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D-STATE EFFECTS IN THE $^6\text{Li} \left( \vec{d}, \alpha \right) ^4\text{He}$ REACTION

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Résumé - On montre que les pouvoirs d'analyse tensorielle de la reaction $^6\text{Li} \left( \vec{d}, \alpha \right) ^4\text{He}$ revèle, pour la première fois, la presence de la petite composante d'état D dans la configuration $\alpha - d$ du $^6\text{Li}$. Calculs de DWBA pour une energie $E_d=10\text{MeV}$ conduisent à $-0.015 < \eta \left( ^6\text{Li} \right) < -0.010$.

Abstract - It is shown that the tensor analysing powers of the reaction $^6\text{Li} \left( \vec{d}, \alpha \right) ^4\text{He}$ provide the first direct evidence for the small D-state component of $^6\text{Li}$. DWBA calculations at $E_d=10\text{MeV}$ give $-0.015 < \eta \left( ^6\text{Li} \right) < -0.010$.

Cross section and analysing powers of the $^6\text{Li} \left( \vec{d}, \alpha \right) ^4\text{He}$ reaction have been measured at deuteron energies from 1.5 to 11.5 MeV /1/ and more recently up to 22 MeV /2/. A distinctive feature of the reaction is the large tensor analysing powers (TAP) which reaches values close to their theoretically maximum values. In particular $A_{yy}$ is very large for $8 < E_d < 10 \text{ MeV}$ and $60^\circ < \Theta < 120^\circ$ reaching its maximum value $A_{yy} = 1$ at $E_d = 8.8 \text{ MeV} /3/$. For $E_d = 8\text{MeV}$ the energy dependence of the polarization observables suggests the presence of two overlapping resonances at $E_d = 0.8$ and $3.75 \text{ MeV}$. For energies $E_d > 8 \text{ MeV}$ all coefficients from the Legendre polynomial analysis of the reaction observables /1/ show a fairly flat behaviour with energy indicating that only very broad resonances might exist and therefore that the reaction mechanism is predominantly direct. Here we present an analysis of the reaction based on the direct reaction mechanism and on the $\alpha - d$ cluster model of $^6\text{Li}$.

Since the exit channel spin is zero the orbital angular momentum transfer in the reaction $\ell$ is equal to the entrance channel spin $s=0,1,2$. The expansion of the transition amplitude into terms with definite $\ell$ gives

$$< E_{\alpha} | T | 1 \sigma_d l \sigma : E_d ^{\ell} > = \sum _{\ell} (-1)^{1-\sigma} ( \ell \lambda 1 \sigma_d l 1-\sigma ) B^{\ell \lambda} (k_{\alpha} , k_d )$$

where $\sigma_d$ and $\sigma$ are the $^2\text{H}$ and $^6\text{Li}$ spin projections. In a direct reaction model, with no spin dependent forces in the entrance channel, $\vec{L} = \vec{L} - \vec{L}^\prime$ where $\vec{L}$ and $\vec{L}^\prime$ are the orbital angular momentum of the transferred deuteron in $^6\text{Li}$ and $^4\text{He}$. Thus with pure S-states $\ell$ can only be zero. A more detailed analysis /4/ shows that the amplitudes $B^{2\ell}$ are essentially determined by the D-state components in $^6\text{Li}$ and $^4\text{He}$ while $B^{00}$ and $B^{1\lambda}$ are determined by the S-state components with central and spin-orbit interactions in the entrance channel, respectively. Because of the high reaction Q-value the momentum transfer is very large. Transitions with $\ell=2$ are strongly enhanced because they lead to better momentum and angular momentum matching. This results in a strong amplification of the D-state effects. In the Madison coordinate system with y axis along $k_d \times k_{\alpha}$ and z axis along $k_d$, parity conservation in the reaction implies that there are 5 independent complex amplitudes $B^{00}$, $B^{11}$, $B^{20}$, $B^{21}$, $B^{22}$. By expressing the reaction observables in terms of the amplitudes $B^{2\ell}$ we can determine their relative sensitivity to specific interactions and in particular to the D-states. Interferences terms of the form $B^{00} B^{2\ell \ast}$ will show strong D-state effects since the dependence on $B^{2\ell}$ is amplified.
by the relatively large $B^{00}$ amplitude. Such terms are only present in the TAP, which, in the Madison coordinate system, are given by /4/

