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NUCLEAR PHYSICS WITH INTERNAL TARGETS IN ELECTRON STORAGE RINGS

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ABSTRACT

Two key experiments in nuclear physics will be discussed in order to illustrate the advantages of the internal target method and demonstrate the power of polarization techniques in electron scattering studies. The progress of internal target experiments will be discussed and the technology of internal polarized target development will be reviewed.

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INTRODUCTION

It is both an honor and a pleasure for me to participate in this thirty-fifth anniversary celebration of electron scattering from nuclei. A perusal of the seminal article[1] by Lyman, Hanson and Scott and the presentations yesterday by Professors Kerst and Hanson indicated that a major obstacle to the early experiments was the extraction of the electron beam from the betatron, and it is ironic that today I shall discuss experiments performed inside an accelerator.

The internal target method is essential for applications which require thin targets, for example, rare targets such as polarized gases or vapors or targets with special isotopic content, and experiments requiring the detection of massive recoiling particles such as electrofission or π^0 production where the recoil nucleus is detected. An indication of the growing interest in the use of internal targets in electron accelerators is summarized[2-6] in the workshops and proposals for electron rings during the past five years (see Refs. 2-6). In addition, there is work[7-8] in progress at Novosibirsk, SLAC and Frascati.

The feasibility of operating an internal target in an electron storage ring is demonstrated by recent work[7] at Novosibirsk where a ^{16}O target in the form of a steam jet was placed in the VEPP-I ring as illustrated schematically in Fig. 1. Here, an average luminosity of 3×10^{31} cm^{-2} s^{-1} at an electron energy of 130 MeV was achieved. Note that the target region was surrounded by NaI crystals which intercepted a total solid angle of 0.6 sr! This is possible only in a high-duty factor and low-background environment. A typical $^{16}O(e,e'\alpha_0)^{12}C$ spectrum from this technique is shown in Fig. 2. The use of the ultra-thin target in this case permitted low-energy recoiling α-particles as low as 2.4 MeV to be detected and underscores the usefulness of the internal target technique for detecting heavy recoil particles emerging from the target.

Today, I shall discuss two types of experiments, not only as models for internal target experiments, but also to demonstrate the power of the polarization technique in electron scattering. These two experiments are designed to isolate the charge and quadrupole

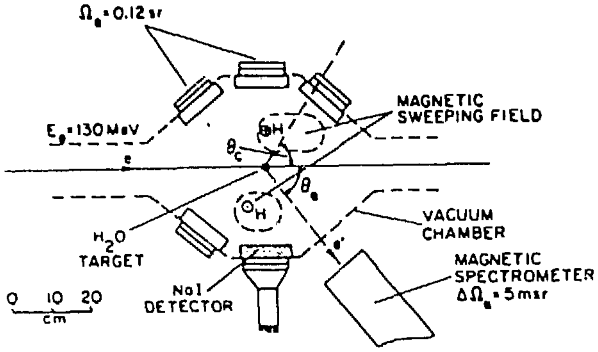

Fig. 1. Schematic diagram of the experimental apparatus at Novosibirsk to perform A(e,e'x) measurements in an internal target geometry. Note the total solid angle of the hadron detectors is 0.6 sr and the average electron beam current is 300 mA.

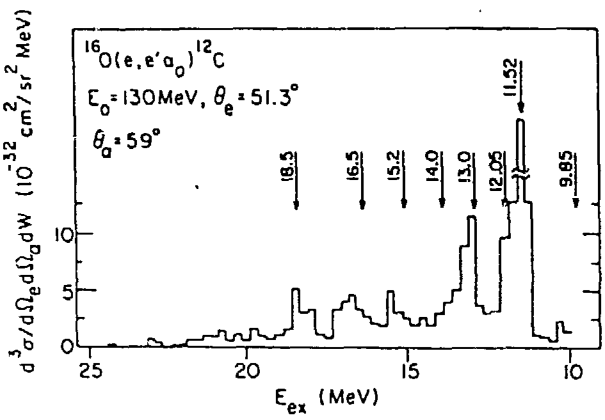

Fig. 2. Typical spectrum for the $^{16}O(e,e'\alpha_0)^{12}C$ reaction. The internal target geometry permits detection of the α-particle at energies as low as 2.4 MeV.

form factors of the deuteron and determine the charge form factor of the neutron, respectively. It will be shown that the central problem with the internal polarized target method is the low target thickness presently available and the development of techniques to improve significantly the target thickness will be discussed.

