Study of the $Li^7+d\rightarrow 2\alpha+n$ Reaction at Low Energy

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In the case of incident deuteron energies below 2.8 MeV, the $Li^7+d\rightarrow 2\alpha+n$ reaction may proceed in different ways: (1) direct three-body break-up (one step); (2) by He^5 formation; (3) by Be^8 formation. Be^8 and He^5 may be in different excited states including the ground state.

Neutron spectra from the reaction Li^7+d have been investigated by many authors.[1] They generally do not find the same positions for the monoenergetic groups. The essential reasons for this are poor statistics and a superimposed continuous background. Yet the ground, 2.9-, 11.4-, 16.62-, and 16.92-MeV states of Be^8 can be considered as well established.

The study of α-particle spectra from Li^7+d shows the existence of a monoenergetic group corresponding to the ground state of He^5 in a very intense background. Some authors also pointed out the existence of a state in He^5, but its position and the computation of its width are uncertain because of the continuum. So, only the existence of process (2) (through the ground state of He^5) and process (3) (through the 0-, 2.9-, and 11.4-MeV states) appear to be certain.

This is not enough to account for the intensity of the observed n and α continua. It is essential then to study the different process further and a few kinematic considerations prove to be necessary.

KINEMATICS

Let us consider the one-step three-body breakup in the nonrelativistic case: $a+x_0\rightarrow x_1+x_2+x_3+Q_t$, where a is the target nucleus and x_0 the incoming particle with energy E_0 and mass m_0 and x_i an outgoing particle with mass m_i and energy E_i. The total Q value of the reaction is Q_t.

In the case of this one-step process, classical mechanics gives:

$$E_0+Q_t=E_1+E_2+E_3 \qquad \text{(a)}$$

$$\mathbf{P}_0=\mathbf{P}_1+\mathbf{P}_2+\mathbf{P}_3$$

from which Eq. (A) may be deduced:

$$2m_k(E_0+Q_t-\sum_{i=1}^{3}E_i)=(\mathbf{P}_0-\sum_{i=1}^{3}\mathbf{P}_i)^2 \qquad (i\neq k). \quad \text{(A)}$$

In a two-step process

$$a+x_0\rightarrow x_1+x_{2,3}+Q_1,$$

$$x_{2,3}\rightarrow x_2+x_3+Q_2,$$

$$Q_t=Q_1+Q_2,$$

where $x_{2,3}$ is the intermediate nucleus.

For the first step,

$$E_0+Q_1=E_1+E_{2,3}, \qquad \text{(b)}$$

$$\mathbf{P}_0=\mathbf{P}_1+\mathbf{P}_{2,3};$$

for the second

$$E_{2,3}+Q_2=E_2+E_3, \qquad \text{(c)}$$

$$\mathbf{P}_{2,3}=\mathbf{P}_2+\mathbf{P}_3.$$

The system (a) may be deduced from (b) and (c) hence, so may the Eq. (A). So the two-step process is a particular case of the one-step three-body breakup.

(b) gives:

$$2m_{2,3}(E_0+Q_1-E_1)=(\mathbf{P}_0-\mathbf{P}_1)^2. \qquad \text{(B)}$$

(c) gives:

$$2m_{2,3}(E_2+E_3-Q_2)=(\mathbf{P}_2-\mathbf{P}_3)^2. \qquad \text{(C)}$$

Equation (A) defines in the (E_i, E_j) plane with $i\neq j\neq k$ a set of curves having the angular cosines $(0, i)$, $(0, j)$, (i, j) as parameters when E_0 is given. These curves will be noted as curves (A).

In the special case of the two-step process with $k=1$ let us consider the (A) and (C) curves in the (E_2, E_3) plane [Eq. (C) also defines a set of curves according to the different values of (2, 3) angular cosine]. If the three cosines are given, the corresponding (A) and (C) curves intersect at different points whose ordinates are the possible values of E_2 and E_3.

In the case of $k=i$ (for example $k=2$) intersections of a curve (A) in the (E_1, E_3) plane for a definite set of parameters and a curve (B) [determined by Eq. (B) for the same values of (1, 3) angular cosine] give the possible values of E_1 and E_3. These conclusions may be extended to a breakup case involving n particles and p steps.

