Heavy-Particle Stripping and the Structure of N^{14}

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A qualitative explanation is found for the interesting contrast observed between the angular distributions of the groups going to the ground state and the second excited state in the reaction $C^{12}(Li^6,\alpha)N^{14}$. The ground-state group of alphas has a peak only in the backward direction because only the mechanism of "heavy-particle stripping" can satisfy the requirements on the orbital angular momentum for the ground state of N^{14} (primarily a ^3D). The "deuteron" of the incident Li^6 initially has insufficient angular momentum about the final core but acquires more because the force attracting it toward the target nucleus is not directed toward the center of mass of the twelve nucleons (eight from the target C^{12} and four from Li^6) which form the core of the final N^{14}. The other four nucleons from the target form the product alpha. The second excited state of N^{14} is approximately a ^3S and there is no such angular momentum limitation so both light- and heavy-particle stripping occur and give rise to forward and backward peaks. The validity of the cluster model for Li^6 is discussed.

INTRODUCTION—THE NATURE OF Li^6

IN an interesting study of the reaction $C^{12}(Li^6,\alpha)N^{14}$ at 1.7 Mev, Pham-Dinh-Lien and Marquez at Saclay[1] have shown that the alphas leading to the ground state (1^+) of N^{14} are almost entirely backward, while those to the second excited state (also 1^+) are distributed somewhat more strongly forward than backward. In discussing the backward distribution of the ground-state alphas, they have sought to justify the "heavy-particle stripping" process[2] by treating the ground state of N^{14} as ^3D, which is close to correct,[3,4] and the ground state of Li^6 as a mixture $^3S+^3D$, of which they use the ^3D component. Their assumption $^3S+^3D$ is apparently based on an oversimplified scheme to make the magnetic moments come out right, being taken from Blatt and Weisskopf,[5] which antedates references 3 and 4 where the intermediate coupling in the p shell was first recognized. According to the shell model with central forces, one expects[3,4] the ground state of Li^6 to be about 99% ^3S, 1% ^1P, and 0% ^3D. With tensor forces, the ^3D component would be increased slightly.[6]

Since Li^6 and N^{14}, both involved in this reaction, correspond in the shell model to two nucleons or two holes in the p shell, the intermediate-coupling transitions of their energies both appear on the same graph, Fig. 1, (which is based on central forces and reproduces a portion of Fig. 1 of reference 3). For Li^6 the appropriate strength of spin-orbit coupling,[7] given by $A/K=1.3$, is so close to the (LS) coupling limit that the ground state is depressed only slightly below the straight line of the ^3S by the small ^1P admixture. The admixtures are plotted in Fig. 20 of reference 4.

However, recent experimental studies at Orsay[8] indicate that the shell model does not apply to Li^6, and that this nucleus seems to be represented better by a

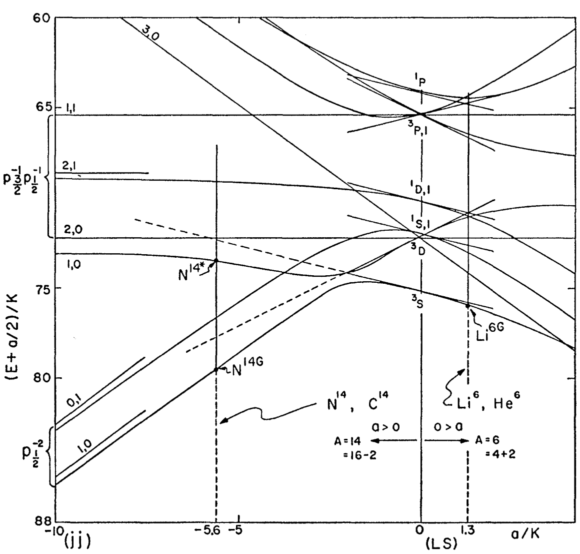

FIG. 1. The intermediate-coupling transition of the energies for the final nucleus N^{14} according to the shell model with a central exchange interaction (for which K is a parameter) and individual-nucleon spin-orbit coupling (for which a is a parameter). The shell-model energies for the incident nucleus Li^6 also happen to appear on this graph, but for this particular nucleus the cluster model is considered to apply instead.