ELECTRON-DEUTERON ELASTIC SCATTERING

First we consider electron elastic scattering from the deuteron, where three form factors - charge G_0, quadrupole G_2 and magnetic G_1 – describe the scattering process. The primary constraint one can place on present theoretical calculations is to measure the location of the first zero in the charge form factor, since it is very sensitive to the model. Indeed, there is great sensitivity to the presence of an isoscalar meson exchange current[9] as well as to that of quarks in the form of a hybrid model[10] of the deuteron. The location of the first zero in G_0 can only be determined from a polarization measurement. This is evident by noting the form of the unpolarized cross section and the expression for the tensor polarization t_{20} given below.

$$\frac{d\sigma}{d\Omega} = \sigma_M \left[A(Q^2) + B(Q^2) \tan^2(\theta/2)\right]$$

$$t_{20} = -\sqrt{2}\,\frac{x(x+2) + y/2}{1 + 2(x^2+y)}$$

where x depends on the ratio of the quadrupole to the charge form factor,

$$x = \frac{2}{3}\,\tau\, G_2/G_0 \ ,$$

and y depends on the square of the ratio of the magnetic to the charge form factor and is very small below $2(\mathrm{GeV}/c)^2$,

$$y = \frac{2}{3}\,\tau\,(G_1/G_0)^2\, f(\theta) \ ,$$

where

$$f(\theta) = \frac{1}{2} + (1+\tau)\tan^2\left(\frac{\theta}{2}\right) \ ,$$

and

$$\tau = Q^2/4M_d^2 \ .$$

Clearly, only A and B can be isolated in a measurement of the cross section and the first zero in G_0 is masked by the presence of G_2 in the quantity A. The quantity $B(Q^2)$ has been well determined[11,12] up to a momentum transfer of $2.5(\mathrm{GeV}/c)^2$ and it is found that G_1 has little influence on the value of t_{20} in this momentum transfer range. Then, t_{20} is essentially providing information on the ratio of G_2/G_0 and, in fact, as $G_0 \rightarrow 0$, $t_{20} \rightarrow -\frac{1}{\sqrt{2}}$ in this approximation that G_1 is negligible. Thus, a measurement of the quantity t_{20} provides the best information on the location of the first zero in G_0.

Although there has been much previous speculation[13,14] that perhaps the effects of perturbative QCD might be observed in t_{20} in this momentum transfer region, the recent measurements[11] of $B(Q^2)$ at SLAC indicate that an explanation of the deuteron in terms of hadrons appears to be predominant up to a momentum transfer of $2.5(\mathrm{GeV}/c)^2$.

