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PROSPECT OF POLARIZED TARGETS IN ELECTRON RINGS*

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ABSTRACT

The feasibility of performing electron scattering experiments with polarized targets in electron storage rings is discussed. Three examples of the physics which would be accessible with this novel method are given. It is noted that this new method is compatible with recent proposals for linac-stretcher-ring accelerator designs. A new method for producing a polarized hydrogen or deuterium target is proposed and some preliminary results are described. A brief summary of laser-driven polarized targets as well as conventionally-produced polarized atomic beams is included.

INTRODUCTION

Although there is great interest in polarization phenomena in electromagnetic interactions with nuclei, this area remains essentially unexplored experimentally. The reasons for the interest are manifold, but fall primarily into three categories: (i) much greater sensitivities to small form factors, such as the electric form factor of the neutron, (ii) allow separation of elastic form factors for nuclei with spin ≥ 1 , e.g., the deuteron, (iii) permit unravelling of multipole excitations of resonances in nuclei and isolation of structure functions.

Unfortunately, the experiments are extremely difficult, and in most cases, appear unfeasible with present techniques. In this report we wish to discuss a novel method which should provide accessibility to polarization measurements in a broad range of interesting cases. Namely, we consider the situation where a thin polarized target is located inside an electron storage ring and the ring would be designed in such a manner as to provide longitudinally polarized electrons at the target position. There would be many advantages to this technique. First, one would make very efficient use of the electron beam, and thus, the demand on the electron injector is minimal. If the electron does not interact with the target, it merely would circulate in the ring until an interaction would occur; whereas, in the single-pass geometry the non-interacting electrons would pass directly to the beam dump. Another important advantage is the prospect of low background near a storage ring. At present, with storage rings which operate below a few GeV in energy there is essentially no background. This is due to the fact that only $\sim 10^{12}$ electrons are in the ring at any given moment and if all were lost at once the radiation dosage would be very small.

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However, the primary advantage of the method is that with large circulating currents, one can consider much thinner targets than with the single-pass geometry. Thus, one can employ polarized atomic beams as targets. The advantages of polarized atomic beams over conventional polarized targets are, (i) the target material is pure or the contaminating host is small, (ii) the direction of the quantization axis can be changed readily with only a few gauss field, (iii) tensor as well as vector polarized targets are feasible, and (iv) the target polarization would not be compromised by beam heating or radiation damage as with the conventional targets.

In the remainder of this talk we shall focus on some of the physics problems which this method should render feasible, the counting rate advantages over external-beam geometries, and the feasibility of producing polarized targets. A new method for producing a polarized atomic beam will be discussed, along with a brief summary of the Workshop on Polarized Targets in Storage Rings, which was held at Argonne on May 17-18, 1984.

POLARIZATION IN ELECTRON SCATTERING

Three examples of physics measurements which could be performed as polarized internal target experiments are discussed below. These problems include the determination of the electric form factor of the neutron, the electric form factors of the deuteron, and the C2 transition in excitation of the free Δ .

A long-standing and most fundamental problem has been the uncertainty of the charge distribution of the neutron. The primary problem is that the electric form factor G_E of the neutron is small in comparison with the magnetic form factor G_M . Thus, a measurement of the cross section for quasi-free scattering from the neutron in deuterium has little sensitivity to G_E . Previous measurements of this kind are illustrated in fig. 1. The curves in the figure represent predictions¹ based on the cloudy bag model. The quantity R is the bag radius in fm.

Fig. 1

Electric form factor of the neutron for various values of the bag radius (solid curves) and measured values (vertical lines).

On the other hand, a measurement of the analyzing power A_x from polarized electron scattering on a polarized deuterium target depends on the interference term between G_E and G_M according to the expression:

$$A_x = \frac{-2 \sqrt{\eta(\eta+1)} G_E G_M \tan(\theta/2)}{G_E^2 + \eta G_M^2 [1 + 2(\eta+1) \tan^2(\theta/2)]}$$

where $\eta = q^2/4M_d^2$, θ is the electron scattering angle and q is the four-momentum transfer. The quantity actually measured would be the asymmetry a_x from polarization transfer:

$$a_x = h p_T A_x$$

where h is the longitudinal polarization of the incident electron beam and p_T is the vector polarization of the neutron in the deuteron.