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[1] Pham-Dinh-Lien and L. Marquez (to be published).

[2] L. Madansky and G. E. Owen, Phys. Rev. **98**, 1608 (1955).

[3] D. R. Inglis, Phys. Rev. **87**, 915 (1952), especially Fig. 1.

[4] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953), especially Fig. 20, p. 440.

[5] John M. Blatt and Victor F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952).

[6] J. P. Elliott, Proc. Roy. Soc. (London) **A218**, 345 (1953); D. H. Lyons, Phys. Rev. **105**, 936 (1957).

[7] This value of A/K was chosen to fit the ratio of the energy separations of the three known states. The graph of Fig. 1 then successfully predicted the other low states and identifications as subsequently observed [A. Galonsky, R. A. Douglas, W. Haeberli, M. T. McEllistrem, and H. T. Richards, Phys. Rev. **98**, 586, 597 (1955)]. There have been other theoretical treatments with various amounts of tensor force (reference 6). The fact (discussed below) that the apparently successful shell-model treatment (with only a weak tensor force) now has to be abandoned, both points to the surprising degree of near-equivalence of quite different models and also suggests that a new treatment with central-plus-tensor forces is needed, based on a fully developed cluster model (not just the so-called *a-d* model of Lyons in reference 6).

[8] J. P. Garron, J. C. Jacmart, M. Riou, C. Ruhla, J. Teillac, and C. Caverzasio, Phys. Rev. Letters **7**, 261 (1961).

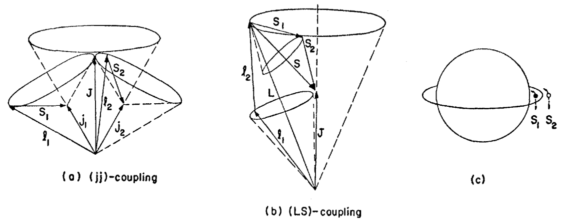

FIG. 2. For the ground state of N^{14}, which is actually close to (jj) coupling but contains a great preponderance of one (LS) coupling state, the vector-precession diagrams show that in either of these extreme coupling schemes the two "holes" (or nucleons missing from the p shell) tend to circulate together to make their orbital angular momenta add. In (jj) coupling this is also true for the two $p_{\frac{1}{2}}$ nucleons added by the reaction, as represented in (a). The vector J is fixed in space and the other vectors precess as indicated.

cluster model instead.[8a] It is very interesting to note that the shell model finally fails for this very light nucleus, while still applying to Li^7. Apparently the two nucleons outside a closed s shell in Li^6 are simply too few to succeed in the cooperative effort to form a p shell, whereas the three nucleons in Li^7 do succeed in forming one. The free deuteron is considerably larger than either the triton or the alpha, and the modification required to make it fit into the same shell-model potential with an alpha is too expensive energetically.

As a rough approximation one might describe the cluster model of Li^6 as a deuteron, very much like a free deuteron, barely clinging to an alpha. Perhaps a better description[9] is to say that the two nucleons are each clinging to the alpha, but also clinging to each other in such a way that they do not have enough energy to swing clear around the alpha separately, as is required for the validity of the shell model and as happens in Li^7. Instead, they stop and turn back toward each other when still less than 180° apart (probably much less). To say that they stop and turn back is a way of describthe fact that they have a zero-momentum component in their wave functions in momentum space, just as in the case of the free deuteron in which the nucleons have only radial motion. The existence of this zero-momentum component distinguishes them in the $(p,2p)$ angular experiments from the p-shell nucleons which keep on circulating and never stop. (See Appendix.)