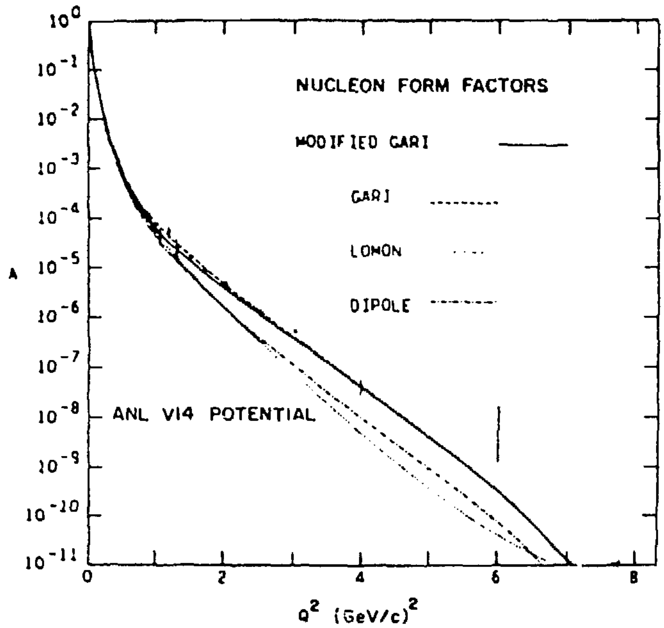

Fig. 3. The quantity $A(Q^2)$ as a function of Q^2. The data are from Ref. 21, and the calculations are performed for three different nucleon form factors. Above a momentum transfer of 1 $(GeV/c)^2$ the choice of the nucleon form factor is critical to the interpretation of the data.

Another issue which is re-emerging is the uncertainty in the nucleon form factors. A recent analysis[15] of cross section data for the nucleon has indicated that the charge form factor of the neutron is much larger than previously believed. The effect of this present uncertainty on the quantity $A(Q^2)$ is illustrated in Fig. 3 where recent calculations by Chung et al.[16] are provided kindly by F. Coester for this 35th anniversary celebration. These calculations employ the Argonne V14 potential[17] for the deuteron wave function and the relativistic front-form dynamics[18] which has recently been applied to electromagnetic interactions by Coester. There is a rather large discrepancy between the recent form factors by Gari[15] and the more conventional[19] form factors. Note that the choice of the Gari form factors would rule out a correction from the isoscalar meson exchange current of the type discussed by Gari and Hyuga.[20] It is clear from this graph that more work on the nucleon form factors is necessary in order to advance our understanding of the deuteron. In a few moments I will discuss the role that polarization studies will have in improving measurements of the nucleon form factors.

The tensor polarization in electron deuteron scattering, however, has little dependence on the choice of the nucleon form factors owing to the fact that it is primarily dependent on the ratio of the electric form factors of the deuteron. Calculations of the tensor polarization, given in Fig. 4, exhibit a strong

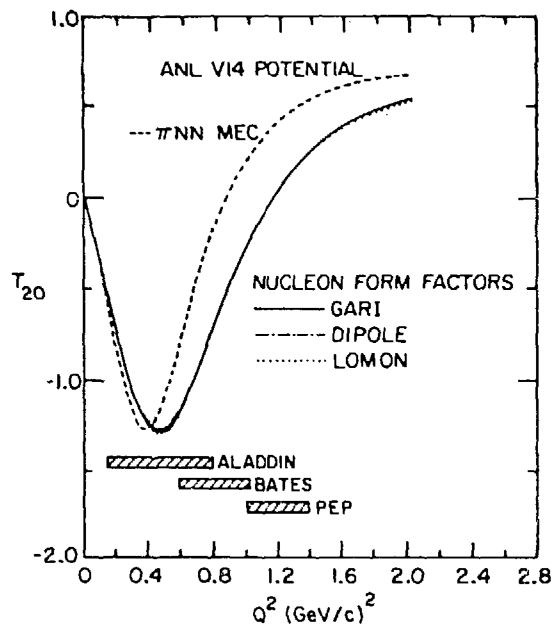

Fig. 4. Calculations of the tensor polarization both with and without the isoscalar meson exchange current. The effect of employing the different nucleon form factors is negligible for t_{20}. The hatched regions indicate the momentum transfer region for three separate proposed experiments.

dependence on the isoscalar meson exchange current, while simultaneously showing no discernible effect from the choice of the nucleon form factors. In addition, the tensor polarization has a small dependence on the choice of realistic deuteron wave functions. I believe that this represents the most sensitive test available for the isoscalar meson exchange current in nuclei. Of course, there are other calculations involving hybrid, six-quark bag models[10] and deltas in nuclei,[22] which indicate that t_{20} might be sensitive to the presence of quarks or deltas in the deuteron. Unfortunately, these calculations have not achieved the same degree of sophistication as that of the calculations presented here. For example, with regard to detecting the presence of deltas in nuclei, there is the open question of the effect of including the delta-delta interaction and the choice of the form factors for the delta. However, measurements of the polarization which occur significantly outside the region bound by the curves in Fig. 4 would be a signature for new physical processes of this kind. An indication of the momentum transfer region for new measurements of t_{20} are shown by the hatched regions at the lower part of the figure. Proposed internal target experiments[14,23,24] are denoted by the label Aladdin or PEP, which represent existing electron storage rings of energy 1

