Experiments with Polarized Electrons and Polarized ^{3}He

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Abstract

A polarized ^{3}He target based on optical pumping of metastables is under development. Such a target would allow fundamental measurements on the neutron and a program of three-body physics at present and planned electromagnetic facilities. The present status of the target development and two of the proposed measurements are described.

1. Introduction

A polarized ^{3}He target for nuclear physics is of interest for several reasons. Firstly, polarization observables have proved to be very successful in extracting small components of wave-functions and reaction mechanisms. Some examples are the measurements of the D-state admixture in the ground state wave-functions of ^{3}He [1] and ^{4}He [2]; measurement of t_{20} in π-deuteron elastic scattering[3]; measurement of t_{20} in electron-deuteron elastic scattering[4]; deep-inelastic asymmetry measurements on the nucleon[5]; parity measurements in electron-deuteron elastic scattering[6].

Secondly, the three-body system is unique in that it is the largest nucleus where exact non-relativistic calculations can be performed. Thus, it serves as a stringent testing ground between theory and experiment in nuclear physics. A program of measurements of electromagnetic polarization observables on a nuclear system where accurate calculations can be performed would be an important test of our understanding of the nucleus. For example, in the $\Delta(1232)$ resonance region the measurement of charged pion asymmetries in scattering of polarized electrons from polarized ^{3}He can provide a sensitive test of the presence of Δ components in the ground state of ^{3}He [7]. In addition, the ^{3}He nucleus has the very interesting property that, to a good approximation, its spin is due to the spin of the neutron. This has the implication that for some particular kinematics in electromagnetic physics, a polarized ^{3}He target is an approximate polarized neutron target[8,9]. Using this technique, it should be possible to carry out measurements on the neutron which are difficult to perform in any other way.

Polarized ^{3}He targets for low energy strong interaction experiments have been in use since 1963[10]. They have all been based on the technique of optical pumping of metastables invented by Colegrove, Schearer, and Walters [11]. However, they have been limited in pressure to $\approx$ 1 to 5 torr and in polarization to $\approx$ 10%. The Caltech work has been made possible by two technological developments. The first is the availability of high power lasers at 1.083 μm to optically pump ^{3}He with a resulting nuclear polarization in excess of 50% [12,13]. The other is a continuous diffusive transfer of polarized ^{3}He atoms between a room temperature cell, where optical pumping occurs, to a cold glass cell (4 K) to obtain a density of 10^{18}cm^{-3} [14]. The Caltech technique is an adaptation of the double cell scheme to a configuration where the cold atoms are contained in a copper cell. This permits the passage of a high flux beam of charged projectiles through a sample of polarized ^{3}He nuclei. The present work has also been motivated by the proposed construction of electron storage rings in the GeV energy range. The replacement of the end windows on the target by pumping impedances provides an internal target of polarized ^{3}He which is very suited to such facilities.

I would also like to mention work in progress by other groups on polarized ^{3}He target development for electromagnetic physics. A group at Mainz, in collaboration with Ecole Normale, Paris, is developing a laser pumped compression machine to produce 1 atmosphere of 50% polarized ^{3}He also using the optical pumping of metastables[15]. This work is based on a scheme developed at the University of Toronto[16]. It is planned that the compression machine would be ready in late 1989. Also there have been significant advances recently by a Princeton-Harvard group in polarizing high densities (10^{20}cm^{-3}) of ^{3}He using the technique of spin exchange optical pumping[17]. They have obtained polarizations of order 50% in glass spheres of volume ≈ 5 cm^3 with pump-up times of order several hours.

Work on a target of polarized ^{3}He for electromagnetic physics using this technique is in progress by a Harvard-MIT collaboration[18].

2. Caltech polarized target development

As a first step in the development of a double cell polarized ^{3}He target, a double cell prototype has been constructed and successfully tested with a low energy proton beam at Caltech[19]. The prototype employed an infrared laser to polarize ^{3}He atoms in a pyrex cell which is connected by a capillary to a copper cell at liquid nitrogen temperature. The method used to polarize ^{3}He in the Caltech target involves direct optical pumping of the metastable state. The relevant energy levels of the ^{3}He atom are shown in Figure 1. If a weak electric discharge is maintained in a low pressure ^{3}He gas, a small fraction of the atoms ($\approx 10^{-6}$) will be in the long-lived 2^3S_1 metastable state. Circularly polarized pumping light incident upon the sample along a weak applied magnetic field excites transitions between the $^3S_1$ and $^3P_0$ states. Angular momentum is thus transferred from the pumping light to the metastable atoms, and the metastable atoms become polarized. Transfer of polarization to the ground-state atoms is achieved through metastability exchange collisions.

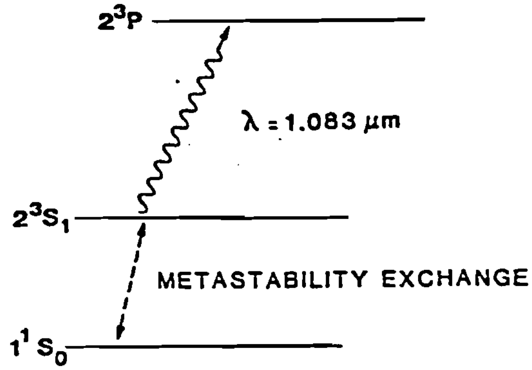

Figure 1. The important energy levels in the helium atom for the optical pumping process.

