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SPIN-POLARIZATION OBSERVABLES AT THE $J=3/2^+$ RESONANCE
IN THE REACTIONS $^3\text{H}(d,n)^4\text{He}$ AND $^3\text{He}(d,p)^4\text{He}$

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SPIN-POLARIZATION OBSERVABLES AT THE $J=3/2^+$ RESONANCE
IN THE REACTIONS $^3\text{H}(d,n)^4\text{He}$ and $^3\text{He}(d,p)^4\text{He}^*$

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With the assumption that a single s-wave $J=3/2^+$ reaction amplitude contributes to the $^3\text{H}(d,n)^4\text{He}$ or $^3\text{He}(d,p)^4\text{He}$ reaction at the $J=3/2^+$ resonance, the relative values of the spin-space transition matrix elements are fixed. These are used to calculate all of the spin-polarization observables.

1. INTRODUCTION

The charge-symmetric reactions $^3\text{H}(d,n)^4\text{He}$ and $^3\text{He}(d,p)^4\text{He}$ have an extensive history of both experimental and theoretical study¹⁾. In particular, it was early shown that at the near-threshold s-wave $J=3/2^+$ resonance, these reactions could serve as analyzers of low energy tensor-polarized deuterons and as sources of polarized nucleons from unpolarized incident deuterons^{2,3)}. Later studies examined the effects of including a $J=1/2^+$ reaction amplitude⁴⁾ and, in addition, calculations of some polarization-transfer coefficients were made⁵⁾. More recently it was noted⁶⁾, for the case of the single non-zero $J=3/2^+$ reaction amplitude, that the cartesian component $A_{yy}(\theta)$ of the deuteron tensor analyzing power was a constant,

$$A_{yy}(\theta) = -\sqrt{1/2} T_{20}(\theta) + \sqrt{1/3} T_{22}(\theta) = 1/2,$$

which was implicit in the earlier expressions for the spherical components of the tensor analyzing powers^{4,5)}. Also, a very recent investigation showed that the $^3\text{H}(d,n)^4\text{He}$ fusion reaction rate could be enhanced by a factor of 3/2 if the fusion plasma consisted of both polarized deuterons and tritons, forming exclusively the channel-spin $s=3/2$, $J=3/2^+$ state⁷⁾. This result follows simply from the statistical weights of the quartet $s=3/2$ and doublet $s=1/2$ initial states, with the assumption of the single $J=3/2^+$ reaction amplitude.

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It was this latter result which motivates this paper, since this result should be seen in the expression for the cross section with deuteron polarization components p_{zz} , $p_z(1)$ and triton (or ^3He) polarization $p_z(1/2)$,

$$I(\theta) = I_0(\theta)(1 + 1/2 p_{zz} A_{zz} + 3/2 p_z(1) p_z(1/2) C_{z,z}),$$

Where $I_0(\theta)$ is the cross section with unpolarized participants, A_{zz} is a tensor analyzing-power component, and $C_{z,z}$ is a spin-correlation coefficient^{8,9}).

So, for $p_{zz} \approx p_z(1) = p_z(1/2) = 1$,

$$I(\theta) = I_0(\theta)(1 + 1/2 A_{zz} + 3/2 C_{z,z}). \quad (1)$$

Although $A_{zz} = \sqrt{2} T_{20} = -1/2 (3 \cos^2 \theta - 1)$ was available from the previous work^{4,5}, $C_{z,z}$ and other spin-correlation and polarization-transfer coefficients were not. This work provides the values of these remaining polarization observables.

2. METHOD OF CALCULATION

All of the polarization observables for this system, with the spin structure $1 + 1/2 \rightarrow 1/2 + 0$, have been tabulated^{8,9} in terms of the elements of the transition matrix M between the initial and final spin states, $X_f = M X_i$. Here $M \equiv [M_{\alpha\beta\gamma}]$, where α, β, γ label the magnetic substates of the initial state spin-1, spin-1/2, and final state spin-1/2 particles, respectively. This is the uncoupled representation. Partial-wave expansions of the transition matrix elements are more readily available in the coupled (channel-spin) representation $X_f = K \Phi_i$ with $K \equiv [K_{s'v'sv}]$, where s, v (s', v') are the initial (final) state channel-spin and its substates and Φ_i is the set of initial-state channel-spin functions. Since here $X_f = M X_i = K \Phi_i$, the transformation between the elements of M and K is the same as that between the spin-functions X_i and Φ_i . The procedure, then, is to obtain the K -matrix elements from the partial wave expansions and transform these to the M -matrix elements, from which the polarization observables are calculated.

From Lane and Thomas¹⁰ or Sachs¹¹),

$$K_{s'v'sv}(\theta) = -\frac{i\pi^{1/2}}{k} \sum_{\ell\ell'J} (2\ell+1)^{1/2} (s\ell v 0 | J v) (s'\ell'v'v-v' | J v) Y_{\ell'v'}^{v-v'}(\theta) U_{s'\ell's\ell}^J \quad (2)$$

where $\ell(\ell')$ is the initial (final) state orbital angular momentum and $U_{s'\ell's\ell}^J$ are the scattering (collision) matrix elements in the state of

total angular momentum J . The Coulomb phase-shift terms are included in these elements. The $(s, \lambda, \mu | J, M)$ are the usual vector-addition coefficients.

