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Resonance-like production of tensor polarization in the interaction of an unpolarized deuteron beam with graphite targets

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Abstract. As shown in a recent paper, an initially unpolarized beam of deuterons can acquire appreciable tensor polarization by traversing a graphite foil. Here those results are presented which result when the earlier linear fits to the measured data are replaced by quadratic fits, taking into account slight non-linearities. The parameters of the fit to the energy dependence of the tensor polarization are discussed. Measured asymmetries confirm the azimuthal symmetry of the beam behind the targets. The values of $p_{zz}$, achievable with graphite foils, are discussed.

1. Introduction

Nuclear spin dichroism leads to the appearance of tensor polarization in an initially unpolarized, forward-transmitted beam of (spin 1) deuterons behind a target composed of spin-zero nuclei like carbon [1]. The direction of the primary and the transmitted beam defines the quantization axis. Because of the azimuthal symmetry, the polarization of the beam behind the target is described by the tensor-polarization component $p_{zz}$. In the unpolarized initial beam of total intensity $I_{\text{tot}}(0)$, the relative intensities of deuterons in the substates $m = +1$, $m = 0$ and $m = -1$ are $I_{+1}(0) = I_{0}(0) = I_{-1}(0) = \frac{1}{3}I_{\text{tot}}(0)$. Due to its definition (e.g., [2]) $p_{zz}(0) = (I_{\text{tot}}(0) - 3I_{0}(0))/I_{\text{tot}} = (I_{+1}(0) + I_{-1}(0) - 2I_{0}(0))/I_{\text{tot}}(0)$ is equal to 0. Accordingly, $p_{zz}$ behind the target reads

$$p_{zz}(pd) = \frac{I_{+1}(\rho d) + I_{-1}(\rho d) - 2I_{0}(\rho d)}{I_{+1}(\rho d) + I_{-1}(\rho d) + I_{0}(\rho d)},$$

where $\rho$ is the number density of nuclei in the target (per unit of volume) and $d$ its thickness (in units of length). The interaction of deuterons of energy $E$ with the spin-zero target nuclei is described by total cross sections $\sigma_{+1}$, $\sigma_{-1}$ and $\sigma_{0}$. The symmetry in the interaction allows to set $\sigma_{+1} = \sigma_{-1} = \sigma_{\pm 1}$. For a thin target of thickness $\delta$ and negligible energy loss of the deuterons,
\[ I_{+1}(\rho \delta) = I_{-1}(\rho \delta) = \frac{1}{4} e^{\rho \delta} \sigma_{\pm 1}(E) \delta \] and \[ I_0(\rho \delta) = \frac{1}{4} e^{\rho \delta} \sigma_0(E) \delta. \] For a thick target, \( p_{zz} \) results from integration over the range of deuteron energies in the target as

\[ p_{zz}(\rho \delta) = \frac{2 \rho \int_0^{d} \sigma_{\pm 1}(E(x)) dx - 2 \rho \int_0^{d} \sigma_0(E(x)) dx}{2 \rho \int_0^{d} \sigma_{\pm 1}(E(x)) dx + \rho \int_0^{d} \sigma_0(E(x)) dx}. \]  

(2)

The integrals cover the cross section values between those at the initial beam energy, \( \sigma_{\pm 1,0}(E_{\text{in}}(x = 0)) \), and those at the beam energy behind the target, \( \sigma_{\pm 1,0}(E_{\text{out}}(x = d)) \).

Measurements of \( p_{zz} \), produced by a set of graphite targets, have been performed with unpolarized deuteron beams from the HVEC FN Van de Graaf tandem accelerator of the Institut für Kernphysik of the Universität zu Köln. The experimental setup with the polarimeter, based on the \( \vec{d} + ^3\text{He} \rightarrow p + ^4\text{He} \) reaction, was described in a recent paper [3]. The values of \( p_{zz} \) were derived from linear fits to the ratios of counts in the five proton detectors of the polarimeter, measured as function of the deuteron energy in the polarimeter cell. The results of the present contribution were obtained by replacing the earlier linear fit functions by quadratic functions to account for slight non-linearities.