As a source of 1.083 μm photons we have used an infrared laser system[13]. A 4 mm diameter × 79 mm long crystal of Yttrium Aluminum Perovskite (YAP) was the lasing medium in a Lasermetrics 9550 YAG cavity with totally reflecting end-mirrors. The YAP gain curve has peaks at 1.0795 and 1.0845 μm. A Lyot filter was used for coarse tuning onto the 1.0845 μm peak. Uncoated etalons of thickness 0.25 to 1 mm were used for fine tuning to the 2^3S_1-2^3P_0 1.083 μm helium transition. The laser system was tuned up by polarizing sealed 5 cm diameter × 4.4 cm long pyrex cells filled with ^{3}He gas at a known pressure located at the center of a Helmholtz coil system that provided a static magnetic field of 13 gauss. A 200 kHz oscillator excited a weak discharge in the ^{3}He sample. The laser pumping beam was sent through the ^{3}He cell along the direction of the static magnetic field. Routine polarizations of 40% and 30% were obtained for cells with ^{3}He pressures of 0.8 and 2 torr respectively. The polarization in the pumping cell was measured using a technique developed by Laloë[20,21]

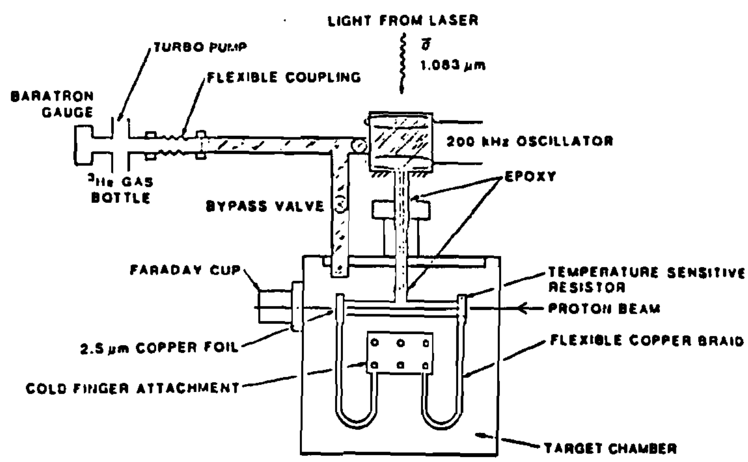

Figure 2. The target apparatus of the double cell prototype.

The target apparatus is shown in Figure 2. The double cell was mounted on one flange of a rectangular aluminum target chamber. The double cell consisted of a 5 cm diameter × 4.4 cm long pyrex pumping cell connected by a 0.16 cm i.d. × 9 cm long pyrex capillary tube to a 1 cm i.d. × 10 cm long copper cell. The pumping cell was connected to a turbomolecular pump, a ^{3}He gas bottle, and a baratron gauge through a teflon-glass valve. The copper target cell was connected with copper braids to a detachable cold-finger which could be cooled to 77 K. The double cell system was attached to the target chamber solely at the capillary tube. The copper braids served to mechanically isolate and thermally connect the target and the cold finger. This mechanical isolation was necessary to minimize the risk of fracturing the glass from the thermal stresses that occurred during cooling of the target. The temperature of the target was measured by a temperature sensitive carbon resistor, which was potted in thermally conducting grease at one end of the target. At each end of the copper cell was a 2.5 μm thick copper foil which was attached by electron beam welding. The volume of the pumping and target cells was 75 cm^3 and 7.8 cm^3 respectively. The cell required several days of cleaning before maximum polarization was attained. This was accomplished by alternately discharging with a bright discharge and heating to $\approx$ 70°C. Cooldown of the target from room-temperature to base temperature took about 30 minutes. The spin of the target was directed normal to the direction of the incident beam. A Faraday cup at the rear of the target measured the incident proton beam current.

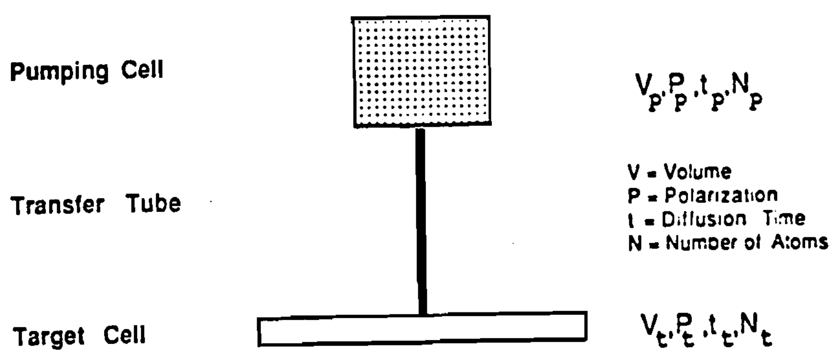

Figure 3. A schematic diagram of the double cell target.

It is clearly vital for use of the apparatus as a target for nuclear physics that we have an accurate measurement of the polarization in the target cell. This cannot be done directly via NMR techniques because the cell is constructed from metal. However, the polarization of the target cell can be inferred from the measured polarization of the pumping cell because the pumping and target cells are coupled through the diffusion of atoms along the transfer tube. Figure 3 shows a schematic diagram of a double cell system. We denote by V_p, P_p, N_p and t_p the volume, polarization, number of atoms and average sitting time of an atom in the pumping cell. Similarly, we have quantities V_t, P_t, N_t and t_t for the target cell. The total number of atoms in the double cell system is $N = N_p + N_t$. The volume of the capillary tube is neglected as it amounted to only 2% of the volume of the target cell. From the known volumes of the pumping and target cells and the measured target temperature, N_p and N_t can be determined. Also, in a steady state condition we have

$$\frac{N_p}{t_p} = \frac{N_t}{t_t} . \tag{1}$$

Two independent methods have been used to deduce the polarization of the target cell in terms of the polarization of the pumping cell. One technique uses adiabatic fast passage NMR (AFP) to reverse the polarization of the atoms in the pumping cell, P_p, without affecting the polarization of the atoms in the target cell, P_t. The double cell system is first polarized with the laser, then the optical pumping light is shuttered and the pumping cell spins reversed by AFP. The reversed spins in the pumping cell come into diffusive equilibrium with the unchanged spins in the target cell. This occurs with a time constant given by the communication time between the two cells

$$t = [\frac{1}{t_p} + \frac{1}{t_t}]^{-1} . \tag{2}$$

In the AFP process some of the pumping cell atoms are depolarized and so one must use the value of the pumping cell polarization after the spin-flip, P_p^a. The equilibrium polarization in the pumping cell after transfer between the cells, P_p^e, is given by the polarizations immediately after spin-flip, P_p^a and P_t in the pumping and target cells respectively, weighted by the number of atoms in each cell. Thus, we have

