Direct mechanism of $^6Li+^6Li\rightarrow 3\alpha$ reaction at low energy

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The $^6Li+^6Li\rightarrow 3\alpha$ reaction has been studied in a kinematically complete experiment at 2.4 and 4.2 MeV incident energy. Information on the behavior of quasifree effects around the Coulomb barrier is discussed.

The recent work of Norbeck *et al.*[1] has renewed interest[2] in the investigation of the 3-α final state from the $^6Li+^6Li$ interaction at incident energies around the Coulomb barrier. Much work was done in this field,[3–5] and recently the 3-α and four-body final states have been studied by Warner *et al.*[6] at higher energies, with particular attention to the single and double spectator pole model.

A characteristic feature of both single and coincidence α-particle spectra from the $^6Li+^6Li\rightarrow 3\alpha$ reaction is the presence, even at low incident energies, of broad peaks which cannot be attributed to sequential decay (SD) through an intermediate ^8Be level. Considering an α-d structure for ^6Li, it has been assumed[1,2] that a single pole spectator process takes place in which only a d cluster, either in the target or in the projectile, interacts with the other ^6Li nucleus. In this picture the α cluster is considered a spectator of the process, and therefore it retains, after the interaction, the same momentum $\vec{p}_s$ it had in the parent ^6Li.

Because of the s-wave relative motion of the α and d clusters in ^6Li, enhancements of the α-α coincidence cross section are expected at those detection angles accepting events for which $\vec{p}_s$ is around zero. By fixing one detection angle, there are two values of the second detection angle for which this occurs, corresponding to the presence of an α cluster acting as a spectator in the target or in the projectile, respectively. From now on these processes will be referred to as standard quasifree (SQF) processes. At incident energies of 6 MeV or more[3] the presence of SQF peaks has been experimentally verified. At 2 MeV, however,[1–3] only one sharp peak appears in the spectra and in the angular correlation, at an intermediate position between the two SQF configurations. At such low energy the two ions interact only when their relative motion is stopped by the Coulomb repulsion and the two QF processes are no longer distinguishable.[1,2] Therefore the spectator α particle will retain the velocity of the slowed-down system, i.e., the c.m. velocity. Let us refer to this mechanism as the anomalous quasifree (AQF) process.

The triple differential coincidence cross section is related in the plane-wave impulse approximation (PWIA) to the spectator momentum distribution $G^2(\vec{p}_s)$ by the relationship

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_1}=F_k P\left[\frac{d\sigma}{d\Omega}\right]_{\text{d-Li}} G^2(\vec{p}_s)\ ,$$

where subscripts 1 and 2 refer to the two detected α particles, F_k is a kinematical factor, $(d\sigma/d\Omega)_{\text{d-Li}}$ is the off-energy-shell two-body cross section for the virtual $d+{}^6Li\rightarrow 2\alpha$ process, and P takes into account α-d clustering probability and reabsorption effects. In the SQF mechanism the spectator momentum $\vec{p}_s$ can either be given by $\vec{p}_s^{\,(T)}=\vec{p}_3$ (spectator in the target), where $\vec{p}_3$ is the momentum of the undetected α particle, or by $\vec{p}_s^{\,(P)}=\vec{p}_3-\frac{2}{3}\vec{p}_0$ (spectator in the projectile), where $\vec{p}_0$ is the momentum of the incident ^6Li. For the AQF process instead, $\vec{p}_s^{\,(A)}=\vec{p}_3-\frac{1}{3}\vec{p}_0$.

To achieve a better understanding of the reaction mechanism, it seemed worthwhile[1,2] to follow the behavior of the α-α angular correlation by increasing the incident energy from about 2 MeV, where the AQF peak has been found,[3] to about 6 MeV, where only the two SQF contributions are clearly evident. The transition is, in fact, expected to occur at energies close to the Coulomb barrier, which is, for two ^6Li ions, around 5 MeV in the laboratory system. In this paper we report the data taken at two energies, namely 2.4 and 4.2 MeV.

The experiment was performed at the Demokritos Nuclear Research Center, Athens. A $^6Li^{++}$ beam, whose intensity ranged from 15 to 50 particle nA, was produced by the T11/25 Tandem accelerator and was used to bombard an isotopically enriched ^6Li target evaporated on a carbon backing. One silicon surface barrier detector ($\Delta\Omega=2.9$ msr) was placed at $\theta_1=-60°$ in coincidence with a position sensitive detector (PSD) set up on the opposite side of the beam in a coplanar geometry. Two measurements were performed at 2.4 MeV by placing the PSD at $\theta_2=90°$ and 97°, with an angular acceptance of $\Delta\theta_2=35°$. At 4.2 MeV the PSD was placed at $\theta_2=78°$ and 106° in order to cover a complete angular correlation. Each piece of information, consisting of the E_1 and E_2 energy signals, the x_2, and the timing signals, was stored in an event-by-event mode on magnetic tape.

