the absorption cross section at the (Doppler-broadened) peaks. The maximum peak absorption calculated is only about twice the average value found in the experiment. Since the average energy loss on scattering is about 400 ev and scattering is ten times as probable as absorption, the self-shielding at a single resonance must be completely negligible.

APPENDIX II. NOTES ON SPECIAL CASES

Mg^{26}.—The upper limit is based on failure to find a distinct gamma-ray peak and the poor statistics associated with this short-lived activity and low abundance (11.1%).

Cl^{37}.—A sample of CCl_4 was used and a correction of a few percent was made for evaporation.

K^{41}.—The upper limit is set by K^{41} background in the gamma-ray spectrometer.

Cu^{63}.—A layer of unactivated copper was used around the sample during gamma-ray counting to absorb all of the positrons.

Br^{81}.—Lump CBr_4 was used.

Rb^{85}.—The energetic beta-rays were also counted to increase sensitivity in this case. The efficiency was determined by mixing a known activity into inert Rb_2SO_4 under the same conditions as in the Sb–Be irradiation.

Zr^{96}.—The cross section might be somewhat lower as the gamma-ray spectrum peak was distorted by other activities in this case.

Mo^{100}.—The Tc^{100} daughter activity was also observed, as indicated in Table I.

I^{127}.—$NaIO_3$ was used.

Er^{170}.—The value of γ/dis is taken from yet unpublished work of M. E. Bunker. We would like to thank Dr. Bunker for permission to use his results before publication.

Re^{185} and Re^{187}.—$KReO_4$ was used.

Hg^{202}.—Hg_2Cl_2 was used.

Th^{232}.—The Pa^{233} daughter was extracted for the activity measurement.

U^{238}.—The Np^{239} daughter was extracted for the activity measurement.

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B^{12}, C^{12}, and the Red Giants*

C. W. Cook, W. A. Fowler, C. C. Lauritsen, and T. Lauritsen
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
(Received March 25, 1957)

Alpha-particle emission associated with the β decay of B^{12} has been detected and the energy spectrum investigated. These studies show that $(1.3\pm0.4)\%$ of all decays of B^{12} lead to the second excited state of C^{12} and that this state breaks up predominantly into three alpha particles with one alpha particle and the ground state of Be^8 as an intermediate stage in the process. The most probable spin and parity assignments for the state appear to be $J=0^+$, and analysis of the alpha-spectrum yields $Q(C^{12*}-Be^8-He^4)=278\pm4$ kev, corresponding to an excitation energy in C^{12} of 7.653 ± 0.008 Mev. A new determination of the disintegration energy of Be^8 yields $Q(Be^8-2He^4)=93.7\pm0.9$ kev and hence $Q(C^{12*}-3He^4)=372\pm4$ kev. It is concluded, from the general principle of reversibility of nuclear reactions, that the second excited state of C^{12} as predicted by Hoyle is of a suitable character to act as a stellar thermal resonance in the Salpeter process, $2He^4\rightleftharpoons Be^8$; $Be^8(\alpha,\gamma)C^{12}$ under conditions expected in red giant stars.

INTRODUCTION

It has been suggested[1,2] that the fusion of alpha particles through the reactions

$$He^4+He^4\rightleftharpoons Be^8,$$

$$Be^8+He^4\rightarrow C^{12*}\rightarrow C^{12}+\gamma,$$

or, more simply,

$$3He^4\rightleftharpoons C^{12*}\rightarrow C^{12}+\gamma,$$

plays an important role in energy generation and element synthesis in red giant stars. These processes are believed to occur at a late stage of the red giant evolution in which the hydrogen in the central core has been largely converted into helium, and in which gravitational contraction[3] has raised the central temperature to $\sim10^8$ deg K, and the density to $\sim10^5$ g/cc. Under these conditions, as has been shown by Salpeter,[2] an equilibrium ratio of Be^8 to He^4 nuclei equal to $\sim10^{-9}$ is established. This conclusion followed from experimental measurements[4–6] which established the fact that Be^8

* Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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2 E. E. Salpeter, Astrophys. J. **115**, 326 (1952); *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.

3 F. Hoyle and M. Schwarzschild, Astrophy. J. Suppl. **2**, 1 (1955).

4 A. Hemmendinger, Phys. Rev. **73**, 806 (1948); Phys. Rev. **75**, 1267 (1949).

5 Tollestrup, Fowler, and Lauritsen, Phys. Rev. **76**, 428 (1949).

6 Early measurements by O. Laaff, Ann. Physik **32**, 760 (1938), and K. Fink, Ann. Physik **34**, 717 (1939) were analyzed by J. A.

was in fact unstable to disintegration into two alpha particles but only by 95 kev with an uncertainty of about 5 kev.