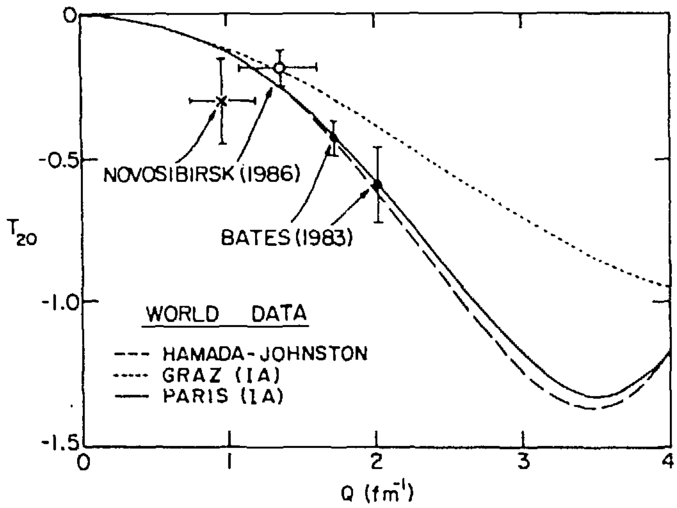

Fig. 5. Summary of all measurements of t_{20}. The two values at the highest momentum transfer were measured in an experiment at MIT-Bates where a polarimeter was employed to measure the polarization of the recoil deterons. The other two values were measured in an internal target geometry at Novosibirsk.

GeV and 14.5 GeV, respectively. The region labelled Bates represent the momentum transfer range which should be accessible in an experiment proposed[25] at the MIT-Bates Laboratory.

MEASUREMENT OF POLARIZATION IN ELECTRON SCATTERING

Previous measurements[26] of tensor polarization have been performed up to a momentum transfer of 0.16 $(GeV/c)^2$ with the use of a deuteron tensor polarimeter at the MIT-Bates Laboratory and are shown in Fig. 5. Additional measurements of t_{20} are planned at Bates to extend this range between 0.5 and 1.0 $(GeV/c)^2$. Experiments involving deuteron tensor polarimeters are extremely difficult in that it is necessary to perform the calibration of the polarimeter at a separate laboratory and ensure that the same conditions exist at the electron scattering facility. This additional source of systematic error is not present in an internal polarized target geometry. The amount of hardware for the external beam experiment is frequently cumbersome involving a large acceptance magnetic spectrometer in order to detect the electrons, a complicated large acceptance S-bend magnetic channel to direct the deuterons to the polarimeter, massive amounts of shielding and a high-power liquid deuterium target in addition to the calibrated polarimeter.

The advantages which the internal target method holds over an external beam experiment is best illustrated by considering a pilot

