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EXPERIENCE WITH A POLARIZED ^{3}He TARGET FOR NUCLEAR SCATTERING EXPERIMENTS *

P.J.T. VERHEIJEN, R.H. McCAMIS, P. DRAKOPOULOS and W.T.H. van OERS

Department of Physics, University of Manitoba, Winnipeg, Canada R3T 2N2

J.M. DANIELS and A.D. MAY

Department of Physics, University of Toronto, Toronto, Canada M5S 1A7

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A polarized ^{3}He target, which uses conventional optical pumping with ^{4}He discharge lamps, is described. Emphasis is given to the experience gained with its use during nuclear scattering experiments using proton beams from the University of Manitoba cyclotron. An analysis of possible errors in present and past experiments is given.

1. Introduction

As one phase in a programme of experiments studying in detail the proton–^{3}He scattering system, a polarized ^{3}He target has been constructed for the measurement of ^{3}He analyzing powers between 20 and 45 MeV. The target is based on the system developed by Daniels et al. [1], where polarized ^{3}He was obtained by the optical pumping of triplet metastable ^{3}He atoms using circularly polarized light at 1083 nm from a ^{4}He discharge lamp [2]. This method derives from a coincidental matching of the 2 $^3S_1$; $F = 3/2$–2 $^3P_0$; $F = 1/2$ transition in ^{3}He and the 2 $^3S_1$–2 $^3P_0$ transition in ^{4}He. In this work, ^{4}He discharge lamps have still been used, but it should be noted that recent developments in laser technology [3,4] may allow the replacement of the ^{4}He lamps by more intense tunable lasers.

Central to our experiments is the accurate determination of analyzing powers, A_y, which are related to the target polarization, P, and the nuclear scattering asymmetry, ε_n, by:

$$\varepsilon_n = P \cdot A_y. \qquad (1)$$

Here, the statistical error in A_y is mainly determined by counting statistics, because ε_n is relatively small (< 0.05) and because the count rates are low due to the low target density (0.2 to 0.7 kPa). The systematic or normalization error in A_y, however, depends on the proper interpretation of the polarization measurement, which has been subject to various explanations [2,5–8].

In the following, a description is given of the target cell construction and of the apparatus. Subsequently, the polarization measurement is analyzed and finally, the use of this setup in actual experiments is discussed.

2. Target description

The geometry of the target cell (see fig. 1) was adopted after trials with thin spherical cells and cells having one extension only, at the proton beam entrance. In-beam tests of empty ^{3}He target cells proved that the background from spherical cells was excessive. Protons which scattered upon their entrance to the cell and then rescattered from the cell walls into the detectors were the principal cause of this background. Cells having

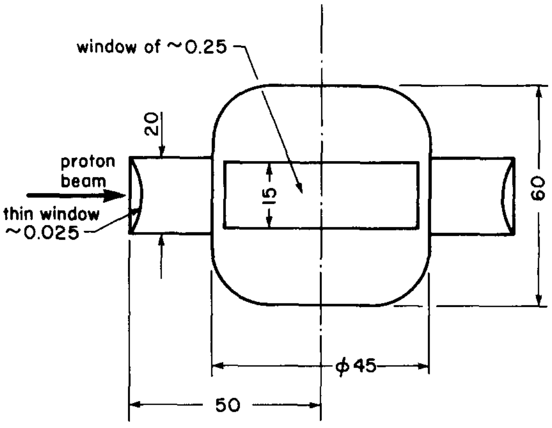

Fig. 1. Target cell (dimensions in mm).

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only one extension, at the beam entrance, proved adequate for the forward angles. However, for measurements at angles greater than 90°, cells with two extensions (fig. 1) were necessary, to minimize the effects of large angle scattering from the beam exit point. The cell walls in the scattering plane were etched to the minimum thickness, consistent with a pressure differential of one atmosphere, using concentrated hydrofluoric acid to decrease the energy loss of scattered protons and to reduce the background caused by rescattered protons. The cell diameter, 45 mm, is of the same order as that selected by other authors [5,9].