Even though very small, the equilibrium concentration of Be^8 is sufficient to lead to considerable production of C^{12} through radiative alpha-particle capture by the Be^8, and of O^{16}, Ne^{20}, etc., by succeeding alpha-particle captures. Salpeter's equilibrium calculations, in which resonance effects due to the Be^8 ground state are properly taken into account, indicated a rate for the "helium burning" considerably greater at a given pressure and temperature than that previously calculated by Öpik using nonresonant reaction rates (see discussion by Öpik in the second part of reference 1). Detailed consideration of the reaction rates and of the resulting relative abundances of He^4, C^{12}, and O^{16} led Hoyle[7] to the prediction that the second reaction, in which C^{12} is produced, must exhibit resonance within the range of energies at which the interaction between Be^8 and He^4 effectively occurs. Hoyle's predicted value for the resonance energy was 0.33 Mev, corresponding to an excited state in C^{12} at 7.70 Mev.

Hoyle's prediction of resonance was made in the face of conflicting evidence in regard to the existence of an excited state in C^{12} in the vicinity of 7.7 Mev. Early investigators had reported such a state but some later research had failed to confirm its existence. Holloway and Moore[8] and Guggenheimer *et al.*,[9] in measurements of the range of alpha particles from $N^{14}(d,\alpha)C^{12}$, had reported a level in C^{12} at 7.62 Mev and 7.3 Mev, respectively. However, magnetic analysis of the alpha-particle groups from the same reaction by Malm and Buechner[10] gave no evidence of a transition to a level in this neighborhood.

Early studies[9,11,12] of the neutron spectrum from deuteron bombardment of natural boron targets revealed a group with a Q-value of about 6 Mev, which could be ascribed either to the ground-state transition in $B^{10}(d,n)C^{11}$ or to a transition to an excited state at $\sim$7.5 Mev in C^{12}, through the reaction $B^{11}(d,n)C^{12*}$. An investigation by Gibson,[13] who used separated B^{10} and B^{11} targets, showed that the main contribution to the group in question was in fact from $B^{10}(d,n)C^{11}$, but it was suggested that a residual peak observed with B^{11} targets was probably due to a genuine C^{12} level at $\sim$7.7 Mev. Still later work by Johnson[14] failed to reveal such a level, although a weak group could not be excluded.

In the reaction $Be^9(\alpha,n)C^{12}$, a neutron group corresponding to a 7.5-Mev level[15] has been observed. In addition, 7-Mev electron-positron pairs ($e^{\pm}$) attributed to a monopole transition ($0^+ \to 0^+$) to the ground state,[16] and 3.16-Mev cascade radiation[17] through the state at 4.43 Mev have been reported. Protons inelastically scattered from C^{12} also gave evidence for a level at 7.5 Mev.[18]

With the realization of the possible astrophysical significance of such a level, the matter was reinvestigated by Hoyle *et al.*,[19] using the reaction $N^{14}(d,\alpha)C^{12}$. With a high-resolution magnetic spectrometer they clearly identified the alpha-particle group leading to the excited state of C^{12} in question and obtained a level energy of 7.68 ± 0.03 Mev and a width of less than 25 kev. The low intensity of the group—some 6% of the next higher energy group—accounts for some of the earlier difficulties. Later work by Pauli[20] and Ahnlund[21] on the same reaction yielded excitation energies of 7.66 ± 0.02 and 7.658 ± 0.027 Mev, respectively.

The reaction rate for the conversion of helium into carbon by the $2He^4 \rightleftharpoons Be^8$; $Be^8(\alpha,\gamma)C^{12}$ process is given by

$$p=-\frac{1}{x_\alpha}\frac{dx_\alpha}{dt}=3^{\frac{3}{2}}8\pi^3\frac{\hbar^5}{M_\alpha{}^5(kT)^3}(\rho x_\alpha)^2\frac{\Gamma_\gamma\Gamma_\alpha}{\Gamma_\gamma+\Gamma_\alpha}\times\exp\left(-\frac{Q}{kT}\right)\text{ sec}^{-1},$$

where ρ is the density, T the temperature, x_α the concentration by weight of helium, M_α the alpha-particle mass, Γ_γ and Γ_α the partial widths of the C^{12*} for γ and α decay, and Q is the energy equivalent of the mass difference ($C^{12*}-3He^4$). For ρ in grams/cc, T_8 in 10^8 deg K, Q in kev, Γ_γ in ev, and $\Gamma_\gamma \ll \Gamma_\alpha$ as discussed later, we have:

$$p=2.37\times10^{-4}(\rho x_\alpha)^2\frac{\Gamma_\gamma}{T_8{}^3}\exp\left(-\frac{Q}{8.62T_8}\right)\text{ sec}^{-1}.$$

Since Q/kT appears in the argument of the Maxwell-Boltzmann exponential factor and since the range of values of T is limited by other considerations, the reaction rate depends critically on Q. This energy can be calculated somewhat indirectly from the results

Wheeler, Phys. Rev. **59**, 27 (1941), to yield an energy of instability of 125 kev with an uncertainty of 25 kev.