It is clear from these results that we have to use two detectors to count two of the three emitted particles and measure their energies. The angular parameters and coincidences from both detectors give a proof that the particles come from the same event. Such an ex-

[1] F. Ajzenberg-Selove, Nucl. Phys. **11**, 1 (1959); *Nuclear Data Sheets* (National Academy of Sciences—National Research Council, Washington, D. C., 1961), NRC 61 5, 6, Set 5.

periment corresponds to one curve of the set (A) for a given E_0. In a (E_2, E_3) [or (E_1, E_3)] diagram we may find alternatively: a one-step three-body breakup process for which events are scattered on curve (A); or a two-step process: each type for each intermediate excited state corresponding to one curve (C) [or (B)] shown by a concentration of points at the intersections of (A) and (C) [or (A) and (B)]. However, the existence of such groups is no absolute proof of the existence of two-step processes. These groups, indeed, will be localized on the one-step curve (A) in any case; they may be due to a process of this type. The connection between the results obtained for different experimental conditions generally makes it possible to distinguish between the different processes. A further argument for the sequential process can be given in some cases. For convenience we will discuss the case of the reaction which, in fact, has been studied:

$$Li^7+d \rightarrow n+Be^8(16.62\ \text{MeV}), \qquad Be^8(16.62) \rightarrow 2\alpha.$$

For $E_0 = 1.9$ MeV, the 16.62-MeV level in Be^8 cannot be excited, but for $E_0 = 2.1$ MeV its production becomes energetically possible. If the two-step process by Be^8 excited at 16.62 MeV takes place, we will get at 2.1 MeV significant groups which have no equivalent at 1.9 MeV. This threshold method can be successful in the case where the first-emitted particle is a neutron. In the case of a charged particle, Coulomb effects make it more difficult.

DISCUSSION OF THE DIFFERENT PROCESSES OF THE $Li^7 + d \rightarrow 2\alpha + n$ REACTION

(1) Among the processes through the Be^8 levels, those which go through levels at 0, 2.9, and 11.4 MeV are well known. We have already shown[2] with other authors[3] that processes through levels at 16.62 and 16.92 MeV do also take place. We have given the cross section for the process through the 16.62-MeV level.[4] If we compare this cross section with that given by Dietrich[5] for the $Li^7(d, n)Be^8$ (16.62 MeV) reaction it follows that the γ decay of this level would be very weak. The same conclusions may be drawn for the 16.92-MeV level. These results agree with other experiments showing no γ decay.

(2) The first He^5 excited state at 2.6 MeV has been found by Fessenden[6] by studying the $Li^7(d, \alpha)He^5$ reaction. We have also observed its formation in the $Li^6+t \rightarrow 2\alpha+n$ reaction as an intermediary He^5 level. So the two-step reaction through the He^5 in the ground state and the 2.6-MeV state seems certain. No intermediate γ decay is possible.

(3) The reactions going through Be^9 excited states [$Li^7(d, \gamma)Be^9$] must not be forgotten but their probability seems to be much weaker. No γ rays are reported and our results have not shown such processes.

(4) The one-step reaction seems to exist, according to our experimental results. But its intensity appears to be weak. The observation is made difficult because of the width of the intermediate states which scatter the significant two-step points along the (A) curve.

CONCLUSIONS

The $Li^7+d \rightarrow 2\alpha+n$ reaction goes essentially through two-step processes involving Be^8 and He^5 levels as far as their excitation is energetically possible and, with a weak probability, through direct three-body breakup.

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[2] R. Bilwes, B. Bourotte, and D. Magnac-Valette, J. Phys. **22**, 568 (1961); **24**, 948 (1963).

[3] P. Paul and D. Kohler, Phys. Rev. **129**, 2698 (1963; see also, E. Matt, H. Pfander, H. Rieseberg, and V. Soergel, Phys. Letters **9**, 174 (1964).

[4] R. Bilwes, B. Bourotte, and D. Magnac-Valette, *Comptes Rendus du Congrès International de Physique Nucléaire* (Centre National de la Recherche Scientifique, Paris, 1964).

[5] F. S. Dietrich and L. Cranberg, Bull. Am. Phys. Soc. **5**, 493 (1960).

[6] P. Fessenden and D. R. Maxson, Phys. Rev. **133**, B71 (1964).