with both the two-neutrino decay and with unfavored no-neutrino decay.

The background studies indicate limits on the double beta lifetimes that can be reached with expansion chambers.

VIII. ACKNOWLEDGMENTS

I wish to thank D. Connolley, C. Creager, T. Fesser, and P. Hoekstra for extensive assistance in the construction and operation of the equipment and in the scanning of the cloud-chamber photographs.

PHYSICAL REVIEW VOLUME 99, NUMBER 1 JULY 1, 1955

Scarcity of Low-Energy Levels of Be^8 Appearing in Two Boron Reactions

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(Received March 3, 1955)

A careful search is made for evidence of possible excited states in Be^8 in the reactions $B^{11}(p,\alpha)Be^8$ and $B^{10}(d,\alpha)Be^8$, by magnetic momentum analysis at a variety of angles and bombarding energies. In spite of observing the region corresponding to 3 to 8 Mev several times independently under different conditions, with several thousand counts per point on points spaced only about 100 kev apart, no indication was found of any of the states in this region reported by others on the basis of poorer statistics, mostly in other reactions. Each alpha-particle spectrum observed consists of a sharp ground-state peak and a broad peak of the alpha particles giving rise to the well-known 3-Mev excited state of Be^8 superposed on a continuous background from the break-up of this state and from three-particle break-up. Peaks observed near the equivalent of 10 and 11 Mev in Be^8 are identified as arising from a target impurity.

I. INTRODUCTION

THE interesting nucleus Be^8 may be expected to be especially simple because it is so light.[1] It contains just enough nucleons to make up two alpha particles. The nucleus which is twice as heavy, O^{16}, may consist of four alpha particles in a tetrahedral structure differing rather little from a sphere, and it does indeed show a strong evidence of collective motion of a body with tetrahedral symmetry, as epitomized by the alpha-particle model.[2] The even-even nucleus with mass between these two, C^{12}, appears not to follow the alpha-particle model,[1] and this may be associated both with the great difference between a triangle and a sphere and with the fact that the energy of dissociation into three alpha particles is as great as the average binding-energy of a nucleon. Although in Be^8 the possible alpha-particle structure, a line or "dumbbell," is also very different from a sphere, no energy is required to dissociate it into two alpha particles; so here again, there might be a tendency for the low states to be approximated by the alpha-particle model. In either the shell model or the alpha-particle model, or indeed in a blend of the two, the expected sequence of low-energy levels is very simple. The shell-model expectation is determined by the calculations which show in (LS) coupling a series of singlets, ${}^1S_1$, ${}^1D_2$, ${}^1G_4$, and similar widely-spaced levels in (jj) coupling and so also in intermediate coupling.[1] It should, however, be mentioned that states probably not belonging to the ground configuration p^n appear in the neighboring nuclei Li^7 at 6.4 Mev and C^{12} at 7.7 Mev, and might also appear in Be^8 at a comparable energy. The expectation of possible simplicity should not prejudice one, but does add interest to the experimental investigation of Be^8.

The evidence concerning the spectrum of low states in Be^8 remains conflicting. Some experiments suggest quite a number of low excited states, and other experiments, particularly those in which it has been possible to collect the most convincing statistical evidence, show only the well-known broad excited state at about 3 Mev. It is unfortunate that there are intrinsic difficulties which make it very time-consuming to collect adequate numbers of counts per point in some of the work showing the "extra" states, for the demonstration that certain other reactions do not show these states does not disprove their existence. It is always possible that an adverse matrix element is suppressing a given transition, but in the absence of some general selection rule, it becomes unlikely that this should happen at a variety of bombarding energies and angles, because a special selection that might apply for a given state of the compound nucleus or at a given angle would not be expected to apply at others. The present work is confined to reactions wherein it is not very difficult to obtain many counts per point with relatively good resolution. We have tried to vary the experimental conditions to exclude the possibility that some chance cancellation in the matrix element is hiding some of the states from us.

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* Now at Bell Telephone Laboratories, Whippany, New Jersey.
† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] D. R. Inglis, Revs. Modern Phys. 25, 390 (1953).
[2] D. M. Dennison, Phys. Rev. 96, 378 (1954); J. W. Bittner and R. D. Moffat, Phys. Rev. 96, 374 (1954).