Since in eq.(2) the z -axis is taken along the projectile direction and the y -axis along $\mathbf{k}_i \times \mathbf{k}_f$, this K -matrix representation is that of the projectile helicity frame. For our case of

$$J=3/2, s=3/2, l=0, s'=1/2, l'=2,$$

eq.(2) reduces to the single term

$$K_{1/2\nu'3/2\nu}(\theta) = -\frac{i\pi^{1/2}}{k^{3/2}} (3/2 \ 0 \ \nu \ 0 | 3/2\nu) (1/2 \ 2\nu' \nu-\nu' | 3/2\nu) Y_2^{\nu-\nu'}(\theta) \quad (3)$$

An important fact is that U^J is independent of the projection of J along the quantization (z) direction, due to rotational invariance, so it is a common factor in these K -matrix elements. Suppressing all of the (fixed) indices except ν and ν' in eq. (3) we obtain

$$\begin{aligned} K_{1/2 \ 3/2} &= K_{-1/2 -3/2} = (\pi/5)^{1/2} U Y_2^1(\theta) \\ K_{1/2 \ 1/2} &= -K_{-1/2 \ 1/2} = (2\pi/5)^{1/2} U Y_2^0(\theta) \\ K_{1/2 -1/2} &= K_{-1/2 \ 1/2} = (3\pi/5)^{1/2} U Y_2^{-1}(\theta) \\ K_{1/2 -3/2} &= -K_{-1/2 \ 3/2} = (4\pi/5)^{1/2} U Y_2^2(\theta), \quad U = (i/k) U^{3/2}. \end{aligned} \quad (4)$$

In general, there would be 6 independent elements in the parity-conserving 2 by 6 K -matrix, but here the doublet to doublet elements $K_{1/2\nu'1/2\nu}$ are set to zero. Transformation to the M -matrix elements then gives

$$\begin{aligned} M_{1/2,1 \ 1/2} &= (\pi/5)^{1/2} U Y_2^1(\theta) = (-iA-D)/\sqrt{2} \\ M_{1/2,0 \ 1/2} &= (4\pi/15)^{1/2} U Y_2^0(\theta) = F \\ M_{1/2,-1 \ 1/2} &= (\pi/5)^{1/2} U Y_2^{-1}(\theta) = (-iA+D)/\sqrt{2} \\ M_{1/2,1 -1/2} &= (2\pi/15)^{1/2} U Y_2^0(\theta) = (-B-C)/\sqrt{2} \\ M_{1/2,0 -1/2} &= (2\pi/5)^{1/2} U Y_2^{-1}(\theta) = E \\ M_{1/2,-1 -1/2} &= (4\pi/5)^{1/2} U Y_2^2(\theta) = (-B+C)/\sqrt{2} \end{aligned} \quad (5)$$

The right hand side of eqs. (5) is the M -matrix representation in which the calculated polarization observables are tabulated^{8,9}). From (5)

$$\begin{aligned} A &= 0 & D &= E = -N(3 \sin \theta \cos \theta) \\ B &= N & F &= -N(3 \cos^2 \theta - 1), \\ C &= N(3 \cos^2 \theta - 2) & & \text{with } N = -U/2 \sqrt{3} \end{aligned} \quad (6)$$

3. RESULTS

Using eqs. (6), the tabulated polarization observables have the following values.

$$3.1 \quad \vec{1} + \vec{1} \rightarrow 1/2 + 0 \quad \text{Observables}$$

$$A_y(1) = A_y(1/2) = p_y' = 0$$

$$A_{yy} = 3/4 C_{y,y} = 1/2$$

$$A_{xz} = 3/2 C_{z,x} = 3/2 C_{x,z} = -3/2 \sin \theta \cos \theta$$

$$A_{xx} = -3/2 C_{z,z} = 1/2 (3 \cos^2 \theta - 2) \quad (7)$$

$$A_{zz} = -3/2 C_{x,x} = -1/2 (3 \cos^2 \theta - 1)$$

$$C_{xy,x} = C_{yz,x} = C_{xz,y} = C_{xx,y} = 0$$

$$C_{yy,y} = C_{zz,y} = C_{xy,z} = C_{yz,z} = 0$$

3.2 $\vec{1} + 1/2 \rightarrow 1/2 + 0$ Observables

$$K_{x'}^{x'} = -1/3 (3 \cos^2 \theta - 1) \quad K_{y'}^{y'} = -2/3$$

$$K_{x'}^{x'} = K_{z'}^{z'} = \sin \theta \cos \theta \quad K_{z'}^{z'} = 1/3 (3 \cos^2 \theta - 2)$$

$$K_{xy}^{x'} = K_{yz}^{x'} = K_{xz}^{y'} = K_{xx}^{y'} = 0 \quad (8)$$

$$K_{yy}^{y'} = K_{zz}^{y'} = K_{xy}^{z'} = K_{yz}^{z'} = 0$$

3.3 $1 + 1/2 \rightarrow 1/2 + 0$ Observables

$$K_{x'}^{x'} = -1/3 (3 \cos^2 \theta - 1) \quad K_{z'}^{z'} = 1/3 (3 \cos^2 \theta - 2)$$

$$K_{y'}^{y'} = -2/3 \quad K_{x'}^{x'} = K_{z'}^{z'} = \sin \theta \cos \theta$$

Since Oniscen^{5,8)} describes the final-state particles in their own cm helicity frame, his $K_{z'}^{x'}$ and $K_{z'}^{z'}$ are related to those of (8) by a rotation through the angle θ around the y-axis. With the values (7) of A_{zz} and $C_{z,z}$, integration of eq. (1) over the 4π solid angle gives $\sigma = 3/2 \sigma_0$.

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