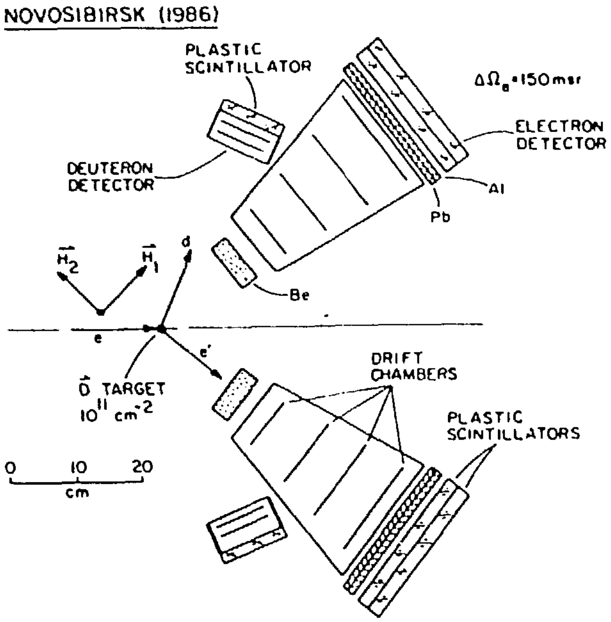

Fig. 6. Schematic diagram of the internal polarized deuterium target experiment at Novosibirsk. Note that large solid angle detectors were employed in the experiment in the presence of a 300 mA electron beam. The target thickness was only 10^{11} nuclei/cm^2.

experimen[27] which was performed at Novosibirsk and is illustrated schematically in Fig. 6. The most instructive lesson to be learned from this experiment is the relative simplicity and small scale of the detector system. Since the background in an internal target geometry is minimal, large solid angle detectors can be employed for both the scattered electrons and deuterons. The use of an average electron current of approximately 0.3 A and along with the large solid angle detectors (150 msr) emphasizes the small background in the internal target geometry. Even with the high current and large solid angle detectors, the experiment was limited by two key factors: small target thickness (10^{11} nuclei/cm^2) and low electron beam energy (400 MeV). A review of the internal target technology will be discussed in a moment, but it is expected that a target thickness of $\gtrsim 10^{14}$ nuclei/cm^2 can be achieved. Thus, the internal target method could, perhaps, represent the most powerful method for the study of polarization in electron-deuteron scattering.

CHARGE FORM FACTOR OF THE NEUTRON

One of the most elusive problems for electron scattering has been the determination of the charge form factor of the neutron.

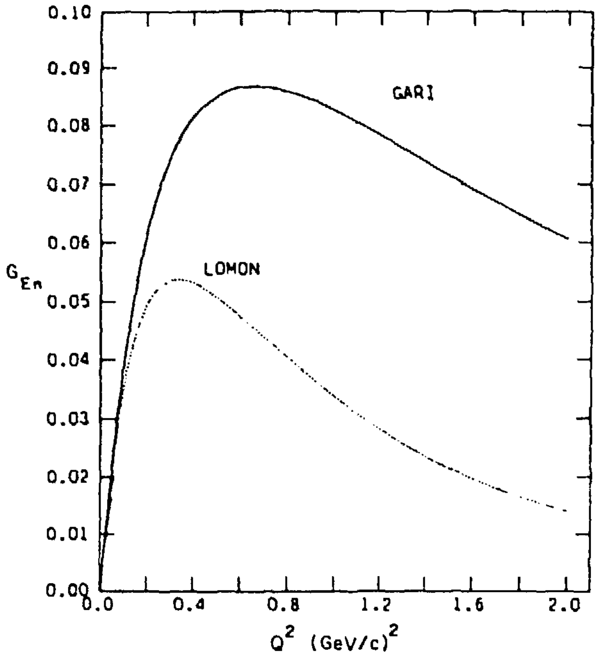

Fig. 7. Results of two analyses of the charge form factor of the neutron.

Earlier I emphasized the importance of measuring the nucleon form factors, and especially that of the neutron, in order to resolve issues in electron-deuteron scattering. Yesterday, Professor Hofstadter presented beautiful results for the form factor of the neutron based upon quasifree electron scattering from the neutron in the deteron. However, an ambiguity in the analysis of these kind of data seems to persist even today. As an indication of this ambiguity the charge form factor extracted from two analyses are illustrated in Fig. 7. The most recent analysis by Gari constrains the model to obey vector dominance at low momentum transfer and perturbative QCD at very high momentum transfer. The result is that the Dirac form factor F_{1n} becomes vanishingly small throughout the entire momentum transfer region and leads to a rather large form factor for the neutron. The difficulties of the measurement arises from the fact that there is no "clean" neutron target and that the charge form factor G_E is much smaller than the magnetic form factor G_M. Unlike the case for a spin-one nucleus a standard Rosenbluth separation can, in principle, resolve the charge and magnetic form factor of the nucleon, the charge form factor is obscured since G_E and G_M appear in the cross section as the sum of the squares of these quantities.