As an estimate of the feasibility of such an experiment, we will assume that a 1-GeV electron beam with $h=0.4$ and a circulating current of 40 mA will be available. (Such a facility has been proposed by the Massachusetts Institute of Technology for the Bates Linear Accelerator Center.) In addition, we assume a target with a thickness of 4×10^{15} atom/cm² and $p_T=1$ will be available. Cheung and Woloshyn² have calculated the cross section at $q^2=10 \text{ fm}^{-2}$ to be $10^{-2} \text{ } \mu\text{b/sr-MeV}$. With an electron spectrometer of $\Delta\Omega_e=50 \text{ msr}$, the expected event rate is 130 events/hr. Thus, it should be possible to determine G_E to an accuracy of $\pm 10\%$ over the momentum transfer region of $5 \leq q^2 \leq 15 \text{ fm}^{-2}$ (see fig. 1) in approximately one month. An internal target facility at the Continuous Electron Beam Accelerator Facility (CEBAF) which has been proposed by the Southeastern Universities Research Association (SURA) should render experiments of this kind even more viable.

Another fundamental problem in nuclear physics is the fact that the electric form factors of the deuteron, charge F_C and quadrupole F_Q , have never been isolated in electron scattering studies. This problem can be seen from the form of the Rosenbluth formula for the cross section:

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_M} [A(q^2) + B(q^2) \tan^2(\frac{\theta}{2})]$$

where

$$A(q^2) = F_C^2 + \frac{8}{9} \eta^2 F_Q^2 + \frac{2}{3} \eta F_C^2, \quad B(q^2) = \frac{4}{3} \eta(1+\eta) F_M^2,$$

and $\frac{d\sigma}{d\Omega_M}$ is the Mott cross section. Clearly, only A and B can be separated by cross section measurements, and thus, only F_M can be isolated. One important question in e-d scattering is concerned with the location of the first zero in the charge form factor of the deuteron. The exact location of the first zero, expected near $q \sim 4 \text{ fm}^{-1}$, is sensitive to the deuteron model³ as well as the isoscalar meson exchange currents.⁴ Unfortunately, the quadrupole form factor masks the location of the zero in F_C , and thus, the location cannot be determined from a measurement of $A(q^2)$. However, a measurement of the tensor polarization in e-d scattering would permit one to isolate the charge and quadrupole form factors. The expression for t_{20} is given in terms of $X = \frac{2}{3} \eta F_Q/F_C$ and $Y = \frac{2}{3} \eta f(\theta) F_M^2/F_C^2$ below:

$$t_{20} = -(2)^{1/2} [X(X+2) + Y/2] / [1+2(X^2+Y)]$$

where the dominant contribution to t_{20} is from F_C and F_Q for $q < 8 \text{ fm}^{-1}$, and $f(\theta) = 1/2 + (1+n) \tan^2(\theta/2)$.

If perturbative QCD is valid for the deuteron for $q \gtrsim 5 \text{ fm}^{-1}$ as suggested by Brodsky and Chertok⁵ and, more recently, by Carlson and Gross,⁶ then $X \rightarrow 1$ as $q^2 \rightarrow \infty$, and thus, one might expect $t_{20} \rightarrow -(2)^{1/2}$ rather than a positive value as predicted by the conventional meson exchange model. Of course, the validity of perturbative QCD at such low values of momentum transfer is a matter of current debate.⁷ Predictions for various models are shown in fig. 2. The two data points in the figure were determined⁸ with the use of deuteron tensor polarimeter in which the polarization of recoil deuterons from e-d elastic scattering was measured.

Fig. 2

The curves represent predictions of t_{20} in e-d elastic scattering for various deuteron wave functions. The isoscalar meson-exchange currents produce a significant impact on t_{20} for $q \gtrsim 3 \text{ fm}^{-1}$. The perturbative QCD limit illustrated here is discussed in the text. The two data points are from ref. 8.