Previous work[3] on this subject up to about a year ago is summarized in the preliminary report on the present investigation[4] and in a subsequent discussion by Titterton.[5] More recently, Trail and Johnson,[6] using a counter technique for measuring neutron energies, have repeated the work on $Li^7(d,n)Be^8$. With somewhat improved statistics, but rather poor resolution, they fail to find the states at 4.09, 4.9, and 7.5 Mev inferred from the earlier photographic emulsion work on this reaction[7] and observation[8] of alpha-gamma coincidences in Li^7 $(p,\gamma)Be^8$.

Among the investigations revealing some of the disputed states, the work of Cüer, Jung, and Bilwes[9,10] on $B^{10}(d,\alpha)Be^8$ seems to us to display the most impressive statistical evidence. The peaks which they considered significant consisted of at least four high points in succession isolated by a valley of at least two low points in succession. Their results suggest that the questionable states may be more easily observed near the forward direction, at least in this reaction.

II. APPARATUS AND RESULTS

Proton and deuteron beams for bombardment of B^{11} and B^{10}, respectively, were obtained from the ANL statitron at well-stabilized energies up to over 3 Mev. The energy of the alpha particles produced was analyzed by means of the 16-inch two-dimensional-focusing magnetic spectrometer previously described.[11] Targets used in some of the early work were prepared by evaporating natural boron on a thick backing, but trouble was experienced with losing the target during bombardment even with beams below 1 μa. The targets used in most of the work were kindly prepared for us by Louis Basile by heating prepared metal backings in diborane containing either enriched B^{10} (with about 5 percent B^{11} remaining) or natural boron. The heating and gas flow had to be limited to avoid getting the targets too thick. Thick-sheet tantalum backings were simply heated by induction. Thin backings of 0.02-mil nickel foils (5×10^{-5} cm) were each held between the halves of a small nickel frame. The frame was mounted against a steel plate heated by induction, and radiation from the plate in turn heated the nickel foil. The frame fit snugly enough against the steel plate to inhibit circulation of the diborane behind the foil, but a small amount of boron was deposited on the back side of the foil.

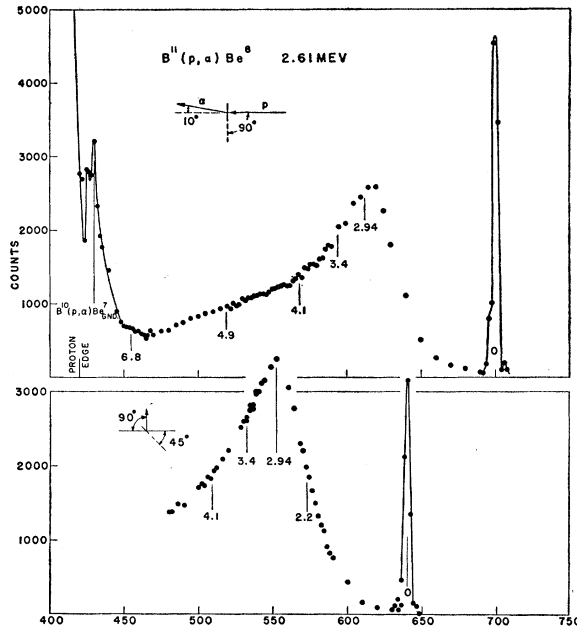

FIG. 2. Yield of alpha particles of various momenta from the reaction $B^{11}(p,\alpha)Be^8$ at a proton energy of 2.61 Mev, as observed at 10° and 90°. The numbers under the curves indicate Be^8 excitation energy in Mev.

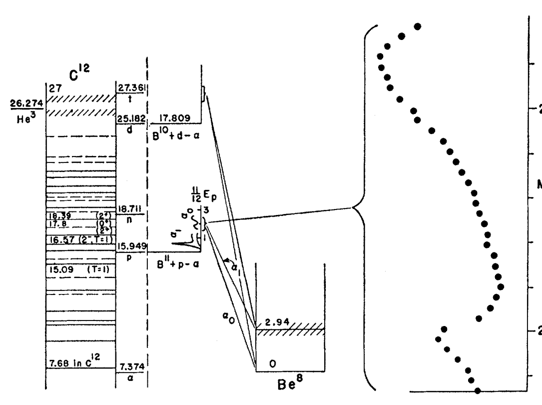

FIG. 1. Excitation curve for the reaction $B^{11}(p,\alpha)Be^8$.