This problem can be alleviated greatly with the use of a polarization technique, where it is necessary to utilize a polarized electron beam as well as a polarized target. Consequently, it would be essential to have a dedicated ring for internal target studies of this kind and it is good to hear that proposals for internal target facilities exist at both the MIT-Bates and NIKHEF Laboratories. Fortunately, Norum has discussed[28] a technique for preserving longitudinal polarization of the electrons at an internal target location in a storage ring.

Although this experiment has been discussed[29] by H. Jackson elsewhere, I wish to summarize the essential points here. The expression for the cross section for longitudinally polarized electrons scattering from a polarized nucleon target as indicated in Fig. 8 is given according to Donnelly and Raskin[30] as

$$\sigma(\theta_e,\theta^*,\phi^*) = \sigma_M\, f_{rec}^{-1}\, \{V_L(1+\tau^2)G_E^2 + 2\, V_T\tau(1+\tau)G_M^2 +$$

$$-2\, P_eP_T\, [\tau(1+\tau)V_T'\, G_M^2 \cos\theta^* - (2\tau)^{1/2}(1+\tau)^{3/2}V_{TL}'G_EG_M \sin\theta^* \cos\phi^*]\}$$

where the V's, τ and f_{rec} are kinematic factors given by in Ref. 30, P_e and P_T are the electron and nucleon polarization, respectively. The most significant feature of this expression is the last term in which G_E and G_M enter linearly rather than as the sum of the squares and thus a polarization measurement remarkably increases the sensitivity to G_E. The orientation angles θ^* and ϕ^* of the target spin can be changed rapidly and precisely with an internal target geometry since only a magnetic field of several gauss is employed as a guide field; whereas, this process could consume hours for an external polarized target in which a 35 kg field must be reversed. The time required for a measurement of G_E to an accuracy of ± 20% with a luminosity of 10^{33} cm^{-2} s^{-1} and an energy (0.88 GeV) suitable for the proposed MIT-Bates ring is shown in Fig. 9. Note that a somewhat higher energy (1.3 GeV) produces a large reduction in the time required for the experiment. However, an energy higher than 2 GeV does not improve substantially the result, since the electrons for a given momentum transfer are scattered more foreward in angle and the resulting asymmetry becomes smaller.

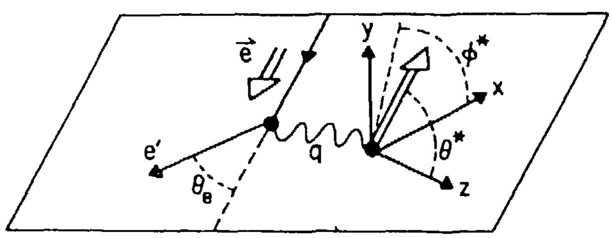

Fig. 8. Orientation of the spins of the electrons and the nucleon target in an electron-nucleon elastic scattering process.

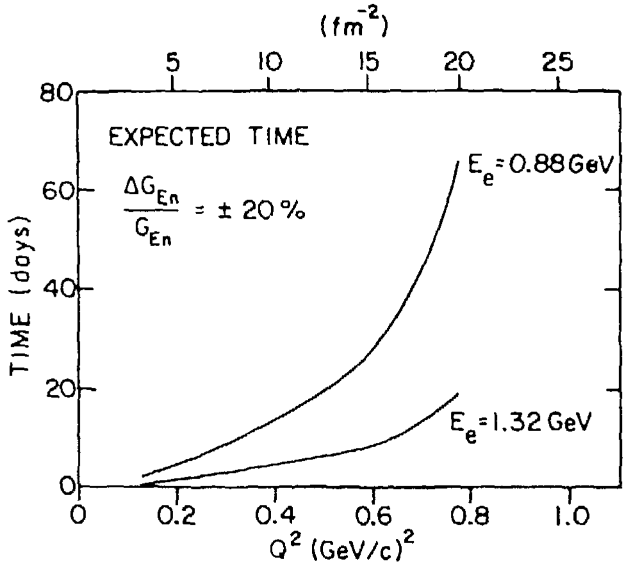

Fig. 9. Time estimate for a typical experiment at the proposed MIT-Bates ring to measure the charge form factor of the neutron to an accuracy of ± 20% and at two electron energies.

