The 2 $Li^6 \rightarrow 3\alpha$ Reaction*

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The study of the reaction 2 $Li^6 \rightarrow 3\alpha + 20.9$ MeV at energies near or below the Coulomb barrier has been a major item in the Van de Graaff programs at Saclay,[1–6] the University of Chicago,[7] and the University of Iowa, and has been studied also at Harwell[8] and the University of Minnesota.[9] This reaction differs from most other reactions that result in three alpha particles not only by having a larger Q value, but also by proceeding primarily by way of a direct interaction which does not involve states in C^{12}.

The energy spectrum shows peaks which can be attributed to known states in Be^8 and one very prominent, rather broad peak which has been shown by a simple type of coincidence experiment to represent the division of almost all of the reaction energy between two of the three alpha particles.[7] Most of the literature on this reaction is concerned with the behavior of this large peak. Its angular distribution is essentially isotropic and its width increases slowly over the energy range studied. In a series of papers the group at Saclay have considered this behavior from a number of interesting points of view.[1–6]

Since the lowest state of Be^8 is energetically unbound, all of the peaks in the alpha spectrum can and do contain contributions from the breakup of intermediate Be^8 states. Most peaks in the alpha spectrum can still be attributed to states in Be^8, but the widths and the details of the change of amplitude with angle and with beam energy may be affected considerably. Because of its large width, the detailed shape of the large peak is especially susceptible to such effects, but because of its large size its gross behavior is not strongly affected. Careful angular correlation measurements remove most of the ambiguities, but not the more fundamental one caused by the identity of the three final products. For every set of three alpha-particle energies there corresponds, in general, three distinct excitation energies for a possible intermediate state in Be^8. In practice, one of these can usually be eliminated on the grounds that Be^8 has no state of that particular energy. This kind of ambiguity can be resolved by varying the bombarding energy in which case only one of the three calculated excitation energies remains constant.

It is not difficult to show that the equipment necessary for detailed angular correlation studies must involve something more than two movable detectors of a conventional type mounted in a target chamber. To get a reasonable single-particle angular distribution, one would like to make at least 10 and preferably 20 separate measurements. Something like the square of this number needed for an angular correlation between two particles in a plane. A complete set of angular correlations,

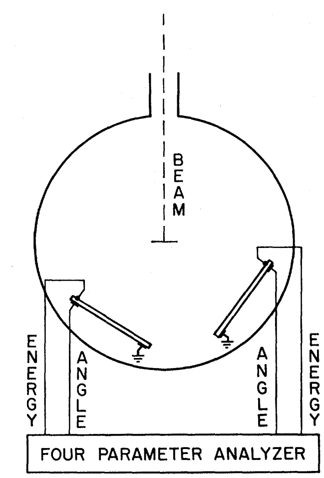

FIG. 1. Target chamber showing two solid-state counters, each of which produces an angle signal and an energy signal for each particle incident upon it.

including measurements out of the plane, might well involve over a thousand separate measurements even after making full use of all symmetries. When beam energy is included as an important variable, the experiment recedes beyond the range of feasibility.

One way to reduce the time required to complete a single experiment is to increase substantially the number of counters in the target chamber. We have, however, chosen a different approach.[10] The number of counters in the chamber is held to the number two, but each counter measures the energy and the position of impact of reaction products over an angular range of 50° (see Fig. 1). The angular resolution is about ½°

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9 Private communication.
10 R. R. Carlson and E. Norbeck in *Proceedings of the Third Conference on Reactions between Complex Nuclei, Asilomar, 1963*, edited by Albert Ghiorso, R. M. Diamond, and H. E. Conzett, pp. 181–185; E. Norbeck and R. R. Carlson, *Instrument Techniques in Nuclear Pulse Analysis* (National Academy of Science—National Research Council), Publ. 1184, pp. 42–45.

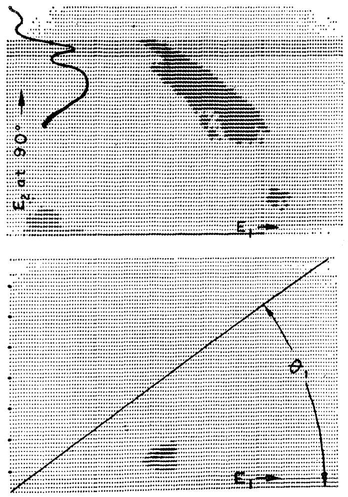

FIG. 2. A part of the two-particle, four-parameter coincidence spectrum for the reaction $2Li^6 \to 3\alpha$. In the top picture the contour level is set at 64 events. In the bottom picture the lower, fainter contour is set at 32 events and the brighter at 96. The very top of the peak is at 124.

which is very much better than one would try to attain with conventional detectors, and is in fact better than is required in our experiments.

