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How a Polarized Beam and Target Experiment Could Help Unravel the E1 Transition Amplitudes in the $^3He\,(n,\gamma)\,^4He$ Reaction *

R.G. Seyler and H.R. Weller†

Department of Physics, Ohio State University, Columbus, Ohio 43210
†Department of Physics, Duke University, Durham, N.C., 27706 U.S.A.
†Triangle Universities Nuclear Laboratory, Durham, N.C., 27706, U.S.A.

The E1 capture amplitudes in the $^3He(n,\gamma)^4He$ reaction are of two types corresponding to channel spin S=0 and S=1. Considerations of the $^4He(\gamma,p)$ - to - $^4He(\gamma,n)$ cross section ratios have indicated the importance of knowing the magnitude of the S=1 E1 strength present in these reactions (or their inverses). Basically this is because whereas T=0 strength is "spurious" for the S=0 E1 terms, both T=0 and T=1 strength is present in the S=1 type terms.

We choose the z axis along $\vec{k}_n$, the momentum vector of the neutron, and the y-axis along $\vec{k}_n \times \vec{k}_\gamma$. As in Ref. 1 the cross section for vector polarized neutron capture followed by E1 gamma emission is of the form

$$\frac{d\sigma}{d\Omega}(p_y) \propto 1 + a_2P_2(\cos\theta) + b_2P_2^1(\theta)p_y \quad , \tag{1}$$

$$\text{where } a_2 = -\frac{|R_o|^2-\frac{1}{2}|R_1|^2}{|R_o|^2+|R_1|^2} \simeq -1 \quad , \tag{2}$$

$$\text{and } b_2 = \frac{1}{\sqrt{2}}\,\frac{\mathrm{Im}\,(R_oR_1^*)}{|R_o|^2+|R_1|^2} \simeq \frac{1}{\sqrt{2}}\,\frac{1}{|R_o|^2}\,\mathrm{Im}\,(R_oR_1^*) \tag{3}$$

The symbol R_s is shorthand for the reduced matrix element or transition amplitude. From the ^4He ground state and the E1 operator we know that the S=0 element is dominant, i.e., $|R_o| \gg |R_1|$, which results in the final approximate forms of Eq's (2) and (3). Note that $a_2 = -1$ implies that $(d\sigma/d\Omega)_u \propto \sin^2\theta$. (4)

We seek the magnitude $|R_1|/|R_o|$, and from Eq. (3) we see that

$$b_2 \simeq \frac{1}{\sqrt{2}}\,|R_1|/|R_o|\,\sin(\phi_o - \phi_1) \quad , \tag{5}$$

where $\phi_o - \phi_1$ is the phase difference of the S=0 and S=1 complex amplitudes.

Previous measurements of polarized neutron capture on an unpolarized ^3He target yielded a value for the quantity b_2 of $b_2 = 0.088 \pm 0.015$.[2] Taken alone, this result could imply either a small R_1 amplitude, or a small relative phase $(\phi_o - \phi_1)$. A very accurate measurement of a_2 or equivalently of the ratio $\frac{d\sigma}{d\Omega}(0^o)/\frac{d\sigma}{d\Omega}(90^o)$, which is equal to $|R_1/R_o|^2$, would appear to settle the question when combined with the b_2 value, but in reality these measurements are experimentally difficult and theoretically ambiguous due to the presence of other (here ignored) small contributions. To avoid such ambiguity it is desirable that the $|R_1|^2$ contributions have a unique angular signature. Such a signature along with independent information regarding the ratio $|R_1/R_o|$ and the relative phase angle (actually its cosine) can be obtained if both the target and projectile are polarized. The TUNL polarized target facility affords us the opportunity to produce a polarized ^3He target (see contribution to this conference: "A Solid ^3He Polarized Target" by D.G. Haase and

C.R. Gould). Together with our pulsed polarized neutron beam, produced via the $^{2}H(\vec{d},n)^{3}He$ reaction, this provides us with the capability of studying the capture of polarized neutrons on polarized ^{3}He.