The choice of a target for the polarized neutron is critical, and thus far, ^{2}H and ^{3}He have been identified as candidates. Although the deuteron is considered the best case for the study of the neutron form factor, Blankleider and Woloshyn[31] point out that ^{3}He has the advantage that the magnetic scattering from the two protons in ^{3}He is minimized owing to the paired-off spins in the dominant configuration of the ^{3}He wave function. Thus, it is expected that both polarized deuterium and ^{3}He targets will have a major role in these measurements and I would like to turn to a discussion of recent developments in the internal polarized target technology.

DEVELOPMENTS IN INTERNAL POLARIZED TARGET TECHNOLOGY

The most significant progress in polarized gas or vapor targets in recent years has been reported[32,33] by two optical-pumping groups. In particular, it has been instructive to follow the progress of the groups at KEK and TRIUMF where relatively high densities of Na have been optically pumped in order to fabricate a high flux H$^-$ source. The approximate geometry of the KEK and TRIUMF work is illustrated schematically in Fig. 10. The two prominent features of this Na target are that it is windowless and no buffer gas is used in the optical pumping process. The TRIUMF group recent reported[33] a new record in target thickness: a Na↑ target thickness

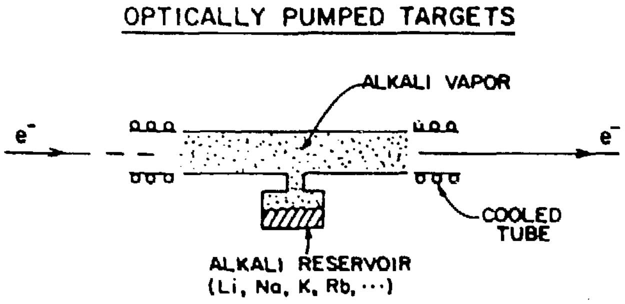

Fig. 10. Illustration of a possible geometry for a polarized internal vapor target.

of nearly 10^{14} nuclei/cm^2 and a polarization of 60% have been achieved. The TRIUMF group reports that no fundamental limitations have been observed as yet and they are planning to double the laser power in order to improve upon these results.

LeDuc et al.[34] have demonstrated that high densities (~ 10^{17} nuclei/cm^3) and polarization (~ 50%) of ^{3}He nuclei can be achieved in the laboratory by direct optical pumping of metastable ^{3}He. Work[35] is in progress at Caltech in order to assess the suitability of this technology for producing an internal or external polarized target of ^{3}He. Note that present-day, conventional external polarized ^{3}He targets[36] involve driving ^{3}He into its frozen solid state and heat from even the smallest amount of electron beam (picoamps) would destroy the target polarization. Thus far, the Caltech group have drawn two conclusions: (i) development of an internal polarized ^{3}He target of density $\gtrsim 10^{15}$ nuclei/cm^2 and a polarization $\gtrsim$ 50% appears to be practical, (ii) a high-density polarized ^{3}He target for use in an external electron beam appears to be practical for polarized electron beam currents exceeding 80 μA. In addition, it appears that recent developments[37] in polarized electron sources, particularly the ionization of optically-pumped metastable ^{4}He atoms, will be beneficial to the new generation of CW electron accelerators and this high current of polarized electrons should be practical.

