Isospin breaking effects in the reaction $^4He(d,{}^3He)^3H$ at low energies

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We report on a new measurement of the reaction $^4He(d,{}^3He)^3H$ to study isospin breaking effects near threshold. We compared the results with microscopic calculations and infer on the importance of specific isosopin-breaking S-matrix elements. This analysis does not support the idea of an unknown ^6Li resonance causing the observed effects.

I. INTRODUCTION

The importance of isospin-breaking effects in the reaction $^4He(d,{}^3H)^3He$ at low energies is revealed by the Barshay-Temmer theorem[1] which implies a symmetric differential cross section around 90° in the center-of-mass (c.m.) system. The strength of this breaking can be parametrized conveniently by the asymmetry

$$W(\theta)=\frac{\sigma(\theta)-\sigma(\pi-\theta)}{\sigma(\theta)+\sigma(\pi-\theta)} . \quad (1)$$

In this connection is previous paper[2–4] we have performed a systematic comparison between microscopic calculations in the framework of the refined resonating group model (RRGM) and measurements of cross sections and vector and tensor analyzing powers for the reaction $^4He(d,{}^3He)^3H$ measured in the $\alpha+d$ energy range between 22 and 33 MeV in the (^4He+d) c.m. system. Since the agreement for differential cross sections is qualitatively satisfactory and rather insensitive to the role of tensor forces,[2] it seems interesting to check the microscopic theory even at low energies where multistep processes and Coulomb-induced effects might play a more important role. At these low energies the number of partial waves is drastically reduced, so one may expect a direct comparison between data and calculation to be more favorable.

Furthermore, close the reaction threshold, the calculation and also old measurements[5–9] reveal a strong energy dependence of the asymmetry of the cross sections. A few hundred keV above the threshold the asymmetry is forward peaked, rapidly varying with energy, and reaching a maximum around 16 MeV,[3,5,6,10] which one can conjecture to be related to an $A=6$ resonance.[4] Hence a good description of the asymmetry at these energies is an interesting challenge for any theoretical model.

We use the RRGM method to reach a deeper understanding of the physical reasons causing the asymmetry and its energy variations. The model is microscopic, in the sense that it explicitly uses a nucleon-nucleon interaction, totally antisymmetric wave functions, and correctly accounts for the center-of-mass motion. A detailed description of the theoretical formulation of the RRGM may be found in Refs. 11. In Refs. 2 and 3 we have used the fragmentations of the initial $(\alpha+d)$ and the final ($^3He+{}^3H$) channels, together with the ground and first two excited states of ^5He and ^5Li plus a nucleon; in addition, we also here consider the fragmentation containing a singlet deuteron $d^*(S=0,T=1)$ and a ^4He cluster. This partition was expected to play an appreciable role at low energies, because it has been seen in three-body breakup reactions.[12] The actual calculations, however, have shown that this new fragmentation does not affect the results for the reaction under investigation, because it couples only weakly to the $^3He+{}^3H$ channel due to the additional spin flip necessary.

In order to have a quantitative test of the microscopic calculations we have performed a measurement at three different energies around 16 MeV. The experimental details and the results are given in Sec. II, with a discussion and conclusions following in Sec. III.

II. EXPERIMENT AND RESULTS

A. The experiment

The measurements have been carried out using the deuteron beam accelerated by the 16 MV Tandem of the Laboratori Nazionali di Legnaro at three different energies 23.50, 24.13, and 24.85 MeV. A scattering chamber 1 m in diameter was used; the deuteron beam was focused into a cylindrical gas target with a system of three collimators defining the direction and the size of the beam (about 2 mm in diameter). After passing the target the beam was collected in a Faraday cup. The gas target was similar to the ones previously used in other experiments;[13–15] the entrance and exit windows were 2.5-μm Havar foils allowing the target to stand a static pressure of the order 100 kPa.

The $^4He(d,{}^3He)^3H$ reaction has a Q value of -14.3

MeV; therefore, the kinematical conditions allow the detection of ^{3}He and H in an angular range restricted to $\theta_{lab} \le 30°$ ($\theta_{c.m.} \le 90°$). The whole angular distribution can be obtained since in the center-of-mass system a ^{3}H emitted in the forward direction at a scattering angle $\theta_{c.m.}$ and azimuthal angle $\phi_{c.m.}$ corresponds to a ^{3}He emitted at $\pi-\theta_{c.m.}$ and $\pi+\phi_{c.m.}$ A telescope with three silicon-surface-barrier detectors has been used to discriminate these particles from protons, deuterons, and ^{4}He by a ΔE-E technique. The two first detectors in coincidence can be used as ΔE and E for the ^{3}He and ^{4}He nuclei, while all the three detectors yield ΔE_1, ΔE_2, and E for protons, deuterons, and ^{3}H. Detecting with this telescope ^{3}He and ^{3}H at the same angle, geometrical uncertainties cancel. The detectors were 16, 50, and 2000 μm thick, selected in order to have at different angles and energies an adequate discrimination of the particles.

