Kinematically Complete Measurement of Cross Sections and Vector Analyzing Powers of $^4He(d_{pol},p\alpha)n$ at $E_d = 18$ MeV

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Differential cross sections and vector analyzing powers have been measured for the breakup reaction $^4He(d_{pol}, p\alpha)n$ at $E_d = 18$ MeV in a kinematically complete coincidence experiment. The analysis in the framework of the Faddeev theory yields satisfactory agreement between theory and experiment even for the polarization observables.

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The d-α system is one of the few systems that can be treated as a three-body system in the framework of the Faddeev theory. Three-body calculations of the d-α elastic scattering cross sections have been done successfully by Shanley,[1] Charnomordic, Fayard, and Lamot,[2] and Koike,[3] who also applied his theory to the deuteron breakup induced by α particles.[4] Quite recently, this theory has been applied with good success to a kinematically incomplete polarization experiment at $E_d = 15$ MeV.[5] Since the agreement between theory and experiment is good for these experiments, a kinematically complete polarization experiment seems to be of appreciable interest as a test of refined three-body calculations, as it is expected to provide information on the two-body interaction and the reaction mechanism in a more sensitive way.

In this Letter we report on the first coincidence-type experiment with vector-polarized deuterons of the $d_{pol} + \alpha \to p + \alpha + n$ reaction. The use of a vector-polarized deuteron beam allows a determination of the differential cross sections $d\sigma/dS\,d\Omega_3\,d\Omega_4$ and of analyzing powers $A(S, \theta_3, \varphi_3, \theta_4, \varphi_4)$ for the breakup reactions with the particles numbered in the sequence $d_{pol}(1) + \alpha(2) \to p(3) + \alpha(4) + n(5)$, where S is the length of arc of the kinematic locus parametrized suitably. In addition, by specializing to the sequential decay reaction mechanism in $d_{pol}(1) + \alpha(2) \to p(3) + {}^5He_{pol}(R) \to p(3) + \alpha(4) + n(5)$, the polarization of the intermediate state ^{5}He(g.s.) produced in the first step of the reaction can be determined by measuring an angular correlation between particles 3 and 4[6,7] in noncoplanar geometry. When a polarized beam is used certain polarization transfer coefficients of the first reaction step can be obtained and compared to a theoretical model of this reaction leading to particle unstable states. Results of this aspect of the present experiment will not be discussed here but are presented elsewhere.[8]

The experimental setup consisted of an Ortec 2800 scattering chamber with a ^{4}He gas target cell. An arrangement of one detector on one side of the beam and up to six detectors on the other side, centered circularly around the ^{5}He recoil axis and inside the decay cone of this recoil nucleus, allowed the measurement of four simultaneous α-p coincidences.[7] The condition of observing the sequential decay of $[^5He(g.s.)]_{pol}$, the energy loss of the α particles in the target exit foils, and separation of competing reactions led to a choice of angles $\theta_3(lab) = 52°$, $\varphi_3(lab) = 0°$, $\theta_R(lab) = 32.2°$, $\varphi_R(lab) = 180°$. The beam from the polarized ion source LASCO[9] was accelerated by the Super-FN-Tandem Van de Graaff accelerator of the University of Cologne to 18 MeV and focused to a beam spot of <2 mm into the target. Beam currents on target of up to 300 nA were obtained with a beam of deuterons purely vector polarized perpendicular to the reaction plane. The beam polarization was simultaneously monitored via d-α elastic scattering by two detectors at $\theta_{lab} = 90°$ left and right of the target and looking at a part of the coincidence volume. The d-α analyzing power was extrapolated from the 17-MeV value of Ohlsen *et al.*[10] with use of the near energy independence at $\theta_{lab} = 90°$ shown by the phase-shift analysis of Grüebler *et al.*[11] The beam polarization p_y was always 70–75% of the theoretical values of $\pm\frac{2}{3}$. The data, consisting of both energies E_3 and E_4 of the particles in coincidence and their time-of-flight difference, were written on magnetic tape event by event and analyzed off-line on the CYBER 76 computer of the University of Cologne. The intensity along the kinematical