A special glass type, Corning no. 1720, had been used previously [10], because of its low helium permeation rate and its low depolarizing effect on polarized ^{3}He gas. However, it is a brittle glass, which is difficult to handle with standard glass-blowing techniques, resulting in high breakage rates. The second disadvantage proved to be the short lifetime of thin window seals under proton beam irradiation, despite the use of a special sealing technique [11]. Still, successful nuclear scattering experiments have been performed [12,13] with a few cells of this glass type.

Cells of standard laboratory Pyrex, Corning no. 7740, have better mechanical properties without a detectable decrease in polarization compared to similar cells of no. 1720 glass. The thicknesses of the thin windows in fig. 1 are the minima at which a pressure differential of one atmosphere could be maintained with no. 7740 glass. The method of attaching the thin windows to the cell body [14] was specially developed for the present application using no. 7740 glass.

Decontamination of the cells was achieved by rinsing with dilute (10%) hydrofluoric acid, water and acetone, followed by a bakeout period of five days under vacuum at 280°C [15]. Subsequently, the cells were cleansed by a discharge introduced into 0.1 kPa (0.133 kPa = 1 Torr) of ^{3}He rather than ^{4}He as used previously [16], because the latter could form an impurity. The final filling was obtained by diffusion through a quartz cell [15].

To find the optimal cell pressure, an analysis was made of the expected experimental duration (assuming some desired statistical uncertainty in the analyzing powers), taking into account the pressure dependence of the polarization [8] and data obtained from background studies of proton scattering from empty cells. The optimum pressure was 0.21 kPa, with a range from 0.15 to 0.45 kPa, when an increase in running time of 30% was considered acceptable.

The experimental layout (see fig. 2) for the production and measurement of polarization was similar to that developed by the Toronto group [8]. The Helmholtz coils gave a uniform magnetic field of 4.2 mT to provide an orientation axis for the polarized atoms. One ^{4}He lamp above and one below the target cell supplied polarized pumping light with opposite helicity. Metastable atoms were produced by the 1 MHz oscillator. Polarization measurement was carried out by observation of the fluorescent light. A set of coils was included to create an inhomogeneous magnetic field for instantaneous depolarization. The weak discharge electrodes, the light detector and the depolarizing coils were located inside the scattering chamber vacuum.

The level of weak discharge was set for each cell to achieve maximum polarization, which was normally slightly above the lowest sustainable discharge, but below the ignition voltage. The optimal frequency and intensity of the weak discharge have been studied previously [15,17].

The pumping light sources [1] were operated at maximum output power. The power supplies for both lamps were driven from one master oscillator to avoid the existence of a beat frequency which could otherwise have been picked up by the surface barrier detectors in

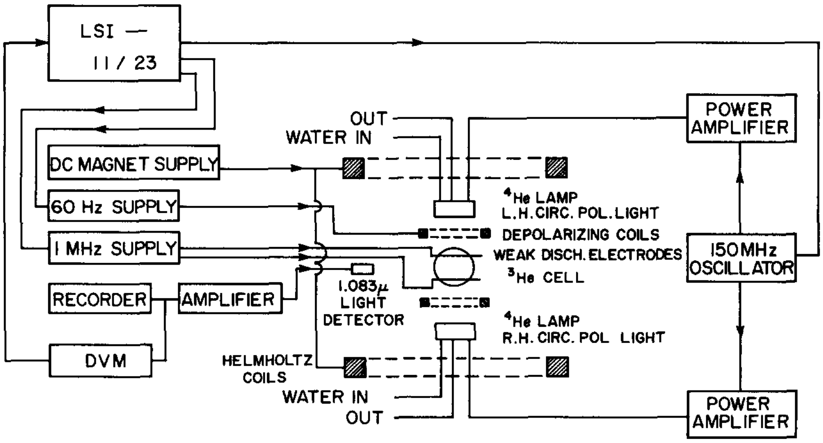

Fig. 2. Experimental layout of the apparatus for polarization and its measurement.

the vicinity of the target cell. One lamp could have been replaced by a mirror [18], but this was not equally effective in our case, and it introduced uncertainties into the polarization measurement, due to the possibility of introducing changes in the relative transition rates induced by the pumping light (see the discussion of the R_m coefficients in the following section).