THE NATURE OF N^{14}

In speaking of stripping reactions and particularly of heavy-particle stripping, it is necessary to become rather pictorial and it is desirable to do so on the basis of plausible models of the constituents. Let us then treat Li^6 in terms of the cluster model and treat C^{12} and N^{14} pictorially in terms of the shell model. Figure 1 on the left side applies to the two "nucleon holes" of N^{14}, and shows that the ground state lies almost on a linear extrapolation from the (LS) coupling state $^3D_1$. Its energy is depressed only slightly by the admixture of other multiplets and it therefore consists almost entirely of this state, again according to the coefficients plotted in Fig. 20 of reference 4. One also sees in Fig. 1 that the ground state of N^{14} is the (jj) coupling state $p_{\frac{1}{2}}^{2}$, with the two $j=\frac{1}{2}$ vectors nearly parallel to make $J=1$. This means that the two $p_{\frac{1}{2}}$ nucleons can be thought of as circulating outside of the spherical "C^{12} nucleus" or filled $p_{\frac{3}{2}}$ shell. The vector diagram for this state appears in Fig. 2(a). In it, the vectors l_1 precess rapidly around the small cones because of the strong spin-orbit coupling, and the vectors j_i precess slowly around the large cone. The corresponding diagram for the almost equivalent $^3D_1$ state is shown in Fig. 2(b). In both diagrams, the l_i on the average point nearly parallel to one another and forward along J while the s_i are nearly parallel to one another and backward along J. Because their orbital angular momentum vectors are nearly parallel, they are circulating in nearly the same plane. The low energy of this ground state is associated partly with the fact that the space function (for $L=2$) is symmetric in space, meaning that the two nucleons are frequently close together in azimuth. They may thus be thought of as staying fairly close together as they swing around in the C^{12} core [Fig. 2(c)]. The situation is thus rather like having a deuteron swinging around, mostly just inside the edge of the core but partly outside of it, with its spin vector $S=1$ almost antiparallel to its angular momentum. This is an example of the frequent equivalence of shell-model and cluster-like concepts. A characteristic feature is that, as long as they are nearly equivalent, the cluster remains mainly within the shell and its size is determined by the same parameter that determines the size of the shell.[9]

LIGHT-PARTICLE STRIPPING

Let us consider why the mechanism of light-particle stripping does not lead to the ground state of N^{14}—both why there is no forward peak and why the heavy-particle stripping mechanism is needed to explain the backward peak. Two requirements must be satisfied for the process to succeed. First, the two nucleons "stripped" from the Li^6 must together have two units of angular momentum when they are in N^{14}. Second, the energy Q released by the binding process in the final nucleus must exist in the initial state as kinetic energy of the four departing nucleons if it is to appear directly as kinetic energy of the product alpha. Otherwise forces would have to act on these nucleons during the reaction and this would make it a higher-order process and reduce its probability.

In order to emphasize the selection imposed by the angular momentum, we may first discuss the angular-momentum requirement alone. The favorable case is shown in Fig. 3(a), with the center-of-mass motion of the Li^6 and the internal vibrational motion of the "deuteron" in Li^6 adding to contribute the tangential veloc-

[8a] *Note added in proof*. New measurements with higher resolution at Uppsala (according to a personal communication from Th. A. J. Maris) display the "p-shell dip" for Li^6, thus seeming to contradict the Orsay evidence for a cluster model. Brown's doubt, mentioned in the Appendix, thus appears to have been justified.

[9] D. R. Inglis, Revs. Modern Phys. 34, April (1962).

ity of the two nucleons at the edge of the C^{12} core to form N^{14} in its ground state. The tangential momentum required for each p nucleon is $\hbar/R$. Here R is taken to be the radius of N^{14}, $R=(14)^{\frac{1}{3}}r_0$ with $r_0=0.36(e^2/mc^2)$ to give the "Stanford radii."[10] The kinetic energy of this tangential motion is $p^2/2M=6.8mc^2=3.5$ Mev. (This is, of course, considerably less than the average kinetic energy of a p nucleon, since it refers to only one component of motion and to the special circumstance that the nucleon happens to be at the edge of the nucleus, well outside of the peak of its radial wave function.)

