determined from Ref. [3]), resulting in the most sensitive measurement of G_E^n for a given statistical accuracy. Consequently, the electron detector was positioned at a central angle of 40°, with an acceptance for the electron scattering angle of $35° \leq \theta_e \leq 45°$, resulting in a central value of $Q^2 = 0.21$ (GeV/c)^2.

Neutrons and protons were detected in a time-of-flight (TOF) system made of two subsequent and identical scintillator arrays. Each array consisted of four 160 cm long, 20 cm high, and 20 cm thick plastic scintillator bars stacked vertically. Each bar was preceded by two (δE and ΔE) plastic scintillators (3 and 10 mm thick, respectively) of equal length and height, used to identify and/or veto charged particles. Each of the 24 scintillators was read out at both ends to obtain position information along the bars (resolution ~4 cm) and good coincidence timing resolution (~0.5 ns). The TOF detector was positioned at a central angle of 58° and covered a solid angle of about 250 msr. Protons with kinetic energies in excess of 40 MeV were detected with an energy resolution of about 10%. The $e'N$ trigger was formed by a coincidence between the electron arm trigger and a hit in any one of the eight TOF bars. By simultaneously detecting protons and neutrons in the same detector, one can construct asymmetry ratios for the two reaction channels $^2\vec{\mathrm{H}}(\vec{e}, e'p)n$ and $^2\vec{\mathrm{H}}(\vec{e}, e'n)p$, in this way minimizing systematic uncertainties associated with the deuteron ground-state wave function, absolute beam and target polarizations, and possible dilution by cell-wall background events.

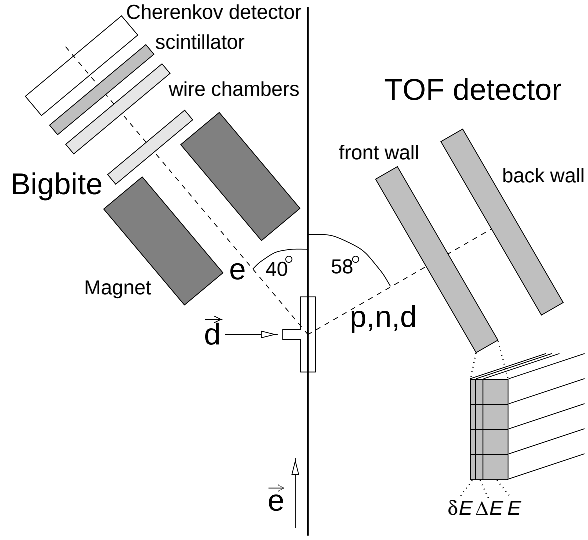

FIG. 1. Layout of the detector setup. The electron spectrometer consists of a 1 T m magnet, two drift chambers of four planes each, a scintillator, and a Čerenkov detector. The time-of-flight system consists of two identical walls of four E-scintillators preceded by two (δE and ΔE) veto scintillators.

An experimental asymmetry (A_{exp}) can be constructed, via

$$A_{\mathrm{exp}} = \frac{N_+ - N_-}{N_+ + N_-}, \tag{2}$$

where $N_\pm$ is the number of events that pass the selection criteria, with hP_1^d either positive or negative. A_{exp} for the $^2\vec{\mathrm{H}}(\vec{e}, e'p)n$ channel, integrated up to a missing momentum of 200 MeV/c, is shown in Fig. 2 as a function of time for part of the run. These data were used to determine the effective product of beam and target polarization by comparing to the predictions of the model of Arenhövel *et al.* [4].

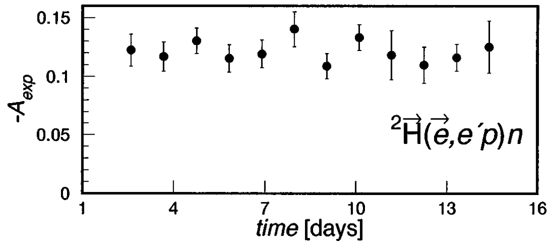

FIG. 2. Asymmetry for the reaction $^2\vec{\mathrm{H}}(\vec{e}, e'p)n$ integrated up to a missing momentum of 200 MeV/c versus time for a two-week period.