3. Polarization measurement

The fluorescence or absorption signal, $I(P)$, is a direct measure of the occupation distribution of the various magnetic sublevels and therefore a measure of the nuclear polarization [2]. In a first approximation:

$$I(P) = I(0) \sum_{m=-1}^{+1} R_m \frac{(1-P)^{1+m}(1+P)^{1-m}}{1+P^2/3} \times \left(1 - \frac{m}{2} P\right), \qquad (2)$$

where m is the change in magnetic quantum number due to the absorption of pumping light, P is the polarization and R_m are the relative rates of $m = -1$, 0, or $+1$ transitions. This was derived [19] assuming low absorption rates of the light and assuming that the pumping light only excites the 2 $^3S_1$; $F = 3/2$–2 $^3P_0$; $F = 1/2$ transition.

The measurement procedure used here consisted of observing the fluorescence light signal before and immediately after depolarization. The ratio $[I(0) - I(P)]/I(0)$ is a function of P alone when the constants R_m are known. The method was adopted because of its reliability and flexible implementation as only one light detector needed to be placed in the scattering chamber. As the measurement cycle consisted of a series of observations at various combinations of on or off states of the weak discharge and the pumping lights before and after depolarization, it became expedient to do this under the control of an LSI-11/23 microprocessor, connected to a Hewlett-Packard 3456A programmable voltmeter (see fig. 2).

With an ideal pumping light source (of parallel, 100% right-hand circularly polarized light), the constants R_m [see eq. (2)] are 0, 0 and 1 for $m = -1$, 0 and $+1$ respectively. If P_0 is the polarization calculated with eq. (2) for these values of R_m, then, for a non-ideal case, to a first approximation:

$$P = P_0 (1 + R_0 + 2R_{-1})(1 + \tfrac{1}{2} p_a) \times [1 + 0.24(1 - f)/f], \qquad (3)$$

where p_a is the probability for the pumping light to be absorbed in the cell and f is the fraction of the pumping light that excites the 2 $^3S_1$; $F = 3/2$–2 $^3P_0$; $F = 1/2$ transition. The three factors in brackets describe the effect of a non-ideal light source and the estimated contributions of the two assumptions made in the derivation of eq. (2).

Table 1
Various estimations for the constant f in eq. (3) and the renormalization factor necessary to obtain the correct polarizations for $f = 1$ (see text for details).

Previous value for "f"	Renormalization factor	Reference
0.50	0.80	[2]
0.75	0.91	[5,27]
0.80	0.94	[9]
0.84	0.95	[6]
1.00	–	[7]

The first factor is derived directly from eq. (2) and is estimated to be 1.06 ± 0.03 [12,15] for the present pumping lamps. The second factor can be derived when the absorption in the cell is described by an exponential function [20] along the path of the pumping light. As the total absorption probability, p_a, is on the order of 0.02 [2], it is estimated that this factor might be about 1.01, although for a cell at a higher pressure, 0.65 kPa, this was estimated to be 1.04 [12].

The constant f in the last factor of eq. (3) has been subject to various estimations (see table 1). However, it has been shown [21] that no transition other than that mentioned above is affected so that $f = 1$ and the last factor of eq. (3) can be deleted.

For the calculation of the polarization we have utilized the whole of eq. (2) and the second factor of eq. (3). The total normalization error came to ± 0.05, which could be improved when the absorption probability p_a and the constants R_m are better known.

