

Loss of polarization by a deuteron beam in hydrogen

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Measurements are reported of the loss of tensor polarization of a deuteron beam with energy between 60 and 370 keV passed through hydrogen gas at a pressure of 20 Torr. At one energy (229 keV) the polarization has been measured for pressures between 1 and 20 Torr. Monte Carlo computer calculations lead to polarization losses which are too high and, therefore, at low energies the polarization of a beam transmitted by a gas must be determined experimentally.

1. INTRODUCTION

When polarized ion sources were developed for tandem accelerators well over ten years ago, it was established^[1] that the beam polarization remains practically unaffected during charge transfers between fast ions and a solid target, but in gaseous targets there were polarization losses, especially at low energies. This is due to the fact that the polarized particle spends some time in the neutral state and, in the case of charge transfers in gaseous, i.e., extended targets, this time is much longer than in a solid, i.e., compact, target. The spin of the polarized particle precesses in the magnetic field of the electron coupled to it, and there is a resulting reduction in the initial polarization.

Despite this fact, gas targets are widely used, for example, in the study of nuclear reactions with polarized beams. Special depolarization measurements must however be carried out for such targets. Lindstrom et al.^[2] have determined the polarization losses for a beam of deuterons with $E_d = 160$ keV in a thin helium target (thickness $\Delta E_d \leq 1$ keV) at pressures between 0.15 and 70 Torr, and have used an approximate method for calculating the polarization losses.

The aim of the present research was to investigate polarization losses for a beam of deuterons with energies between 60 and 370 keV in a hydrogen target with thickness ΔE_d of the order of 40 keV.

2. EXPERIMENT

The experiments were carried out on a Cockroft-Walton accelerator incorporating a source of polarized deuterons (and protons). The tensor-polarization analyzer was a solid tritium-zirconium target which could be mounted at the center of the chamber filled with the hydrogen gas at a distance of 9.4 cm from the entrance aluminum film. The latter could withstand a pressure drop of not more than 25 Torr. Two photomultipliers with thin CsI (Tl) phosphors were mounted at 90° and 135° to the beam. These recorded α particles from the $H^3(d, \alpha)n$ reaction. The tensor analyzing power of this reaction at about 200 keV was investigated in some detail in^[3]. If we use these results, we can determine the tensor polarization of the deuteron beam from the counting rates in the two scintillation counters for two orientations of the magnetic field in the source, which fixes the direction of polarization of the deuterons.

To eliminate the effect of the vacuum conditions in the source on the magnitude of the polarization, we carried out measurements of background counts and introduced the relevant corrections.

Since we are interested only in the relative values of the tensor polarization T/T_0 (T_0 is the tensor polarization

of the beam entering the chamber and T is the tensor polarization at the center of the chamber), the polarization T obtained for the energy E_d at the center of the gas-filled chamber was normalized to T_0 measured in the same chamber with both the gas and the aluminum film removed. This was done at beam energy $E'_d = E_d + \Delta E_d$, i.e. at the energy corresponding to the entrance point into the gas. The thickness of the aluminum film and the energy spread ΔE_d in the hydrogen gas were measured for different values of the energy E_d at the center of the chamber in special calibrating experiments, using the $F^{19}(p, \alpha\gamma)O^{16}$ ($E_p = 340.5$ keV) and $Li^7(p, \gamma)Be^8$ ($E_p = 441.2$ keV) reactions in the same chamber with and without the hydrogen gas.

Figure 1 shows the results of measurements of the relative tensor polarization T/T_0 of a deuteron beam which has traversed a path of 9.4 cm in hydrogen at 20 Torr for different values of E_d between 60 and 370 keV. Figure 2 shows the experimental data obtained at the single energy $E'_d = 229$ keV, but for different pressures in the range between 1.05 and 20 Torr.

3. CALCULATION OF POLARIZATION LOSSES

In a sufficiently dense gas, the deuteron will frequently capture and lose unpolarized electrons along its

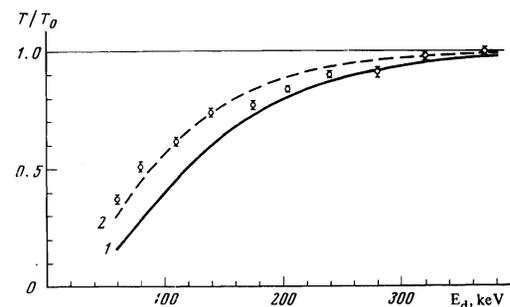


FIG. 1. Relative tensor polarization T/T_0 of a deuteron beam traversing a length of 9.4 cm in hydrogen at a hydrogen pressure of 20 Torr as a function of the deuteron energy E_d at the end of the path: \circ —experimental data obtained in this work, 1—Monte-Carlo calculations, 2—Monte-Carlo calculations with σ_{10} reduced by a factor of two as compared with the value given in^[4].