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[12] T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

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[15] Guier, Bertini, and Roberts, Phys. Rev. **85**, 426 (1952); B. G. Whitmore and W. B. Baker, Phys. Rev. **78**, 799 (1950).

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[17] Beghian, Halban, Husain, and Sanders, Phys. Rev. **90**, 1129 (1953).

[18] R. Britten, Phys. Rev. **88**, 283 (1952).

[19] Hoyle, Dunbar, Wenzel, and Whaling, Phys. Rev. **92**, 1095 (1953); Dunbar, Pixley, Wenzel, and Whaling, Phys. Rev. **92**, 649 (1953).

[20] R. T. Pauli, Arkiv Fysik **9**, 571 (1955).

[21] K. Ahnlund, Arkiv Fysik **10**, 369 (1956).

discussed above and from tabulated mass values[22] as 385±17 kev. One objective of the present experiments was a more direct determination of this energy.

It is of course crucial to the theory that the C^{12} level be of such a character that it can be formed by Be^8+He^4, i.e., that it have even spin and even parity or odd spin and odd parity, and a nonvanishing alpha-particle width. It must also have a reasonable probability for γ or $e^{\pm}$ decay if C^{12} is to be formed. These questions could best be explored by bombarding Be^8 with alpha particles, but since Be^8 is unstable, recourse must be had to a study of the two possible modes of decay of the excited state of C^{12}, namely $C^{12*}\rightarrow Be^8+He^4$ and $C^{12*}\rightarrow C^{12}+\gamma$ (in case γ radiation is forbidden or weak, the emission of $e^{\pm}$-pairs must be considered). By the principle of reversibility of nuclear reactions, it is evident that observation of α and γ decay of the 7.7-Mev C^{12} state would guarantee the feasibility of the process in question; in fact, a measurement of the decay widths for these processes would make it possible to calculate the cross section for $Be^8(\alpha,\gamma)C^{12}$ by using the one-level Breit-Wigner formula.

Experimental evidence on the character of the 7.7-Mev C^{12} state is not entirely clear. It seems well-established that the state does not radiate directly to the ground state but rather cascades via the 4.43-Mev state.[17,23] The absence of ground-state transitions suggests $J=0$ or $J\geqslant 3$; the reported observation of 7-Mev electron-positron pairs favors $J=0$, since a one-photon radiative transition for $0\rightarrow 0$ states is strictly forbidden, while $e^{\pm}$ emission is allowed. Inelastic scattering of alpha particles by C^{12} yields a group of alpha particles corresponding to this level, with no corresponding C^{12} recoils, indicating that the C^{12} state must break up mainly by alpha emission.[24] Analysis of the angular distribution of the inelastically scattered alpha particles in this reaction is in good agreement[25] with $J=0^+$. A $\gamma-\gamma$ correlation experiment[26] in $N^{14}(d,\alpha)C^{12}$ is consistent with $J=0$ but does not exclude $J\geqslant 3$. The angular distribution[27] of electrons inelastically scattered from C^{12} at 187 Mev indicates $J=0^+$. It would thus appear reasonably certain that $J=0^+$ is the correct assignment. However, emission of alpha particles has not heretofore been observed, and estimates of the fraction of decays leading to alpha-particle emission vary from $\ll 50\%$[23] to $>97\%$.[28,29] It was the object of

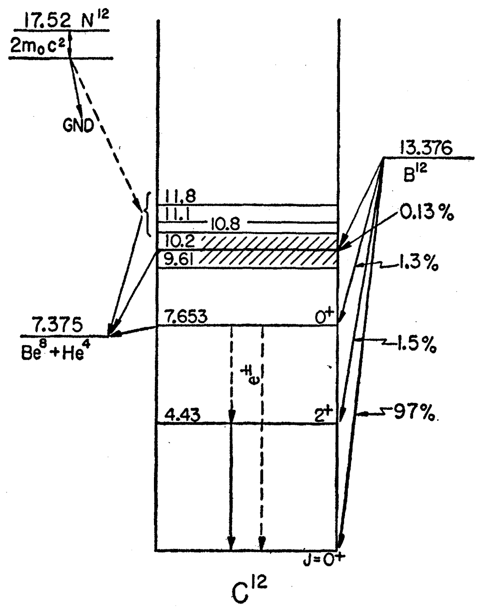

FIG. 1. Energetics of B^{12} decay; only the low-lying levels of C^{12} are shown.

