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Investigation of the $^3\overrightarrow{He}(\vec{d}, p)^4He$ Reaction with Polarized Beam and Target at 430 keV

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The efficiencies of the $^3\overrightarrow{He}(\vec{d}, p)^4He$ reaction for selected combinations of deuteron and ^3He-polarization have been measured at $E_d = 430$ keV. An analysis of the data shows resonant element $R_1 = (2, \frac{1}{2}, \frac{3}{2}^+ \mid R \mid 0, \frac{3}{2}, \frac{3}{2}^+)$ to be the dominant contribution, while p- and d-wave admixtures amount to a few percent of R_1.

I. INTRODUCTION

At energies below 1 MeV the $^3He(d, p)\,^4He$ reaction proceeds mainly through a $\frac{3}{2}^+$ compound state formed by incoming s-waves. There exists however evidence for small contributions from incoming partial waves with $l > 0$ as well as a $\frac{1}{2}^+$ intermediate state [2]. The present investigations aim at a unique parametrization of the reaction in terms of reaction matrix elements

$$R_i = (l_i', s_i', J_i^\pi \mid R \mid l_i, s_i, J_i^\pi).$$

The present work permits determination of the matrix elements with $l = l' = 1$ at 430 keV.

II. FORMALISM AND MODEL ASSUMPTIONS

Describing beam and target polarization by tensor moments $t_{m,n}$, $t_{M,N}$ respectively the differential cross section can be written as [3]

$$\sigma_p(\theta, \varphi) = \sum_{\substack{m,n\geqslant 0\\ M,N}} C_{m,n,M,N}(\theta) \left\{\begin{matrix}\mathrm{Re}\\ \mathrm{Im}\end{matrix}\right.(t_{m,n} \cdot t_{M,N} e^{-i(n+N)\phi})\Big\}, \tag{1}$$

Re for $m + M$ even
Im for $m + M$ odd.

The summation includes all possible values of N for $n > 0$, and $N \geqslant 0$ for $n = 0$. The quantities $C_{m,n,M,N}(\theta)$ which are the polarization sensitivities multiplied by $\sigma_0(\theta)$ can be expanded in a Legendre series

$$C_{m,n,M,N}(\theta) = \lambda\!\!\!^{-2} \sum_L a_{m,n,M,N}(L) \cdot P_{L,|n+N|}(\cos\theta), \tag{2}$$

where $\lambda\!\!\!^{-}$ is the reduced wavelength of the incoming particles in the CM System and the $P_{L,|n+N|}(\cos\theta)$ are defined according to Jahnke–Emde [4]. The expansion coefficients are functions of the reaction matrix elements

$$a_{m,n,M,N}(L) = \sum_{i,k\geqslant i} \alpha_{m,n,M,N}(L;\, i,\, k) \left\{ \begin{matrix}\mathrm{Re}\\ \mathrm{Im}\end{matrix} (R_i \cdot R_k{}^*) \right\} \tag{3}$$

where the coefficients $\alpha_{m,n,M,N}(L, i, k)$ can be computed according to the theory of angular momentum [3].

For the ^{3}He (d, p) ^{4}He reaction at low energies all other matrix elements are small compared to $R_1 = (2, \frac{1}{2}, \frac{3}{2}^+ \mid R \mid 0\, \frac{3}{2}\, \frac{3}{2}^+)$ and Eq. (3) therefore is reduced to [4]

$$a_{m,n,M,N}(L) = \sum_k \alpha_{m,n,M,N}(L;\, 1,\, k) \left\{ \begin{matrix}\mathrm{Re}\\ \mathrm{Im}\end{matrix} (R_1 \cdot R_k{}^*) \right\}. \tag{4}$$

For the present discussion only matrix elements with $l \leqslant 2$ and $J = \frac{1}{2}$ or $\frac{3}{2}$ have been retained based on penetrability considerations and studies of the (n, α)- and (p, α)-system [4]. A complete experiment yields a sufficient number of independent Eqs. (4) to allow an unique solution in terms of $\mathrm{Re}\,(R_1 \cdot R_i{}^*)$, $\mathrm{Im}\,(R_1 \cdot R_i{}^*)$. In addition there exist linear relations between different coefficients $a_{m,n,M,N}(L)$ which provide a test for the validity of the model, i.e. the choice of contributing matrix elements.