The two nucleons must be moving fairly close together with about the same velocity when they are stripped from Li^6 if they are to form the ground state of N^{14} as it has been described. We refer to them together with the subscript "d" although they need not form a deuteron. Their common "tangential" velocity relative to the C^{12} core to form orbits in N^{14} is then made up as

$$v_{dt}=v_{di}+v_b+v_c=v_{di}+v_b(1+M_b/M_c)=v_{di}+\tfrac{3}{2}v_b,$$

where t stands for tangential (relative to the core), i stands for internal (within Li^6), b stands for beam or bombarding or bullet (or Li^6) in the c.m. system, and c stands for core (or target or C^{12} in the c.m. system). The kinetic energy of the two nucleons d moving at velocity v_{dt} is $\frac{1}{2}M_dv_{dt}^2=2\times 3.5$ Mev$=7$ Mev. With a bombarding energy of 1.7 Mev (lab) or 1 Mev in the c.m. system, the deuteron's share (in the c.m. system), $\frac{1}{2}M_dv_b^2$, is $\frac{1}{3}$ Mev. In order to combine and give the required tangential energy (relative to C^{12}), the deuteron's share $\frac{1}{2}M_dv_{di}^2$ of the internal kinetic energy of vibration is then $[7^{\frac{1}{2}}-\frac{3}{2}(\frac{1}{3})^{\frac{1}{2}}]^2$ Mev$=3.2$ Mev. The alpha's share of this energy is half as great so the total energy of vibration would have to be 4.8 Mev. This seems about as large as could seem plausible in the cluster model, in view of the fact that the "cohesive energy" of the two clusters is only 1.47 Mev. (Another relevant fact is that the energy required to carry the two nucleons on past the alpha on opposite sides in p orbits of reasonable shell-model size, namely about 7 Mev as estimated above for the circulation of two p nucleons in N^{14}, is only slightly more than this 4.8 Mev. Thus if they had more kinetic energy it would form the basis for a shell-model ground state of Li^6, contrary to the cluster-model assumption.) The internal backward motion of the alpha (1.6 Mev) is enough to surpass its incident motion ($\frac{2}{3}$ Mev) to give a backward motion (in the c.m. system) of $[(1.6)^{\frac{1}{2}}-(\frac{2}{3})^{\frac{1}{2}}]^2$ Mev$=0.2$ Mev. This is much less than enough to satisfy the second requirement since the energy release of the reaction is $Q=8.8$ Mev. Thus we see that by using about as large a vibrational energy as might be available in the cluster model of Li^6, we can satisfy the first requirement (concerning angular momentum) but not the second (concerning energy).

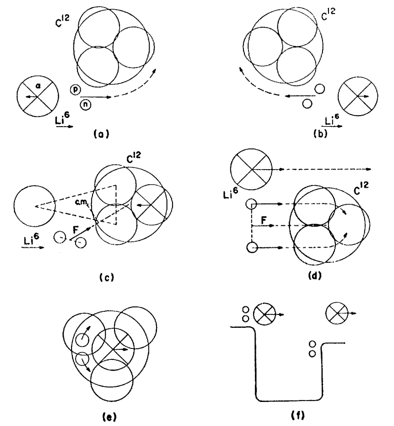

FIG. 3. Schematic representation of various mechanisms for the reaction $C^{12}(Li^6,\alpha)N^{14}$, including light-particle stripping (a), (b), and (d) and heavy-particle stripping (c).