The four-parameter analyzer is of the type described previously,[11] which has as its heart a small general-purpose digital computer. A preliminary examination of the data can be done very well with the small computer, but the multitudinous sortings that are required to extract all of the desired information requires the services of a large computer.

Figure 2 provides one view of the $2\ Li^6 \to 3\alpha$ reaction. The curve in the upper left corner shows the alpha-particle energy spectrum collected in the $90\pm2°$ part of one counter which is produced by those alpha particles which are in time coincidence with any alpha particle which is incident on the other counter, which spans an angle of 50°. The second peak from the top corresponds to the 2.9-MeV state in Be^8. The single-particle angular distributions for this state show a strong forward–backward peak at all energies from 2.0 to 4.4 MeV and a smaller peak at about 90° for the higher beam energies.[5,12] The upper picture shows a contour plot, or map display, of the coincident events just described. A bright spot means that at least 64 events were tallied for that particular location in the matrix. The peak from the ground state of Be^8 does not have sufficient altitude to be seen with this particular choice of the contour level. The horizontal stripe across the top of the picture marks out those events which correspond to the 2.9-MeV state of Be^8. The lower picture then shows the angle and energy in the second counter for these marked events. It follows then that the lower picture shows the angular correlation between the alpha particles formed along with the 2.9-MeV 2^+ state in Be^8 and the breakup alphas from this same state. The sharpness of the peak shows that this angular correlation is very anisotropic. The direction taken by these breakup alphas is within a few degrees of being the same direction as that followed by the Be^8 before the breakup.

[11] E. Norbeck, in Proceedings of the EANDC Conference on the Automatic Acquisition and Reduction of Nuclear Data, 1964 (to be published). E. Norbeck and R. R. Carlson, *Instrument Techniques in Nuclear Pulse Analysis* (National Academy of Science—National Research Council), Publ. 1184, pp. 283–285.

[12] G. D. Ford, thesis, State University of Iowa, 1964 (unpublished); J. Howard Shafer, Phys. Rev. **133,** B920 (1964).

Discussion

PHILLIPS: Have you calculated the direction of recoil of the Be^8 system?

NORBECK: The alpha particles that we saw in this particular view are going in almost the same direction as the Be^8 system.

PHILLIPS: Right. That's the answer I expected. So I will now attempt to explain the phenomena—explain it in the sense that we have observed this effect, also. And you will notice, or you can refer to the figures that Dr. Duck showed this morning of his calculations, in the set of histograms of alpha-particle spectra there was a very large, sweeping sort of a peak that occurred around 50 or 60 degrees and Dr. Duck pointed out that he was able to fit that.

Now that peak tends to occur in all of our experiments very close to the Be^8 recoil direction, and this seems to be fitted by a certain theory that Dr. Duck described this morning; fitted in a very natural sort of way. Exactly why it comes out this way, I am not at all clear.

MOLLENAUER: I would like to offer one comment, and ask a question as well. The forward peaking of alphas with respect to Be^8 recoils is similar to the effect we have seen in the $(\alpha, 2\alpha)$ reaction on O^{16}. In the energy region in which there was evidence of a sequential decay, the alpha angular distribution peaked along the C^{12} recoil direction and also at 180° to it; this bears out your observation.

I would like to inquire in reference to the apparent spectator alpha particle, whether this occurs under conditions in which the other two alpha particles are ripe for a state of Be^8 or not?

NORBECK: When it was first found that the reaction resulted mostly in a division of the total energy between only two of the three alpha particles, it was assumed that there must be a state in Be^8 which could just be reached with the beam energy that was used (see Refs. 1 and 7 in this paper). This point of view was encouraged by the observation that the required excitation in Be^8 was very close to the energy reported by Mr. Temmer, our chairman this morning, for the lowest (Li^6+d) cluster in Be^8. The reaction seemed to be of the deuteron transfer type and so the very high yield was interpreted simply as additional evidence for the cluster nature of the state.

This interpretation lost popularity when it was found that the energy required for the alleged state followed the change in beam energy in such a way that one alpha particle continued to be precipitated out, so

$$\begin{array}{ll} 2\ Li^6 \to & \to 2\alpha \\ & \downarrow \\ & \alpha \end{array}$$

to speak, without any reference to energy levels in Be^8.

The large peak does have some fine structure superimposed upon it. I think it is likely that a careful study of this fine structure will show that the very highly excited states in Be^8 do indeed make some contribution.

MOLLENAUER: An effect we have seen in some reactions with simple nuclei, and which will be discussed tomorrow, is a large peak occurring under conditions where the momentum transfer to one of the particles involved is close to zero. These reactions are less complex than this case, in which if Be^8 is formed it must be by a subsequent step, given that a knockout is the first step.

