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Transverse polarization transfer in the $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ reaction at $\theta=0°$

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The transverse polarization transfer coefficient $K_y^{y'}$ has been measured for the $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ reaction at 0° for deuteron energies around 13 MeV, using a purely vector-polarized deuteron beam. At 0.666 ± 0.013, $K_y^{y'}(0°)$ was found to be significantly larger than the values used frequently in the past to deduce the neutron polarization from the polarization of the deuteron beam. [S0556-2813(98)01105-4]

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With the availability of intense polarized ion sources, the $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ reaction has become the preferred source of polarized neutrons for many nuclear physics experiments. At 0°, the cross section is $\geqslant$70 mb/sr for deuteron energies between 4 and 40 MeV, and the transverse polarization transfer from the deuteron to the neutron is very large. With a pulsed beam and active target, the low-energy continuum from the $^{2}\mathrm{H}(d,n)pd$ break-up reaction can easily be separated by time-of-flight.

It has been observed early on that, at 0° and for energies above 4 MeV, this process appears to be consistent with a simple stripping model [1]. In this picture, the polarization p_n of the outgoing neutrons should be equal to their polarization *inside* the deuteron, which is given by [1,2]

$$P_{n*}=(1-3/2P_D)p_d, \tag{1}$$

where P_D is the D-state probability and p_d the vector polarization of the deuterons. With P_D about 5% [3,4], a value around 0.62 would then be expected at all energies for the polarization transfer coefficient which, for a pure vector-polarized beam, is given [5] by the expression

$$K_y^{y'}(0°)=2/3p_n/p_d. \tag{2}$$

For deuteron energies around 10 MeV, where most of the previous measurements were made, experimental values for $K_y^{y'}(0°)$ range from 0.59 ± 0.03 [6] to 0.72 ± 0.03 [7]. The most comprehensive study in the range between $E_d=4$ MeV and $E_d=15$ MeV was done by Lisowski *et al.* [8]. Their results, centering around 0.63 and showing a slight energy dependence, have frequently been used by other experimenters to deduce the neutron polarization from the polarization of the deuteron beam. Average values calculated from the weighted results of different authors are given in Table I for four energies between 5 and 50 MeV. As Table I shows, the existing data scatter appreciably. In our own polarized-neutron experiments at deuteron energies between 13 and 24 MeV [13,14] we have consistently found higher values. Therefore we have decided to remeasure $K_y^{y'}(0°)$ for the $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ reaction carefully in two dedicated experiments in order to help clarify the situation.

The experiments were performed at the cyclotron neutron facility of the Institut für Strahlen- und Kernphysik at Bonn University. The apparatus and data taking techniques have been described in detail elsewhere [13,15]. In brief, an

TABLE I. Representative sample of published values for the polarization transfer coefficient $K_y^{y'}(0°)$. For each energy bin, the results of all quoted references have been weighted and averaged. No distinction was made between the reactions $^{2}\mathrm{H}(\vec{d},\vec{n})^{3}\mathrm{He}$ and $^{2}\mathrm{H}(\vec{d},p)^{3}\mathrm{H}$. The errors are standard deviations including normalization uncertainties and were estimated from the data given in the references.

Energy E_d (MeV)	$K_y^{y'}(0°)$	References
6 ± 1	0.65 ± 0.01	[1], [6], [7], [8]
10 ± 0.5	0.64 ± 0.01	[1], [6], [7], [8], [9]
14 ± 1	0.61 ± 0.01	[1], [6], [8]
50.4 ± 0.6	0.63 ± 0.03	[10], [11]
42.8	0.67 ± 0.05[a]	[12]

[a] This value is for the highest neutron energies ($E_n>30$ MeV) at 0° in the $^{1}\mathrm{H}(\vec{d},\vec{n})pp$ reaction, corresponding to the p-p FSI, as explained in the main text.

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TABLE II. Summary of our measurements for the polarization transfer coefficient $K_y^{y'}(0°)$ in the $^2\mathrm{H}(\vec{d},\vec{n})\,^3\mathrm{He}$ reaction. Columns 4 and 5 each give the *sum* of the absolute polarization values measured with spin ‘‘up’’ and spin ‘‘down.’’ The one standard deviation errors are relative except for the average, where it includes the normalization uncertainty of 1.4%.

Energy E_d (MeV)	d polarim.	n polarim.	p_d	p_n	$K_y^{y'}(0°)$
13.5[a]	He gas	He gas	0.998 ± 0.008	1.016 ± 0.015	0.679 ± 0.012
13.0[a]	He gas	liquid He	0.909 ± 0.002	0.884 ± 0.019	0.648 ± 0.014
				average:	0.666 ± 0.013[b]

[a] Given is the energy of the deuteron beam in the center of the gas target; the energy of the beam coming from the cyclotron was 17 MeV.

[b] This error includes the normalization uncertainty.

atomic-beam ion source was used to provide a purely vector-polarized deuteron beam of 17 MeV, corresponding to a mean energy between 13.0 and 13.5 MeV in the high-pressure, liquid nitrogen-cooled gas target. The neutrons were collimated at 0° to form a circular beam of 21 mm diameter. The energy spread was 2–3 MeV [full width at half maximum (FWHM)], depending on the gas pressure. The deuterons were stopped behind the gas target which served as a Faraday cup.