Let us, however, relax the assumption of a cluster model and permit the pair of nucleons to have arbitrary energy E_{di} of forward internal motion. The corresponding energy of backward internal motion of the alpha is half as great $E_{\alpha i}=\frac{1}{2}E_{di}$. The total kinetic energy of the reaction products (in the c.m. system) is $(8.8+1)$ Mev and the alpha's share, (10/14) of this, is 7 Mev (not the 7 Mev of rotational energy encountered in the preceding paragraph). This arises from the internal energy $E_{\alpha i}$ decreased by the $\frac{2}{3}$ Mev associated with the incident motion, so $E_{\alpha i}=[7^{\frac{1}{2}}+(\frac{2}{3})^{\frac{1}{2}}]^2$ Mev$=12$ Mev, and the energy of the "deuteron" is twice this so $E_{di}=24$ Mev. The energy of tangential motion is then $[(24)^{\frac{1}{2}}+\frac{3}{2}(\frac{1}{3})^{\frac{1}{2}}]^2$ $=33.2$ Mev, or 16.6 Mev per nucleon. This is more than 4 times the 3.5 Mev required to form a p nucleon at the surface, and the velocity is more than twice as great, so it is adequate for a p nucleon with an impact parameter less than $\frac{1}{2}R$. The p wave functions have sufficient amplitude at this short distance to include this situation (and thus provide some overlap in the matrix elements). However, the rather high value $E_{di}=24$ Mev implies a shell-model Li^6 state $(1p)^2\ {}^3S$ with the two nucleons moving forward on opposite sides of the center, each again at about $\frac{1}{2}R$ from the center. They are thus too far apart to satisfy the requirement of circulating fairly close together in N^{14} and one would for this reason expect very small overlap and thus no ground-state reaction. Our conclusion that a light-particle stripping reaction cannot give a sufficiently energetic backward peak thus holds for either a cluster model or a shell model of Li^6.

LACK OF FORWARD GROUND-STATE PEAK PRODUCED BY LIGHT-PARTICLE STRIPPING

If the alpha goes forward, again with 7 Mev as required by Q, its energy is composed of an internal energy $E_{\alpha i}$ within the Li^6 aided by the forward motion of the

[10] U. Meyer-Berkhaut, K. W. Ford, and A. E. S. Green, Ann. Phys. (New York) 8, 119 (1959). Their remark that Li^6 alone shows a less-than-normal density seems in retrospect like an interesting prognostication of the validity of the cluster model in this nucleus.

Li^6 in the beam [Fig. 2(b)]. The required internal energy is thus less than before, $E_{\alpha i}=[7^{\frac{1}{2}}-(\frac{2}{3})^{\frac{1}{2}}]^2$ Mev$=3.36$ Mev. In this case the internal kinetic energy of the "deuteron," $E_{di}=6.72$ Mev, corresponds to a backward motion so the nucleons will circulate in the opposite sense when captured in N^{14}. The energy of their tangential motion thus includes a negative contribution from the forward beam motion so that $E_{dt}=[(6.72)^{\frac{1}{2}}-\frac{3}{2}(\frac{1}{3})^{\frac{1}{2}}]^2=3$ Mev. This is less than half of the 7 Mev needed to satisfy the angular-momentum requirement if the stripping is to take place at the N^{14} surface. It could be satisfied at somewhat more than $\sqrt{2}R$, at about $1.5R$, but the amplitude of the p-wave function this far outside of N^{14} is presumably so small as to suppress the reaction strongly. If this were not enough, another factor of suppression could be found in the lack of an energy of internal vibration as high as $E_i=3\times3.36$ Mev$=10$ Mev if it is to be consistent with the validity of the cluster model in Li^6. With the magnitude of the internal energy thus selected to provide the required motion of the product alpha, the "deuteron" is too slow to provide the proper angular momentum if it goes backward while the alpha goes forward, just as it is too fast if they go the other way, and in neither case does light-particle stripping attain the ground state.

HEAVY-PARTICLE STRIPPING MECHANISM

This mechanism was introduced in the first place[2] mainly because the backward motion of the target nucleus in the c.m. system provides nucleons moving backward to make a backward peak. In order to give them enough energy one recognizes also that some of the nucleons in the target have backward internal momentum with which they can carry on if the forces binding them are suddenly released by the presence of other nucleons from the incident nucleus.