2. Experimental procedure and results

As discussed in Ref. [3], for each of the seven graphite targets and the gold reference target a set of primary beam energies \( E_{\text{in}} \) with steps of 0.1 MeV was utilized, chosen such that the deuteron energies \( E_c \) in the \(^4\text{He} \) gas cell of the polarimeter ranged from 5 to 8 MeV (see table 1). The

| Table 1. Target material \( M \) and areal density \( d_t \), target label, run (I: 2003, II: 2006), minimal and maximal primary deuteron beam energies \( E_{\text{in}} \), and minimal and maximal mean deuteron energies \( E_c \) in the \(^4\text{He} \) polarimeter cell. |
|-----------------|--------------------|--------|----------------|-----------------|
| \( M \) | \( d_t \) [mg/cm\(^2\)] | \( \delta \) | Run | \( E_{\text{in}} \) [MeV] | \( E_c \) [MeV] |
| Au  | 5.0 ± 0.3 | Au5 | II | 6.20 | 7.90 | 5.56 | 7.36 |
| C   | 35.90 ± 0.19 | C36 | II | 9.50 | 10.50 | 6.06 | 7.41 |
| C   | 57.69 ± 0.32 | C58 | I  | 10.80 | 12.20 | 5.73 | 7.83 |
| C   | 93.59 ± 0.37 | C94 | II | 13.00 | 14.00 | 5.72 | 7.46 |
| C   | 129.49 ± 0.42 | C129 | II | 14.80 | 15.90 | 5.41 | 7.55 |
| C   | 152.63 ± 0.75 | C153 | I  | 16.20 | 16.70 | 5.94 | 6.97 |
| C   | 165.39 ± 0.46 | C165 | II | 16.70 | 17.50 | 5.70 | 7.39 |
| C   | 187.93 ± 0.74 | C188 | I  | 17.50 | 18.70 | 5.11 | 7.78 |

The tensor polarization of the beam behind a target for a value of \( E_c \) is derived from the ratio

\[ r(E_c) = \frac{N_L(E_c) + N_U(E_c) + N_R(E_c) + N_D(E_c)}{N_F(E_c)}. \]  

(3)

The \( N_i(E_c) \) denote the counts of protons from the polarimeter reaction in the four side detectors, positioned at polar angles of 24.5° and azimuthal angles 0°, 90°, 180°, and 270° (labelled L, U, R, D), and the forward detector (labelled F). Figure 1 shows the deviation of the measured ratios \( r^{C_i}(E_c) \) and the quadratic fits \( r_{\text{fit}}^{C_i}(E_c) \) from the fit \( r_{\text{fit}}^{Au5} \) to the reference data \( r^{Au5}(E_c) \). The figure corresponds to figure 2 of reference [3] for the linear fits. From the \( r_{\text{fit}}^{C_i}(E_c) \) and
Figure 1. Difference between the fits and measured ratios \( r(E_c) \) and the fit to the Au5 data. To ease readability, data points were combined. The fit lines cover the full energy ranges given in table 1. The given errors include the statistical errors of the measured ratios and the sample standard deviation \([5]\) of the fit to the Au5 ratios.

\[ r_{\text{fit}}^{\text{Au5}}(E_c) \] the following expression for \( p_{zz} \) of the beam is obtained \([3]\),

\[
p_{zz}^{C_z}(E_c) = \frac{2 \cdot [r_{\text{fit}}^{\text{Au5}}(E_c) - r_{\text{fit}}^{C_z}(E_c)]}{r_{\text{fit}}^{C_z}(E_c) A_{zz}(E_c, 0^\circ) - r_{\text{fit}}^{\text{Au5}}(E_c) A_{zz}(E_c, 24.5^\circ)}.
\] (4)

It is obvious from equation 2 that, for two targets of different thickness but identical \( E_c \), the difference in \( p_{zz} \) has to be attributed to the additional range of higher deuteron energy in the thicker target. Therefore, in figure 2 the seven sets of \( p_{zz} \) are plotted as a function of the initial beam energy \( E_{\text{in}} \). The coarse structure of the energy dependence corresponds to that derived with the linear fit functions \([3]\), figure 3), whereas the energy dependence within the data sets for the individual targets are modified by the use of the quadratic fit functions. The deviation from the calculated \([4]\) smooth energy dependence is more pronounced than that resulting from the linear fit functions (cf. figure 3 of reference \([3]\)).