$$P_t = \frac{N}{N_t}\left(P_p^e - \frac{N_p}{N}P_p^a\right) . \tag{3}$$

The communication time between the two cells, t, can be measured directly. Thus, from equations (1) and (2), t_p and t_t can be deduced. t_p and t_t can also be calculated straightforwardly and good agreement was found between measured and calculated values. For the target described above we calculate $t_p = 53$ sec and $t_t = 19$ sec. Thus, $t = 14$ sec. Figure 4 shows the data for a 2 torr cell without beam. A continuous decrease in the polarization signal due to ground state relaxation in the presence of the discharge can be seen. This has been measured precisely and the data analysis includes this effect. The transfer time between the two cells is measured to be t = 14.5 ± 0.7 seconds which is in good agreement with calculations. For this data set P_p^a = -0.066 ± 0.004, P_p^e = -0.007 ± 0.003, and P_p = 0.142 ± 0.002, corresponding to P_t = 0.155 ± 0.018. The ratio, $\frac{P_t}{P_p}$ = 1.09 ± 0.13, is consistent with the polarizations of the two cells being equal when no beam is present. This technique can also be used when there is a charged particle beam passing through the target cell. This has been done with $\frac{P_t}{P_p}$ = 0.92 ± 0.07, and the best fit to the data for the transfer time is t = 14.4 ± 0.3 seconds, a value in very good agreement with both the calculations and the beam-off measurement.

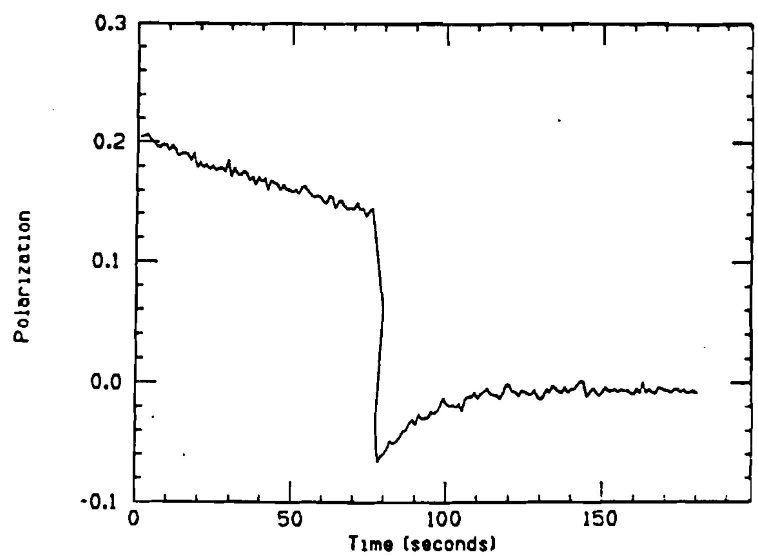

Figure 4. The polarization in the pumping cell for the double cell target of figure 3 with a pressure of 2 torr of ^{3}He and the target cell at a temperature of 87 K. The target has been polarized and at zero time the laser shuttered. The polarization in the pumping cell decays due to the presence of the discharge. After 80 sec the polarization in the pumping cell has been reversed with partial depolarization resulting. The change in polarization from 80 to 130 sec represents the communication between the pumping and target cells as described in the text. In addition, there is relaxation due to the discharge, as in the first 80 sec, and this has been taken into account in the data analysis.

A second method is used to determine the polarization of the target cell when a particle beam is incident. Consider an optically pumped double cell system which is in equilibrium without beam in the target cell. After the beam enters the target cell, the added depolarizing effects of the ionizing particles will drive the polarization of the pumping cell to a lower equilibrium value, and the polarization of the target cell, which is in general not equal that of the pumping cell, can be determined from the polarizations and the time constants for relaxation, optical pumping, and diffusive transfer. The rate equation for the pumping cell polarization can be written as

$$\frac{dP_p}{dt} = \frac{1-P_p}{T_p} - \frac{P_p}{\tau_d} - \frac{P_p - P_t}{t_p} \tag{4}$$

where the first term is the polarizing contribution from the optical pumping of the laser light, the second is the relaxation due to depolarizing effects in the pumping cell, and the third term is the coupling between the two volumes. T_p denotes the time constant associated with the polarization of ground state atoms in the absence of relaxation processes, τ_d the ground state relaxation time constant, and t_p is as defined above. τ_d is dominated by the effects of the discharge and magnetic field inhomogeneities over the cell volume. Before the beam is passed through the target cell, the polarizations in both target and pumping cells are equal to a good approximation, as verified by AFP. Hence

$$T_p = \tau_d \left(\frac{1-P^0}{P^0} \right) \tag{5}$$

and so T_p can be determined from the equilibrium polarization and the measured relaxation time. With the beam passing through the target cell the polarizations are not equal, so P_t can be determined from the parameters mentioned above and the new equilibrium pumping cell polarization, P_p.

$$P_t = P_p \left[1 - \frac{t_p}{\tau_d} \left[\frac{P^0(1-P_p)}{P_p(1-P^0)} - 1 \right] \right] . \tag{6}$$

P^0, t_p, and τ_d are measured in the absence of beam. A known current of charged particles is passed through the target and P_p is measured. Hence, P_t can be calculated.

Figure 5 shows data obtained on the double cell system at a pressure of 2 torr. The target cell was at a temperature of 87 K and $P^0 = 0.26$. After 300 sec, a beam stop

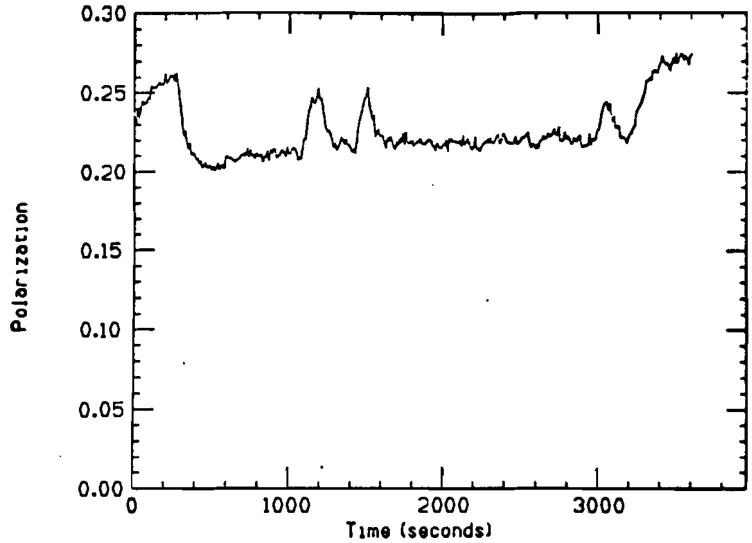

Figure 5. The polarization of the pumping cell for the double cell system during a 1 hour run with 1 microamp of 5 MeV protons incident on the target with 2 torr pressure and the target cell at a temperature of 87 K. The target is continually being polarized by the laser beam incident on the pumping cell. The beam stop has been opened 5 minutes after the beginning of data taking and closed 5 minutes before the end of the run. Complete recovery of polarization is observed. The three peaks are the result of loss of beam on target.