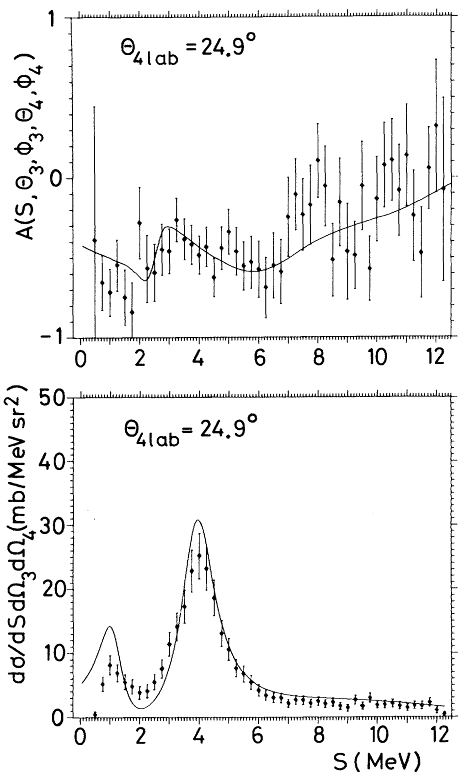

FIG. 1. Cross section $d\sigma/dS\, d\Omega_3\, d\Omega_4$ and analyzing power $A(S, \theta_3, \varphi_3, \theta_4, \varphi_4)$ of ${}^4\mathrm{He}(d_{\mathrm{pol}}, p\alpha)n$ at $E_d = 18$ MeV, $\theta_3(\mathrm{lab}) = 52°$, $\varphi_3(\mathrm{lab}) = 0°$, $\theta_4(\mathrm{lab}) = 24.9°$, $\varphi_4(\mathrm{lab}) = 180°$. Solid line is the unadjusted result of Faddeev calculation.

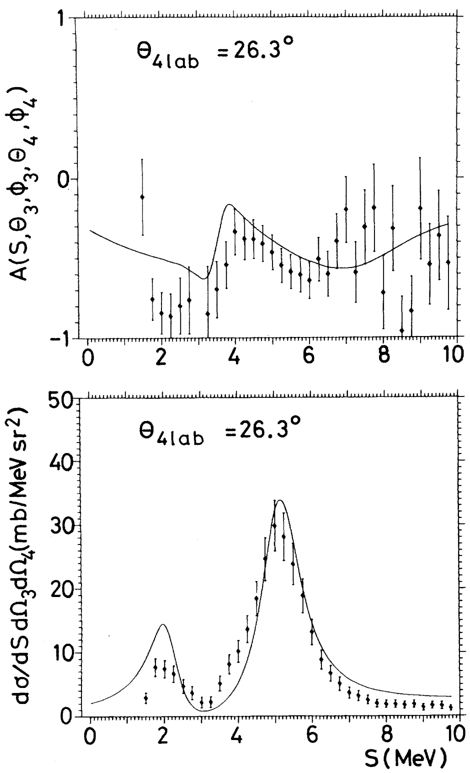

FIG. 2. Same as Fig. 1, but for $\theta_4(\mathrm{lab}) = 26.3°$.

curve was projected[7] onto this curve and absolutely normalized with use of beam current, target density and volume, and the detector solid angles. Details of the method of data reduction will be published elsewhere.[12]

The experimental results obtained are compared with results of calculations with Faddeev theory. With the assumption of Yamaguchi-type separable potentials we solve the Amado-Lovelace equations. The improved CPV-A potential given in Ref. 4 is used in $p_{3/2}$, $p_{1/2}$, and $s_{1/2}$ waves of the N-α subsystem. Only the ${}^3S_1$ wave potential is used for the n-p interaction. The Coulomb effect is neglected in solving the equations and approximately taken into account in the propagator τ describing the p-α final-state interaction (FSI). More details can be found in Ref. 4. To check the numerical accuracy the error function introduced in Ref. 5 is evaluated. The numerical integration was done with 14-point Gaussian rule, partly checked by 16-point Gaussian rule. From these procedures we conclude that the errors in the final results are reasonably small (usually within a few percent, at most about 10% in the region of smaller cross sections).

