Low-Energy Spectra in the Be^9+d Reactions*

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The Be^9+d reactions have been studied in the region of the alpha continua arising from many-particle disintegrations. A search was made especially for alpha and triton groups; no evidence was found for a state in Li^7 at 5.5 Mev or for one in Be^8 at 4.1 Mev.

In an earlier paper[1] we investigated the alpha spectrum from the deuteron bombardment of beryllium up to an excitation energy of 5.3 Mev in Li^7, the proton spectrum up to 4.0 Mev in Be^{10}, and the triton spectrum up to 4.8 Mev in Be^8. In this work no evidence was found for multiplicity of the 2.9-Mev level in Be^8 or for a 4.1-Mev level in the same nucleus, as reported by several observers[2] but not by others.[3] Recently, a level has also been reported in Li^7 at an excitation of 5.5 ± 0.3 Mev.[4] We have continued the study of the Be^9+d reactions in a search for the latter state, and for the 4.1-Mev state in Be^8 under more favorable conditions. The experiment consists largely in an investigation of the three-body breakup of the compound nucleus B^{11}, since particle groups associated with the reported levels would generally fall in the three-particle continua. In addition it is not always easy to distinguish between the onset of a many-body continuum and a particle group corresponding to a state,[5,6] unless a detailed investigation is made.

The apparatus was the same as that used earlier except for the addition of an automatic current stabilizer to the magnetic spectrograph. For most of the spectra, unbacked beryllium foils, about 15 microinches thick, were used for targets. A convenient method of mounting a foil and collimating the reaction products to reduce the yield of scattered deuterons is shown in the inset in Fig. 4. An unbacked foil was essential for the observations made at forward angles and for runs in which scattered deuterons would have been troublesome. Detection of the particles was by means of nuclear emulsions which were scanned under moderate magnification. Particles were identified by observing range in the emulsion. Although this technique fails to separate low-energy $(H^3)^+$, $(He^4)^{++}$, and $(Li^7)^{+++}$ particles, it was possible at higher energies to distinguish the latter from alpha particles and tritons. Energy calibration was obtained from the known energies of prominent particle groups which appear in the spectra. The data are plotted to a momentum scale labeled with the alpha-