In addition to selecting for ejection nucleons which already have a momentum in the backward direction, the heavy-particle stripping mechanism in this ground-state reaction has a second great advantage in permitting the forces attracting the two extra nucleons into the target nucleus to endow them at the same time with the requisite angular momentum about the center of mass of the final core, as illustrated in Fig. 3(c). On the left side we see the constituents of the impinging Li^6 and on the right side C^{12}. The three circles within the target nucleus simply symbolize the division of the group of twelve nucleons into three subgroups of four nucleons each, which we may call alpha groups since they contain the ingredients of an alpha, without specific regard to their position in space. Despite its appearance, the figure is not intended to imply that the cluster model applies to C^{12}. In the heavy-particle stripping process, the alpha of the Li^6 combines with the two alpha groups at the other corners of the triangle in the sketch to form the "C^{12} core" of N^{14}. This happens at such a phase of the internal motion of the target that the other alpha group, denoted by the circle with crossed lines, has momentum toward the left and flies off in the backward direction as the product alpha. At about the stage pictured in Fig. 3(c) the two extra nucleons feel themselves attracted to the target by the force F which gives rise to most of the energy release of the reaction, a force directed approximately toward the center of the target nucleus. This force has a large moment about the center of mass (marked c.m.) of the nascent core of the final nucleus and thus imparts to these particles the requisite angular momentum about that center of mass. This is what makes it possible for the reaction to satisfy the angular momentum requirements to reach the ground state, and explains why the ground-state transition has its peak in the backward direction. The argument must be modified by the fact that the internal attraction within the Li^6 acts at the same time, and a determination of the fraction of the possible configurations of approach in which this F is the predominant force would help to determine the cross section for the reaction.

THE EXCITED-STATE REACTION

The excited state (N^{14*} in Fig. 1) corresponding to the second experimental peak belongs to the (jj) configuration $p_{\frac{3}{2}}^{-1}p_{\frac{1}{2}}$ or roughly to the (LS) state ^3S. Its (jj) picture corresponding to Fig. 2(a) would show $j_1=\frac{3}{2}$ and $j_2=\frac{1}{2}$ as before; but in this case j_2 "points backward" along j_1 so as to make the total $J=1$. Thus l_1 and l_2 point in roughly opposite directions and s_1 and s_2 both point forward along J. These seem to be roughly compatible with the ^3S description in which the two spins are nearly parallel to make $S=1$ and the orbital moments are opposed to make $L=0$, corresponding to having the two last nucleons swing around the core in opposite directions. A conventional view of the light-particle stripping reaction, taking into account this angular-momentum requirement, would then be that the reaction thus proceeds as in Fig. 3(d). The Li^6 comes in with the two extra nucleons straddling the center of the target nucleus, in such a way that the attractive forces accelerate them and they swing around the center of the target nucleus in opposite directions. The alpha of the incident Li^6 is then free to go on as the product alpha. The trouble with this interpretation is that the alpha here has far too little energy to account for the energy release Q. Even if the Li^6 is reoriented in the sketch so that some of the internal energy of vibration contributes to the forward motion of the alpha, there is too little of it if the cluster model is to be valid for Li^6, as has already been seen in a more favorable case. The application of the stripping mechanism to the usual (d,p) or (t,d) reactions does not encounter this difficulty because the deuteron, triton, etc. are more generously endowed with internal kinetic energy (not limited by this cluster-model consideration).

Instead, the mechanism suggested by Fig. 3(e) is helpful in trying to understand the energetic forward

ejection of the alpha incident as a part of Li^6. The Li^6 strikes the target squarely with the alpha leading. As it enters, the phase of the internal motion of the Li^6 may be such as to favor the forward motion of the alpha and leave the "deuteron" with practically no forward motion. The alpha is attracted by the C^{12} with the full force which would bind it into O^{16} if it were to lose its momentum, but instead it retains its momentum. As it leaves the other side, the forces are somewhat modified by the fact that the two extra nucleons have entered and interact with the C^{12} particles. This helps to "saturate" some of the forces which would otherwise fully attract the departing alpha. The retarding force on the alpha is thus less than was the accelerating force on entry, as is suggested very schematically by the asymmetric potential well in Fig. 3(f). In this way the energy release Q may be imparted to the product alpha.

