Proc. Sixth Int. Symp. Polar. Phenom. in Nucl. Phys., Osaka, 1985
J. Phys. Soc. Jpn. 55 (1986) Suppl. p. 912-913

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The $^2H(\vec{d},\gamma)^4He$ reaction at low energy

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It is well known that for deuteron center of mass energies below $E_d = 20$ MeV the $^2H(d,\gamma)^4He$ reaction is dominated by the E2 amplitude $A = \langle {}^4He|E2|{}^1D_2\rangle$, almost entirely determined by the ^4He S-state. The ^4He D-state generates contributions to the amplitudes $B = \langle {}^4He|E2|{}^5S_2\rangle$, $C = \langle {}^4He|E2|{}^5D_2\rangle$ and $D = \langle {}^4He|E2|{}^5G_2\rangle$. Recent experimental[1)] and theoretical[2)] work has shown that the tensor analyzing powers of the reaction are very sensitive to the D-state admixture in ^4He and in particular to the D/S state ratio ρ of ^4He. We report here on improvements in the theoretical description of the reaction and consider specifically a situation where the deuteron energy is low $E_d < 5$ MeV.

The E2 operator is proportional to

$$\sum_{i=1,2} \mathcal{Y}_2^M(\vec{r}_i) = \frac{1}{4}\left[\mathcal{Y}_2^M(\vec{r}+\vec{r}_{13}) + \mathcal{Y}_2^M(\vec{r}-\vec{r}_{24})\right] \tag{1}$$

where $\vec{r}_i$ are the proton position vectors relative to the ^4He center of mass, $\vec{r}$ is the displacement between the centers of mass of the deuteron clusters and $\mathcal{Y}_2^M = r^2 Y_2^M$ is a solid spherical harmonic. In ref. 2 it was assumed that

$$\sum_{i=1,2} \mathcal{Y}_2^M(\vec{r}_i) \cong \frac{1}{2}\mathcal{Y}_2^M(\vec{r}) \tag{2}$$

which is equivalent to a point deuteron approximation in the E2 operator. With this approximation the E2 amplitudes depend on the internal structure of ^4He only through the projection of ^4He into 2 deuterons $\langle\phi_d\,\phi_d|\phi_\alpha\rangle$. The contributions from the $\vec{r}_{13}$ and $\vec{r}_{24}$ terms of the E2 operators were calculated using a gaussian wave function for ^4He that reproduces its rms radius. We find that for $E_d < 20$ MeV such contributions to the amplitudes B and C are typically of the order of 10 per cent of the amplitudes for point like deuterons and negligible in A and D. Furthermore the amplitude $\langle {}^1S_0|E2|{}^5S_2\rangle$ generated by the deuteron D-state was found to be very small compared with the dominant $\langle {}^1S_0|E2|{}^5D_2\rangle$ amplitude. The comparison of tensor analysing power data[1)] at $E_d = 4.85$ MeV with calculations for a complete E2 operator using separable interactions to describe the scattering states does not change the range of ρ values previously obtained[2)], namely $-0.5 < \rho < -0.4$.

As the deuteron energy decreases the amplitude D becomes negligible and A,C are strongly reduced relative to B because of centrifugal effects. Since the initial state in B has channel spin 2 this amplitude is mainly determined by the ^4He D-state. Therefore ^4He D-state effects should increase appreciably for low energy. This phenomenon is particularly noticeable in the tensor analyzing powers but may also be seen in the cross section. The total cross sections for the radiactive capture and the inverse reaction are given by

$$\sigma_T(dd \longrightarrow \gamma\alpha) = 6.4398 \times 10^{-12}\, E_\gamma^5 p^{-1}\ T\ \mu\text{b} \tag{3a}$$

$$\sigma_T(\gamma\alpha \longrightarrow dd) = 7.5226 \times 10^{-7}\, E_\gamma^3\ p\ T\ \mu\text{b} \tag{3b}$$

where E_γ (MeV) is the γ ray energy, $p(\text{fm}^{-1})$ the relative wave number in the scattering state and