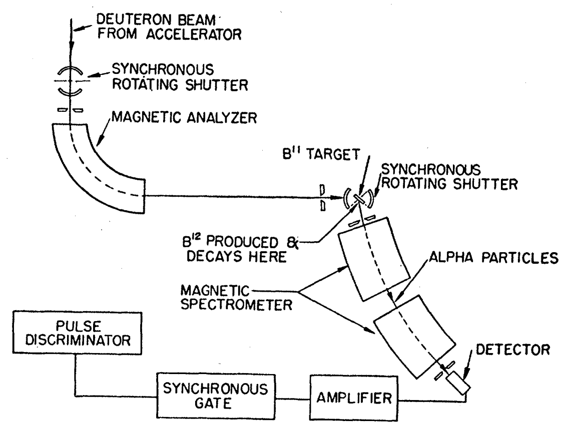

FIG. 2. Schematic diagram of apparatus. The B^{12} is produced by deuteron bombardment of a B^{11} target; alpha particles emerging from the target are focused by a magnetic spectrometer. Synchronous shutters permit alternate bombardment and detection.

the present experiment to observe the alpha particles directly if possible and to make a precise determination of their energy, to permit calculation of the Q-value referred to above.

Since the alpha particles were expected to be of low energy and of relatively low intensity in any easily available reaction, we chose to look for them first in the decay of B^{12}, where advantage could be taken of the radioactive delay to reduce the background due to particles from prompt reactions. The processes in-

[22] A. H. Wapstra, Jr., and R. Huizenga, Physica **21**, 367 (1955).
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[27] J. H. Fregeau and R. Hofstadter, Phys. Rev. **99**, 1503 (1955).
[28] Bent, Bonner, McCrary, and Ranken, Phys. Rev. **100**, 771 (1955).
[29] W. F. Hornyak, Bull. Am. Phys. Soc. Ser. II, **1**, 197 (1956).

volved are:

$$B^{12} \rightarrow C^{12*} + \beta^- + \nu_-,$$

$$C^{12*} \nearrow Be^8 + He^4, \quad C^{12*} \searrow C^{12} + \gamma.$$

Boron 12, with a half-life of 20.6±0.9 milliseconds,[30] is copiously produced in the reaction $B^{11}(d,p)B^{12}$ and is known to decay to both the ground and 4.43-Mev states of C^{12}, the latter to the extent of 1.5%.[31,32] The beta spectrum suggests[33] additional decays to considerably higher states of C^{12}. The decay of N^{12} is known to yield alpha particles[34] from the breakup of higher states of C^{12}, and it seemed thus not impossible that B^{12} could decay through the 7.7-Mev level and yield low-

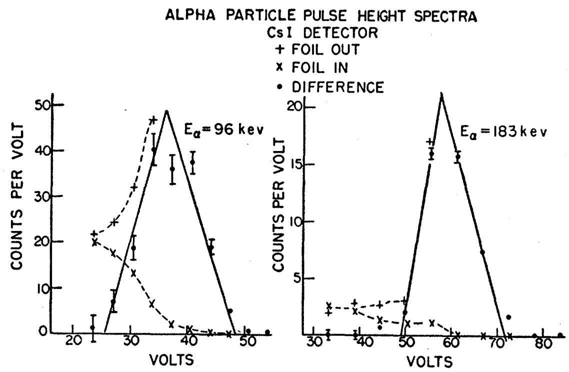

FIG. 3. Typical pulse height spectra for alpha particles of 96 and 183 kev. The particles were focused with a magnetic spectrometer of momentum resolution $\Delta p/p = 5\%$ and detected with a CsI crystal; the pulse heights were recorded with a 10-channel discriminator. A 2.2-mg/cm² Al foil permitted separation of the α particles from background neutrons and γ rays.

energy alpha particles. The energetics involved are shown in Fig. 1.

EXPERIMENTAL ARRANGEMENT

The experiments to be described consisted in producing B^{12} by deuteron bombardment of a B^{11} target, cutting off the beam, and searching for delayed alpha particles with a magnetic spectrometer. The experimental arrangement is shown schematically in Fig. 2. The deuteron beam from an electrostatic accelerator passed through a magnetic analyzer to bombard a thin isotopic B^{11} target[35] located at the focal point of a low-

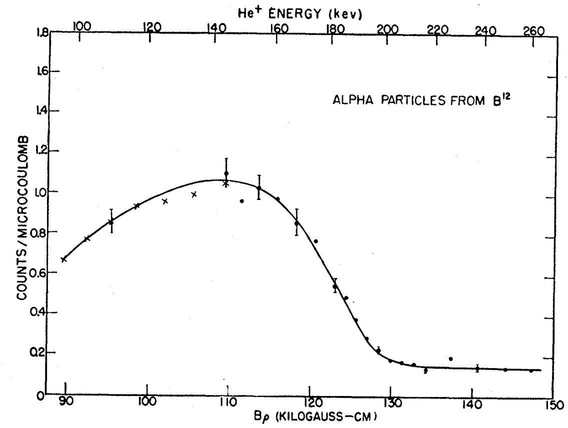

FIG. 4. Observed momentum spectrum of the alpha particles formed in the deuteron bombardment of a 39-μg/cm² isotopic B^{11} target placed at 15° grazing angle to the beam. Dots and crosses represent data taken with a spectrometer momentum resolution of $\Delta p/p = 5\%$ and 11% respectively, the latter being normalized to fit the former.