$$T_{20}(\Theta) = \frac{1}{\sigma(\Theta)} \left[ \frac{1}{3\sqrt{2}} |B^{11}|^2 + \frac{2}{\sqrt{5}} \text{Re}(B^{00}B^{20*}) + \sqrt{\frac{6}{5}} \text{Re}(B^{11}B^{21*}) + O \right]$$  \hspace{1cm} (2a)

$$T_{21}(\Theta) = \frac{1}{\sigma(\Theta)} \left[ \frac{2}{\sqrt{5}} \text{Re}(B^{00}B^{21*}) - \frac{\sqrt{3}}{5} \text{Re}[B^{11}(B^{20} - \frac{2}{\sqrt{3}}B^{22*})] + O \right]$$  \hspace{1cm} (2b)

$$T_{22}(\Theta) = \frac{1}{\sigma(\Theta)} \left[ -\frac{1}{2\sqrt{3}} |B^{11}|^2 + \frac{2}{\sqrt{5}} \text{Re}(B^{00}B^{22*}) - \frac{1}{\sqrt{5}} \text{Re}(B^{11}B^{21*}) + O \right]$$  \hspace{1cm} (2c)

where $O$ represents terms quadratic in the $B^{2\lambda}$ amplitudes and $\sigma(\Theta)$ is proportional to the unpolarized cross section. The eqs.(2) show that $T_{21}$ and the linear combination $T_{20} - \sqrt{\frac{2}{3}} T_{22}$ are very sensitive to the D-state effects.

It is of particular interest to consider the observable

$$A_{yy} = 1 - \frac{1}{\sigma(\Theta)} |B^{00} + \frac{1}{\sqrt{10}} (B^{20} + \sqrt{6}B^{22})|^2$$  \hspace{1cm} (3)

which reaches its maximum value $A_{yy} = 1$ for

$$B^{00} = -\frac{1}{\sqrt{10}} (B^{20} + \sqrt{6}B^{22})$$  \hspace{1cm} (4)

Eq.(4) shows that when $A_{yy} = 1$ the contributions from $\ell=0$ and $\ell=2$ transitions are of comparable magnitude. The observation of large $A_{yy}$ and in particular $A_{yy} = 1$ confirms that the peculiar kinematic conditions in the reaction tend to enhance $\ell=2$ transitions and therefore to magnify the effects of the D-states. Furthermore when $A_{yy} = 1$ it is in principle possible to determine completely the amplitudes $B^{2\lambda}$ from the measurement of the unpolarized cross section and all analysing powers in the $^{6}\text{Li}(d,\alpha)^4\text{He}$ and $^{2}\text{H}(^6\text{Li},\alpha)^4\text{He}$ reactions. Since $A_{yy}$ is equal in both reactions the number of independent observables is 7 and there are 4 $B^{2\lambda}$ amplitudes corresponding to 7 real numbers plus an overall phase factor. For $A_{yy} < 1$ the determination of the $B^{2\lambda}$ amplitudes requires also the measurement of spin correlation coefficients. However it is interesting that the full determination of the transition amplitudes from relatively simple experiments is, in principle, possible in a situation where the physics of the reaction is particularly significant because of the large $\ell=2$ contributions.