In the off-line analysis, the events from the $^6Li+{}^6Li\rightarrow 3\alpha$ reaction were kinematically identified ($Q=20.9$ MeV). The rate of the random coincidences was always found to be a few percent. From each measurement, 12 two-dimensional E_1-E_2 spectra were obtained at different θ_2 angles, with an angular acceptance of about 3°. The two-dimensional spectra were then projected on the E_1 axis. The triple differential cross section thus obtained was finally averaged over a 1 MeV wide interval around the E_1 energy value corresponding to the minimum spectator momentum. The procedure allows the exclusion of kinematical regions where contributions from SD are expected. It was repeated twice, for minimum $p_s^{(T)}$ and $p_s^{(P)}$, respectively. Figure 1 shows such distributions for 2.4 MeV incident energy. As expected, the distribution is dominated by a strong peak at $p_3=55$ MeV/c which corresponds to an α particle having the velocity of the c.m. of the system. However, a non-negligible contribution also comes from the two SQF regions.

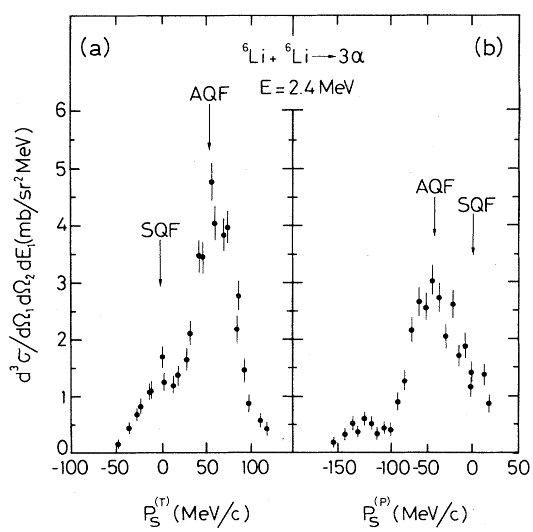

FIG. 1. The α-α angular correlation cross section measured at 2.4 MeV is reported here as a function of the spectator momentum, after averaging over an E_1 interval, as described in the text. The spectator momentum is, for the spectator, in the target 1(a) or in the projectile 1(b).

The result of a similar analysis for the 4.2 MeV data is shown in Fig. 2. The most evident feature of these distributions is the presence of two clear SQF peaks, together with a strong AQF structure centered around $p_3=80$ MeV/c.

From the present results and from what was obtained at 2 and 6 MeV,[1,3] we note the following:

(i) SQF effects show up around 2.4 MeV and are more clearly evident at 4.2 and 6 MeV. This steady increase is to be connected with barrier effects. Also, the excitation functions for the single α-particle measurement of Frois *et al.*[5] and of Norbeck[7] show the same behavior.

(ii) The AQF peak is very clear at 2 and 2.4 MeV, and disappears by increasing the incident energy. Actually, within the interpretation given in Refs. 1 and 2, the Coulomb slow down is meaningful only at energies below and around the $^6Li+{}^6Li$ barrier, i.e., below about 6 MeV incident energy.

In any case what is remarkable is that the two effects are kinematically well separated and that there is no continuous transition between them by increasing the energy. Obviously, it may happen that other effects contribute to the intermediate peak, here called the AQF peak. An influence can come from interference due to the symmetry of the entrance and exit channels with respect to the exchange of two particles. Actually, in the SQF picture, the central peak falls in a kinematical region where $p_s^{(T)}$ and $p_s^{(P)}$ have the same value. An evaluation of the possible influence of this effect is in progress.

On the other hand, if the reaction is dominated by QF effects, it remains to be understood why they appear to take place only at the two extreme conditions, namely at the asymptotic relative velocity and at rest. In fact, the QF process should take place at any intermediate relative velocity as a consequence of the Coulomb slow down for energies around the barrier. Before affording a detailed interpretation, further coincidence data at other incident energies and/or kinematical conditions are needed.

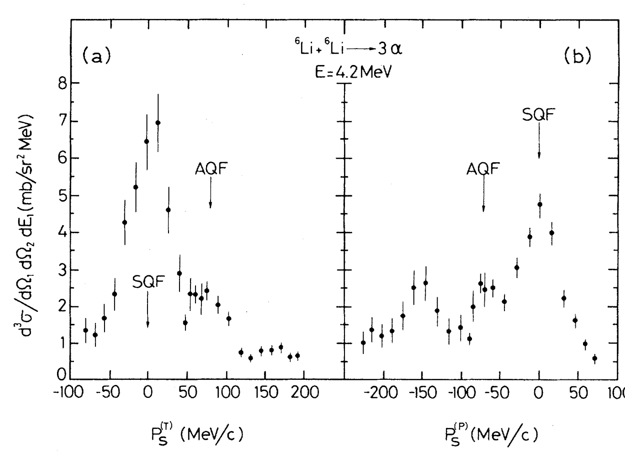

FIG. 2. Same as in Fig. 1 for 4.2 MeV incident energy.

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