A comparison among the expected counting rates is illustrated in fig. 3. The two points in this figure indicate the actual counting rates with a polarimeter. The curve labelled Aladdin arises from the assumption that one could employ the Aladdin synchrotron light source for these studies. Tests will be performed at Aladdin as soon as it comes into operation in order to determine the feasibility of

Fig. 3

Counting rates for measurements of t_{20} in e-d scattering as a function of momentum transfer. The points represent rates actually encountered in an experiment involving a polarimeter, ref. 8. The three curves indicate expected rates for three types of electron rings.

performing an experiment in a synchrotron light-source ring. The assumptions that are involved in this estimate are that the circulating current would be 100 mA, a target thickness of $10^{14} \text{ atoms/cm}^2$, and a solid angle of 75 msr. The primary difficulty of a synchrotron light source is that the target thickness is limited to $10^{14} \text{ atoms/cm}^2$ by bremsstrahlung losses and the requirement of long storage times ($\sim 10 \text{ hrs.}$) The other curves in fig. 3 denote the

expected counting rates if an internal target station were commissioned at the proposed stretcher rings at MIT-Bates and CEBAF (SURA). Here a target thickness of 4×10^{15} atoms/cm² and currents of 40 mA and 100 mA, respectively, were assumed.

The longitudinal E2 transition (C2) between the free nucleon to the delta has received considerable attention in the past few years. Within the framework of the quark model this transition can correspond to an excitation of an s-wave quark in the nucleon to a d-wave quark in the delta, and thus, would be indicative of a deformed delta. Spherical bag models give rise only to M1 spin-flip amplitudes in the nucleon to delta transition. Deformed nucleons can arise quite naturally from the chiral bag model, since the coupling $(\vec{\sigma} \cdot \vec{\nabla} \phi_\pi)$ of the pion field to the quarks can be strongest along the spin axis of the nucleon. This "squashed" quark bag model⁹ of the nucleon can explain the value of the axial vector coupling constant, the ratio of the πNA to the πNN coupling constants and the slope¹⁰ of Regge trajectories. Perhaps more compelling evidence for this C2 transition is found from $H(e, e'p)\pi^0$ coincidence experiments¹¹ where a non-zero C2 coefficient was found. Unfortunately, the coincidence experiments are extremely difficult and the ultimate accuracy of this technique is limited to the accuracy of the relative acceptance of the detectors for different scattering angles.

A far more sensitive determination of the C2 amplitude would be to measure the polarization transfer coefficient in the scattering of longitudinally polarized electrons from a polarized hydrogen target. The C2 amplitude can be measured with greater precision than the coincidence experiment since the detection system remains fixed and since the direction of the target polarization can be controlled readily. Thus, this kind of measurement is well-suited to the polarized internal target method. With the same assumptions as in the previous cases, an estimate 15 days time would be required for a measurement of the ratio of C2 to M1 amplitudes with an accuracy of ± 0.01 and for $q^2=0.05$ (GeV/c)² at the proposed stretcher ring for the MIT-Bates Linear Accelerator Laboratory.

REQUIREMENTS ON INTERNAL TARGET

Now that the prospective advantages of the internal target method have been discussed, we shall turn to a discussion of the limitations imposed on the target by the storage ring itself. Clearly, the synchrotron-light source rings impose the greatest constraints on the target, since the storage times are typically several hours. Bremsstrahlung production represents the largest loss mechanism for electrons in a storage ring. For the Aladdin storage ring the circulation time T_0 is 0.32 μ s and the storage time $T_{1/2}$ should be ~ 10 hrs. Thus, the maximum target thickness for deuterium in this ring is given by

$$n \leq 0.693 \frac{T_0}{\sigma_b T_{1/2}} = 10^{14} \text{ atoms/cm}^2$$

where σ_b is the bremsstrahlung cross section $\approx 0.06 Z^2$ b. In a dedicated ring for internal target experiments, where the electron beam need only be stored for ~ 1000 turns, the target thickness limitation from bremsstrahlung losses would be $\sim 10^{22}$ atoms/cm² for $Z = 1$. Thus, a dedicated electron ring for nuclear physics would be highly desirable.