One and two step (involving the spin-orbit split triplet of low lying excited states of $^6\text{Li}$) DWBA calculations have been performed using a modified version of the program FRESCO /5/ that accounts for the symmetrization in the $\alpha-\alpha$ channel. The d-d configuration in $^4\text{He}$ is taken as a superposition of S and D states. The D-state component has been extensively studied by various authors /6/. It is well established that the asymptotic D/S state ratio $\eta(^4\text{He})$ is negative although the uncertainty in its value is still rather large. Recent theoretical determinations of $D_2$ ( $D_2 = \eta /\alpha^2$ ) range from $-0.24\text{fm}^2$ to $-0.16\text{fm}^2$. The $\alpha$-d configuration in $^6\text{Li}$ is the superposition of 2S and 1D states but the amplitude $a_2$ of the small 1D component is not known. Nishioka et al. /8/ have shown that in the $\alpha$-d cluster model of $^6\text{Li}$ the negative quadrupole moment of $^6\text{Li}$, $Q(^6\text{Li}) = -0.064\text{ fm}^2$, can be reproduced with $a_2 = -0.08$ which corresponds to $\eta(^6\text{Li}) = -0.014$. However 3-body model calculations by Lehman et al. /9/ predict a positive but
Fig. 1 - DWBA calculations of the TAP without D-states - dotted curves - ; only with the $^4\text{He}$ D-state corresponding to $D_2(^4\text{He}) = -0.2\text{fm}^2$ - full curves - ; with both $^4\text{He}$ and $^6\text{Li}$ D-states corresponding to $D_2(^4\text{He}) = -0.2\text{fm}^2$ and $a_2 = 0.08$ - dashed curves - ; and finally with $D_2(^4\text{He}) = -0.2\text{fm}^2$ and $a_2 = -0.08$ - dot-dashed curves.
very small $q_{6Li}$). In the DWBA calculations the bound state wave functions are generated in Wood-Saxon wells and the $^2H$ and $^4He$ optical potential are from references /10/ and /11/. At $E_d=10\text{MeV}$ the calculations do not provide an entirely satisfactory description of the differential cross section data but the absolute value is in reasonable good agreement with experiment. We find that $iT_{11}$ is very sensitive to the spin-orbit potentials involving both the $^2H$ and $^6Li$ spins. The inclusion of the latter in the calculations was needed to obtain a qualitative description of the $iT_{11}(\theta)$ angular distributions. A better determination of the spin-dependent forces requires the measurement of the analyzing powers in $d-^6Li$ elastic scattering.

$^4\text{He}$ and $^6Li$ D-state effects are relatively small in the cross section and $iT_{11}$ but large in the TAP as shown in Fig.1. The predicted $T_{21}$ with pure S-states is about one order of magnitude smaller than the experimental data. Furthermore we find that the interference between $^4\text{He}$ and $^6Li$ D-state effects is destructive for $a_2 > 0$ and constructive for $a_2 < 0$. Considerably better agreement with the data is obtained for $a_2 = -0.08$ than with $a_2 = 0.08$. The magnitude of the D-state effects did not change significantly in calculations where the coupling to the $^6Li$ low lying excited states was included. The reason why $^6Li$ D-state effects are significant although $|\eta_{^6Li}| << |\eta_{^4He}|$, and the constructive interference for $\eta_{^6Li} < 0$ can be well understood with the peripheral plane wave model where the D-state effects are determined by the quantity

$$X = \{ \eta_{^6Li} [1 - a \eta_{^4He} / \sqrt{2}] + a \eta_{^4He} \} / [1 + \eta_{^6Li} \eta_{^4He} a]$$

where $a = 3 B_{^6Li} / (4 B_{^4He})$ and $B$ are the deuteron binding energies. The sensitivity of $X$ to $\eta_{^6Li}$ is amplified by the fact that $a$ is small since $B_{^6Li} << B_{^4He}$. Furthermore the observation that the terms linear in $\eta$ have the same sign indicates that the interference is constructive for $\eta_{^6Li} < 0$.

The present calculations show that the TAP of the $^6Li( d,\alpha)^4\text{He}$ reaction contain the first direct evidence of the small D-state component in the $\alpha-d$ cluster configuration of the $^6Li$ and indicate that $\eta_{^6Li} < 0$. The large sensitivity of the TAP to the $^4\text{He}$ D-state limits the $\eta_{^6Li}$ determination to the uncertainty in $\eta_{^4He}$ obtained from other methods. For $D_{21}(^4\text{He}) = 0.2\text{fm}^2$ the best fit to the TAP at $10\text{MeV}$ is obtained for $-0.015 < \eta_{^6Li} < -0.010$. An analysis of the analysing power data in the $^6Li( d,\alpha)^4\text{He}$ and $^2H( ^6Li,\alpha)^4\text{He}$ reactions over a wide energy range up to intermediate energies can be expected to provide new information on tensor force effects both in $^4\text{He}$ and $^6Li$. In the case of $^4\text{He}$ this investigation is particularly interesting in view of the apparent sensitivity of the $^4\text{He}$ D-state to the N-N tensor force at small distances.

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