Repeated polarization measurements (at $P \approx 0.15$)

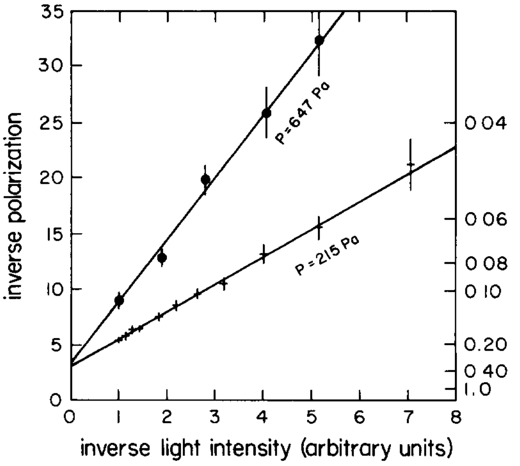

Fig. 3. Pumping light intensity dependence of the polarization.

gave an estimate for the stochastic error of 0.004, which could not be explained by the existence of fluctuations in the pumping light or uncertainties in the signal detection. A possible explanation is the existence of instabilities in the weak discharge. Further, the dependence of the polarization on the weak discharge is complicated [8,12], but with respect to the pumping light it is expected that the inverse of the polarization depends linearly on the inverse of the pumping light intensity [22]. This has been verified (see fig. 3) and it confirms part of the theory describing the polarization kinematics [19] on which also eq. (2) is based.

4. Nuclear scattering experiment

All elements of the scattering chamber (see fig. 4) were constructed of nonmagnetic materials such as aluminum, to avoid depolarizing magnetic field gradients [23] at the target cell. The chamber had two aperture defining systems (whose dimensions are shown, in mm, in fig. 4) which were independently rotatable and were mounted on the lids of the chamber. The scattered protons were simultaneously detected at four angles, each separated by 10°, on either side of the beam. The multiplicity of angles was necessary to get sufficient count rates, due to the low pressures which were necessary in the ^{3}He cell. The front slits were made of tantalum, whose thickness was just equal to the range of the maximum energy protons used, to reduce slit edge scattering. The angular resolution of the slit system is 2.0° and the total resolution is 2.1 to 4.7° (depending on proton energy and scattering angle, due to the variable multiple scattering in the glass walls).

At forward angles ($< 90°$) normally ΔE–E telescopes were used, consisting of a 200 μm surface barrier detector inside the chamber and a NaI detector (38 mm diameter by 13 mm thick) outside the chamber (see fig. 4). The scattering chamber had a 19 mm wide slot in the scattering plane, covered with 0.13 mm thick plastic foil, to allow the particles to reach the NaI detectors with a minimal loss of energy. Telescopes with two surface barrier detectors (100 and 1 000 μm) had to be employed at the back angles ($> 90°$), because the protons were considerably less energetic due to the kinematics of proton scattering from ^{3}He and due to increased energy loss in the glass cell windows at lower proton energies.

The chamber was designed to cover a range of angles from 15 to 165°, but it was only feasible to measure between 30 and 140°, due to restrictions caused by the extensions on the cell body (see fig. 1).

After passing through the target cell, the proton beam entered a well-shielded Faraday cup, which was electrically connected to a current integrator for normalization purposes. The beam currents used were normally between 50 and 100 nA. Factors influencing the selection of beam currents were the desirability of maximum counting rate with the thin ^{3}He gas target and the necessity of limiting any stresses in the thin entrance and exit windows of the glass cells caused by beam heating. Typical beam spots at the target position were 4 mm in width by 10 mm in height.