The investigation was carried out in two stages. In the first set of experiments, the polarization of the neutrons was determined with a He-gas polarimeter operated at a pressure of 1 bar [13], detecting recoil α particles at $\theta_{\mathrm{lab}}=\pm24°$ with respect to the neutron beam, corresponding to the back-angle maximum of the n-α analyzing power at $\theta_{\mathrm{c.m.}}=132°$ which is accurately known. Although the efficiency of such a gas polarimeter is very low it has the big advantage that no elaborate multiple-scattering corrections are necessary to extract the neutron polarization from the measured asymmetry.

The beam polarization was measured by means of a deuteron polarimeter using d-α scattering for which reliable phase shifts exist [16]. This polarimeter consisted of a small target cell containing He gas at a pressure of 1 bar, closed with 10 μm thick Ti foils. It was contained in a scattering chamber in which recoiling α particles were observed at laboratory angles of 15°, corresponding to the backward-angle maximum of the d-α analyzing power near $\theta_{\mathrm{c.m.}}=150°$. The scattering chamber also contained a ^{12}C polarimeter which was used to cross-check the vector polarization of the beam at $E_d=24.2$ MeV where, at $\theta_{\mathrm{lab}}=47°$, the d-^{12}C analyzing power is known with an accuracy of 2.5% [17]. The results for p_d obtained with the two polarimeters agreed within 1%. No change of the beam polarization was observed when the energy was lowered back to 17 MeV. The tensor polarization was found to be negligible.

In a second set of experiments, a liquid-He polarimeter [15] was employed to measure the neutron polarization. Since due to spatial restrictions the deuteron and neutron polarizations could not be measured simultaneously, the beam was deflected into the scattering chamber containing the d polarimeters before and after the measurement of the neutron polarization. No change of the beam polarization was observed during the experiment.

In all measurements, the polarization of the d beam was reversed approximately every 5 s, controlled by the current integrator, by changing the spin direction at the ion source. After each 10 polarized cycles, a short unpolarized measurement was made. Using a formula given in Ref. [13], the asymmetry ε was calculated in such a way that only the *sum* of the polarizations occurs so that $\varepsilon=(p^+ + p^-)A$, where p^+ and p^- are the absolute values of the polarization with spin ‘‘up’’ and spin ‘‘down,’’ respectively, and A is the analyzing power. This procedure was of considerable advantage in our case because the ion source cannot produce a proper spin-flip, so that p^+ and p^- may be somewhat different.

For the data analysis, Monte Carlo codes were developed [15,18] in which the extended geometry and the energy spread of the beam were taken into account; for the liquid-He polarimeter, corrections were made for multiple scattering in the liquid He as well as scattering involving the material surrounding the target. The results are listed in Table II. The average over all measurements is

$$K_y^{y'}(0°)=0.666\pm0.009\pm0.009,$$

where the first error of one standard deviation comprises the uncertainties from counting statistics, background subtraction, and multiple scattering corrections, and the second one combines the normalization uncertainties of 0.9 and 1.0 % in the analyzing powers $A_y^{d\text{-}\alpha}$ and $A_y^{n\text{-}\alpha}$, respectively. (In the meantime, nearly the same value has been obtained for $K_y^{y'}(0°)$ from a measurement performed at $E_d=9$ MeV [19], corroborating our result.)

This value for the polarization transfer parameter $K_y^{y'}(0°)$ in the $^2\mathrm{H}(\vec{d},\vec{n})\,^3\mathrm{He}$ reaction is higher by more than three standard deviations than the value recommended by Lisowski *et al.* [8] at our energy. It means that the polarization of the ‘‘stripped’’ neutron is equal to the polarization of the deuteron and thus, according to Eq. (1), that it is larger than it was *inside* the deuteron. Clearly, this cannot be understood in a simple stripping model, and a realistic calculation would be welcome.

However, dynamically exact four-body calculations are not yet feasible, and therefore we have decided to look at the corresponding process in the $n(\vec{d},\vec{p})nn$ reaction instead. For this system, which contains only three nucleons without

Coulomb interaction, rigorous Faddeev calculations can be performed with realistic nucleon-nucleon potentials. If we restrict ourselves to the highest proton energies at $\theta_p = 0°$, this break-up reaction (which can, of course, not actually be measured due to the lack of a free neutron target) has a well-defined two-body exit channel, consisting of the proton and the n-n final-state interaction, i.e., two neutrons with zero relative energy in a $^1S_0$, $T=1$ state.

We have solved the Faddeev equations for the $n(d,p)nn$ reaction at $E_d = 43$ MeV which is the energy at which Nath *et al.* [12] have investigated the analog $^1\mathrm{H}(\vec{d},\vec{n})pp$ reaction. Using the CD-Bonn potential [3] with its small D-state probability ($P_D = 4.8$) and the Nijm93 potential [4] which gives $P_D = 5.8$, we obtained $K_y^{y'}(0°) = 0.68$ in both cases, in perfect agreement with the experimental result of Ref. [12] (see Table I), and again much larger than the stripping prediction. Although this result was obtained for a different system and as such does not apply to the $^2\mathrm{H}(\vec{d},\vec{n})\,^3\mathrm{He}$ reaction, it is nevertheless informative because it shows that it is indeed possible for a ''stripped'' nucleon at 0° to have a polarization which is larger than its polarization inside the deuteron.

Our experimental result for the polarization transfer coefficient of the $^2\mathrm{H}(\vec{d},\vec{n})\,^3\mathrm{He}$ reaction should have consequences for all previous investigations in which much smaller values of $K_y^{y'}(0°)$ were used to deduce the neutron polarization from the polarization of the deuteron beam.

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