As a final example of the technology I shall summarize the progress of attempts at Argonne to harness the spin-exchange optical pumping method in order to produce a polarized deuterium target. Here, the goal is to produce a target thickness of 10^{14} nuclei/cm^2 with a tensor polarization $t_{20} \gtrsim 0.3$. In order to achieve this density, it is necessary to utilize the highest flux source of polarized deuterium available as well as retain the atoms in a storage cell, as illustrated in Fig. 11. With the constraints that the storage cell should not exceed 10 cm in length and the atoms should not surpass 1000 collisions with the walls of the storage container before leaking out the "windows", it is imperative that ~ 4×10^{17} polarized atoms be injected into the storage cell during

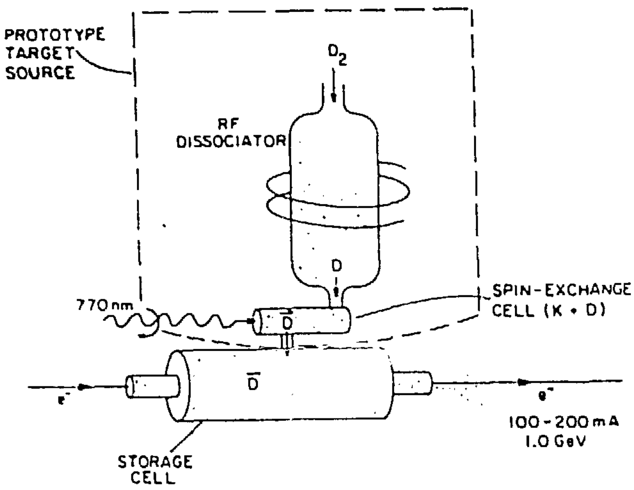

Fig. 11. Illustration of a possible internal polarized deuterium target geometry. The region oulined by the dashed curve denotes the prototype source which is being tested presently at Argonne National Laboratory.

each second. This high flux exceeds the capability of conventional[38] atomic beam sources by an order of magnitude, and consequently, the Argonne group is investigating the spin-exchange optical pumping method as a means of producing a high flux source. The primary difficulty with the conventional source is associated with the use of a hexapole magnet to polarize the atoms. The highest possible density of atoms is presented to the entrance of the hexapole and this density is limited by atom-atom collisions and recombination of the atoms (deuterium or hydrogen) at the entrance. Unfortunately, the hexapole can only transmit a small fraction of these atoms owing to the relatively small solid angle. In the spin-exchange optical pumping method, the hexapole magnet is eliminated and there exist no high-density regions which remove one from the molecular flow regime. At present, it is believed that the flux from this model source is limited only by laser power which would impose a practical flux of approximately 10^{18} atoms/s. Another important advantage of this technique over that of the conventional source is the relatively low gas load from unwanted atoms, and consequently, the novel source is well-suited for use in an electron strorage ring.

Specifically, the process which has been discussed[23,39] previously involves polarization of K atoms by optical pumping and polarization of the deuterium by successive collisions with the K↑ atoms. It is essential that the loss of polarization by atomic collisions with the walls of the spin-exchange cell be minimized. Fortunately, a number of surface coatings have been studied by two groups[40,41] at Wisconsin, and we have found[42,43] a coating known as drifilm to have suitable properties for the spin-exchange method. Presently, a prototype of the polarized source, shown as the outlined region in Fig. 11, is undergoing tests at Argonne. If these tests prove to be positive, the longer range goal is to develop a tensor polarized deuterium target for use in the Aladdin storage ring at Wisconsin, and perhaps, the PEP ring at SLAC.

SUMMARY

It was shown that the hitherto unexploited polarization technique in electron scattering is potentially a very powerful method for nuclear physics. The feasibility of employing internal targets in electron storage rings in conjunction with large solid angle detectors has been demonstrated by the group at Novosibirsk in which $^{16}O(e,e'x)$ experiments and $^{2}\vec{H}(e,e)^{2}H$ measurements were performed recently. Recent progress in optical pumping appears to be very promising for producing polarized targets of practical thicknesses. Finally, I predict that during the next thirty-five years of electron scattering studies, polarization measurements will have an important impact.

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