was opened and 1 μA of 5 MeV protons was incident on the target. This resulted in beam depolarization of the target causing the pumping cell polarization to drop to P_p = 0.21. The incident beam was maintained on the target for 50 minutes, and checked at 10 minute intervals. On three occasions, instabilities in the Pelletron accelarator caused loss of beam on target and, as shown, recovery of the full polarization was immediate. After 50 minutes of beam on target the beam stop was again closed and the double cell system recovered its full polarization. For this system, the relaxation time and sitting time in the pumping cell were measured to be $\tau_d = 330 \pm 30$ sec and $t_p = 53 \pm 3$ sec respectively. Then, $\frac{P_t}{P_p} = 0.94 \pm 0.01$ and so from equation (4), $P_t = 0.19 \pm 0.01$. For this run, the densities in the pumping and target cells were respectively 6×10^{16} cm^{-3} and 2×10^{17} cm^{-3}. The target thickness was 2×10^{18} cm^{-2}. The stopping powers of 5 MeV protons and minimum ionizing electrons in ^3He are 106 and 2.6 MeV/gcm^{-2} respectively. Thus, the depolarization through ionization of Figure 5 should be equivalent to 40 μA of minimum ionizing electrons. The equivalent luminosity for minimum ionizing electrons was $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ with 20% target polarization. This was repeated for a pressure of 4 torr, with $\frac{P_t}{P_p} = 0.90 \pm 0.02$ and $P_t = 0.133 \pm 0.004$.

A cryogenic target is under development at Caltech to allow target temperatures down to 10 K. In addition, development of lasers to allow increased optical pumping capability is in progress. 50% polarization at 2 torr pressure has been achieved by the Ecole Normale group[14]. Thus, by running at 2 torr pressure with the target cell at 40 K it should be possible to obtain $4 \times 10^{18}\text{cm}^{-2}$ thickness with 50% polarization. Testing of this target with low energy proton beam should occur in Fall 1988.

3. Measurement of the Charge Distribution of the Neutron

I would like to present an experiment to obtain information on the charge distribution of the neutron using the target presented in section 2. Experimental information on the charge distribution of the neutron is meager. The slope of G_E^n at $Q^2 = 0$ has been obtained to 2% accuracy by scattering of neutrons from atomic electrons[22]. The neutron electric form-factor at non-zero Q^2 has been estimated from Rosenbluth measurements of elastic electron-deuteron scattering data taken at DESY[23]. To extract $G_E^n(Q^2)$ from the data it is necessary to assume a model for the deuteron structure, and this introduces a large systematic error into the derived values of the neutron electric form-factor. The data are unable to distinguish between $G_E^n = 0$ and $G_E^n = -\tau G_M^n$, the asymptotic prediction of perturbative QCD[24] which is supported by data at high Q^2 on the deuteron.

Measurement of the charge distribution of the neutron, $G_E^n(Q^2)$ is interesting for several reasons. Firstly, it is a fundamental quantity, about which we have very little experimental information. The charge distribution of almost one half of all matter around us in the form of neutrons contained in atomic nuclei is essentially unmeasured. In addition, $G_E^n(Q^2)$ is essential for interpretation of all Coulomb and electric multipoles in nuclei. A good example of this is the dependence of the deuteron electric structure function $A(Q^2)$

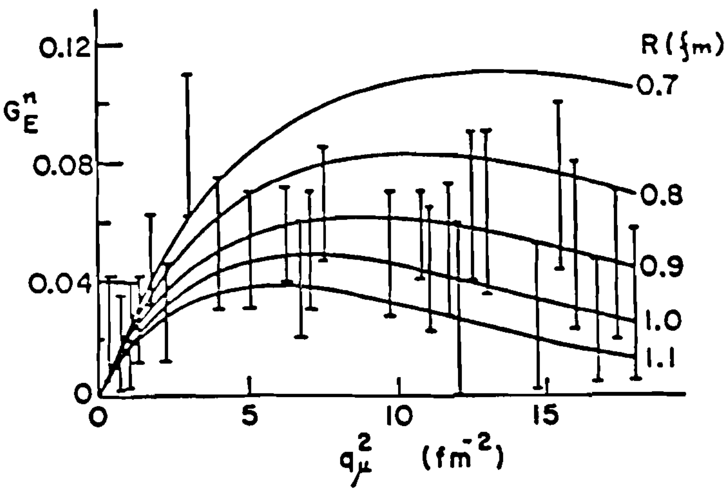

Fig. 6 This figure, from reference 25, shows the neutron electric form-factor for different bag radii (solid lines) and the data of reference 23.

on G_E^n at high Q^2. Of most relevance to the present discussion, $G_E^n(Q^2)$ is an important constraint on our understanding of the nucleon.

Sensitivity of G_E^n to nucleon models is illustrated in Figure 6, where the data of Galster, analysed with the Feshbach-Lomon model of the deuteron, are compared with the expectations of the Cloudy Bag Model[25]. It must be emphasized that the data as plotted are misleading as there is a large systematic error due to the dependence on deuteron structure, which has not been included in the estimation of the error bars.

