Electron scattering at NIKHEF with polarized beam and targets

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We present the Internal Target Facility of the NIKHEF 900 MeV polarized electron storage ring. We give some results which illustrate the presently unique opportunity offered by this facility to study the spin structure of the nucleon, 2-body and 3-body system by the measurement of spin-dependent electron scattering observables.

1 Introduction

In the scattering of leptons from hadronic targets the leptonic part of the interaction is presumed to be well understood, thereby studies can be focused on the strong-interaction vertex and the underlying structure and dynamics of the nucleus. The ultimate probe consists of fully spin-dependent scattering with polarized leptons and polarized targets [1], and the last decade has seen a large effort devoted to the realization of such experiments. Although relatively low in luminosity, spin-dependent electron scattering experiments from polarized gas targets internal to storage rings have the advantages that (i) they can be well matched with the application of large-acceptance detectors; (ii) rapid polarization reversal and flexible orientation of the nuclear target spin can be obtained, reducing systematical uncertainties; and (iii) low-energy recoiling particles can escape the ultra-thin targets and be detected. So far, electro-nuclear spin-correlation observables from internal gas target experiments have been obtained only at HERMES, DESY, in the deep-inelastic scattering regime.

Here, we present selected results from two experiments which illustrate important features of polarized internal targets. In the first experiment unpolarized electrons are scattered from tensor polarized deuterium, while the second experiment utilizes longitudinally polarized electrons incident on a polarized ³He target. The experiments were performed at the Amsterdam Pulse Stretcher (AmPS) ring [2] at NIKHEF.

2 Tensor Polarized Deuterium

The deuteron is often used as a benchmark to test nuclear theory, since reliable calculations can be performed in both non-relativistic and relativistic models. Observables such as its binding energy, static magnetic dipole and charge quadrupole moment, asymptotic D/S ratio, and the three elastic electromagnetic form factors place strong constraints on models for the nuclear interaction. Cross section measurements yield the structure functions A and B, which combined with T_{20} allow the determination of these form factors [1]. We recently obtained accurate measurements of T_{20} [3, 4] in the four-momentum transfer range $1 < Q < 3 \text{ fm}^{-1}$ and an experiment at TJNAF has produced new data in the range $4 < Q < 7 \text{ fm}^{-1}$ [5]. However, the data set for this observable remains of limited accuracy, and additional measurements are required.

The spin-dependent density distribution can be probed by quasi-elastic electron scattering from tensor-polarized ^2H targets, which yields data complementary to the elastic channel where the *total* nuclear current (i.e. nucleon and meson contributions) is probed. In a cross section measurement with tensor-polarized deuterons one can define the tensor analyzing power A_d^T :

$$A_d^T = \sqrt{\frac{1}{2}} \frac{\sigma_+(p_m) + \sigma_-(p_m) - 2\sigma_0(p_m)}{\sigma_+(p_m) + \sigma_-(p_m) + \sigma_0(p_m)} \stackrel{\text{PWIA}}{=} - \frac{2R_0(p)R_2(p) + \sqrt{\frac{1}{2}}R_2^2(p)}{R_0^2(p) + R_2^2(p)} d_{0,0}^2(\theta), \quad (1)$$

with $\sigma_{0,\pm}$ the cross section as a function of missing momentum p_m measured with spin projection $m_z = 0, \pm 1$, $R_{0,2}(p)$ the usual radial wave functions for orbital angular momentum $L = 0, 2$ in momentum space, and $d_{0,0}^2 = \frac{3}{2} \cos^2 \theta - \frac{1}{2}$ with θ the angle between the polarization axis and the relative momentum $\mathbf{p}$ of the two nucleons. In the limit $R_2 \ll R_0$, A_d^T directly relates to the ratio R_2/R_0 . Furthermore, when $R_0 = -\sqrt{2}R_2$, then (in PWIA) $\sigma_0 = 0$ and A_d^T is maximum with a value of $+\sqrt{\frac{1}{2}}$ for $\theta = 0$. Even when FSI and all other effects are included, the cross section is expected to be small for electron scattering from deuterons with $m_z = 0$. Similarly, when $R_0 = \sqrt{\frac{1}{2}}R_2$, the PWIA cross section for deuterons with $m_z = \pm 1$ vanishes and A_d^T reaches a minimum of $-\sqrt{2}$.