The signals were recorded, event by event, in a PDP-11 computer storing separately the events where the three signals were in coincidence and the events with only the first two in coincidence and the third one in anticoincidence.

A further detector was used to count the elastically scattered α particles and deuterons and so to check the stability of the measuring conditions including pressure, temperature, and charge collection. This detector allowed us to extract the elastic cross sections which resulted in good agreement with previous measurements.[16]

B. Results

The experimental cross sections for the ^{4}He(d,^{3}He)^{3}H reaction are compared with theoretical predictions in Fig. 1, at the three different energies measured in the present experiment. One observes that the experimental angular distributions are bell shaped and do not change much within the energy range considered. On the other hand, the absolute value of the cross section increases and roughly doubles going from the lowest to the highest energy.

A Legendre polynomial expansion

$$\sigma(\theta)=\sum_L c_L P_L(\cos\theta) \tag{2}$$

has been carried out and it was found that Legendre polynomials up to $L=4$ are sufficient to describe the experimental data as shown in Fig. 1.

The theoretical calculations reproduce correctly the shape and energy dependence of the measured cross section. They overestimate, however, its magnitude by about a factor of 2, which appears to be rather energy independent, since a similar factor was already reported in the energy range 32–50 MeV in a previous paper.[3] For a discussion of the asymmetry, however, the absolute value of the cross sections is irrelevant [see Eq. (1)].

In order to compare with theoretical calculations we show in Fig. 2 the Legendre interpolation of the experimental asymmetry together with the theoretical prediction, for the case of the maximal asymmetry, i.e., for 24.1 MeV which corresponds to 16.1 MeV in the (^{4}He+d) c.m. system. We emphasize that the maximal asymmetry occurs in an angular region which is not directly measured in our experiment. While we are confident in our extrapolation procedure, which is in agreement with previous measurements,[5,6] we stress, however, that direct measurements in the relevant angular range will be very valuable.

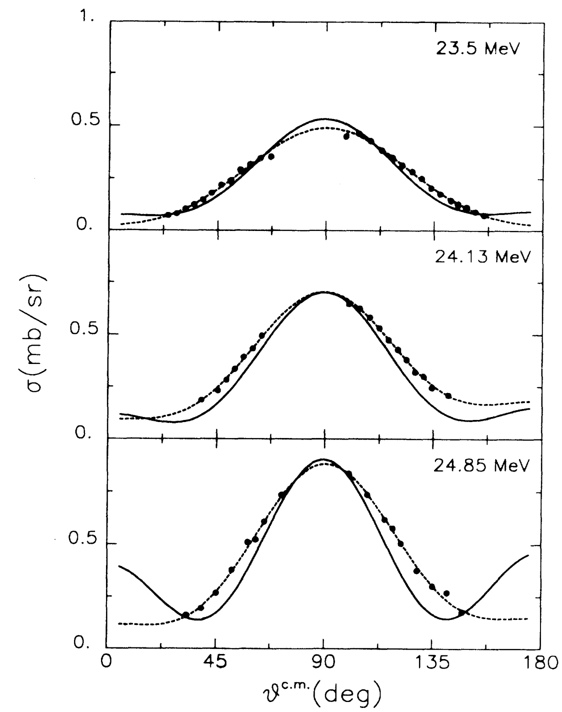

FIG. 1. Angular distributions of the reaction ^{4}He(d,^{3}He)^{3}H at different deuteron incident laboratory energies. The points are the results of the present experiment; the errors are not shown since they are smaller than the size of the points. The dashed curves are the result of the Legendre polynomial fits; the continuous lines are the RRGM predictions multiplied by 0.45 independent of energy.

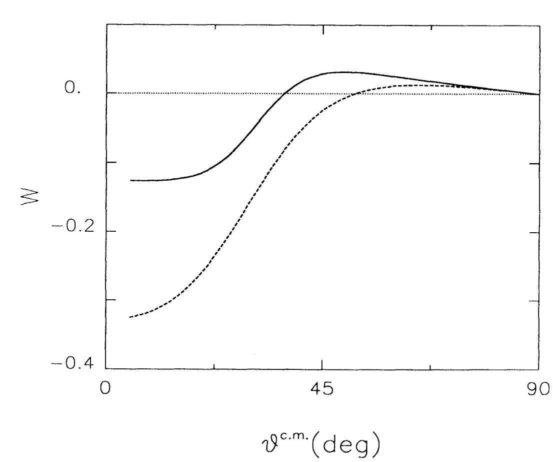

FIG. 2. Angular distribution of the asymmetries of differential cross sections at 24.1 MeV. The dashed curves are obtained from the Legendre polynomial expansion and the continuous lines are the theoretical RRGM predictions.