Another consideration is the effect of multiple scattering on the electron beam. In the case of a synchrotron light source such as Aladdin, bremsstrahlung losses override the effect of multiple scattering. For the Aladdin ring and a target thickness of 10^{14} atoms/cm² of deuterium the multiple scattering angle becomes 5 μ rad and thus, is negligible. However, for a dedicated ring of, say, a storage time of 1000 turns and an angular acceptance of the ring of 1 mrad, the deuterium target thickness would be limited to 4×10^{18} atoms/cm². Thus, in a synchrotron light source bremsstrahlung losses are the primary limitation, while in a dedicated ring multiple scattering is a more important consideration than bremsstrahlung. In a dedicated ring a more stringent constraint is ionization loss of the target polarization.

In order to estimate the polarization loss from ionization we will assume that if an atom is ionized then the polarization of the nucleus is lost. The ionization rate I_i is given by $I_i \leq \rho I_e E_1^{-1} dE/d\rho$, where ρ is the target density, $dE/d\rho$ is the energy loss in the target, I_e is the circulating electron current and E_1 is the ionization energy of the target atom. With the choice of $dE/d\rho = 2$ MeV-cm²/g, $E_1 = 20$ eV and $I_i < 0.1 I_A$, where I_A is the rate at which polarized atoms in the target can be replenished, the maximum luminosity $\mathcal{L}$ is given by $\mathcal{L} \leq 6 \times 10^{17} I_A/A$ cm⁻¹s⁻¹. An atomic beam source which could provide 10^{17} polarized atoms/s would give a luminosity limit of 6×10^{34} A⁻¹ cm⁻² s⁻¹. It is expected that polarized atoms could be replenished at rates in excess of 10^{18} atoms/s with optical pumping techniques which will be described later. At present it would be difficult to fabricate a low-A target which could attain this luminosity limit, but it might very well represent the limitation on target thicknesses for $A \geq 100$. Note, that the luminosities for experiments discussed in the previous section do not exceed 2.4×10^{33} cm⁻² s⁻¹, and thus, ionization losses do not limit any of these experiments.

TARGET DESIGN CONSIDERATIONS

In the following conceptual design for an internal target, we shall consider a storage bottle which is replenished continuously with polarized atoms from an atomic beam source. In addition, we shall consider a tensor polarized deuterium target which could be employed in the Aladdin storage ring, i.e. a thickness of 10^{14} atoms/cm². Moreover, we will assume a spherical storage bottle of 10 cm diameter and two 7-mm orifices which permit the primary electron beam to enter and exit from the target chamber. The target density in the bottle would be 10^{13} atoms/cm³. Then, the atoms would leak from the storage bottle at a rate of 4×10^{17} atoms/s at $T=500^\circ\text{K}$ or 8

$\times 10^{16}$ atoms/s at $T=20^\circ\text{K}$. An atomic beam source must supply polarized atoms at this rate to the bottle. Unfortunately, a conventional atomic source operating at room temperature could provide only 3×10^{16} atoms/s. It is expected that a low temperature atomic beam source would provide $\geq 10^{17}$ atoms/s at $T=20^\circ\text{K}$. Although two groups^{12,13} are attempting to provide polarized atomic beams of hydrogen from this kind of source, it has not been demonstrated as yet. Another method which has the prospect of achieving $10^{17}-10^{19}$ polarized atoms/s is spin-exchange optical pumping. We shall consider the latter method in detail since it has implications not only for the Aladdin storage ring but also for a dedicated ring for nuclear physics.

