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Mechanism of the ^{6}Li + ^{6}Li $\rightarrow 3\alpha$ reaction at low energy

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The angular distribution of the two α-particle coincidence cross sections, measured at 2 MeV incident energy, is interpreted. Since the momentum transferred to the outgoing α particles is high enough to minimize peripheral effects in a quasifree process, the apparent narrowing of the impulse distribution of the α-d motion in ^{6}Li is attributed to Coulomb effects in the entrance channel.

[NUCLEAR REACTIONS ^{6}Li + ^{6}Li $\rightarrow 3\alpha$ at 2 MeV. Discussed angular distribution of two α-particle coincidence cross section. Proposed subthreshold mechanism.]

In a recent work[1] Norbeck *et al.* have interpreted their coincidence measurement of the ^{6}Li + ^{6}Li $\rightarrow 3\alpha$ reaction at 2 MeV in a distorted-wave Born approximation (DWBA) framework. Their analysis shows that the reaction can be described by a quasifree process in which one of the α clusters, belonging either to the target nucleus or to the projectile, is spectator of the ^{6}Li + $d \rightarrow 2\alpha$ virtual reaction. There is, however, no kinematical separation between the two processes because of the low incident energy. In fact, the reaction is considered to take place when the relative motion of the two ^{6}Li is stopped by the Coulomb repulsion, so that it is not possible to distinguish between the two different contributions.

A similar explanation has already been suggested in Refs. 2 and 3 to interpret the shape of the spectra of the α particles produced in the same reaction. The hypothesis was made of the formation of an $\alpha dd\alpha$ quasimolecular state. This structure eventually decays leaving one α particle in its state of motion while the other two share almost all the energy released by the high Q of the reaction (20.9 MeV).

Here we want to point out that both interpretations are able to predict the position of the maxima in the energy spectra[2,3] or in the angular correlation,[1] while no consistent interpretation is given for their shapes. In fact, Ref. 1 uses a simplified method for the DWBA analysis including only the interaction between the two deuterons through the introduction of a Gaussian shaped contribution with an adjustable width parameter β, while in Refs. 2 and 3 the binding energy B of the quasimolecular state is considered as a parameter to be changed with the incident energy.

In an effort to have a better understanding of the reaction mechanism, we have reinterpreted the data of Ref. 1 in the plane-wave impulse approximation (PWIA), by considering one of the α clusters of ^{6}Li as spectator of a quasifree process, once the two ^{6}Li ions are brought at rest in their c.m. system by the Coulomb repulsion. The momentum distribution $G^2(\vec{p}_s)$ of the α-d cluster structure of ^{6}Li was taken as the Fourier transform of the intercluster wave function $\phi_{2s}(r)$ which, in turn, was calculated by integration of the Schrödinger equation with the potential reported in Ref. 4. The momentum distribution $G^2(\vec{p}_1)$ of the undetected α particle was deduced by adding the velocity of the spectator to the c.m. velocity:

$$\vec{p}_1 = \tfrac{1}{3}\vec{p}_0 + \vec{p}_s ,$$

where $\vec{p}_0$ is the momentum of the ^{6}Li + ^{6}Li system. The coincidence cross section of the two energetic α particles α_2 and α_3 was then written as

$$\frac{d^3\sigma}{dE_2\, d\Omega_2\, d\Omega_3} = \mathrm{const}(F_K)G^2(\vec{p}_1) , \tag{1}$$

where (F_K) is a kinematical factor[5] which varies smoothly over the kinematical region of interest. To obtain the double differential cross section reported in Fig. 1, a numerical integration was performed over the E_2 spectrum from 9.9 to 11.4 MeV, according to the procedure of Ref. 1. The resulting cross section is reported in Fig. 1 as a dashed curve, with an arbitrary normalization factor, after adding a continuous background contribution, due to other reaction mechanism,[1] reported as a dot-dashed line. While the position of the maximum is again well reproduced, the shape is not. By introducing a cutoff radius R_c in the wave function ϕ_{2s}, a good fit is instead found for $R_c = 8$ fm (continuous curve). Note that the full width at half maximum (FWHM) of the