Simultaneous to our T_{20} elastic scattering experiment [3] we measured tensor asymmetries for quasi-elastic scattering [6]. The setup has been described in detail in Refs. [8, 9]; here only a brief overview is given. The experiment was performed with a polarized gas target [8] internal to the AmPS ring. The 565 MeV electron beam had a lifetime of about 15 minutes and beam currents up to 120 mA were used. An atomic beam source was used to inject a flux of 1.1×10^{16} atoms/s (in two hyperfine states) into a T-shaped storage cell cooled to ~ 100 K. The data were obtained with Teflon-coated aluminum cells (25 μm wall thickness) with diameters of 15 or 20 mm and a length of 400 mm. The tensor polarization of the deuterium atoms was measured *in situ* by a polarimeter [10] that analyzes the fraction of the target gas that has been ionized by the traversing electron beam, and amounted to $P_{zz}^\pm = +0.5/-0.9$.

Electrons scattered from the tensor-polarized deuterium gas were detected in an electromagnetic calorimeter, consisting of 6 layers of CsI(Tl) blocks (180 msr) and two plastic scintillators. The total energy resolution obtained (~ 22 MeV) was sufficient to distinguish between quasi-elastic scattering and pion electroproduction. The ejected protons were detected in a range telescope (300 msr), consisting of 15 layers of 1 cm thick plastic scintillator preceded by a layer of 2 mm thickness. Protons in the range of 30–100 MeV were detected with an energy resolution of ~ 1.5 MeV. The detectors were positioned at

central angles of $\theta_{\text{cal}} = 35^\circ$ and $\theta_{\text{rt}} = 80^\circ$ and were each preceded by two wire chambers for track reconstruction.

Figure 1: A_d^T as a function of $\cos \theta_s$ and of p_m for parallel kinematics (i.e. $\theta_{pq}^{\text{cm}} < 13^\circ$). The curves are explained in the text.

Fig. 1 shows the measured analyzing power A_d^T as a function of the cosine of the angle θ_s between the polarization axis and $\mathbf{p}_m$, and as a function of p_m in approximately parallel kinematics, i.e. the center-of-mass angle between the momentum of the knocked-out proton and the 3-momentum transfer has been restricted ($\theta_{pq}^{\text{cm}} < 13^\circ$). The data are compared to predictions [11] for the Paris potential. The dashed curve represents the results for the plane-wave Born approximation (PWBA) which includes the coupling to the neutron. In the long-dashed curve, effects of final-state interaction (FSI) are included, whereas the solid curve represents the full calculation, i.e. with inclusion of FSI, meson-exchange currents (MEC), Δ -isobar currents, and relativistic corrections. The spread in kinematics in each bin has been taken into account with a Monte-Carlo code that interpolated between a dense grid of calculations that covered the full acceptance of our setup. In Fig. 1 (left), since in PWIA the asymmetry is proportional to $d_{0,0}^2$ (see Eq. 1), the zero crossings of the asymmetry are predicted to be at $\cos \theta_s = \pm \sqrt{1/3}$ (≈ 0.58), while without a D -state component in the ground-state wave function the asymmetry vanishes. The results for PWBA differ slightly from this prediction, indicating that for our kinematics the coupling to the neutron is not completely negligible. The results of the full calculation describe the data well. The inclusion of spin-dependent rescattering effects improves the description at the lowest missing momenta ($p_m \approx 50$ MeV/c), where D -state contributions are small. Note that, the tensor analyzing power is sizable, even at the relatively small missing momenta addressed in the present experiment. This is due to the fact that an interference between the small D -state amplitude and the dominant S -state amplitude is probed (see Eq. 1), whereas in the unpolarized cross section only the sum of the squares of the S -state and D -state amplitudes enter.

In the future data taking should be extended to higher missing momenta, in the region where the tensor analyzing powers are predicted to strongly depend on the details of the deuteron spin structure [12].

3 Polarized ^3He

The ^3He nucleus is the subject of considerable current interest. It is a calculable nuclear system where our understanding of nuclear structure can be precisely compared with data. In addition, it is generally thought that polarized ^3He can serve as an effective polarized neutron target for experiments in nuclear and particle physics. Fundamental properties of the neutron such as its charge and spin distributions remain largely unconstrained experimentally. It is imperative to understand the ground state spin structure of the ^3He nucleus to extract information on neutron structure. Exclusive and semi-inclusive scattering of polarized electrons from polarized ^3He using the reactions $(\vec{e}, e'p)$, $(\vec{e}, e'n)$ and $(\vec{e}, e'd)$, offers a powerful tool to disentangle the S , S' and D -state components of the ground-state wave function. Our method of simultaneously surveying several reactions over a wide range of kinematics is central in our approach to disentangle nucleon and nuclear structure from reaction mechanism effects.