dispersion, strong-focusing magnetic spectrometer.[36] Alpha particles focused by the spectrometer were detected by a CsI crystal wafer, mounted on a photomultiplier tube. The deuteron beam was periodically interrupted at a position remote from the target by a rotating shutter, driven synchronously with a similar shutter which closed off the spectrometer during bombardment of the target. The counting system was electronically gated to permit counting only when the deuteron beam was interrupted. In each cycle of 1/60 sec, the target was bombarded for 6.1 milliseconds, and 2.9 milliseconds later was exposed to the spectrometer for 6.1 milliseconds.

Various combinations of target thickness, target angle, and spectrometer resolution were used in the experiments. The data reported here were mainly obtained with a 39-μg/cm² B^{11} target on a tantalum backing, placed at 15° grazing incidence to the deuteron beam, and using a spectrometer resolution in momentum (p) given by $\Delta p/p = 5\%$. At each spectrometer setting, a complete pulse height spectrum was recorded by means of a 10-channel discriminator. Interposition of a 2.2-mg/cm² Al foil in front of the spectrometer slit permitted separate determination of background due to stray neutrons or γ rays. Typical pulse height spectra are shown in Fig. 3. In general, for a given $B\rho$ setting, one expects two groups, corresponding to He^+-ions and He^{++}-ions, differing in energy and pulse height by a factor of four. Up to an energy of ~200 kev, the doubly charged group is practically negligible; on the other hand, correction for neutral atoms is significant below 500 kev.[37]

Figure 4 exhibits the observed momentum spectrum, extending from $E_\alpha = 100$–260 kev, plotted as actual

[30] Weighted mean of published values including E. Norbeck, Jr., Bull. Am. Phys. Soc. Ser. II, 1, 329 (1956).
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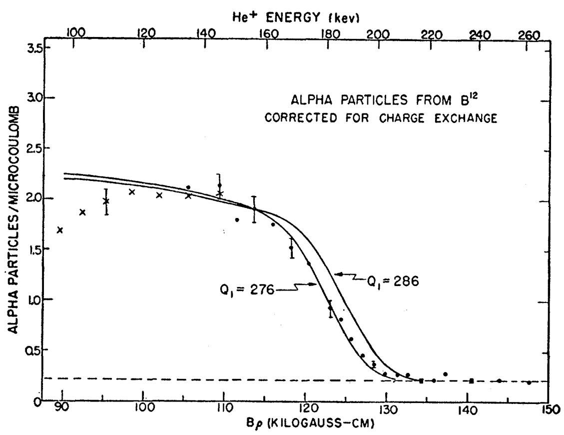

FIG. 5. Momentum spectrum of the alpha particles of Fig. 4 after correction for charge exchange using the data of Stier, Barnett, and Evans.[37] Solid lines are theoretical spectra calculated for $Q(C^{12*}-Be^8-He^4)=276$ kev and 286 kev.

counts recorded *versus* $B\rho$. In Fig. 5 the experimental points are replotted, after correction for charge exchange.[37] The spectrum exhibits a broad distribution of alpha particles, terminating at an energy of about 200 kev. The detailed analysis of this spectrum is discussed in a later section. That these alpha particles are in fact associated with the B^{12} decay was confirmed by several blank experiments using Be, Cu, and Ta as targets and by a lifetime measurement. The lifetime was measured by covering one open section of the lower shutter and then alternately reversing the direction of rotation of the shutter, thus alternately changing the time between bombardment and observation from 2.9 to 18.3 milliseconds. The value found for the half-life was 16 milliseconds, in rough agreement with the β-decay half-life (20.6 milliseconds) of B^{12}.

As may be seen in Fig. 4, the alpha-particle spectrum does not vanish entirely above the "end point," but continues for some distance beyond. In addition, there was observed an appreciable number of high-energy pulses, corresponding to He^{++}-ions, whose intensity increased slowly with increasing $B\rho$. It is believed that these particles result from the excitation of a broad state of C^{12} as shown in Fig. 1. Further investigation of this part of the spectrum is in progress and will be discussed in a separate report.