The experimental and theoretical (solid line) results for the differential cross sections and analyzing powers for the four in-plane detectors at angles $\theta_4(\mathrm{lab}) = 24.9°$, $26.3°$, $32.3°$, and $38.2°$ are shown in Figs. 1–4 as a function of arc length parameter S. With regard to the fact that no adjustable parameter is used in the comparison, the agreement is quite satisfactory not only for the cross sections but also for the analyzing powers, though the experimental (statistical) errors are partly large. This shows that treating the α-d system as a three-particle system is a valid concept even when applied to sensitive polarization observables.

It is most interesting that the calculated analyzing powers at the ${}^5\mathrm{He(g.s.)}$ FSI which appear at two values of S in each angle pair, e.g., at $S = 1$ and 4 MeV in Fig. 1 where prominent peaks in the cross section can be found, usually take values close to a constant of -0.5. The experiment seems to support this prediction, especially in Figs. 3 and 4, where error bars in the analyzing powers are small at ${}^5\mathrm{He(g.s.)}$. Because we have

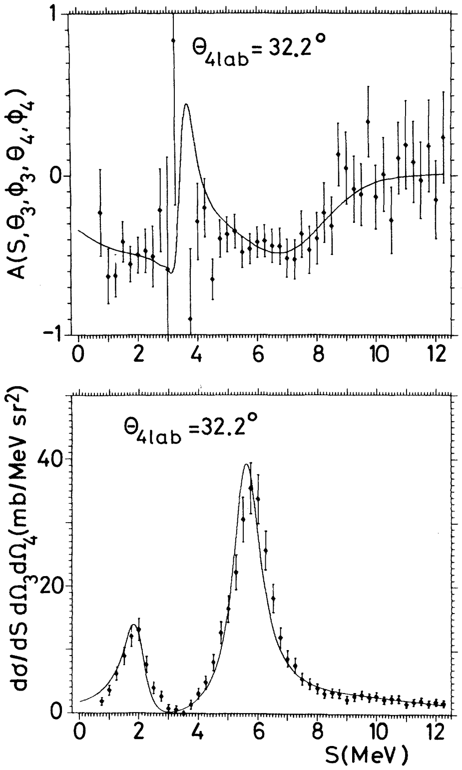

FIG. 3. Same as Fig. 1, but for θ_4(lab) =32.2°.

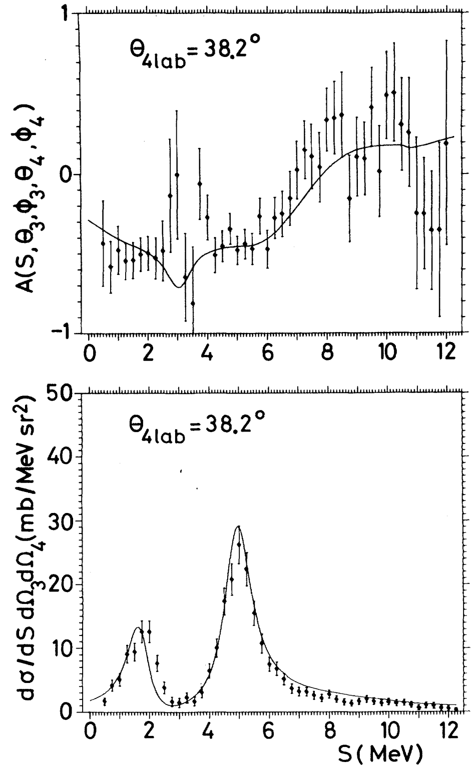

FIG. 4. Same as Fig. 1, but for θ_4(lab) =38.2°.