Reaction $B^{11}(p,\alpha)Be^8$

Before investigating very carefully the distribution in energy of the product alpha particles, an excitation curve of $B^{11}(p,\alpha)Be^8$ was observed for the ground-state alpha particles, α_0, at $\theta=90°$ in the range of bombarding energies 1.9 to 2.7 Mev. The curve is shown on the right side of Fig. 1. The resonances observed at 1.98 and 2.61 Mev correspond to excited states in C^{12} at 17.76 and 18.35 Mev, agreeing with the values 17.8 and 18.39 Mev deduced from gamma-ray observations.[3] The data on the left side of Fig. 1, including the broken lines used to indicate uncertain states, were taken from reference 3. In the small insert for $B^{11}+p-\alpha$, our excitation curve is sketched on a small scale and

[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955). References are based on an advance preprint kindly supplied by the authors.
[4] R. Malm and D. R. Inglis, Phys. Rev. **92**, 1326 (1953).
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[7] Trumpy, Grotdal, and Graue, Univ. Bergen, Naturvitenskap. Rekke No. 8 (1953).
[8] E. K. Inall and A. J. F. Boyle, Phil. Mag. **44**, 1081 (1953).
[9] Cüer, Jung, and Bilwes, Compt. rend. **238**, 1405 (1954).
[10] P. Cüer and J. J. Jung, Compt. rend. **236**, 2401 (1953); also reference 3.
[11] R. Malm and D. R. Inglis, Phys. Rev. **95**, 993 (1954).

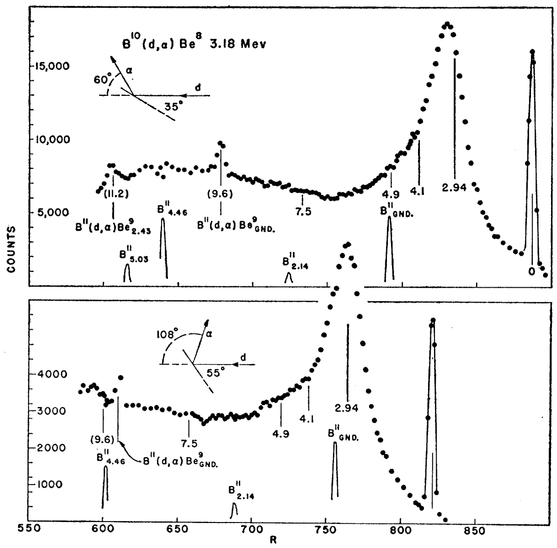

FIG. 3. Yield of alpha particles from $B^{10}(d,\alpha)Be^8$ at a deuteron energy 3.18 Mev, observed at 60° and 108°. In this and the following figures, the low sharp peaks labelled by states of B^{11} should be plotted ten times as high to represent the numbers of protons observed from the prolific competing reaction $B^{10}(d,p)B^{11}$.

compared with those previously observed[12] for energies up to 1.5 Mev for both the ground state and excited state transitions, though we have not established the factor by which to compare intensities.

Alpha-particle spectra were observed at laboratory angles of 10° and 90° for a proton bombarding energy of 2.61 Mev. The results are shown in Fig. 2 in which the abscissa is proportional to magnetic field or particle momentum. Places where one would expect to find alpha groups associated with reported levels in Be^8 are indicated in Fig. 2, labeled by the reported values of the excitation energies. Early results at 90° have been previously published.[4]

At both angles the alpha-particle spectrum showed peaks corresponding to the ground state and the 2.94-Mev excited state of Be^8. The resolution is such that the peaks of the sharp ground state each consist of four high points and in most of the regions carefully covered a peak would likewise be recognized as several successive high points.

The 10° alpha-particle spectrum shows a strong peak at a magnetic field corresponding to an excitation of Be^8 of about 7 Mev. The excitation curve of this alpha-particle group shows a resonance at a proton bombarding energy of 2.28 Mev not shown by the ground-state group α_0. We attribute this group to the reaction $B^{10}(p,\alpha)Be^7{}_{\mathrm{gnd}}$. Such a group is to be expected since a natural boron (19 percent B^{10}) target was used. At 90° this group was not observed because it occurs at magnetic fields below the proton scattering edge. This group gives rise to a double peak, and the ground state also shows some indication of structure. This may be attributed to a small amount of boron on the back of the thin backing used at this angle. Confirmation of this interpretation was obtained by observing the double peak at angles near 108°.