In connection with the determination of the energy of the alpha particles from $C^{12*}\rightarrow Be^8+He^4$ and with the effort to obtain as directly as possible the over-all Q-value for the transition $C^{12*}\rightarrow 3He^4$, a new observation was made of the alpha-particle spectrum of $Be^8\rightarrow 2He^4$ as produced in $Be^9(p,d)Be^8$. With the large aperture of the present spectrometer it was possible to work with thinner targets and to obtain higher counting rates than were possible in an earlier study made in this laboratory.[5] The spectrum obtained, shown in Fig. 6, can be extrapolated with considerable confidence, and leads to $Q(Be^8\rightarrow 2He^4)=93.7\pm0.9$ kev. The proton-beam analyzer was calibrated with the 993.3-kev $Al^{27}(p,\gamma)Si^{28}$ resonance, and the spectrometer fluxmeter was calibrated with protons elastically scattered from Al and Be. A Q-value of 559 ± 1 kev[38] was assumed for $Be^9(p,d)Be^8$. The targets were layers of Be, 1–3 kev thick to 1-Mev protons, evaporated on Al foil. Surface contamination corrections were of the order of 0.3 kev for protons and 2.0 kev for alpha particles. The present value of $Q(Be^8-2He^4)$ may be compared with previously reported values of 103 ± 10 kev,[4] 89 ± 5 kev,[5] and 94.5 ± 1.4 kev.[39]

DISCUSSION

The momentum spectrum shown in Figs. 4 and 5 contains alpha particles (designated α_1) resulting from the disintegration $C^{12*}\rightarrow Be^8+He^4+Q_1$, and the subsequently emitted particles (α_2) from the decay of $Be^8\rightarrow 2He^4+Q_2$. Ignoring for the moment the recoil imparted to the C^{12*} nucleus by the β decay, the α_1 particles will constitute a monochromatic group, with $E(\alpha_1)=\frac{2}{3}Q_1$, or momentum $p_0(\alpha_1)=(4Q_1M_\alpha/3)^{\frac{1}{2}}$ (the zero subscript is appended to indicate neglect of the C^{12*} recoil from the B^{12} β decay). The Be^8 nucleus so formed is in motion in the laboratory system, and its velocity will be added to the velocities resulting from the breakup into two alpha particles. On the assumption that the breakup is isotropic, the number of α_2 particles produced with momentum $p(\alpha_2)$ per unit momentum interval is

$$\frac{dN(\alpha_2)}{dp(\alpha_2)}=\frac{2N(\alpha_1)}{(Q_2M_\alpha)^{\frac{1}{2}}}\frac{p(\alpha_2)}{p_0(\alpha_1)},$$

where $N(\alpha_1)$ is the total number of α_1 particles. The limits on $p(\alpha_2)$ are $|(Q_1M_\alpha/3)^{\frac{1}{2}}\pm(Q_2M_\alpha)^{\frac{1}{2}}|$. As will appear below, $Q_1=278$ kev and $Q_2=94$ kev, so the

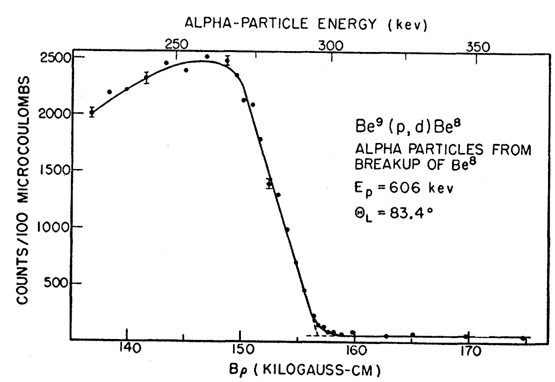

FIG. 6. Momentum spectrum of the alpha particles from the breakup of Be^8. A thin Be layer (3-kev to 1-Mev protons) evaporated on Al foil was bombarded with 606-kev protons. Spectrometer momentum resolution and laboratory angle were $\Delta p/p=1.8\%$ and $\theta_L=83.4°$ respectively.

[38] D. M. Van Patter and Ward Whaling, Rev. Modern Phys. **26**, 402 (1954).

[39] Jones, Donahue, McEllistrem, Douglas, and Richards, Phys. Rev. **91**, 879 (1953).

α_2 distribution has a triangular shape, extended from a minimum $p(\alpha_2)\simeq 0$ to a maximum $p(\alpha_2)\simeq p_0(\alpha_1)$. The predicted thin-source spectrum is shown schematically in Fig. 7(a).

When the β recoil is taken into account, it is found that the α_1 particles are distributed over a range $p_0(\alpha_1)\pm\frac{1}{3}p_{\max}(\beta)$, where $p_{\max}(\beta)$ is the maximum β-particle momentum. Because of the relatively high energy available, 5.7 Mev, this effect is quite appreciable, amounting to a spread of $\pm 5.5\%$ in $p(\alpha_1)$. With the assumption that the β particles and associated neutrinos have a simple Fermi distribution and that the beta-neutrino correlation is characterized by the tensor coupling $(1+\frac{1}{3}\cos\theta)$, the α_1 distribution may be shown to be:

$$\frac{dN(\alpha_1)}{dp(\alpha_1)}=\frac{5}{16p_{\max}(\beta)}\frac{p(\alpha_1)}{p_0(\alpha_1)}(7-6x^2-x^4),\quad -1\leq x\leq 1$$

where $x\equiv 3[p(\alpha_1)-p_0(\alpha_1)]/p_{\max}(\beta)$. In consequence of this distribution, the α_2-particle spectrum is rounded off at the upper limit as indicated in Fig. 7(b). Since there are two α_2 particles for each α_1 particle, the area of the broad distribution is twice that in the α_1 group. It has been tacitly assumed throughout that the C^{12*} and Be^8 decay before slowing down, as would be expected from their lifetimes.