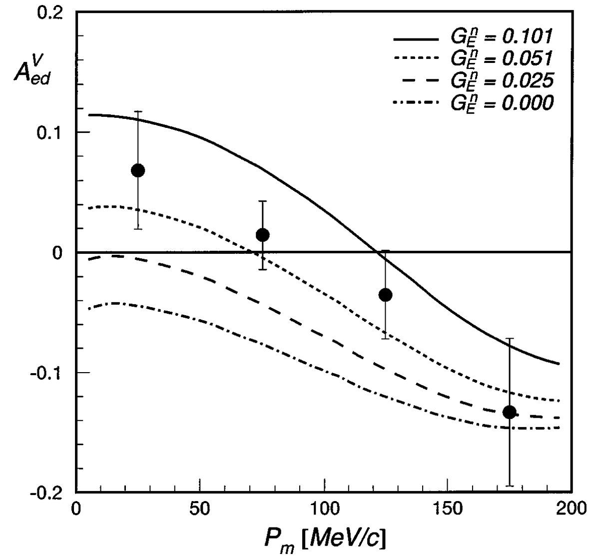

FIG. 3. Data and theoretical predictions for the sideways asymmetry $A^V_{ed}(90°, 0°)$ versus missing momentum for the $^2\vec{\mathrm{H}}(\vec{e}, e'n)p$ reaction. The curves represent the results of the full model calculations of Arenhövel *et al.*, assuming G^n_E equals 0, 0.5, 1.0, and 2.0 times the Galster parametrization [21], which results in the values of G^n_E at $Q^2 = 0.21$ (GeV $/c)^2$ as shown in the legend. A PWIA calculation for $G^n_E = 0$ would result in $A^V_{ed}(90°, 0°) = 0$, independent of p_m.

This advanced, nonrelativistic model includes the effects from final-state interaction, meson-exchange currents, isobar configurations, and relativistic corrections, and has been shown to provide good descriptions for quasifree proton knockout from tensor-polarized deuterium [14]. Finite acceptance effects were taken into account with a Monte Carlo code that interpolated the model predictions between a dense grid of calculations over the full kinematical range and detector acceptance. In this way, the effective product of beam and target polarization (i.e., including the effect of background events and electron depolarization) was determined to be 0.42 with a statistical precision of better than 1% and a systematic uncertainty of 3%, mainly limited by the knowledge of the proton form factors.

Neutrons were identified by a valid hit in one E scintillator or two neighboring E scintillators (to allow for events that deposit energy in two neighboring E-scintillators) and no hits in the preceding (δE and ΔE) scintillators, which resulted in an eightfold to twelvefold veto requirement. Minimum-ionizing particles and photons were rejected by a cut on the time of flight, resulting in a clean sample of neutrons, with only a small proton contamination. The spin-correlation parameter was obtained from the experimental asymmetry by correcting for the contribution of protons misidentified as neutrons [less than 1%, as determined from a calibration with the reaction $^1\mathrm{H}(e, e'p)$], and for the product of beam and target polarization, as determined from the $^2\vec{\mathrm{H}}(\vec{e}, e'p)n$ channel.

The main effect of cell wall events is a reduction of the effective target polarization. Therefore, the effects largely cancel in the asymmetry ratio. We have studied the cell wall contribution by measuring with an empty storage cell. The background contribution to the $(e, e'p)n$ and $(e, e'n)p$ channels amounted to $(5 \pm 1)\%$, stable over the entire run. A possible dependence on the target density was investigated by injecting various fluxes of unpolarized hydrogen into the cell and measuring quasifree nucleon knockout events. The target density dependence was found to be negligible at ABS operating conditions.