Consideration of possible experiments to improve our knowledge of $G_E^n(Q^2)$ has largely concentrated on the polarization degree of freedom. One scheme is to transfer polarization from a longitudinally polarized electron beam to a quasielastically scattered neutron from the deuteron[26,27]. I would like to present another method to extract information on G_E^n - one first suggested by Blankleider and Woloshyn[8]. The essential idea is that the asymmetry in polarized electron- polarized ^{3}He quasielastic scattering is expected to be extremely sensitive to the neutron electromagnetic form-factors. To a good approximation, the spin of the ^{3}He nucleus is due solely to its neutron. This is demonstrated by the fact that the magnetic moments of ^{3}He and the free neutron are equal to within 10%. In addition, a Faddeev calculation of the ground state wave-function of ^{3}He demonstrates that 90% of the wave-function is in a spatially symmetric state. Thus, the two protons are mainly in opposite spin states and in the vicinity of the quasielastic peak spin-dependent effects should be determined primarily by scattering from the neutron.

The asymmetry A may be written as

$$A = \frac{\sigma(\theta, \theta^{\star}, +) - \sigma(\theta, \theta^{\star}, -)}{\sigma(\theta, \theta^{\star}, +) + \sigma(\theta, \theta^{\star}, -)} \tag{7}$$

where $\sigma(\theta, \theta^{\star}, +)$ is the cross section for scattering of longitudinally polarized electrons with positive helicity off a polarized target whose polarization lies in the scattering plane and where the angle $\theta^{\star}$ is the angle between the nuclear spin and the direction of momentum transfer.

For elastic scattering of a polarized electron from a free polarized neutron this becomes[28]

$$A_{en} = \frac{2\tau {G_M^n}^2 \cos\theta^{\star} v_T' + 2\sqrt{2\tau(1+\tau)} G_M^n G_E^n \sin\theta^{\star} \cos\phi^{\star} v_{TL}'}{v_L(1+\tau){G_E^n}^2 + v_T 2\tau {G_M^n}^2} \tag{8}$$

where v_L, v_T, v_T', and v_{TL}' are kinematic factors and $q^2 = Q^2 + \nu^2$ in conventional notation. By varying $\theta^{\star}$, the angle between the nuclear spin and the direction of momentum transfer, it is possible to pick out the longitudinal and transverse pieces of the quasielastic spin-dependent cross-section. In particular, if $\theta^{\star} = \frac{\pi}{2}$, then the asymmetry ($A_{\perp}$) is proportional to G_E^n ; if $\theta^{\star} = 0$, the asymmetry ($A_{\parallel}$) is sensitive only to G_M^n. This reflects the power of the spin degree of freedom to pick out the interesting pieces of the cross-section.

An experiment has been approved to run at the 1 GeV Bates Laboratory at MIT to study the neutron form-factors by spin-dependent quasielastic scattering from ^{3}He using the Caltech polarized ^{3}He target [29]. The principal goal of this measurement is to test our understanding of spin-dependent quasielastic scattering from ^{3}He. Thus, it will measure $A_{\parallel}$ to ±10% at $Q^2 = 0.2$ (GeV/c)^2. This results in a ±6% measurement of G_M^n at this Q^2. At present G_M^n is known to about ±12% in this kinematic region. In addition, the experiment will undertake a feasibility study for future measurements of the neutron electric form-factor using this technique. The experiment should take data early in 1989. The luminosity of 10^{33}cm^{-2}s^{-1} with 50% target polarization should allow future ±20% measurements of the neutron electric form-factor up to Q^2 of 0.5 (GeV/c)^2 at the Bates facility. An interesting possibility is that the neutron form-factors are modified in the ^{3}He nucleus compared to their free values. Indeed, as pointed out by Terry Goldman at this symposium, such an effect has been predicted in a calculation of the nuclear ground state. where nucleon substructure has been included[30].

The use of this target with a large acceptance detector at the 4 GeV Continuous Electron Beam Accelerator Facility (CEBAF) facility at Newport News, Virginia should permit increases in both precision and kinematic range in measurement of G_E^n using this technique. An interesting question is at what Q^2 does the perturbative QCD prediction $G_E^n = -\tau G_M^n$ become applicable? There is some evidence from measurement of $A(Q^2)$ on the deuteron that this is valid already at $Q^2 = 2\ (\mathrm{GeV/c})^2$. A letter of intent to undertake such measurements has been submitted to the CEBAF scientific director[31]. It is anticipated that CEBAF would be in a position to run this experiment in the mid 1990's.

4. A Polarized ^{3}He Target for Storage Rings

Internal polarized targets in storage rings have great potential for studying polarization phenomena in nuclear physics. They make very efficient use of the stored beam, have low associated backgrounds, and require small holding fields. Several facilities, which would make use of such targets, are under construction[32]. It is clear that a simple extension of the target apparatus described above would provide an internal target of polarized ^{3}He very well suited to such facilities. In addition, for the same luminosity the beam ionization depolarization mechanism for ^{3}He should be much smaller for an internal target than for an external target.

Figure 7 is a schematic diagram of a proposed target of polarized ^{3}He for an electron storage ring. The end windows of the copper cell in the double cell scheme of section 2 are replaced by pumping constrictions. In this way, the target cell becomes a storage bottle where the density of polarized ^{3}He atoms is enhanced. Large pumps are required at each end of the target cell to pump the helium away to minimize the impact on the average ring vacuum. Unlike the double cell system described above, the copper storage bottle would be at room temperature. For polarized ^{3}He, unlike for the proton or the deuteron, depolarization by wall collisions is much less severe. The data obtained on the double cell system have demonstrated that one can have storage times with polarized ^{3}He in a copper bottle of hundreds of seconds. In the internal target configuration. storage times are of order 10 ms and so clearly wall depolarization is totally negligible in the case of ^{3}He.

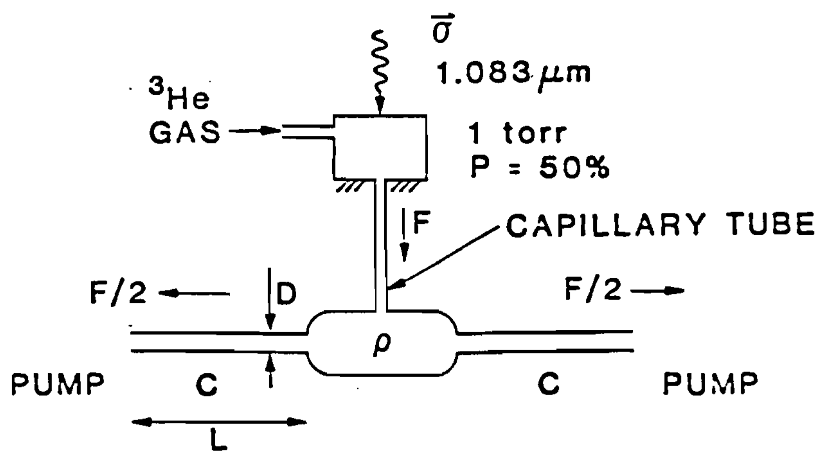

Figure 7. This is a schematic diagram of an internal target for a storage ring. Polarized ^{3}He atoms are fed at a rate F into a storage bottle with pumping constrictions of conductance C at each end. This results in a density ρ of polarized ^{3}He in the bottle.