III. Experimental Results

Using the polarized deuteron beam of the Basel 1 MeV accelerator and, when needed, an optically pumped ^{3}He target the quantities $C_{m,n,0,0}(\theta)$, $C_{1,n,1,N}(\theta)$ and $C_{2,0,1,1}(\theta)$ have been measured at 430 keV. The deuteron polarization was measured using the $T(d, n)$ ^{4}He reaction at 100 keV. While further experimental details are reported elsewhere [5], the results are shown in Figs. 1 and 2 and Table I. The expansion coefficients for $\sigma_0(\theta)$ were obtained using the data of Yarnell et al. [1] at 455 keV. No coefficients are given for $C_{2,0,1,1}(\theta)$. The low counting rates with polarized beam and target (50–100 min^{-1}) did not allow sufficient statistics for a useful fit in the case of this small effect.

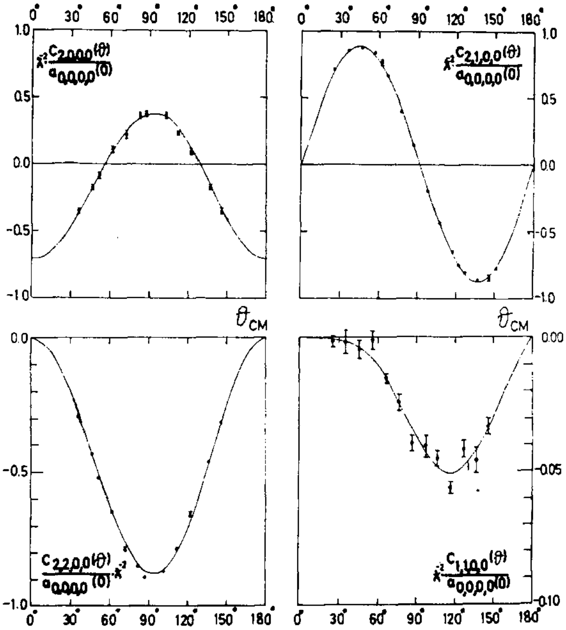

FIGURE 1

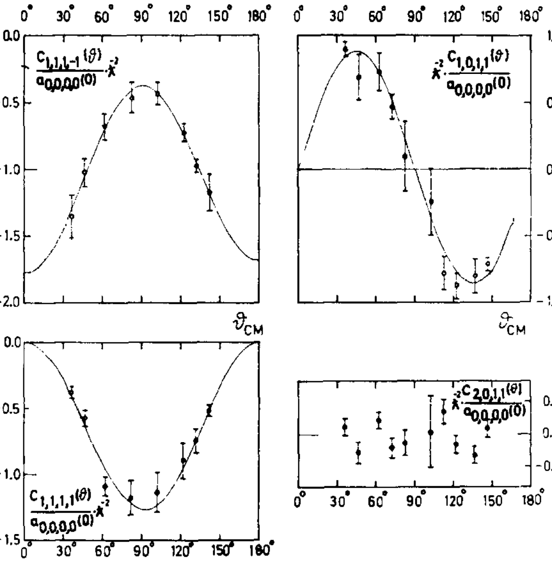

FIGURE 2

TABLE 1

Coefficients $a_{m,n,M,N}(L)/a_{0,0,0,0}(0)$
(The value for $R_1 \neq 0$ only are given in parentheses)

m, n, M, N \ L	0	1	2	3	4
0, 0, 0, 0	1 (1)	0.046 ± 0.006 (0)	−0.025 ± 0.007 (0)	—	—
1, 1, 0, 0	—	−0.0352 ± 0.0016 (0)	0.0143 ± 0.0012 (0)	—	—
2, 0, 0, 0	0.013 ± 0.005 (0)	−0.044 ± 0.009 (0)	−0.730 ± 0.013 (−0.7071)	+0.046 ± 0.020 (0)	—
2, 1, 0, 0	—	0.045 ± 0.005 (0)	0.587 ± 0.003 (0.5774)	−0.015 ± 0.003 (0)	0.009 ± 0.003 (0)
2, 2, 0, 0	—	—	−0.294 ± 0.002 (−0.2887)	0.007 ± 0.002 (0)	−0.0010 ± 0.0005 (0)
1, 1, 1, −1	−0.830 ± 0.011 (−0.8165)	−0.047 ± 0.020 (0)	−0.902 ± 0.038 (0.8165)	—	—
1, 1, 1, 1	—	—	−0.419 ± 0.014 (−0.4083)	0.007 ± 0.004 (0)	—
1, 0, 1, 1	—	0.019 ± 0.044 (0)	0.578 ± 0.023 (0.5774)	—	—