The angular-momentum requirement of the two p nucleons captured to form N^{14} may be explained by noting that in the deuteron the internal kinetic energy is much larger relative to its binding energy than in most other bound systems. (This was the main point in Wigner's original introduction of short-range forces into nuclear physics to account for the small binding of the deuteron compared with that of the alpha.) When the approach of the Li^6 has the right phase, with the two nucleons of the "deuteron" flying apart just as they enter the target, this kinetic energy can contribute to the individual angular momenta of these p nucleons in the final nucleus. This process is not the same as the usual simple stripping process, because the alpha from the incident Li^6, before going on as the product alpha, is required to penetrate past the region of the Coulomb barrier and right into the target nucleus. Here it does not form a compound nucleus in the sense of sharing its energy with the other individual nucleons there but rather squeezes its way through and emerges from the other side without loss of momentum by scattering.

In analyzing the scattering of alphas with energies of 20 Mev or more by fairly heavy nuclei, the optical-model is used with a complex potential strong enough to make nuclei opaque to alphas.[11] In the $C^{12}(Li^6,\alpha)$ reaction, the penetration of the low-energy alpha through the C^{12} target nucleus must be quite a different process, involving some adiabatic readjustment as the alpha passes through relatively slowly. Dennison's success[12] in interpreting some of the excited states of O^{16} in terms of the alpha model indicates that the internal dynamics of this system have some similarity to the vibration-rotation motion of a tetrahedral system of four alphas. One of the possible motions here is the "tunnel motion" or exchange of two alphas, which may also be described as a reflection in which one alpha jumps from one side to the other of the plane of the other three. Incidentally, there is[12] a fairly narrow metastable state (2^+) involving this process at 9.84 Mev in O^{16}, 2.7 Mev above the $C^{12}+\alpha$ threshold, and it is plausible that the alpha from Li^6, with $\frac{2}{3}$ Mev of incident energy and a roughly equal amount as its share of the internal vibrational energy of Li^6, should impinge on the C^{12} with an energy of the order of 2.7 Mev. Even though, in the reaction, the alpha presumably does not linger long enough to form a metastable state, it seems likely that at these energies it can penetrate and pass the C^{12} nucleons by a mechanism similar to that of the tunneling process, perhaps squeezing the other nucleons apart a bit as it passes through.

Thus there is no angular-momentum requirement to impede the light-particle stripping reaction to the second excited state as there is to the ground state. But there is also here, as in the ground state, no obstacle to the occurrence of heavy-particle stripping, so that a backward peak as well as a forward peak is observed for this group of alphas. Presumably C^{12} is a somewhat flattened, oblate nucleus without enough further clustering for the cluster model to apply. It is tempting to speculate, though this has very little meaning, that light-particle stripping might occur more frequently in flat-side encounters in which the alpha can "tunnel" from one side of the C^{12} plane to the other while heavy-particle stripping might predominate in edgewise encounters.

APPENDIX

A reservation concerning the cluster-model interpretation of the Orsay results for Li^6 has been expressed by Brown.[13] He points out that if the motion of the deuteron relative to the alpha in Li^6 is described by an s state, and if (as indicated above) the proton is plucked out from a condition of zero momentum, then the neutron left behind also has zero angular momentum and is thus left in an s state, whereas the "ground state" of He^5 is a $p_{\frac{3}{2}}$ state. The answer to this objection is that there is no need for the neutron to be left in this "ground state," which is better described as a broad virtual state at a positive energy of about 1 Mev. Part of its near-binding comes from spin-orbit coupling, and this tends to concentrate its probability amplitude predominantly near a normal shell-model radius. This state is recognized by a strong energy dependence of the p-wave phase shift and polarization in scattering experiments.[14] However, it is not necessary that the neutron be left in this p state. The analysis of the scattering data also involves a substantial s-wave phase shift, which is zero at the threshold and increases with neutron energy. The peak of the $Li^6(p,2p)$ spectrum for this group of protons in Fig. 1 of reference 8 happens to fall within less than 1 Mev of where it should be if the "ground state" of He^5 were involved; but experimentally this peak is much broader, particularly toward the low-energy side where it has an experimental half-width of about 5 Mev. The