$$T = 7.5\pi N^2 \left[|B|^2 + (|A|^2 + |C|^2)/5 + |D|^2/9\right]. \quad (4)$$

In eq. (4) the amplitudes A,B,C,D, defined in ref.2, are assumed to be calculated with the point deuteron form of the E2 operator and with the S and D-state part of $\langle \phi_d \phi_d | \phi_\alpha \rangle$ normalized to unit probability. N^2 is the probability of the 2-deuteron configuration in ^{4}He in a relative S-state. Calculations of $\sigma_T(\gamma\alpha\to dd)$ for E_d<20 MeV, shown in Fig.1, were performed as in ref.2. Coulomb effects were estimated using an energy dependent penetration factor and are found to decrease the cross section by 30% and 5% at E_d = 1 and 5 MeV, respectively. The best fit to experiment over the energy range 1 MeV< E_d < 20 MeV is obtained for a 2-deuteron S-state probability of N^2 = 0.55. The D-state probability in the 2-deuteron configuration depends on the value of ρ and is of the order of 15% of the S-state probability. As shown in ref.2 the tensor analysing power A_{yy} is particularly favourable for an empirical determination of ρ. Fig.2 shows the result of calculations of A_{yy} at θ = 45° (where the cross section is larger) as a function of incident energy and for different values of ρ. We find that A_{yy} is strongly sensitive to ρ down to energies of the order of 2 MeV. At lower energies the amplitude B is dominant and the tensor analysing powers become independent of ρ. In particular as $E_d \to 0$, $A_{yy}(\pi/4) \to 1/4$.

We conclude that the ^{4}He D-state effects increase both in the low and high energy limits. In the low energy because of the absence of centrifugal effects in B and at high energy because of the D-state high momentum components. The measurement of A_{yy} close to θ =45° and 135°, within the low energy range 2<E_d<20 MeV, should be particularly useful for the determination of ρ.

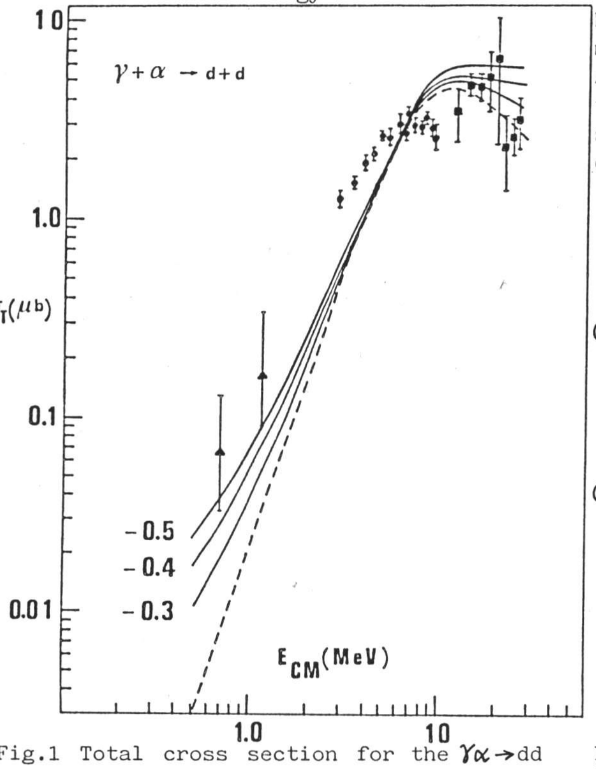

Fig.1 Total cross section for the $\gamma\alpha\to$dd reaction. The data is from Ref.3). The broken curve is obtained with A ≠ 0 and B=C=D=0. The 3 full curves include the effect of B,C,D, and correspond to ρ equal to -0.5, -0.4 and -0.3.

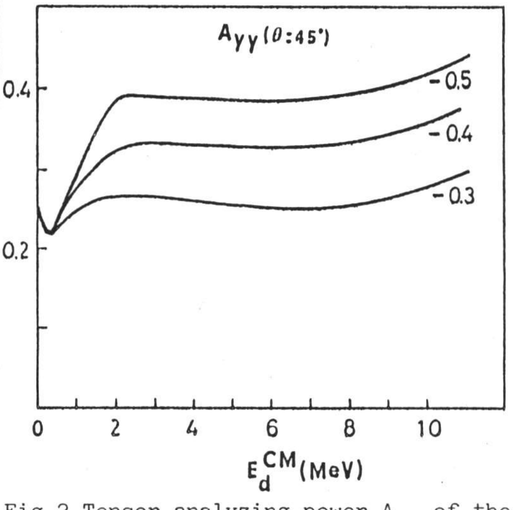

Fig.2 Tensor analyzing power A_{yy} of the ^{2}H($\vec{d}$,γ)^{4}He reaction at θ =45° calculated as in Fig.1 including the amplitudes A,B,C,D, and for the same values of ρ .

References

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