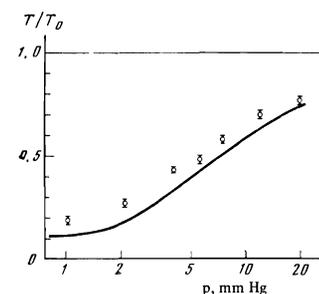


FIG. 2. Relative tensor polarization T/T_0 of the deuteron beam which has traversed a path of 9.4 cm in hydrogen (initial energy 229 keV) as a function of pressure p : \circ —experimental data obtained in this work, curve—calculated.

path. Let us consider a segment of the path, x_1 , between electron capture and electron loss events. The tensor polarization at the end of this path is ¹⁾

$$\frac{T}{T_0} = 1 - \frac{4}{3} \sin^2 \left(\frac{\pi \nu_0 x_1}{v_d} \right), \quad (1)$$

where $\nu_0 = 327.4$ MHz is the fine splitting frequency of the deuteron atom and v_d is the deuteron velocity. The segments x_i have the distribution

$$w_{01}(x_i) = n\sigma_{01} \exp(-n\sigma_{01}x_i), \quad (2)$$

and the segments y_i which the deuteron traverses without the electron have the distribution

$$w_{10}(y_i) = n\sigma_{10} \exp(-n\sigma_{10}y_i), \quad (3)$$

where σ_{01} is the ionization cross section of the atom and σ_{10} is the electron capture cross section of the ion. If the beam traverses a distance l in the gas, the mean number of charge transfers is $M = nl\sigma_{10}\sigma_{01}/(\sigma_{01} + \sigma_{10})$. It is shown in ^[2] that when l is small enough to ensure that energy losses experienced by the beam in the gas can be ignored, and sufficiently large to ensure that the large-number rule can be used for M ($M > 4$), the tensor polarization is given by

$$\frac{T}{T_0} = \left(1 - \frac{2}{3} \frac{f}{1+f} \right)^M, \quad f = \frac{2\pi\nu_0}{v_d n \sigma_{10}}. \quad (4)$$

Calculations based on this equation are given in ^[2] but, instead of the cross sections σ_{10} and σ_{01} for helium, use was made of the data for air (curve 3 in Fig. 3).

In our case, when the energy losses amounted to up to 60 keV, it was more convenient to employ a Monte-Carlo computer calculation. The program incorporated the energy dependence of the capture cross section σ_{10} and the ionization cross sections σ_{01} , taken from the paper by Stier and Barnett, ^[4] as well as the energy-range relation given in ^[5]. The program generates a series of random segments $x_1, y_1, x_2, y_2, x_3, \dots$, satisfying the distributions (2) and (3), calculates the mean deuteron velocity v_d in these segments, and determines the random change in the polarization T/T_0 ($M \approx 100$) by the successive application of (1). Repeated application of this procedure yields the mean value of T/T_0 with sufficient accuracy. In addition, the program generates the mean values of E_d and the mean charge of the beam.

Figure 1 (curve 1) and Fig. 2 show the results of the computations carried out on the BESM-6 computer for the polarization losses in hydrogen under the conditions of our experiments. The results of calculations of the deuteron polarization losses in helium over a path of 0.55 cm with $E_d = 160$ keV for pressures between 1 and 100 Torr (i.e., under the experimental conditions prevailing in ^[2]) are shown in Fig. 3 [curve 1—Monte-Carlo calculations, curve 2—calculations based on (4)]. The cross sections σ_{01} and σ_{10} for hydrogen in helium were taken from ^[4].

4. DISCUSSION

If we compare our experimental data for hydrogen and the data of Lindstrom et al. ^[2] for helium with the results of the above calculations, we note that the computed curves are in qualitative agreement with experiment but predict in both cases a polarization loss which is too high (especially at low energies).

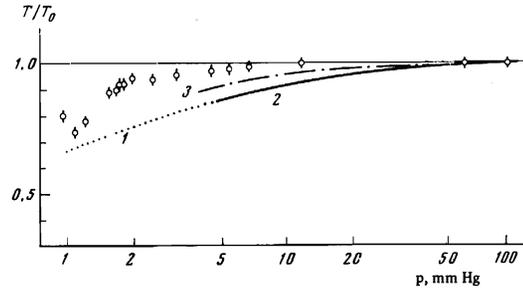


FIG. 3. Relative tensor polarization T/T_0 of the deuteron beam which has traversed a path of 0.55 cm in helium (initial beam energy 160 keV) as a function of pressure p : O—experimental data from ^[2], curve 1—Monte-Carlo calculations, curve 2—calculations based on (4) carried out in this work, curve 3—calculations based on equation (4) in ^[2] (using the cross sections for air instead of helium).

To obtain agreement between the calculated and experimental data, we attempted to take into account the difference between the energy losses for neutral atoms and positive ions. The result was a difference in the spread in the final energy E_d , but no effect on the polarization was obtained.

The difference between the calculated and measured polarizations may be due to systematic experimental errors in σ_{01} and σ_{10} for hydrogen and helium in ^[4]. It is important to note, however, that agreement between the calculations and the measurements would require a very substantial change in σ_{01} and (or) in σ_{10} , well outside the limits of experimental error quoted in ^[4]. For example, the assumption that σ_{10} is in reality smaller by a factor of two than the value given in ^[4] will produce satisfactory agreement with experiment (curve 2 in Fig. 1) especially below 160 keV. This assumption is not in conflict with, for example, the theoretical work of Jackson and Schiff, ^[6] which predicts a value for σ_{10} ($E_d = 200$ keV) which is lower by a factor of two than the result reported in ^[4]. Our experiments do not, however, enable us to conclude unambiguously which of the two cross sections σ_{10} or σ_{01} should be corrected.

Thus, our conclusion is that, when polarization experiments with gas targets are carried out at low energies, it is essential to carry out polarization calibrations in each case.

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¹⁾The relative vector polarization is $P = P_0 [1 - 4/9 \sin^2(\pi \nu_0 x_1 / v_d)]$.

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