[11] C. E. Porter, Phys. Rev. **99**, 1400 (1955).
[12] D. M. Dennison, Phys. Rev. **96**, 378 (1954).
[13] G. E. Brown (private communication).
[14] R. K. Adair, Phys. Rev. **86**, 155 (1952); F. Demanins, G. Pisent, G. Poiani, and C. Villi, *ibid.* **125**, 318 (1962).

best fiducial mark in the He^5 spectrum is the $\frac{3}{2}^+$ state at 16.69 Mev, which happens to be very close to the triton-plus-deuteron threshold and is seen as the low-energy proton peak. If the high-energy proton peak were to correspond to the "ground state" it should thus be 16.69 Mev higher, rather than about 16.0 Mev as observed (but with an uncertainty too large to allow distinguishing between these two values).

This leaves the possiblity that the protons may depart with less energy and, consequently, that the neutron may later depart from the alpha with a greater energy than that corresponding to the "ground state." Assume that the proton is snatched out from its zero-momentum region just as the two nucleons of the deuteron cluster are at the end of their swing and turning back toward each other. The neutron is left outside the alpha at an uncertain distance corresponding to its distribution in the cluster model and thus considerably larger than usual shell-model radii. It is unbound, having suddenly lost its interaction with the proton, and its uncertain position and lack of angular momentum should be described by a wave packet somewhat like a virtual s state, having small amplitude within the alpha and a maximum at perhaps 2 or 3 times the radius of the alpha, because of the relatively large size of the cluster model. This uncertainty of position corresponds to a kinetic energy of only a few Mev to be carried away by the departing neutron. The shape of the peak in the observed proton spectrum may thus correspond to the energy distribution required by the uncertainty principle in view of the particle distribution in the cluster model. Further $(p,2p)$ observations with higher resolution may thus reveal interesting geometrical details of Li^6.

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Low-Energy Neutrons from the Reaction $Be^9(\alpha,n)C^{12}$ *

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Experiments carried out on the detection of slow neutrons from the (α,n) reaction in Be^9 show an increasing number of low-energy neutrons beginning at an alpha particle energy of 4.3 Mev, and extending to 5.6 Mev. The energies and angular distribution of these neutrons for $E_\alpha=4.92$ and 5.11 Mev have been measured using the polyethylene sphere-moderated neutron spectrometer. The results indicate a peaking in the forward direction and an energy distribution consistent with their origin from inelastic alpha-particle scattering leaving Be^9 excited to the level at 1.75 Mev, which subsequently breaks up with neutron emission. At an alpha-particle energy of 5.11 Mev, the mean energy of these neutrons and the differential cross sections are: 0°(0.33 Mev, 22 mb/sr); 70°(0.21 Mev, 8 mb/sr); and 120°(0.07 Mev, 2 mb/sr). The neutron spectrum of a Pu-Be source has been determined to have a large number of low-energy neutrons with a peak intensity at 0.3 Mev.

INTRODUCTION

THE (α,n) reaction with Be^9 has been studied extensively both with natural radioactive sources[1] and more recently with helium ions from a Van de Graaff accelerator.[2] The total yield of neutrons at 0° and 90° has been measured by Bonner, Kraus, Marion, and Schiffer[2] from 1.5 to 5.3 Mev. The cross section and angular distributions of the neutrons leading to C^{12} in the ground state and the first excited state have been measured by Risser, Price, and Class.[3] Recently the cross sections and angular distributions have been studied for three groups of neutrons including those which leave C^{12} in its second excited state at 7.66 Mev.[4]

The present experiment was undertaken to search for the threshold of neutrons to the 7.66-Mev state and to study the low-energy neutrons that had previously been observed in this laboratory when alpha particles with energies greater than approximately 4.3 Mev struck a thin beryllium target.

EXPERIMENTAL PROCEDURES

The counter ratio technique[5] was used to detect the presence of "threshold-neutrons" in the presence of high-energy neutrons. Data were taken with two counters simultaneously, one placed directly behind the other. The forward or "slow counter" was a Li^6I scintillator at the center of a 3-in. polyethylene moder-

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