III. DISCUSSION AND CONCLUSIONS

In the forward domain the asymmetry is well characterized by the ratio of the sum of the odd Legendre expansion coefficients to the sum of the even ones:[13]

$$\frac{c_1+c_3}{c_0+c_2+c_4} . \tag{3}$$

As already pointed out in Ref. 3, the asymmetry is dominated by the interference of the large non-spin-flip positive-parity S-matrix elements with the non-spin-flip negative-parity ones. Let us denote the S-matrix elements with the symbol $S^J_{l_{\rm in} l_{\rm out} s_{\rm out}}$, $s_{\rm in}=1$ being fixed. The most important interference terms contributing to c_1 and c_3 are presented in Fig. 3.

Let us consider c_3 first. None of the individual contributions shows any particular structure, all being linearly increasing in modulus with the energy, adding up to a coefficient c_3 increasing in magnitude smoothly with energy. In this case negative-parity matrix elements with $l_{\rm in}=1$ interfere with positive-parity ones of $l_{\rm in}=2$.

The coefficient c_1 is characterized by strong cancellations of different pairs of opposite contributions, leading to a final result much smaller than the individual contributions. This means that the theoretical isospin breaking is much higher than it would be judged from the experimental information. In particular, c_1 is mostly determined by the interference of the negative-parity matrix elements with the positive ones of $l_{\rm in}=0$ and $l_{\rm in}=2$ yielding opposite sign. One might be tempted to relate these findings to the elastic $d+\alpha$ scattering via the Watson theorem.[17] Due to a different behavior of various contributions c_1 crosses zero around 16 MeV. The increase of the numerator in Eq. (3), together with an increase of the denominator, leads to a maximum in the asymmetry around 16 MeV (see Fig. 5 in Ref. 2). The above discussion, together with the phase-shift analysis, does not support the idea of a resonance in ^{6}Li leading to a maximum in the asymmetry.

We would also like to comment on the relative weight of the coefficients c_1 and c_3. The calculated c_1 is smaller than c_3, as illustrated in Fig. 2. While theoretically c_3 is larger than c_1 by at least an order of magnitude, the corresponding empirical result of the fit gives a ratio of about 2. One should notice, however, that due to the limitation of the angular range of the data points, the uncertainties in the determination of the odd Legendre coefficients are appreciable.

In conclusion, from the theoretical point of view the most important result is that there are strong cancellations between different rather large isospin-breaking contributions. This makes it impossible to analyze experimental data with a simplified R-matrix approach.

From the experimental side it is clear that measurements at small (below 20°) and large angles (above 160°) in the center of mass would be extremely important to determine the details of the shape of the angular distribution. This requires a dedicated experiment, because of the very small laboratory angles involved. We would like to emphasize the necessity of a new generation experiment, dedicated to very small angle measurements, in order to confirm the theoretical findings.

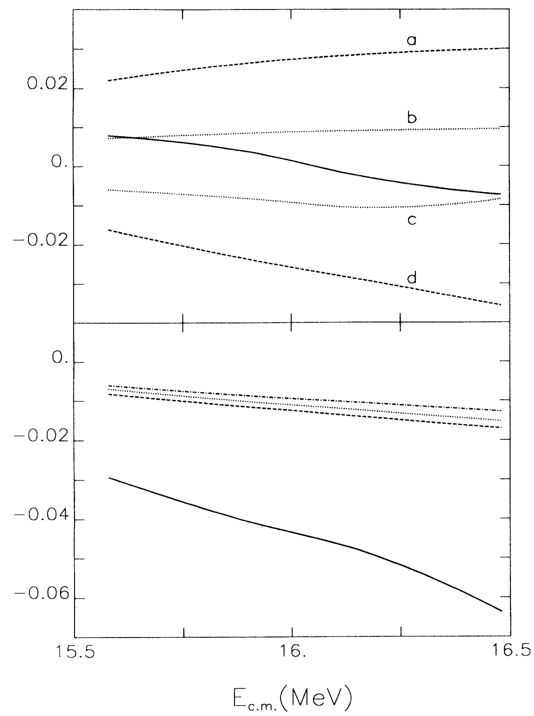

FIG. 3. Contributions to c_1 (upper) and c_3 (lower) Legendre expansion coefficients. The continuous line is the sum of all the interference terms. The broken lines denote single interference terms (only the largest contributions are shown). In the upper part ($L=1$) the line (a) corresponds to $S^{2*}_{111}\cdot S^{1}_{001}$, the line (b) corresponds to $S^{1*}_{111}\cdot S^{1}_{001}$, the line (c) corresponds to $S^{2*}_{311}\cdot S^{1}_{201}$, and the line (d) corresponds to $S^{2*}_{111}\cdot S^{3}_{221}$. In the lower part ($L=3$) the dashed line corresponds to $S^{2*}_{111}\cdot S^{2}_{221}$, the dotted line corresponds to $S^{2*}_{111}\cdot S^{3}_{221}$, and the dot-dashed line corresponds to $S^{1*}_{111}\cdot S^{3}_{221}$.

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