Derivation of the thick-source spectrum requires a knowledge of the distribution of the B^{12} in the target. Although the B^{11} layer is itself only about 75 kev thick to outgoing 200-kev alpha particles, a large fraction of the B^{12} nuclei are actually driven to a considerable depth in the target backing in the course of their formation, thus increasing the escape distance for the alpha particles. In the reaction $B^{11}(d,p)B^{12}$, the bombarding 1.6-Mev deuterons impart a velocity of 1.9×10^8 cm/sec to the center-of-mass of the system, and the ejected protons impart a velocity of 1.8×10^8 cm/sec to the recoiling B^{12}. Combination of these velocities gives the B^{12} nuclei a maximum energy of 860 kev in the forward direction and a minimum energy of 2 kev in the same direction. On the assumption that the angular distribution is isotropic in the center-of-mass system and that the range is proportional to velocity, these recoil effects combine to produce an approximately uniform distribution of B^{12} nuclei with a maximum range of about 1 mg/cm^2 in Ta. Measured in the direction of the emerging alpha particles (83° from the deuteron beam, 22° from the target normal), the depth amounts to about 0.7 mg/cm^2, nearly equal to the range of the maximum-energy α_1 particles. Thus, again under the assumption of a constant rate of momentum loss, a simple integration of the calculated $N(\alpha_1)$ and $N(\alpha_2)$ distribution functions yields the required thick-source spectrum, illustrated in Fig. 7(c).

When the calculated integral spectrum is folded with the known resolution function of the spectrometer, a

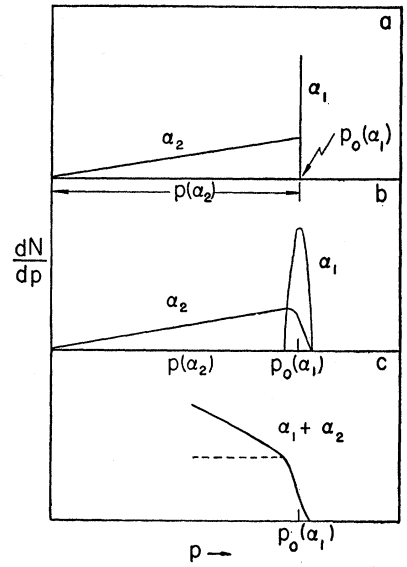

FIG. 7. Predicted momentum spectra of alpha particles from the decay of B^{12}. See text for particle and momentum designations. (a) Thin-source spectrum neglecting C^{12} recoil. (b) Thin-source spectrum with C^{12} recoil. (c) Thick-source spectrum.

final curve is obtained which may be compared with the experimental points. Two such curves, calculated for $Q_1=276$ kev and $Q_1=286$ kev, with $Q_2=94$ kev, are shown in Fig. 5, where it will be seen that the general shape observed is well accounted for, at least in the top 25% of the spectrum. The deviations at lower momenta may result from uncertainty in the charge-exchange corrections or from straggling in energy loss of alpha particles emerging from deep layers in the source. Interpolation between the curves shown in Fig. 5, together with other observations not reproduced here, yields $Q_1=278\pm 4$ kev, or $C^{12*}-C^{12}=7.653\pm 0.008$ Mev. The difference $(C^{12*}-3He^4)$ is given more precisely by $Q_1+Q_2=372\pm 4$ kev.

In the analysis described above, it has been assumed that the alpha-particle emission actually proceeds in two stages, with Be^8 in its ground state as an intermediate product, and the width of the Be^8 state has been neglected. Direct evidence on the latter point is available in the observed small width of particle groups from various reactions leading to the ground state of Be^8: for example, observations made here on the spread of the deuteron group in $Be^9(p,d)Be^8$ permit an upper limit of about 1 kev to be placed on this width. Considerably smaller values, $\lesssim 3.5$ ev[40] and 4.5 ± 3 ev[41] are obtained from analysis of scattering of alpha particles in helium. These values correspond to a mean life of $\sim 2\times 10^{-16}$ sec or more, which is long compared to characteristic nuclear times, a fact which is to be expected on the basis of the small barrier-

[40] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **104**, 123 (1956).
[41] Russell, Phillips, and Reich, Phys. Rev. **104**, 135 (1956).

TABLE I. Expected partial widths for α- and γ-ray transitions for two possible assignments of the 7.65-Mev state of C^{12}.