We find for $W(\theta)$ the correlation function, which is $\propto \frac{d\sigma}{d\Omega}$,

$$
\begin{aligned}
W(\theta) &= \frac{3}{4}\sqrt{3}\,|R_o|^2\,(1-\vec{p}.\vec{P})\sin^2\theta \\
&+\frac{3}{8}\sqrt{3}\,|R_1|^2\,(1-\frac{2}{3}\,\vec{p}.\vec{P}+p_zP_z)\,(1+\cos^2\theta) \\
&+\frac{3}{4}\frac{\sqrt{3}}{2}\sin 2\theta\,[\,\mathrm{Im}(R_oR_1^*)\,(p_y+P_y)+\mathrm{Re}(R_oR_1^*)\,(p_xP_z-p_zP_x)\,] \\
&+\frac{1}{8}\sqrt{3}\sin^2\theta\,|R_1|^2\,(p_xP_x-p_yP_y)\quad, \qquad (6)
\end{aligned}
$$

where p and P denote the polarization of the neutron and ^{3}He respectively. We can express W in terms of the unpolarized W_u and the analyzing powers,

$$
\begin{aligned}
W(\theta) = W_u(\theta)\;[\,&1+p_yA_{y,}(\theta)+P_yA_{,y}(\theta)+p_zP_zA_{z,z}(\theta)+p_xP_xA_{x,x}(\theta)+p_yP_yA_{y,y}(\theta) \\
&+p_xP_zA_{x,z}(\theta)+p_zP_xA_{z,x}(\theta)\,] \qquad (7)
\end{aligned}
$$

where from (6) $W_u(\theta) = \frac{3}{4}\sqrt{3}\,[\,|R_o|^2\sin^2\theta+\frac{1}{2}|R_1|^2\,(1+\cos^2\theta)]$,

or for $\theta \gg |^{R}1/R_o|^2$ $\quad W_u(\theta) \simeq \frac{3}{4}\sqrt{3}\,|R_o|^2\,\sin^2\theta$, $\qquad$ (8)

$$W_u(\theta)\,A_{y,}(\theta) = W_u(\theta)A_{,y}(\theta) = \frac{3}{4}\frac{\sqrt{3}}{2}\sin 2\theta\;\mathrm{Im}\,(R_oR_1^*), \qquad (9)$$

and $W_u(\theta)A_{x,z}(\theta) = -W_u(\theta)\,A_{z,x}\,(\theta) = \frac{3}{4}\frac{\sqrt{3}}{2}\sin 2\theta\;\mathrm{Re}\,(R_oR_1^*)$, $\qquad$ (10)

Comparing Eqs. (9) and (10) we see that a measurement of $A_{x,z}(\theta)$ (or $A_{z,x}$) would compliment measurement of $A_{y,}\ (\theta)$ (or $A_{,y}(\theta)$) by being sensitive to the product of $|R_1/R_o|$ and $\cos\,(\phi_o-\phi_1)$.

If one could make $\vec{p}.\vec{P}=1$ we would expect the channel spin to have unit value, and we see from Eq (6) that the $|R_o|^2$ contribution vanishes in this case. For $\vec{p}.\vec{P}=1$ and $p_y = o$ we have

$$W(\theta) = \frac{1}{4}\sqrt{3}\,|R_1|^2\,[\,1+3p_zP_z-2p_zP_z\sin^2\theta\,]\quad, \qquad (11)$$

and forming the ratio of Eqs. (11) and (8), (for $\theta \gg |R_1/R_o|^2$)

$$\frac{W\,(p_xP_x+p_zP_z=1)}{W_u} = \frac{1}{3}\left|\frac{R_1}{R_o}\right|^2\left(\frac{1+3p_zP_z-2p_zP_z\sin^2\theta}{\sin^2\theta}\right)\quad, \qquad (12)$$

which allows the θ dependence to be tested and doesn't involve the subtraction of large numbers as does an analyzing power measurement. On the other hand, the analyzing power measurements (say A_y and $A_{x,z}$) do not require $\vec{p}.\vec{P}=1$, which is necessary if one wants to eliminate the large $|R_o|^2$ contribution from Eq. (6), and therefore may be more practical.

References

1) R.G. Seyler and H.R. Weller, Phys. Rev. C20, 453 (1979).
2) H.R. Weller et al., Phys. Rev. C25, 2111 (1982).

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