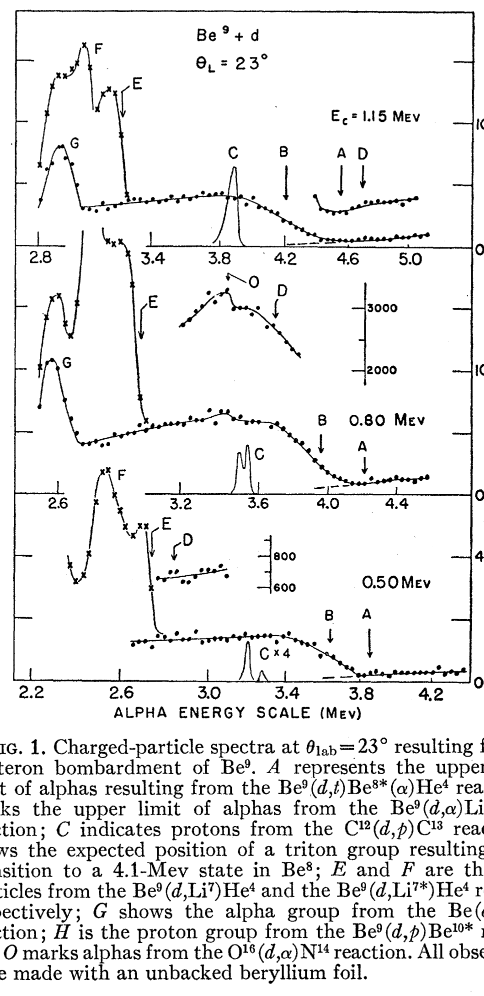

FIG. 1. Charged-particle spectra at $\theta_{lab}=23°$ resulting from the deuteron bombardment of Be^9. *A* represents the upper energy limit of alphas resulting from the $Be^9(d,t)Be^{8*}(\alpha)He^4$ reaction; *B* marks the upper limit of alphas from the $Be^9(d,\alpha)Li^{7**}(\alpha)H^3$ reaction; *C* indicates protons from the $C^{12}(d,p)C^{13}$ reaction; *D* shows the expected position of a triton group resulting from a transition to a 4.1-Mev state in Be^8; *E* and *F* are the Li^{7+++} particles from the $Be^9(d,Li^7)He^4$ and the $Be^9(d,Li^{7*})He^4$ reactions, respectively; *G* shows the alpha group from the $Be(d,\alpha)Li^{7**}$ reaction; *H* is the proton group from the $Be^9(d,p)Be^{10*}$ reaction; and *O* marks alphas from the $O^{16}(d,\alpha)N^{14}$ reaction. All observations were made with an unbacked beryllium foil.

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[1] R. W. Gelinas and S. S. Hanna, Phys. Rev. **89**, 483 (1953).

[2] See, for example: W. M. Gibson and D. J. Prowse, Phil. Mag. **46**, 807 (1955); Cüer, Jung, and Bilwes, Compt. rend. **238**, 1405 (1954); E. K. Inall, Phil. Mag. **45**, 768 (1954); M. J. Brinkworth and E. W. Titterton, Phil. Mag. **42**, 952 (1951); Erdös, Scherrer, and Stoll, Helv. Phys. Acta **26**, 207 (1953); H. Glättli and P. Stoll, Helv. Phys. Acta **26**, 428 (1953).

[3] See, for example: C. C. Trail and C. H. Johnson, Phys. Rev. **95**, 1363 (1954); Holland, Inglis, Malm, and Mooring, Phys. Rev. **99**, 92 (1955); C. M. Moak and W. R. Wisseman, Phys. Rev. **101**, 1326 (1956); R. T. Frost and S. S. Hanna, Phys. Rev. **99**, 8 (1955); La Vier, Hanna, and Gelinas, Phys. Rev. **103**, 143 (1956).

[4] Erdös, Scherrer, Stoll, Wachter, and Wataghin, Nuovo cimento **12**, 639 (1954).

[5] Moak, Good, and Kunz, Phys. Rev. **96**, 1363 (1954); L. L. Lee and D. R. Inglis, Phys. Rev. **99**, 96 (1955); Almqvist, Allen, and Bigham, Phys. Rev. **99**, 631(A) (1955).

[6] Rasmussen, Miller, Sampson, and Gupta, Phys. Rev. **100**, 851 (1956); Gossett, Phillips, Schiffer, and Windham, Phys. Rev. **100**, 203 (1956); Bockelman, Leveque, and Buechner, Bull. Am. Phys. Soc. Ser. II, **1**, 280 (1956).

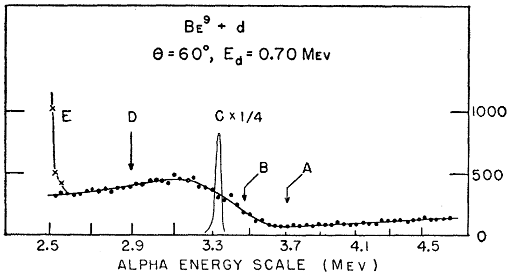

FIG. 2. The charged particle spectrum at $\theta_{lab}=60°$ of the Be+d reactions. The letters are defined in the caption to Fig. 1. The run was made with a target on thick backing.

particle energy. The spectra are uncorrected for the change in solid angle with particle momentum which amounts to about 20% in going from E to $2E$.

Figure 1 shows the spectra of three observations at $\theta_{lab}=23°$ and bombarding energies of 1.15, 0.80, and 0.50 Mev. At the high-energy end of each spectrum there is a low background of tritons, attributed to the direct $Be^9(d,t)Be^{8*}$ reaction (leading to the 2.9-Mev state of Be^8) as well as to the three-particle disintegration $Be^9(d,\alpha)Li^{7**}(t)He^4$. The marked increase in the yield below the arrow marked A is due to alpha particles from three-particle breakup. At the low end of each spectrum appear lithium particle groups corresponding to the ground and first excited states of Li^7 and an alpha group associated with the 4.62-Mev state. The expected position of a triton peak corresponding to a 4.10-Mev state in Be^8 is shown by the arrow labeled D in each spectrum. For the run at 1.15-Mev bombarding energy the expected location falls in the region of low triton background, for the 0.80-Mev run the expected location is in the rising part of the alpha background, and for the 0.50-Mev run it falls just above the lithium particle peaks. To obtain better statistics throughout the interesting regions, adjacent swaths in the emulsion were read, instead of only one 200-micron swath every millimeter along the plate. These data are also plotted in the figure.