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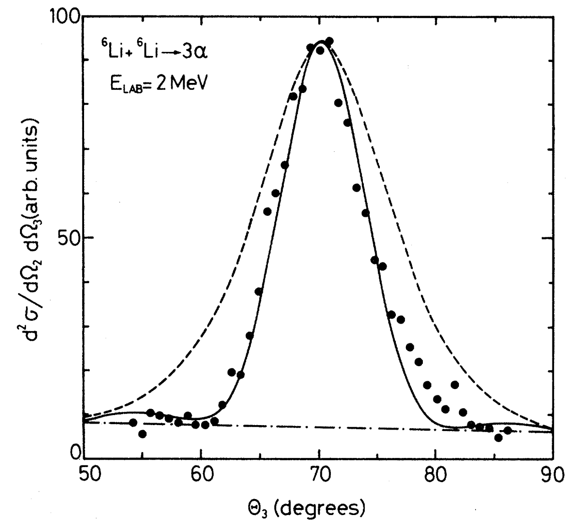

FIG. 1. Coincidence cross section for two α particles detected at $\theta_2=-90°$ and θ_3, from Ref. 1. Only events corresponding to E_2 between 9.9 and 11.4 MeV are retained. The dot-dashed line is an evaluation of the background due to sequential processes. The continuous and dashed curves are calculated in the PWIA framework, with and without a cutoff radius as described in the text.

momentum distribution is lowered from 68 to 45 MeV/c.

It is well known that the introduction of a cutoff radius in the PWIA analysis is able to simulate absorption effects which seem to take place mainly at small intercluster distances. However, the momentum transfer (about 290 MeV/c) is here high enough to minimize such effects.[6] We have already pointed out[6,7] that in quasi-free reactions or scattering involving the α-d cluster structure of ^{6}Li, the experimental momentum distribution has a FWHM of about 70 MeV/c only when the momentum q transferred to the outgoing particles is of the order of 300 MeV/c or more. The introduction of a cutoff radius is needed to reproduce the apparent narrowing of the momentum distribution, for smaller value of q. This not being the case here, we propose a different explanation.

For a laboratory energy of 2 MeV, the distance of closest approach of two pointlike ^{6}Li nuclei is 13 fm, i.e., well beyond the range of nuclear forces. Even by considering a radius of $1.3A^{1/3}$ fm for spherical ^{6}Li nuclei, the two nuclear surfaces are still 8 fm apart. The possibility for a sizable interaction lays then in the loosely bound α-d cluster structure of ^{6}Li. In fact, for large intercluster distances it is possible for the two deuterons to get within the range of the nuclear forces if the two α particles are at a distance large enough to lower the overall Coulomb energy. For instance, for a stretched α-d-d-α configuration, with an α-d distance of 10 fm for each ^{6}Li, it is possible for the c.m. of the two deuterons to get within 4.6 fm. This distance is comparable to twice the deuteron rms radius which is 2.1 fm.

Equation (1) is then still valid for the interpretation of the data, provided only large α-d distances are retained in the ^{6}Li wave function. This picture is well in agreement with the procedure adopted for the fit, namely, the introduction of a cutoff radius. Note that $R_c=8$ fm implies a rms intercluster distance of about 10 fm, which is just the distance considered in the example reported above.

The analysis reported here evidences then that the peripheral nature of the process is due to a subthreshold effect, connected with the entrance channel of the reaction, and not to reabsorption effects for small intercluster distances, which usually show up at smaller momentum transfer.

According to this interpretation, by lowering the incident energy one would expect the reaction to take place at still larger intercluster distances. The need for a larger value of R_c implies not only a smaller cross section, but also shapes of the coincidence energy spectra and of the angular correlation with a smaller width. By increasing the energy, the inverse effect is expected, but at or above the Coulomb barrier (about 5 MeV in the laboratory system) the phenomenon should disappear by giving rise to quasi-free processes where the two contributions given by the spectator α particle in the projectile and in the target can be separated. Coincidence measurements performed[8] at 6 and 13 MeV have already confirmed this point. Single α-particle spectra should instead be less sensitive to the details of the model. Actually, they do not show evidence[3] for two separate contributions up to an incident energy of 24 MeV, were it not for a broadening of the inclusive peak which was accounted for in Ref. 3 by increasing the binding energy of the quasimolecular state.

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