At $\theta=65°$ and $E_p=2.61$ Mev, one hasty run was made which is not presented in a figure because the points through most of the spectrum were too widely spaced to be significant and because of the adverse circumstance that the target was only about 5 percent B^{11}, the rest being B^{10}. In it a weak peak was observed at a position equivalent to $E^{\alpha}=3.61$ Mev, with an intensity about 5 percent of the ground-state peak. It is presumed to arise from another reaction but the data are insufficient to identify the target impurity.

Reaction $B^{10}(d,\alpha)Be^8$

Both thick-backed and thin-backed B^{10} targets were available, each of which had presumably about 5 percent B^{11} impurity. With these targets the reaction $B^{10}(d,\alpha)Be^8$ was observed at a variety of angles and energies in a further search for possible states of Be^8. The data shown in Figs. 3, 4, and 5 were taken with a thick-backed target, while the data in Fig. 6 were taken with a target with a thin backing (0.02-mil nickel foil). The competing reaction $B^{10}(d,p)B^{11}$ yields four groups of protons with energies in the range of interest. The protons were easily separated from the alpha particles since the sodium iodide crystal used as a detector gave considerably larger pulses for protons than for alpha particles of the same energy.

By using the known Q's for the ground-state alpha

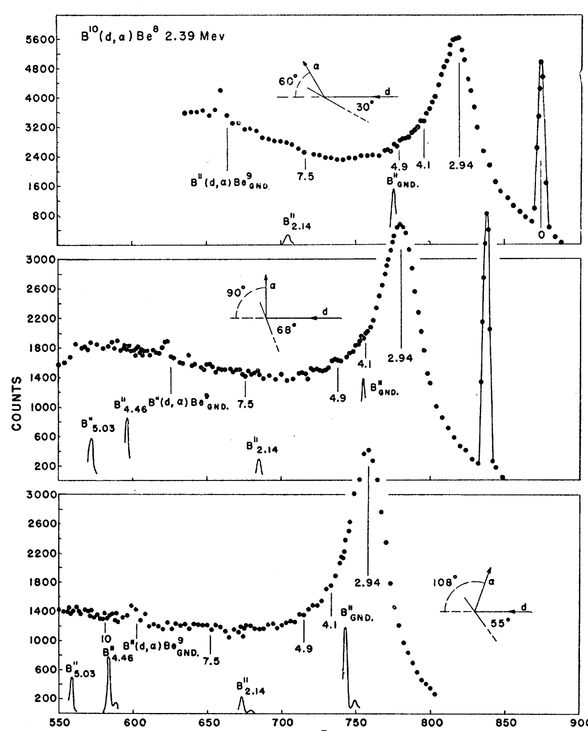

FIG. 4. Yield of alpha particles from $B^{10}(d,\alpha)Be^8$ at 2.39 Mev, observed at 60°, 90°, and 108°.

[12] Beckman, Huus, and Zupančič, Phys. Rev. 91, 606 (1953).

particles and the $B^{10}(d,p)B^{11}$ protons, a consistent calibration of the magnet was obtained. Above an alpha energy of 15 Mev, this curve deviates from the parabola through the low-energy points by about 10 percent. This deviation occurs because the edges of the poles, where the field is measured, saturates at a lower field than the middle of the pole pieces, where the particles travel.

All of the data are consistent with this calibration to about $\frac{1}{4}$ percent except in the case of the two spectra at a bombarding energy of 3.18 Mev, shown in Fig. 3. In this figure energies according to the original calibration were satisfactory at low fields but were about one percent too high at high fields. The numbers indicating excitation energy in Be^8 were placed so as to be consistent with the $B^{10}(d,p)B^{11}$ proton groups. The source of the discrepancy has not been identified but it is felt that it does not affect the smoothness of the curves or the apparent scarcity of levels in Be^8.