To describe the production of polarization during deceleration in the targets with the use of equation 2, the energy dependences of the cross sections \( \sigma_{\pm 1}(E) \) and \( \sigma_0(E) \) are assumed to be
Gaussian-distributed,

\[
\sigma_{\pm 1.0}(E) = \sigma_{\pm 1.0}(E_0) \cdot e^{-2.7707 \cdot \frac{(E-E_0)^2}{\Gamma_{1/2}^2}}.
\]

The integrals of equation 2 are replaced by sums over thin target layers, the deuteron energy \(E(x)\) within each layer is calculated with the use of the Bethe-Bloch energy-loss formula. The parameters \(\sigma_{\pm 1.0}(E_0)\), \(E_0\) and \(\Gamma_{1/2}\) were varied in a manual procedure to reproduce the measured energy dependence. Either \(\sigma_{\pm 1}(E_0) > 0\), \(\sigma_0(E_0) = 0\), resulting in \(p_{zz} < 0\), or \(\sigma_{\pm 1}(E_0) = 0\), \(\sigma_0(E_0) > 0\), resulting in \(p_{zz} > 0\), were chosen to reproduce the slope in the energy dependence. The parameters of the 15 cross-section distributions, requested for a reasonable fit (figure 3), are given in table 2.

Unfortunately, the present measurements do not cover the range between \(E_{\text{in}}=14.0\) and 14.8 MeV. The distinct jump in \(p_{zz}\) requests the peak no. 10 around \(E_0=14.4\) MeV. The estimated errors of the data given in table 2, are \(\leq 0.3\) MeV for \(E_0\) and \(E^*(14^N\text{N})\), \(\leq 20\%\) for \(\Gamma_{1/2}\), and 10 to 20\% for \(p_{zz}\). The excitation energies in the compound nucleus \(E^*(14^N\text{N})\), calculated from the \(d, 12^C, 14^N\) masses and the laboratory energy \(E_0\), are in surprising agreement with the energies of known \(14^{N}\) states [6]. This finding indicates resonance formation of compound states in the \(d-12^C\) interaction at appropriate deuteron energies during deceleration in the targets. A similar interpretation has been given for the measured selective structure of the excitation function in elastic \(d-12^C\) scattering [7] at lower deuteron energies. The present data for the cross sections at \(E_0=14.4\) and 15.6 MeV reflect the structure in the excitation function of the reaction \(12^C(d, \alpha)^{10}\text{B}^*(1.74\text{ MeV})\) [6]. These similarities may lead the way to interpret the present results.

### Table 2. The parameters \(E_0\), \(\sigma(E_0)\), and \(\Gamma_{1/2}\) of the cross-section distributions describing the deuteron-carbon interaction, the tensor polarization \(p_{zz}\) produced by the single peak, and the excitation energy in the compound nucleus \(14^{N}\) at the laboratory energy \(E_0\) (error estimates are given in the text).

| no. | \(E_0\) [MeV] | \(\sigma(E_0)\) [b] | \(\Gamma_{1/2}\) [keV] | \(p_{zz}\) | \(E^*(14^N\text{N})\) [MeV] |
|-----|--------------|----------------|----------------|---------|----------------|
| 1   | 19.0         | 300            | 500            | 0.13    | 26.5           |
| 2   | 17.8         | 150            | 500            | -0.06   | 25.5           |
| 3   | 17.5         | 860            | 150            | 0.10    | 25.3           |
| 4   | 17.1         | 50             | 200            | 0.01    | 24.9           |
| 5   | 16.7         | 1050           | 80             | -0.07   | 24.6           |
| 6   | 16.5         | 240            | 200            | 0.04    | 24.4           |
| 7   | 16.1         | 2300           | 100            | -0.18   | 24.1           |
| 8   | 15.9         | 140            | 500            | 0.05    | 23.9           |
| 9   | 15.6         | 380            | 900            | 0.24    | 23.6           |
| 10  | 14.4         | 1100           | 520            | -0.39   | 22.6           |
| 11  | 13.9         | 500            | 500            | 0.16    | 22.2           |
| 12  | 12.7         | 530            | 500            | -0.16   | 21.1           |
| 13  | 12.1         | 500            | 500            | 0.15    | 20.6           |
| 14  | 11.0         | 220            | 500            | -0.06   | 19.7           |
| 15  | 10.3         | 220            | 320            | 0.04    | 19.1           |