fixed the detected proton angle throughout the four angle pairs, we have to assume that the analyzing power at ^{5}He(g.s.) does not depend on the relative outgoing angle of the resonating n-α system but is mainly determined by the first step of the sequential decay process. However, it is surprising that the cross section of the FSI peak obviously depends upon this relative n-α angle, as can be seen in Figs. 1–4. The calculation also shows that the analyzing power changes its value when the relative n-α energy moves slightly away from the resonance. The rapidity of the change in the analyzing power, both in the calculation and in the experiment, seems to indicate a rapid change of reaction mechanism and strong interference effects between the two FSI peaks. In this region the relative n-α energy is smaller than the resonance energy of ^{5}He(g.s.) where the dominant contribution is that from the n-α $p_{3/2}$ wave. The three-body breakup amplitude has three terms corresponding to the three different FSI's. The n-α FSI term has a phase depending on the direction of the relative n-α motion since it contains a spherical harmonic about this direction. However, this phase does not affect the analyzing power in a region where only this one amplitude is dominant (FSI). In the region of small relative n-α energy between the FSI peaks this amplitude will be small and comparable to other minor amplitudes. Therefore interference between these different amplitudes will cause strong variations of the analyzing power despite very small cross sections due to a rather rapid variation of the direction of the relative n-α motion. From this we conclude that the analyzing power clearly distinguishes FSI-dominant regions from other regions and is therefore sensitive to the reaction mechanism.

The present paper shows that the Faddeev theory is very powerful even when it is applied to the kinematically complete polarization experiment of the breakup reaction. Our findings also have some bearing on the N-d breakup reaction.[13]

Stolk and Tjon have found that the calculated analyzing power at $E_{n-p}=0.1$ eV ($^1S_0$ FSI) is extremely different from the one at $E_{n-p}=1$ MeV.[14] Again, the analyzing power distinguishes the $^1S_0$ FSI region from other regions. The $^3S_1$ FSI is assumed to be dominant at 1 MeV because the calculated analyzing power at this energy is quite similar to that of N-d elastic scattering. Stolk and Tjon's calculation is not sufficient to decide whether the $^3S_1$ FSI is dominant or not, because it was carried out only for a particular direction of the relative n-p motion. However, we believe from the present result that the analyzing power does not vary so rapidly with this direction of motion if the $^3S_1$ FSI is dominant. A kinematically complete polarization calculation and/or experiment should be very helpful to solve this problem. From the present results it appears feasible and useful to continue these measurements with use also of tensor-polarized deuterons in order to obtain these data as a function of energy. Faddeev calculations[5] predict significant changes to lower energies and one can expect to see the influence of the 1^+ resonance of ^{6}Li as a three-body resonance on the breakup, especially on the polarization observables.

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Evidence for Deuteron *D*-State Effects on the Polarization of the 2.58-MeV State in ^{57}Ni Excited in the (p,d) Reaction

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Deuteron-γ angular correlation measurements and their analysis indicate significant effects of the deuteron D state on the spin-statistical tensors of the 2.58-MeV $(\frac{7}{2}^-)$ state in ^{57}Ni excited in the reaction ^{58}Ni$(p,d)^{57}$Ni at an incident energy of 30 MeV.

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Since the early works of Johnson and Santos[1] and of Delic and Robson[2] the role of the deuteron D state in direct (d,p) and (p,d) reactions has been the subject of many theoretical and experimental studies. It now seems well established that the deuteron D state has only small effects on differential cross sections at low energies, while it has significant effects on tensor analyzing powers.[3] The D-state effects on cross sections are shown[4] to be quite important at several-hundred megaelectronvolts, where large momentum transfers are involved. The D-state effects on the polarization transfer have also been reported.[5] The polarizations, or, more strictly, the spin-statistical tensors, of the residual nuclear states also give information on the reaction