The rate at which ground state atoms are polarized, f, can be expressed in terms of the optical pumping parameters as

$$f = \frac{NP}{t_p} \tag{10}$$

where N is the number of ^{3}He atoms in the pumping cell, P is the polarization attained and t_p is the pump-up time of the He ground state atoms. The feed rate f is strongly dependent on the number of metastable atoms present. At low discharge levels, f may be increased by increasing the discharge level. However, a saturation sets in at higher discharge levels as the depolarization of the metastables becomes significant. Thus, for a given laser power and number of atoms, there is an optimum discharge level which is a compromise between maximum f and maximum ground state polarization, P. f may also be increased by increasing the pumping cell size.

The pumping cell is constantly polarizing ^{3}He gas to 50% at an equilibrium pressure of 1 torr. The time constant, t_p, associated with the approach of the ground state atoms to equilibrium polarization, must be significantly shorter than the residence time in the pumping cell. We define the feed rate of polarized ^{3}He atoms per second to be F. Then $\frac{F}{2}$ atoms will escape through each end of the storage bottle. Let ρ be the average density in the storage bottle and C the conductance of each pumping constriction. Then

$$\frac{F}{2} = \rho\, C\,. \tag{9}$$

If we take the pumping constrictions to be circular tubes of inner diameter D cm and length L cm, then

$$C = 3.81 \times 10^4 \frac{D^3}{L}\ \mathrm{cm^3 s^{-1}} \tag{10}$$

and so the density in the storage bottle will be

$$\rho = 1.31 \times 10^{-5} \frac{FL}{D^3}\ \text{atoms cm}^{-3}\,. \tag{11}$$

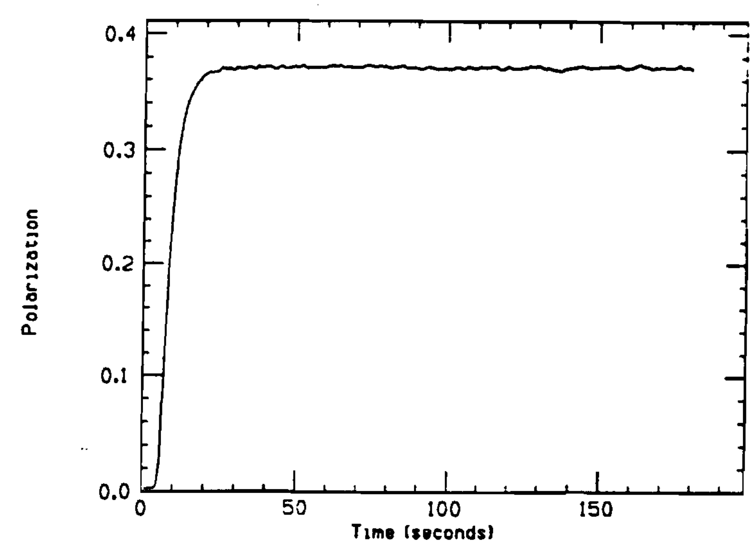

Figure 8. This shows the buildup of polarization in a 80 cm^3 sealed single pyrex cell containing 0.8 torr of ^{3}He gas. The polarization rate of ground state atoms was $f = 1.6 \times 10^{17}\ \mathrm{s^{-1}}$.

Figure 8 shows data taken for a 80 cm^3 sealed single pyrex cell containing 0.8 torr of ^{3}He gas. The value of f was 1.6×10^{17}s^{-1}, $P = 39\%$, and $t_p = 4.9$ sec. At a pressure of 2 torr and a cell size of 206 cm^3, a value of $f = 4 \times 10^{17}$s^{-1} has been achieved. With increased laser power and pumping cell size it should be possible to obtain $f = 10^{18}$s^{-1}. Consider a pumping cell of volume 200 cm^3 and pressure 1 torr. With $f = 10^{18}$s^{-1}, feed rates of $F = 2 \times 10^{17}$s^{-1} should be possible. With $L = 100$ cm, and $D = 0.5$ cm, we have $\rho = 2.1 \times 10^{15}$cm^{-3}. For a feed rate of 2×10^{17}s^{-1} and a pumping cell pressure of 1 torr, a capillary tube of 10 cm length and 0.12 cm i.d. provides the required conductance. The residence time of a ^{3}He atom in a 200 cm^3 pumping cell at a pressure of 1 torr is then 30 sec, which is much longer than the pump up time, t_p, of order 5 sec. With a 10 cm long storage bottle and a circulating current of 80 mA of current, a luminosity of 10^{34}cm^{-1}s^{-1} is achieved. It is clear that the details of such a target will depend on the facility, e.g. more optimal pumping constrictions should take account of the different horizontal and vertical beam sizes at the target, and it will probably be necessary to open up the pumping constriction while the storage ring is being filled. The 10^{34}cm^{-2}s^{-1} luminosity at 50% polarization is a clear order of magnitude in figure of merit over the external target configuration.