3.1 Stored Polarized Electrons

When electrons polarized in the ring plane are injected into AmPS, their spins will precess around the vertical fields provided by the dipole magnets in the ring. However, nuclear physics experiments require electrons with longitudinal polarization at the target. This can be achieved by using a Siberian snake [13] which, in our case, consists of five quadrupole magnets and two superconducting solenoids capable of providing a field integral up to 10.5 Tm. One can define the effective snake strength by $s = \theta/\pi$, with θ the spin rotation for ultra-relativistic electrons within the snake. For a “full” snake one has $s = 1$. Alternatively, one can inject polarized electrons at a so-called “magic energy”, where the number of spin precessions (relative to its momentum) during one electron revolution is equal to an integer. Then, constant longitudinal polarization at the internal target should be possible. However, in such a case, imperfections in the horizontal field distribution of the storage ring can interact coherently with the spins of the electrons and cause rapid beam depolarization. It is expected that stable operation near such so-called imperfection resonances in an electron storage ring could be achieved with a weak solenoid (or “partial” snake) [14], whereas a full snake should allow operation at any beam energy.

Fig. 2 (left) shows an overview of AmPS, and the location of the main components relevant for the present discussion, such as the polarized electron source (PES), spin manipulator (SM), Mott polarimeter (MP), linear accelerator (MEA), Siberian snake (SS), polarized internal target (IT), and laser backscattering polarimeter (L2 & D).

Spin polarized electrons were obtained by means of photoemission of a semiconductor crystal induced by circularly polarized light from a Ti-sapphire laser (700–900 nm), and the electron polarization direction rotated over arbitrary angles with an electrostatic spin manipulator. The transverse polarization of the injected electrons was measured by Mott scattering at 100 keV from a 100 nm thick gold foil. Typically, several beam bunches (of ~ 2 mA each) were stacked in the ring, yielding currents up to 150 (30) mA at 720 (442) MeV with a full (partial) snake. The beam life time was about 3 (20) minutes with (without) injecting polarized gas into the 15 mm diameter cell. The longitudinal polarization of the stored beam was measured with a Compton backscattering polarimeter (CBP) [15] with a short- and long-term reproducibility of $\pm 3\%$. Fig. 2 (right) shows the longitudinal polarization as a function of the spin angles as measured with the CBP in the internal target region with a partial snake setting ($s = 0.107$) and a 442 MeV beam

Figure 2: *Left*: Outline of the AmPS storage ring at NIKHEF (described in the text). Each arrow indicates the stable in-plane polarization direction for stored electrons at 442 MeV with the full snake on. *Right*: Longitudinal polarization measured with the laser backscattering polarimeter versus the spin angle varied with the spin manipulator.

energy. The spin manipulator was used to vary the spin angles, and the data demonstrate the expected spin rotation of the electron polarization. Here the maximum longitudinal polarization of the stored electrons at the internal target interaction point was 0.61 ± 0.03 , whereas the Mott polarimeter gave 0.698 ± 0.013 . Part of the loss is due to the polarization life time of 4500^{+5900}_{-1600} seconds. Similar results were obtained with a full snake. These data demonstrate for the first time that polarized electrons can be injected and their longitudinal polarization preserved in an electron storage ring. Furthermore, it shows that, near a magic energy, a snake operated at about 10 % of its nominal value is sufficient to preserve the longitudinal polarization.

3.2 Polarized ^3He Target and Detector Set-up

A polarized ^3He target, based on metastability-exchange optical pumping [16], was used in the experiment. The polarized gas flows from a Pyrex pumping cell via a glass capillary into a $60\text{ }\mu\text{m}$ wall-thickness ultrapure Al storage cell cooled to 17 K. Here, the target polarization axis was oriented by three pairs of Helmholtz coils. The target polarization was measured through the detection of 667 nm radiation emitted in the $3D \rightarrow 2P$ transition in the ^3He discharge. We obtained a target polarization of $P_T = 0.43$ at a flux of 1×10^{17} $^3\text{He}/\text{s}$, resulting in a target thickness of 7×10^{14} $^3\text{He}/\text{cm}^2$.