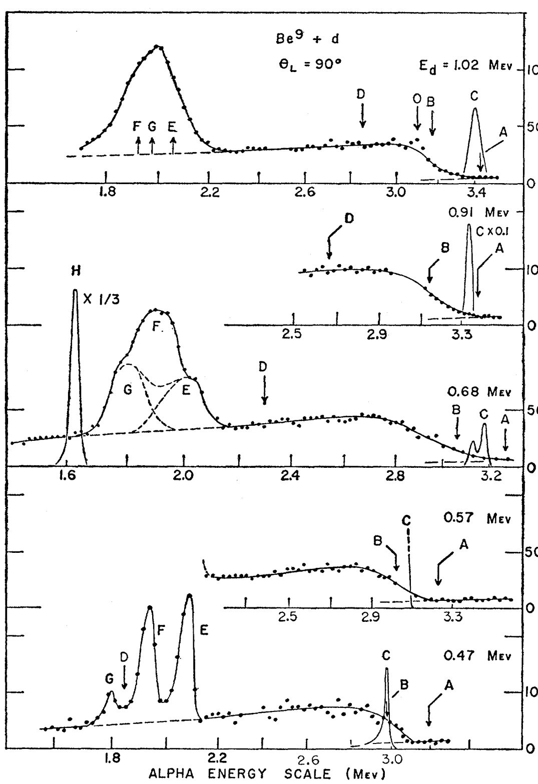

FIG. 3. Charged particle spectra at $\theta_{lab}=90°$ from the Be^9+d reactions. The letters are defined in the caption to Fig. 1. Data at 0.68 and 1.02 Mev were obtained by using an unbacked foil target, others by using a target on a solid backing.

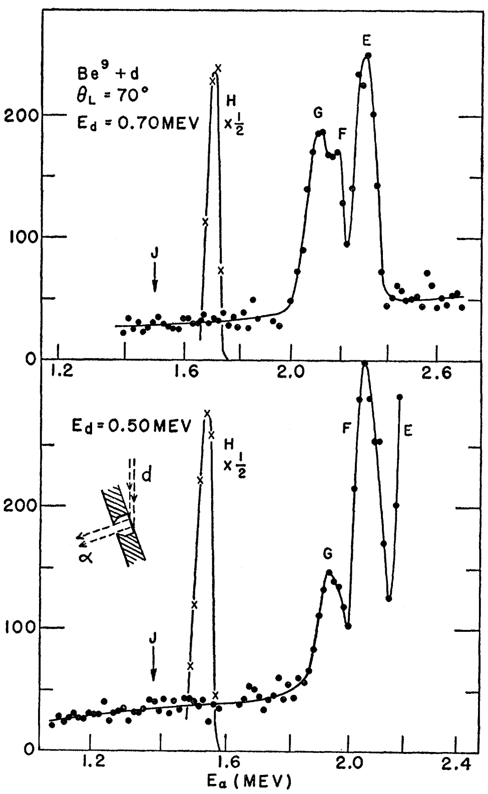

FIG. 4. Spectra taken at $\theta_{lab}=70°$. The letters are defined in the caption to Fig. 1; in addition, J shows the expected location of an alpha peak corresponding to a 5.5-Mev state in Li^7. Observations were made with an unbacked beryllium foil.