5. Measurement of the Deep-inelastic Spin-dependent Structure Functions of the Nucleon

I would next like to describe a very fundamental set of measurements which uses the internal target described in the previous section. Consider deep inelastic scattering of longitudinally polarized electrons from a polarized nucleon. The cross-section is given by[33]

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \Big[W_2 + 2W_1 \tan^2\frac{\theta}{2} \pm 2\tan^2\frac{\theta}{2}(E + E'\cos\theta)MG_1$$

$$\pm 8EE' \tan^2\frac{\theta}{2}\sin^2\frac{\theta}{2}G_2 \Big] . \qquad (12)$$

W_1 and W_2 are the well-known unpolarized structure functions and G_1 and G_2 are two new spin-dependent structure functions. From considerations of the total photoabsorbtion cross-sections, it is found convenient to write A as follows:

$$A = D(A_1 + \eta A_2) \tag{13}$$

where

$$A_1 = \frac{M\nu G_1 - Q^2 G_2}{W_1} \; ; A_2 = \frac{\sqrt{Q}^2}{W_1}(MG_1 + \nu G_2) \tag{14}$$

$$D = \frac{1 - E'/E\epsilon}{1 + \epsilon R} \; ; \eta = \frac{\epsilon\sqrt{Q^2}}{E - \epsilon E'} \tag{15}$$

$$\epsilon = \left[1 + 2(1 + \frac{\nu^2}{Q^2}) \tan^2 \theta/2\right]^{-1} . \tag{16}$$

Here E and E' are respectively the incident and final electron energies; Q^2 is the four-momentum transfer squared; ν is the energy transfer; R is the ratio of longitudinal to transverse cross-sections.

In the Bjorken scaling limit

$$M^2\nu G_1(Q^2, \nu) \rightarrow g_1(x) \; ; M\nu^2 G_2(Q^2, \nu) \rightarrow g_2(x) \tag{17}$$

i.e., the spin-dependent structure functions scale. A_1 and A_2 can be readily expressed in terms of the quark spin distribution functions. It can be shown that the asymmetry A_2 vanishes for massless quarks. The asymmetry A_1 is the dominant term in deep inelastic scattering with longitudinal polarization.

Sum rules govern the behavior of $g_1(x)$. The Bjorken sum rule[34], derived from light-cone algebra, relates the integral of $g_1(x)$ to the axial vector and vector coupling constants, g_A and g_V, measured in nucleon β decay. After correction for QCD radiative effects, this is given by

$$\int_0^1 [g_1^p(x) - g_1^n(x)] \, dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \cdot \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) \tag{18}$$

where the superscripts p(n) refer to the proton (neutron) and $\alpha_s(Q^2)$ is the running coupling constant of QCD. This is a deeply fundamental sum rule and its violation would be unexplainable in the quark parton model of the nucleon. A sum rule of such importance needs to be checked and to do this, measurements of both $g_1^p(x)$ and $g_1^n(x)$ are necessary.

Assuming SU(3) symmetry and that the strange sea quarks are unpolarized, Ellis and Jaffe derived separate sum rules for the neutron and proton[35]. These are

$$\int_0^1 g_1^{p(n)}(x)dx = \frac{1}{12}\left|\frac{g_A}{g_V}\right|\left[-1+\frac{5}{3}\frac{3F-D}{F+D}\right]$$
$$= 0.189 \quad \text{(proton)} \tag{19}$$
$$= -0.002 \quad \text{(neutron)}$$

where F and D are the form factors measured in baryon decay.

In principle, the combination of $g_1^p(x)$ and $g_1^n(x)$ together contain all the information necessary to determine the spin structure of the quarks inside the nucleon. However, present quark models of the nucleon are not based on rigorous QCD calculations. Thus, measurement of the spin-dependent structure functions of the proton and neutron serves as a very tight constraint on existing models of the nucleon and also as an aid to developing improved models. In addition, the entire field of high energy interactions of polarized hadrons depends on an understanding of the spin-structure of the nucleon[36].

Measurements have been made of deep-inelastic spin-dependent scattering from the proton at SLAC[37] in the 1970's and more recently by the EMC group in the muon beam at CERN[38]. The two experiments are in agreement but the EMC results extend lower in x, where the dominant contribution to the sum-rule resides, and hence provide a more precise determination of the integral

$$\int_0^1 g_1^p(x)dx = 0.113 \pm 0.012 \pm 0.025 \tag{20}$$

indicating that the Ellis-Jaffe sum rule is violated. This probably means that the assumptions made in deriving the sum rule are wrong, and Jaffe has conjectured that the violation may be associated with the non-conservation of the U(1) axial current in QCD[39]. However, it could also be a consequence of the violation of the Bjorken sum rule. In addition, if the EMC data are analyzed in the simplest quark parton picture, the fraction of the total spin of the nucleon carried by the quarks is very small[38]. Clearly, measurement of $g_1^n(x)$ would provide the crucial information necessary to resolve these issues.

The EMC experiment uses an ammonia target where the protons in the ammonia molecule are polarized to 80%. To measure spin-dependent scattering from the neutron one could run with deuterated ammonia, measure the asymmetry from the deuteron, and subtract the measured proton asymmetry. Such an experiment has been proposed at CERN[40]. It is possible to use a polarized ^{3}He target as an effective neutron target and one can consider measurements with a 20 GeV longitudinally polarized electron beam from the target described in the previous section[41]. However, with conventional spectrometer acceptances at this momentum the count rate is low, and scattering from the end windows on such a target prevents accurate measurements at small x, where the dominant contribution to the sum rule resides. Here I would like to describe a new technique to measure the asymmetries in deep inelastic scattering of polarized electrons from polarized protons and neutrons[42]. This is to use internal polarized atomic gas targets of density 1 to 3 $\times 10^{14}$cm^{-2} and polarization 50% placed in the circulating polarized electron beam of an electron storage ring. To study the proton a polarized atomic hydrogen target would be used. For the neutron, polarized ^{3}He would be used, since to a good approximation the two protons in this nucleus have opposite spins, and so the asymmetry is due to the neutron. In addition, one would measure the asymmetry from a polarized deuteron target. This would be an independent method of determining the neutron spin-dependent structure functions. These measurements become possible because of the development of a new generation of polarized hydrogen, deuteron, and ^{3}He targets based on the method of optical pumping. With a circulating current of 60 mA, these targets would provide a luminosity of about 10^{32}cm^{-2}s^{-1}.