Scattered electrons were detected at angles $55^\circ \leq \theta_e \leq 65^\circ$ in a magnetic spectrometer, consisting of a 1 T dipole magnet, two sets of wire chambers, a scintillator hodoscope, and an aerogel Čerenkov detector. The spectrometer has a momentum resolution of 0.5 %, a momentum acceptance of $> 50\%$, and a solid angle of 96 msr. Low energy recoiling hadrons were detected in two silicon-strip planes mounted on the scattering chamber at

Figure 3: *Top*: Energy deposition in the 100 μm and 500 μm silicon planes. *Bottom*: missing-mass spectrum for ${}^3\text{He}(\bar{e}, e'{}^3\text{He})$ events.

about 20 cm from the storage cell. Fig. 3 (top) shows that the correlation of the signals for energy deposition in the 100 μm and 500 μm silicon detectors (72 strips each) provides clean particle identification for protons, deuterons, tritons, and ${}^3\text{He}$ nuclei. Deuterons with energies as low as 1 MeV have been detected allowing the separation of electron-induced proton knockout leading to a bound d or unbound np state for relative momenta well below the Fermi momentum of ${}^3\text{He}$. This detector also allowed us to measure the product of beam and target polarization, during data-taking, via the well-known elastic scattering spin-correlation parameters. The bottom panel of Fig. 3 demonstrates that when the information of the electron spectrometer is combined with that of the recoil detector, a clear signature is obtained for coherent spin-dependent neutral pion electroproduction from ${}^3\text{He}$. Similar data were collected for π^+ -electroproduction in this experiment.

Knocked-out protons and deuterons were measured in the range telescope positioned at a central angle of 60° . A neutron detector, consisting of two subsequent scintillator arrays measured the knocked-out neutrons by the time-of-flight (TOF) method. Each array consisted of three layers of scintillator (3, 10 and 200 mm thick). Each scintillator was read out on both ends and neutrons were identified by a twofold coincidence between the double-sided read-out and an 8- to 12-fold veto by surrounding scintillators. The front and back arrays covered ~ 300 and 200 msr resp., each with a neutron detection efficiency of $\sim 20\%$.

Fig. 4 shows preliminary results from our first spin-correlation experiment obtained at an average momentum transfer of $Q^2 = 0.15$ $(\text{GeV}/c)^2$ and with the nuclear polarization oriented along the momentum transfer. The left panel shows the longitudinal spin correlation parameter A'_z for the ${}^3\text{He}(\bar{e}, e'p)$ reaction, the right panel for ${}^3\text{He}(\bar{e}, e'n)$. Data were obtained at a beam energy of 442 MeV¹ and $\theta_e = 60^\circ$. The solid, dashed and dotted

¹This choice was driven by a partially destructive quench in one of the superconducting solenoid which precluded operation with a full snake.

Figure 4: Data and theoretical predictions for A'_z versus p_m for ${}^3\text{He}(\vec{e}, e'p)$ (left) and versus Q^2 for ${}^3\text{He}(\vec{e}, e'n)$ (right).

curves are a result from the calculations of Laget for the two-body break-up channel [17]. The dotted and dashed curves correspond to PWIA, respectively including only the S and $S + D$ components of the ${}^3\text{He}$ wave function. The solid curve is the result of the full calculation also including FSI and MEC. The dot-dashed curve is the result from the model of Nagorny [18]. The calculations were done for the central kinematics of the present experiment.

In summary, polarized ${}^1\text{H}$, ${}^2\text{H}$ and ${}^3\text{He}$ internal gas targets have been constructed, with polarizations of order unity and target thicknesses in the range 2×10^{13} to 7×10^{14} nuclei/cm². For ${}^1\text{H}$ and ${}^2\text{H}$ an atomic beam source is used. With unpolarized electrons and tensor polarized ${}^2\text{H}$ we have obtained precise data for T_{20} in elastic scattering and first data for tensor analyzing powers in quasi-free scattering. For ${}^3\text{He}$ we apply the metastability-exchange optical pumping technique. A polarized electron source was constructed which can deliver to the linac 30 mA peak currents with polarization in excess of 0.8. Subsequent polarized electron pulses can be stacked in the ring with the polarization axis oriented in any direction. A Siberian snake is used to maintain the electron beam polarization at the internal target. In addition, various polarimeters were developed to measure the beam and target polarizations during the experiments. Recently, longitudinally polarized electrons were stored for the first time in the ring with beam currents larger than 150 mA. The polarization at the internal target was determined with a Compton backscattering polarimeter. Polarizations of more than 0.6, with relaxation times of the order of an hour, were measured. Comparable results were obtained at two beam energies, 720 and 442 MeV, with a full and partial snake respectively. We have presented preliminary results for ${}^3\text{He}(\vec{e}, e'N)$ spin-correlation parameters and have shown spectra for low energy recoiling particles which illustrate a unique feature of internal targets. Although the data are still of limited statistical significance, they reveal that it is technically possible to perform spin-dependent electron scattering experiments in a medium-energy electron storage ring. A full exploration of polarization observables [19] permits a detailed investigation of the relevant degrees of freedom in electro-disintegration of the few-body systems, the measurement of spin-dependent momentum distributions, and may address the isobar content

of nuclear wave functions in pion electroproduction experiments.

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