The relative differences of proton-count numbers in the side detectors can be used to investigate the azimuthal property of the beam behind the targets. The figure 4 shows the average values of the ratios \((N_L - N_R)/(N_L + N_R)\) and \((N_U - N_D)/(N_U + N_D)\) for the seven graphite targets. The values are corrected for the count ratios, measured with the gold target, to take into account differences in the counting efficiencies. All values are compatible with zero and the fact that the vector polarization in the beams behind the spin-zero carbon targets has to be zero.

### 3. The possibility to produce tensor polarized deuteron beams

The present data, especially those of the deuteron-energy range around 15 MeV, indicate the possibility to produce tensor polarized deuteron beams by passing initially unpolarized deuteron beams through targets made from graphite. The expected polarization can be calculated with the use of the peak parameters of table 2 and the equation 2. The figure 5 shows the results for
The average asymmetries \( (N_L - N_R)/(N_L + N_R) \) (triangleright) and \( (N_U - N_D)/(N_U + N_D) \) (triangledown), measured with the seven graphite targets and corrected for that measured with the gold target.

initial beam energies of 14.8 and 15.8 MeV. In deceleration from 14.8 to \( \sim 14 \text{ MeV} \) the deuterons pass the energy range, where the cross section is described by the peak around 14.4 MeV with \( \sigma_{\pm 1}(E) > 0 \) and \( \sigma_0(E) = 0 \). A \( p_{zz} \) of about -0.3 and \( E_{\text{out}}=14 \text{ MeV} \) result behind a 20 mg/cm\(^2\) carbon target. The polarization is maintained for thicker targets, allowing the choice of lower values of \( E_{\text{out}} \). For \( E_{\text{in}}=15.8 \text{ MeV} \), a 20 mg/cm\(^2\) target with \( E_{\text{out}}=14.8 \text{ MeV} \) yields \( p_{zz} \) of about +0.2 due to the effect by the peak around 15.4 MeV (\( \sigma_{\pm 1}(E) = 0 \) and \( \sigma_0(E) > 0 \)). For thicker targets and lower values of \( E_{\text{out}} \), \( p_{zz} \) of about -0.1 would result due to the effect by the peak around 14.4 MeV. With the use of a sandwiched material, causing deceleration from 14.8 to 14 MeV without polarizing effects, the positive \( p_{zz} \) could be maintained also for thicker targets and lower values of \( E_{\text{out}} \).

4. Conclusion and outlook
Contrary to the earlier analysis with linear functions, in the present work the measured count-number ratios were fitted by quadratic fit functions (figure 1). The present distribution of the tensor polarization \( p_{zz} \) of the deuteron beam behind the graphite targets as function of the initial beam energy (figure 2) differs slightly from that obtained with linear fit functions (figure 3 in reference [3]). The fit of the present \( p_{zz} \) distribution (figure 3) among the fit parameters of table 2 yields central energies \( E_0 \) slightly differing from those given in reference [3]. The essential structure of the energy dependence, however, is the same. Unfortunately, no measurements have been performed to fill the gaps of initial beam energies from 12.2 to 13.0 MeV and from 14.0 to 14.8 MeV. The setup at Universität zu Köln, used in the present measurements, meanwhile has been disassembled. It would be desirable to continue the measurements at another facility to
confirm and to complete the present results.

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