Peaks corresponding to about 9.5- and 11-Mev excitation of Be^8 appeared in all of the data covering this

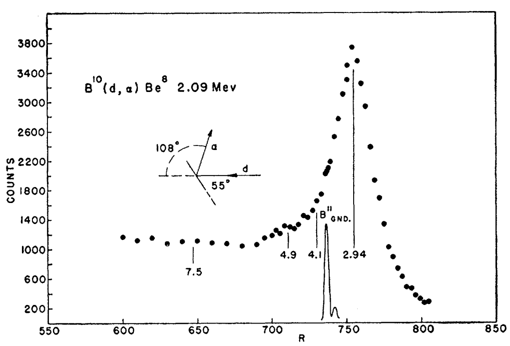

FIG. 5. Yield of alpha particles from $B^{10}(d,\alpha)Be^8$ at $E_d=2.09$ Mev, $\theta=108°$.

interval taken while studying the reaction $B^{10}(d,\alpha)Be^8$. Inconclusive evidence for a state at the lower of these energies is reported in reference 10. The peaks were identified by their variations with angle as coming from the reaction $B^{11}(d,\alpha)Be^9$ due to the 5 percent B^{11} impurity in the target, corresponding to transitions to the ground state and 2.43-Mev state of Be^9, respectively.

Discussion

All of the spectra observed show peaks due to the ground state and 2.94-Mev state of Be^8, superposed on a continuum arising from the breakup of the latter state and perhaps from direct three particle break-up. No other peaks were observed which could not be attributed to other reactions in the target. An upper limit for the intensity of another peak which would be unobserved by us is difficult to set since the accuracy of our data and the magnitude of the alpha-particle

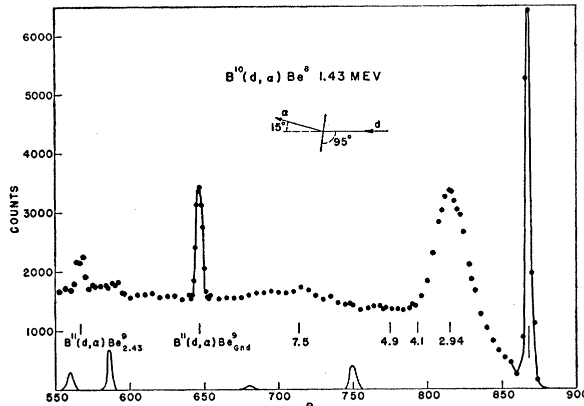

FIG. 6. Yield of alpha particles from $B^{10}(d,\alpha)Be^8$ at $E_d=1.43$ Mev near the forward direction.

continuum vary from spectrum to spectrum and place to place. We feel that for all curves, we would have detected a peak as much as 10 percent of the ground-state transition. Much of the data is considerably better than this, and in many cases in the regions where levels have been previously reported we would have observed a transition with 2 percent of the intensity of the ground-state transition. For peaks broader than the width set by our resolution, these limits would have to be increased accordingly.

In conclusion, it appears to us extremely unlikely that any systematic behavior of the matrix elements involved in the transitions should have hidden the existence of states in Be^8 in the neighborhood of 4, 5, and 7.5 Mev in Be^8. It is difficult to imagine any characteristics[13] that would distinguish these states so completely from the two lower states. We consider the weight of the accumulated evidence to favor the absence of the questionable states.

[13] The excitation curve of the reaction $B^{11}(p,\alpha)Be^8$ for the group α_1 to the broad 3-Mev state is said (see reference 3) to show the resonances at 1.98 and 2.61 Mev which we observed for the ground-state transition α_0 (Fig. 1), and in addition shows (see reference 12) a distinct resonance at 0.67 Mev not shown by α_0, at which α_1 is about 100 times as intense as α_0. Since $B^{11}+p$ (in contrast to $B^{10}+d$) can form $T=1$ states in the compound nucleus, this apparent selection has led to the suggestion (V. Telegdi, private communication) that the resonant state at 0.67 Mev has $T=1$ as is compatible with its high energy in C^{12}, and that the broad 3-Mev state of Be^8 has at least a small percentage of $T=1$, the ground state having none. (Judged by the ground state of Li^8, the lowest primarily $T=1$ state in Be^8 is expected to have $J=2$ and could thus mix with the 3-Mev state, but many other $T=1$ states are expected at slightly higher energies, some of which could mix with the ground state, and it is not clear why there should be an admixture in one and not the other. It might possibly be associated with the ground state alone being a pure alpha-particle-model state.) This proposed admixture of $T=1$ in the 3-Mev state and not in the ground state would not help explain a suppression of the questionable states relative to both. A factor 5 in the ratio α_1/α_0 is expected from the statistical factor $(2J+1)$ aside from any peculiarities of matrix elements, and the ratios of the areas under the corresponding peaks tend to be larger but for several of our curves are not much larger than this.