Bhaskar et al.¹⁴ recently demonstrated nuclear polarization through spin-exchange optical pumping by polarizing ^{129}Xe . In order to understand how the nuclear polarization arises from spin-exchange collisions and how many polarized photons are necessary to produce a high degree of polarization, we will consider the simplest case, i.e. $\text{Na}\uparrow + \text{H}\uparrow \rightarrow \text{Na}\downarrow + \text{H}\uparrow$ where the Na atom is polarized by optical pumping. The proton in hydrogen is polarized by successively polarizing the electron and allowing the hyperfine interaction to act between each collision. The deduced proton polarization as a function of the number of spin-exchange collisions can be shown to be

$$p(n) = 1 - (1/2)^n.$$

This means that very few spin-exchange collisions, and consequently polarized photons, are necessary to polarize the proton. When the same analysis is performed for deuterium the result is not easily reduced to a simple form, but it is straightforward to follow the

vector polarization $t_{10} = (3/2)^{1/2} (N_{+1} - N_{-1})$ and the tensor polarization $t_{20} = (1/2)^{1/2} (1 - 3N_0)$ as a function of the number of spin-exchange scatterings. Here, the N 's refer to the population of the three magnetic substates of the deuteron. The results for t_{10}

and t_{20} are shown in fig. 4. For a given Na atom polarization, only ≥ 5 scatterings are necessary to obtain essentially the maximum polarization of the deuteron.

Fig. 4

Expected polarizations for the deuteron nuclei as a function of the number of atomic spin-exchange collisions.

With the assumption that 5 spin-exchange collisions are necessary to polarize deuterium one can determine that 2 watts of laser power at the Na D1-line is necessary to produce 4×10^{17} polarized atoms/s. This is a reasonable power output of a single CW dye laser. Furthermore, it is reasonable to expect that 20 watts of power could be employed to optically pump Na and one may achieve 4×10^{18} polarized atoms/s.

The density and thickness of alkali atoms that must be optically pumped can be estimated if we consider the process to take place in a tube of length l , diameter $2a$ and one end open so that the polarized atoms can flow from the cell. The laser beam is directed toward the mixture of Na and D atoms in the cell from the direction of the opening in the tube. Then, the density n_{Na} of Na necessary to polarize the deuterium is given by

$$n_{Na} = \frac{N_{se}}{4l\sigma_{se}} \left(\frac{8a}{8a + 3l} \right)$$

where N_{se} is the number of spin-exchange collisions that deuterium atoms make with Na atoms in the cell and σ_{se} is the Na-D spin-exchange cross section which is taken¹⁵ to be 10^{-14} cm². If we take $l = 5$ cm, $a = 2.5$ mm and $N_{se} = 5$, then the Na density is 2.9×10^{12} atoms/cm³ and the thickness is 1.5×10^{13} atoms/cm². These values are consistent with Na densities and thicknesses that have been optically pumped¹⁶ with high polarization and without a buffer gas or special wall coatings. An important consideration for the experiments considered here is the amount of contamination of the host Na atoms. The ratio of the Na density to that of deuterium is given by

$$\frac{n_{Na}}{n_D} = \frac{12\pi a^4 \bar{v}_D N_{se}^2}{lL\sigma_{se}(8a + 3l)^2}$$

where L is the intensity of the incident polarized photon beam (note that 2 watts corresponds to 3×10^{18} photons/s at the Na D1-line) and $\bar{v}_D$ is the mean speed of deuterium atoms in the laser cell. For the tube dimensions discussed above and a 2 watt laser beam, this ratio turns out to be 0.9%, a reasonably small value.

An additional advantage of the spin-exchange method is that all dissociated deuterium atoms are used in the source. In the conventional atomic beam source most of the atoms are rejected by the small acceptance (~ 1 -10 msr) of the hexapole. The novel atomic beam source requires a far less imposing vacuum system, an essential advantage for internal targets in storage rings, and a less elaborate RF dissociator system. However, since every atom passes through the source, one must maintain a high dissociation efficiency. A dissociation efficiency of 97% with an atomic beam rate of 10^{18} atoms/s has been achieved¹⁷ routinely at the Los Alamos National Laboratory and represents an ideal development for the proposed atomic beam source.