Figure 3 shows the spin-correlation parameter for the $^2\vec{\mathrm{H}}(\vec{e}, e'n)p$ channel as a function of missing momentum. The data are compared to the predictions of the full model of Arenhövel *et al.* [4], assuming the dipole parametrization for the magnetic form factor of the neutron and the Paris nucleon-nucleon (NN) potential, folded over the detector acceptance with our Monte Carlo code for various values of G^n_E. Full model calculations are required for a reliable extraction of G^n_E. This can be seen from Fig. 3, as a plane wave impulse approximation (PWIA) calculation for $G^n_E = 0$, would result in $A^V_{ed}(90°, 0°) = 0$, independent of p_m. We extract $G^n_E(Q^2 = 0.21\ (\mathrm{GeV}\ /c)^2) = 0.066 \pm 0.015 \pm 0.004$, where the first (second) error indicates the statistical (systematic) uncertainty. The systematic error is mainly due to the uncertainty in the correction for misidentified protons and the orientation of the holding field (thus the contribution of the spin-correlation parameter $A^V_{ed}(0°, 0°)$ to our experimental asymmetry).

We have investigated the influence of the NN potential on the calculated spin-correlation parameters using Arenhövel's full treatment. The results for $A^V_{ed}(90°, 0°)$ using the Paris, Bonn, Nijmegen, and Argonne V_{14} NN potential differ by less than 5% for missing momenta below 200 MeV/c.

In Fig. 4 we compare our experimental result to other data obtained with spin-dependent electron scattering. Note that all other data have been obtained from a comparison to PWIA predictions and thus without taking into account reaction mechanism effects. The figure also shows the results from Ref. [3], where the upper and lower boundaries of the "shaded" area correspond to their result obtained with the Nijmegen and Reid soft core potentials, respectively. It is seen that our result favors

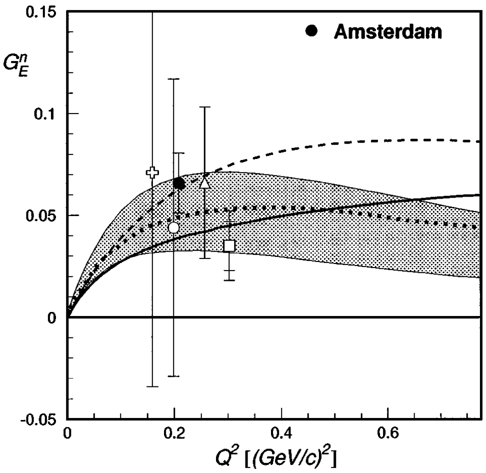

FIG. 4. Data and theoretical predictions for the charge form factor of the neutron as a function of four-momentum transfer. The solid circle shows our result. The cross and open circle represent the results from inclusive measurements performed at MIT-Bates [9,10], where an external polarized electron beam was scattered from polarized ^{3}He. The square represents the datum for an electron-neutron coincidence measurement with polarized ^{3}He obtained at Mainz [7], whereas the triangle represents the result of a $^2\text{H}\,(\vec{e}, e'\vec{n})\,p$ polarization-transfer experiment at Bates [8]. The shaded area indicates the systematic uncertainty from the unpolarized data by Platchkov *et al.* [3]. The dotted curve shows the result of Galster *et al.* [21], while the solid and dashed curves represent the theoretical predictions of Gari and Krümpelmann [22,23] with and without inclusion of ϕ-nucleon coupling, respectively.

their extraction of G_E^n which uses the Nijmegen potential. By comparison to the predictions of the vector meson dominance model by Gari and Krümpelmann, with [22] and without [23] the inclusion of the coupling of the ϕ meson to the nucleon (which these authors identify with the effect of strangeness in the neutron), our datum favors the prediction without strangeness in the neutron included.

In summary, we presented the first measurement of the sideways spin-correlation parameter $A_{ed}^V(90°, 0°)$ in quasifree electron-deuteron scattering from which we extract the neutron charge form factor at $Q^2 = 0.21$ (GeV$/c)^2$. When combined with the known value and slope [1] at $Q^2 = 0$ (GeV$/c)^2$ and the elastic electron-deuteron scattering data from Ref. [3], this result puts strong constraints on G_E^n up to $Q^2 = 0.7$ (GeV$/c)^2$.

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