Observations made at $\theta=60°$ and 90° are shown in Figs. 2 and 3. At $\theta=90°$, $E_d=0.47$ Mev, there are three peaks in the vicinity of D. As the bombarding energy increases, however, none of these peaks moves in the manner prescribed for a triton group. There appears to be no evidence in any of the observations for a state in Be^8 between $E_{ex}=3.4$ and 4.8 Mev. We estimate that a transition having an intensity about 2% of that of the 2.9-Mev group would have been detected. It is also clear that the broad structure below A, which was attributed above to an alpha continuum, could not alternatively be a triton group indicative of a broad state in Be^8, since it does not move correctly with a change in the bombarding energy. As has been pointed out[1,7] this structure is properly assigned to the processes $Be^9(d,t)Be^{8*}(\alpha)He^4$ (cutoff labeled A) and $Be^9(d,\alpha)Li^{7*}(\alpha)H^3$ (cutoff labeled B). The superposition of these continua leads to the characteristic shape displayed by the curves: the former reaction involving a broad intermediate state produces a rise of moderate slope; the latter process involving a narrow state leads to a sharp high-energy cutoff.

It is interesting to compare the three-particle continua observed here with those obtained recently in several different reactions by workers[5,6] investigating states in Be^9. They have found relatively sharp structure at the high-energy end of the many-body continuum. This structure has been interpreted by some[5] to indicate the existence of a state in Be^9 and by others[6] as being due to the presence of a very strong directional correlation among the disintegrating particles. No such sharp structure is observed in any of the Be^9+d continua.

Figure 4 shows the data obtained in the search for a 5.5-Mev state in Li^7. The expected position of an alpha group at $E_{ex}=5.5$ is labeled with the letter J. There is no evidence for a peak in this region of the spectrum. We estimate that a transition having an intensity greater than 5% of the ground-state intensity would have been detected.

We should like to thank Mr. James Lambert for assistance in processing the plates and operating the spectrograph.

[7] P. Cüer and J. J. Jung, Compt. rend. **234**, 204 (1952).

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Energy Levels of O^{18} and F^{21}†

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The reactions $F^{19}(t,\alpha)O^{18}$ and $F^{19}(t,p)F^{21}$ have been studied, yielding the following results: the energy levels of O^{18} up to 6.8 Mev are 1.989, 3.504, 3.929, 5.007, 5.170, 5.311, 5.456, 6.190, and 6.328 Mev. The energy levels of F^{21} up to 2.14 Mev are 0.269, 1.087, 1.694, and 2.036 Mev. The mass defect of F^{21} is measured to be 6.195 Mev, giving a mass of 21.006653 atomic mass units. The yields and cross sections of the levels are studied. These results are compared with data obtained elsewhere and the isobaric systems of mass 18 and 21 are discussed.

INTRODUCTION

INTEREST has been growing in the nuclei whose protons and neutrons number one or two more or less than the closed p shell (O^{16}). A nucleus with just one odd proton or neutron can be described, in part, by shell theory. When one considers a nucleus with two nucleons above the closed shell (as in O^{18} with two extra neutrons), the additional effect of the coupling between these nucleons must be considered. A study of such nuclei, assuming predictable behavior of the core, may give information on the interaction of two nucleons in such a situation. It is with this in mind that the results of an experiment to measure the energy levels of O^{18} are given, with the data on F^{21} coming out more or less as a by-product. The results of these experiments are of interest, also, in the study of reactions with three-particle projectiles.

The levels of O^{18} are obtained from the experimental energies of α particle groups in the reaction $F^{19}(t,\alpha)O^{18}$, using a precision double-focusing magnetic spectrometer. The F^{21} levels are obtained in a similar way from the $F^{19}(t,p)F^{21}$ reaction.

The F^{21} data given here supersede the preliminary information published in 1955.[1] A preliminary report of the O^{18} work has also been published.[2]

EXPERIMENTAL APPARATUS

The apparatus used is shown in Fig. 1. Tritons are accelerated in one of the 2.5-Mev electrostatic generators of the Los Alamos Scientific Laboratory. The energy of the beam is determined to 1 or 2 kev by sending the diatomic (T_2^+) beam through an electrostatic analyzer. The apertures and target are part of an elaborate 22-inch diameter reaction chamber. Fragments from the reaction on the target leave the chamber through a port at 90° to the beam. The fragments then enter a 16-inch radius, double-focusing magnetic spectrometer and are detected at the focus by a scintillation detector employing a thin CsI(Tl) crystal and a 6292 DuMont photomultiplier tube. The

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Nelson Jarmie, Phys. Rev. **99**, 1043 (1955).
[2] Nelson Jarmie, Bull. Am. Phys. Soc. Ser. II, **1**, 28 (1956).