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

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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 $^2\text{H}(\vec{e}, e'n)p$ at a four-momentum transfer squared of $0.21 \text{ (GeV/c)}^2$ from which a value for the charge form factor of the neutron was extracted.

1. Motivation

The charge distribution of the neutron is described by the charge form factor $G_E^n$, which is related to the Fourier transform of the 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\textsuperscript{4,5} to determine this form factor. The shape of $G_E^n$ as function of $Q^2$ is relatively well known from high precision elastic electron-deuteron scattering\textsuperscript{2}, but the absolute scale still contains a systematic uncertainty of about 50\%. The slope of $G_E^n$ at $Q^2 = 0 \text{ (GeV/c)}^2$ is known from measurements where thermal neutrons are scattered from atomic electrons \textsuperscript{3}.\textsuperscript{1,2}}
The systematic 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 $^2\text{H}(\vec{e}, e'N)$ reaction, can be written as

$$S = S_0 \left\{ 1 + P_1^d A^V_d + P_2^d A^T_d + h(A_e + P_1^d A^V_{ed} + P_2^d A^T_{ed}) \right\},$$

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. The target analyzing powers and spin-correlation parameters ($A_i$), depend on the orientation of the nuclear spin. The polarization direction of the deuteron is defined by the angles $\Theta_d$ and $\Phi_d$ in the frame where the $z$-axis is along the direction of the three-momentum transfer ($\vec{q}$) and the $y$-axis is defined by the vector product of the incoming and outgoing electron momenta. The observable $A^V_{ed}(\Theta_d = 90^\circ, \Phi_d = 0^\circ)$ contains an interference term, where the effect of the small charge form factor is amplified by the dominant magnetic form factor (see e.g. Refs. [4,5]). 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, to determine $G^n_E$ via a measurement of $A^V_{ed}(90^\circ, 0^\circ)$.

2. Experimental setup

The experiment was performed with a polarized gas target internal to the AmPS electron storage ring. An atomic beam source (ABS) [6,7] was used to inject a flux of $4.6 \times 10^{16}$ deuterium atoms/s into a cooled storage cell.

Polarized electrons were produced by photo-emission from a strained-layer semiconductor cathode (InGaAsP) [8]. After linear acceleration to 720 MeV the electrons were injected and stacked in the AmPS storage ring. Every 5 minutes 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 Siberian snake principle [9]).

Scattered electrons were detected in the large-acceptance magnetic spectrometer [10]. The electron detector was positioned at a central angle of $40^\circ$, resulting in a central value of $Q^2 = 0.21(\text{GeV/c})^2$. Neutrons and protons were detected in a time-of-flight (TOF) system made of two subsequent and identical scintillator arrays. Each of the four bars in an array was preceded by two plastic scintillators used to identify and/or veto charged particles. By simultaneously detecting protons and neutrons in the same detector, one can construct asymmetry ratios for the two reaction channels $^2\text{H}(\vec{e}, e'p)n$ and $^2\text{H}(\vec{e}, e'n)p$, 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.

3. Results

An experimental asymmetry ($A_{exp} = \frac{N_+ - N_-}{N_+ + N_-}$) can be constructed, 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 $^2\text{H}(\vec{e}, e'p)n$-channel, integrated up to a missing momentum of 200 MeV/c,
was used to determine the effective product of beam and target polarization by comparing to the predictions of the model of Arenhövel et al. [4]. This advanced, non-relativistic model has shown to provide good descriptions for quasifree proton knockout from tensor-polarized deuterium[11]. Finite acceptance effects were taken into account with a Monte Carlo code.

The spin-correlation parameter for the neutron events 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 $^1\text{H}(e,e'p)$), and for the product of beam and target polarization, as determined from the $^2\text{H}(\vec{e},e'p)n$ channel.

![Figure 1](image1.png)

Figure 1. Data and predictions for the sideways asymmetry $A_{V_el}^{V}(90^\circ,0^\circ)$ versus missing momentum for the $^2\text{H}(\vec{e},e'n)p$ reaction. The curves represent the results of the full model calculations of Arenhövel et al. assuming various values for $G_E^n$.

![Figure 2](image2.png)

Figure 2. Data and theoretical predictions for $G_E^n$. The solid circle shows our result, the cross, open circle, and square the results from double polarization measurements on $^3\text{He}$ [12] and the triangle on $^2\text{H}$ [13]. The shaded area indicates the systematic uncertainty from Ref. [2]. The dotted curve shows the results of Ref. [14], while the solid and dashed curves represent the predictions of the VMD-model of Ref. [15].

Figure 3 shows the spin-correlation parameter for the $^2\text{H}(\vec{e},e'n)p$ 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 parameterization for the magnetic form factor of the neutron, folded over the detector acceptance with our Monte Carlo code for various values of $G_E^n$. Full model calculations are required for a reliable extraction of $G_E^n$. We
extract $G_E^n(Q^2 = 0.21 \text{(GeV}/c)^2) = 0.066 \pm 0.015 \pm 0.004$, where the first (second) error indicates the statistical (systematic) uncertainty.

In Fig. 2 we compare our experimental result to other data obtained with spin-dependent electron scattering. The figure also shows the results from Ref. [2]. It is seen that our result favors their extraction of $G_E^n$ which uses the Nijmegen potential.

4. Conclusions

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

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