The proposed technique does not suffer the disadvantages of conventional polarized target technology. (In the conventional approach, polarized deuterons in the form of deuterated ammonia would be used, necessitating the subtraction of the large proton asymmetry to determine the small neutron asymmetry. In addition, the asymmetry is diluted by scattering from large amounts of unpolarized material in the ammonia target. In the internal target method, the polarized atoms are pure atomic species.) Because the proposed target thickness is of order 10^{-11} radiation lengths, the contribution from external radiative corrections in the target is negligible. Also, it should be possible to measure the transverse-longitudinal interference asymmetry A_2. A schematic diagram of a possible configuration

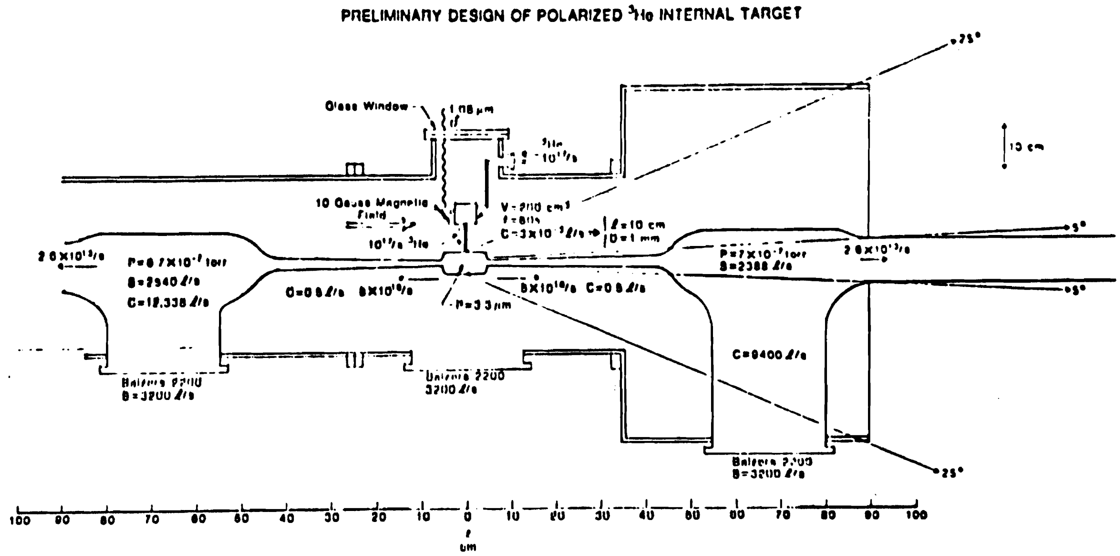

Fig. 9 This figure is a schematic drawing of a polarized ^{3}He internal target.

of the polarized ^{3}He internal target based on the considerations of section 4 is shown in Fig. 9.

The spectrometer is based on the UA6 experiment at CERN, which was successfully used down to 20 mrad. The momenta of scattered particles are analysed with a 1.5 Tm dipole magnet. The stored electron beam is shielded from the large dipole field by means of a flux exclusion tube. Planes of wire chambers allow the tracking of charged particles and a wall of lead-glass serves as a calorimeter to measure the energy. The detector should have large acceptance for electrons with scattering angles between 2° and 15°.

The proposed experiment requires an electron storage ring with tens of GeV energy and longitudinal polarized electron capability. The only such machine planned is the 35 GeV storage ring at the HERA collider at DESY, Hamburg, West Germany. The polarization scheme planned for this storage ring is to build up transverse electron polarization through synchrotron radiation. This occurs with a time constant of order 20 minutes. At the interaction region the polarization is arranged to be longitudinal by means of a series of rotator magnets.

Fig. 10 shows the precision as a function of x attainable in a 20 day run at HERA in a measurement of $A_1^n(x)$ on the polarized ^{3}He target. It is assumed that the 35 GeV electron beam and target polarizations are each 0.5; the electron beam current is 60 mA;

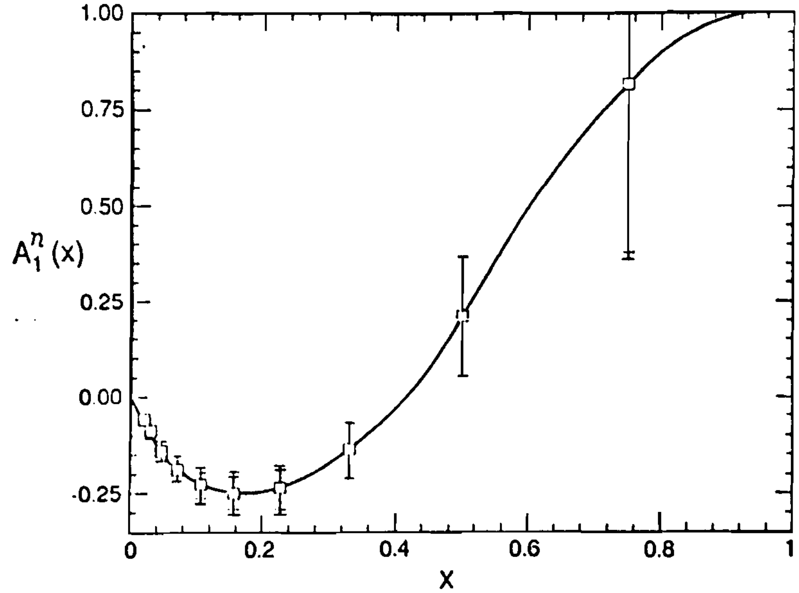

Fig. 10 This figure shows the precision as a function of x in a 20 day run at HERA in a measurement of $A_1^n(x)$ on a polarized ^{3}He target.

the target thickness is $2.5 \times 10^{14}\mathrm{cm}^{-2}\mathrm{s}^{-1}$; the incident electron energy is taken to be 35 GeV; a dilution factor of 0.33 is used becaused the electron can also scatter from the two protons in the ^{3}He nucleus. The region in x extends from 0.02 to 0.8 and in Q^2 from 1 to 20 $(\mathrm{GeV/c})^2$. The low x limit is determined by elastic radiative tails and backgrounds at high $y = \frac{\nu}{E}$. A systematic error of ±15% has been included. The solid line in this figure is the prediction of a modified Carlitz-Kaur model which is in good agreement with the new EMC data and is constrained to obey the Bjorken sum rule[43].

It is planned that construction of the HERA electron storage ring would be completed late in 1988 and polarization studies would commence in 1989. A joint collaboration of the members of PRC-88/1 and PRC-88/2, together with other institutions, is actively pursuing the possibility of performing these measurements.

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