HOLMGREN: Do you see the fine structure for any of the reactions which proceed through sharp levels of Be^8? For example, do you see this effect for the 16.9-MeV level of Be^8 near the recoil direction.

MANCUSI: At the angles that we have made these runs, the 16.6-, 16.9-, and 17.6-MeV levels all come in on top of the ground state on energy–energy plots and cannot be resolved from each other. We were not interested in those states at the time. We should be able to find sets of angles where these states are separated, and as you see, with position counters, it will be quite simple to get an angular correlation.

HOLMGREN: That might be very interesting, because then this other type of process, which apparently is modulating your reaction in the direction of the recoil axis, may not be so sharp in the state.

MANCUSI: I would like to point out that in this reaction, unfortunately, we have a lot more levels contributing to the final state. So if there are interference effects occurring then any calculation would have to take into account more than the ground and 2.9–MeV levels which were included in Dr. Duck's calculation.

DONOVAN: I would like to amplify some of the remarks about angular correlations made in the opening lecture. Professor Zupancic pointed out that in case of isolated states, independent of the mechanism, you get repetition of the angular correlation pattern after 180°. Now in plane-wave Born approximation there is a further simplification which is the prediction that not only do you get repetition after 180°, but the axis of repetition is the recoil axis, rather than some arbitrary axis.

Now if you have many states not interfering or overlapping very badly, then you have an angular correlation pattern with oscillations of different periods, depending on the spin of the state, but they have one common property which is that they always have a maximum at the recoil axis, so if you make an incoherent summation of all of the many states that are contributing, you arrive very naturally with a peak both in the direction of the recoil and also 180° back from it. I am not suggesting that this is what is happening here, but it is a general, expected effect.

I would like to make another remark about experimental technique. The position-sensitive detectors appear to hold great promise. They have a number of advantages; however, I think the principal advantage is not the one that Professor Norbeck pointed out, but rather is due to the fact that in the usual experiments measurements are made at many angles. These measurements usually have to be normalized to one another somehow, but with the position-sensitive detectors they are self-normalizing. However, position-sensitive detectors are not a panacea for taking data faster in coincidence experiments, because if you are running your experiment properly you will use a coincidence resolving time sufficiently short that the principal limitation on coincidence counting rate is pile-up in the detectors. This means that if one uses detectors subtending small angles the beam level can be turned up to make the counting (and pile–up) rate the same as it would be in the larger position-sensitive detectors. Because of this fact the data accumulation rate is, in principle, the same as it would be with the position-sensitive detectors.

NORBECK: This is a good point. In much of our work, however, the counting rates are sufficiently low that pile up is not a limitation even with the largest detectors; and if we were to narrow the aperture of a conventional detector to get the $\frac{1}{2}°$ resolution that is routine with the position-sensitive detectors, our counting rate would be small almost to the vanishing point.

KNOWLES: The Dalitz plot of a reaction in which there is a 'spectator" particle would be very similar to the expected Dalitz plot of the decay of the ω° meson if it had been in the 1+ state, in terms of the interpretation made by Stevenson *et al.* [M. L. Stevenson, L. W. Alvarez, B. C. Maglić, and A. H. Rosenfeld, Phys. Rev. **125**, 687 (1962).] That is, in a symmetrized Dalitz plot, there would be peaks in the distribution near the three edges.

It is possible that there is some overriding consideration about the spin and parity of the intermediate state of the C^{12} formed so that its decay would lead to the presence of a spectator alpha? Or are you changing the bombarding energy sufficiently so that several intermediate states of C^{12} are involved?

NORBECK: The beam energy is so low with these experiments that the Coulomb barrier inhibits the formation of an intermediate C^{12} nucleus. The energy of the intermediate C^{12} when it is formed is very high, about 30 MeV, so that there are many overlapping levels. Also the effects have been observed at more than one energy. But this does not necessarily rule out the possibility that the actual reaction mechanism in effect here does impose restriction of the sort that you have suggested.

TEMMER: I think you are taking a calculated risk by using expressions like precipitated. What our high-energy friends have been saying about this thing may be true, then. That it is all chemistry. If you want that, it's all right.

PHILLIPS: I would like to make a comment about the use of Dalitz plots versus the various other sorts of plots that we have been seeing in the various talks. It seems to me very dangerous, on many experiments, to use the Dalitz plot in the ordinary sense—well, there are various sorts of Dalitz plots but I mean the triangular sort where you effectively average data over a large number of angles.

An example that shows this danger is the sort of picture that I showed this morning where, if one were to take the histograms and add them all together, and one were to take the similar histogram taken in other fixed countered angles—and we have done this—to make up the Dalitz plot, you come to the conclusion that the Be^8 has two excited states; one at 2 MeV and one at 1.5 MeV, and this, of course, is not so at all. So I think that to take the basic data where all of the variables are clearly displayed, is quite an important point.