A prototype of a polarized deuterium target which employs the spin-exchange method is being developed at Argonne and is illustrated in fig. 5. In this scheme the target polarization can be detected by

SCHEMATIC DIAGRAM OF APPARATUS TO MEASURE TARGET POLARIZATION

Fig. 5

Arrangement of a proposed spin-exchange optically pumped polarized deuterium source and the method to detect the polarization.

the $D(^3\text{He}, p)^4\text{He}$ reaction. A 625-keV ^3He beam was incident upon the gas stream of deuterium atoms and the $\sim 14\text{-MeV}$ protons are counted in Si surface-barrier detectors. At the $3/2^+$ resonance this reaction exhibits a 0.7-b cross section¹⁸ and maximum analyzing power¹⁹ for t_{20} , and thus, is ideal for the study of a thin tensor polarized deuterium target. The Helmholtz pair was used to maintain a field of ~ 4 gauss near the target, and consequently, to provide a quantization axis for the spin states of deuterium and Na. The laser cell was heated by forced air to $\sim 500^\circ\text{K}$ in order to vaporize the Na. In a preliminary test we have achieved a 2:1 signal-to-background ratio for observing the $D(^3\text{He}, p)^4\text{He}$ reaction and we have observed 10 mW of absorbed laser power which was driving the spin-exchange reaction of Na with D atoms. This corresponds to only 10^{15} polarized atoms/s flowing through the ^3He beam and would fall below our detection threshold. The major problem during this test was a poor dissociation efficiency, and presently, we are developing a reliable diagnostic for dissociation efficiency before resuming further tests.

SUMMARY OF OTHER TARGET DEVELOPMENTS

A brief summary of other target developments which were reported at the Workshop on Polarized Targets in Storage Rings, held at Argonne on May 17-18, 1984, is given in table I. The first four entries in table I are primarily concerned with producing polarized hydrogen or deuterium, using four different techniques. It appears quite likely that hydrogen or deuterium targets in the range of 10^{14}

$\sim 10^{15}$ atoms/cm² will be available in the near future. The last six entries in the table represent laser-driven polarized targets. The third and fourth entries also rely on spin-exchange as well as optical pumping; whereas, the last four targets are directly optically pumped. One can conclude from a study of this table that the advent of lasers has had a substantial impact on the development of polarized targets.

Table I Polarized Internal Targets in Development or Operation

Type of Target	Nuclei	Institution	Target Thickness Expected
Conventional atomic beam (cyrogenically cooled)	H,D	CERN (SPS) ETH, Zurich	$5 \times 10^{12} - 5 \times 10^{13}$ atom/cm ² (Objective)
Storage Cells	H,D	Wisconsin	$10^{14} - 10^{15}$ atom/cm ² (Objective)
Low-temperature high field storage cell	H,D	BNL-MIT (AGS)	10^{14} atom/cm ² (Objective) (Pulsed)
Spin-exchange optical pumping	H,D,N,...etc.	ANL (Aladdin)	$10^{14} - 10^{15}$ atom/cm ² (Objective)
Spin-exchange optical pumping	Noble Gases	Princeton	10^{19} atom/cm ² (Lab Demonstration for X _e)
Optical pumping of alkali vapors	Li	Bell/MIT Rutgers	10^{15} atom/cm ² (Operational target)
Optical pumping of alkali vapors	Cs	Princeton	10^{16} atom/cm ³ (Lab Demonstration)
Optical pumping of rare earth jets	Eu	ORNL	10^{15} atom/cm ² (Objective)
Optical pumping	³ He	I.E.N.S. (Paris)	10^{18} atom/cm ³ (Lab Demonstration)

SUMMARY

We have demonstrated conceptually that polarized internal targets in storage rings should be a powerful method for the study of nucleons and nuclei. Furthermore, this method should be compatible with the recently-proposed linac-stretcher ring accelerator designs of MIT and SURA. It is clear that a wide variety of suitable polarized targets are technically feasible. At present, laser-driven polarized targets appear to be the most promising technology. Optical pumping combined with spin-exchange scattering provides an even larger array of polarized targets that will benefit from laser techniques.

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