IV. Analysis

Since $C_{1,1,0,0}(\theta)$ and $C_{2,0,1,1}(\theta)$ are the only measured quantities containing Im $(R_1 \cdot R_i^*)$ sufficient information to calculate imaginary parts was not available. The nonvanishing $C_{1,1,0,0}(\theta)$ is the clearest evidence however for the presence of p- and d-waves. From $\sigma_0(\theta)$, $C_{2,n,0,0}(\theta)$ and $C_{1,n,1,N}(\theta)$ the following quantities $M_i = \mathrm{Re}(R_1 \cdot R_i^*)/|R_1|^2$ were calculated using the expansion coefficients $a_{m,n,M,N}(L)$ with odd L:

$$M_3 = +0.017 \pm 0.006 \qquad (l = l' = 1, \quad s = \tfrac{1}{2}, \quad s' = \tfrac{1}{2}, \quad J^\pi = \tfrac{1}{2}^-)$$
$$M_4 = -0.018 \pm 0.005 \qquad (l = l' = 1, \quad s = \tfrac{1}{2}, \quad s' = \tfrac{1}{2}, \quad J^\pi = \tfrac{3}{2}^-)$$
$$M_5 = -0.025 \pm 0.006 \qquad (l = l' = 1, \quad s = \tfrac{3}{2}, \quad s' = \tfrac{1}{2}, \quad J^\pi = \tfrac{1}{2}^-)$$
$$M_6 = +0.012 \pm 0.010 \qquad (l = l' = 1, \quad s = \tfrac{3}{2}, \quad s' = \tfrac{1}{2}, \quad J^\pi = \tfrac{3}{2}^-).$$

The coefficients $a_{m,n,M,N}(L)$ with even L provide in principle enough equations for the determination of the M_i with even l. Difficulties arise however due to the fact that many of them contain $|R_1|^2$ and that differences between the experimental values and those calculated for $R_1 \neq 0$ only are so small that systematic errors of the order of 1% will produce wrong results. It can be said however that the M_i with even l are of the order of a few percent also. The linear relations existing between the coefficients $a_{2,n,0,0}(L)$, $(L = 1, 3)$, are satisfied. Those containing $a_{0,0,0,0}(L)$, $a_{2,n,0,0}(L)$ and $a_{1,n,1,N}(L)$, $(L = 0, 2)$, seem to indicate a systematic error of a few percent in the measurement of beam and/or target polarization. The statistical errors do not allow separation of beam and target polarization errors, but a 4% reduction of the analyzing power of the $T(d, n)\,{}^4\mathrm{He}$ reaction could explain the observed deviations. This would imply a reduction in amplitude of all $C_{m,n,M,N}(\theta)$ reported here and provide further evidence for a contribution from $R_2 = (0\,\tfrac{1}{2}\,\tfrac{1}{2}^+ \mid R \mid 0\,\tfrac{1}{2}\,\tfrac{1}{2}^+)$ in both the $T(d, n)\,{}^4\mathrm{He}$ and the ${}^3\mathrm{He}(d, p)\,{}^4\mathrm{He}$ reactions [2].

V. Discussion

The usefulness of a polarized-beam–polarized-target experiment at very low energies has been demonstrated. The main difficulties consist in the relatively low counting rates obtainable although these are still better by a factor of about 100 compared to equivalent double scattering experiments. Using larger detectors a factor of five could be gained easily compared with the present work and studies to compress polarized ${}^3\mathrm{He}$ gas are in progress [6]. To conclude these remarks two sets of experiments sufficient for determination of all real and imaginary parts of contributing matrix elements are given [7].

	Real parts	Imaginary parts
(A)	$C_{0,0,0,0}(\theta)$	$C_{1,1,0,0}(\theta)$
	$C_{2,n,0,0}(\theta)$, $n = 0, 1, 2$	$C_{0,0,1,1}(\theta)$
	$C_{1,0,1,1}(\theta)$	$C_{2,0,1,1}(\theta)$
	$C_{1,1,1,0}(\theta)$	$C_{2,2,1,0}(\theta)$
(B)	$C_{0,0,0,0}(\theta)$	$C_{1,1,0,0}(\theta)$
	$C_{2,n,0,0}(\theta)$, $n = 0, 1, 2$	$C_{0,0,1,1}(\theta)$
	$C_{1,1,1,-1}(\theta)$	$C_{2,0,1,1}(\theta)$
	$C_{1,1,1,1}(\theta)$	$C_{2,2,1,-1}(\theta)$

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