The measured asymmetries consisted of the nuclear

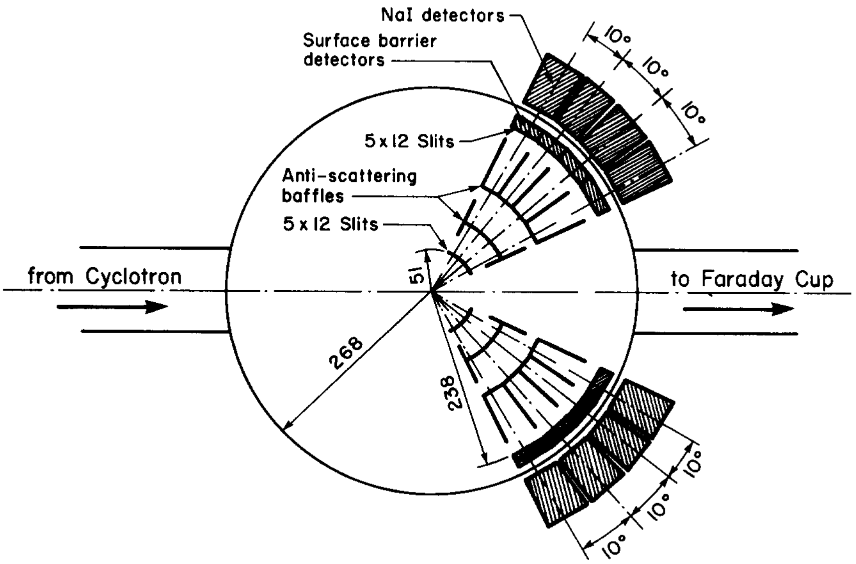

Fig. 4. Scattering chamber (dimensions in mm).

scattering asymmetry ($\lesssim 0.05$), an instrumental asymmetry (< 0.04) and an asymmetry (≈ 0.01) related to the presence of the magnetic field (4.2 mT) for the polarized target, which alters the path taken by the scattered protons on their way to the detectors. A complete cycle of measurements then consisted of four consecutive periods with each possible combination of directions for the polarization and magnetic field. Each run lasted about 2 h and a total cycle took 9 to 10 h. The length of time taken was a result of weighing long-term stability characteristics of the proton beam and the target polarization against the fraction of down time introduced by the necessity of measuring the polarization after each run and of repolarizing the target.

The polarization in a cell could be maintained for several days. Drifts only occurred due to deteriorating pumping lights or the build up of impurities in the cell after prolonged proton bombardment. The average of the polarizations observed before and after a 2 h run was used as the measure for the polarization. The relative error in this was much smaller than that from counting statistics in ϵ_n [eq. (1)], even after accounting for possible polarization drifts.

Target cells have been used with polarizations ranging from 0.11 at 0.65 kPa, to 0.21 at 0.22 kPa.

5. Discussion and conclusions

The use of target cells of Corning no. 7740 glass as shown in fig. 1 and the automation of the polarization measurements facilitated a smooth operation of the polarized target. Its performance can be evaluated using the $P^2\rho$ criterion, the product of the polarization squared and the target density. The present polarized target is approximately twice as efficient as the original design [1] and comparable to or better than other targets, except for that of the Swiss group [6,24], which appears to be another factor of two better yet.

The fact that all these polarized ^{3}He experiments produced similar results is due to a limit on the output from conventional ^{4}He discharge lamps as sources of circularly polarized light. Also, we have found that these lamps are prone to deterioration because they are driven at maximum output. The recent development of tunable lasers at 1083 nm [4] to replace these lamps is most encouraging. Long-term stability has not yet been achieved for these lasers, although intermittent running for continuous periods of a few hours can now be obtained [25]. A typical experiment on an accelerator usually runs for one or more weeks, however. A target polarized by laser light optical pumping could be expected to increase the value of $P^2\rho$ by a factor of five over the present results.

The normalization error in the polarization ($\Delta P/P$) is 5%, which is attributable to uncertainties in R_m and p_a [eq. (3)]. The error can be reduced when a separate, well-collimated measurement beam is used which is completely circularly polarized [6,26]. It would also allow the monitoring of the polarization during a nuclear scattering experiment. However, at present, we observe just the fluorescence signal during an experiment and this has proven adequate for detection of malfunctioning apparatus.

So far, the normalization error had been related to an uncertainty in the constant f of eq. (3) [5,9]. With eq. (3), it is possible to calculate the constant which should be used to renormalize the quoted polarizations, in order to get the correct result for $f = 1$. The second column of table 1 presents these normalization factors, which also include the effect of an absorption probability which has been taken to be $p_a = 0.02$. Further, the spin parameters (analyzing powers, etc.) which have been determined in the past by a number of authors should be corrected by these renormalizations, which lead to higher values of the ^{3}He analyzing powers and spin correlation parameters.

The polarized ^{3}He target herein described has been used to measure ^{3}He analyzing powers for proton–^{3}He elastic scattering between 40 and 90° (laboratory angles) at 25 MeV, between 30 and 140° at both 30 and 35 MeV and between 30 and 100° at 32.5 MeV [12,13], while future experiments are presently being planned at 32.5 and 40 MeV.

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