$J(C^{12*}, 7.65)$	Γ_α max (ev)	Γ_α estimated (ev)	$\Gamma_\gamma(3.22)$ max (sp)[a] (ev)	$\Gamma_\gamma(3.22)$ estimated (ev)	$\Gamma_\gamma(7.65)$ max (sp) (ev)
0^+	$(l_\alpha=0)$		$(0^+\rightarrow 2^+, E2)$		$(0\rightarrow 0$, forbidden$)$
	5	0.5	0.005	0.0014	$\Gamma_{\pm e}\sim 5\times 10^{-5}$ ev[b]
2^+	$(l_\alpha=2)$		$(2^+\rightarrow 2^+, M1)$		$(2^+\rightarrow 0^+, E2)$
	0.1	0.01	0.6	0.1	0.08

[a] (sp) designates single-particle limits for radiation widths: see reference 44.
[b] $\Gamma_{\pm e}$ calculated from $C^{12}(e,e')$; see J. H. Fregeau, Phys. Rev. **104**, 225 (1956); J. R. Oppenheimer and J. S. Schwinger, Phys. Rev. **56**, 1066 (1939).

penetrability factor for two alpha particles with a center-of-mass energy of only 94 kev. We conclude that Be^8 acts essentially like a stable nucleus in "prompt" nuclear transmutations. The front slope of the spectrum of Fig. 5 is consistent with zero width for both the Be^8 and C^{12*} states and places an upper limit of about 10 kev for either.

The possibility that the present results might be equally well explained by a direct three-body disintegration of C^{12} has been given some consideration. In view of the strong electrostatic repulsions, it would be expected that the most probable outcome of such a process would be approximate equipartition of the energy among the three alpha particles, leading to a spectrum peaked more or less sharply at one-third of the energy difference corresponding to $(C^{12*}-3He^4)$. The observed spectrum in this case would exhibit an inflection at this energy, rising to a maximum at a somewhat lower energy, and eventually falling linearly to zero at zero energy. In Fig. 5, the point of inflection occurs at $E_\alpha=180$ kev, leading to a Q-value of 540 kev, clearly inconsistent with previous determinations of the C^{12*} level energy. In addition, the fact that the curve remains approximately level indicates the contribution of just such a lower energy group as α_2 in Fig. 7. We conclude that the present results indicate a two-stage reaction and are inconsistent with a direct three-body process.

Determination of the fraction of B^{12} decays resulting in alpha emission requires, among other things, knowledge of the absolute density of B^{12} nuclei produced in the target. Under the assumptions made earlier with respect to the distribution within the target, the number of B^{12} nuclei per incident deuteron per cm of depth in the target is

$$\rho=n\sigma\sec\phi\frac{\eta(B^{12})}{2p(B^{12})_{\text{c.m.}}},$$

where n is the number of B^{11} nuclei per cm^2, σ the cross section for formation of B^{12}, ϕ the angle of incidence of the deuterons to the target normal, $p(B^{12})_{\text{c.m.}}$ is the momentum of the B^{12} nuclei in the center-of-mass system of the $B^{11}(d,p)B^{12}$ reaction, and $\eta(B^{12})$ is the momentum loss per cm for B^{12} nuclei in tantalum.

Of the B^{12} nuclei produced, only a fraction, f, decay during the counting period: an elementary calculation gives, for the time sequence indicated earlier, $f=0.354$. The number of α_1 particles per incident deuteron which should be observed on the plateau of the thick-target curve is

$$\frac{dN(\alpha_1)}{dp(\alpha_1)}=\frac{x_{\beta\alpha}\rho f\Omega}{4\pi\eta(\alpha)}=x_{\beta\alpha}\left(\frac{n\sigma f\Omega\sec\phi}{8\pi p(B^{12})_{\text{c.m.}}}\right)\left(\frac{\eta(B^{12})}{\eta(\alpha)}\right),$$

where Ω is the solid angle accepted by the spectrometer (0.0063 steradian), $\eta(\alpha)$ is the momentum loss of the α particles per cm in the target, and $x_{\beta\alpha}$ is the branching fraction, relative to all β-decay processes from B^{12}, for those β transitions to the 7.653-Mev level which ultimately result in alpha-particle emission. The quantity $n\sigma$ was directly determined for the target by counting the β rays with a large plastic scintillator; a separate measurement of n by comparing the momentum shift of elastically scattered protons from pure Ta and the Ta-backed target gave $\sigma=0.29\pm0.04$ barn at $E_d=1.65$ Mev, in good agreement with an earlier determination by R. W. Kavanagh[32] at this laboratory.

The experimental value of $dN(\alpha_1)/dp(\alpha_1)$ may be obtained most precisely from the normalization used in fitting the curves of Fig. 5. Using this result in the expression above, one obtains $x_{\beta\alpha}=(1.3\pm0.4)\%$. The major contribution to the uncertainty arises from the ratio $\eta(B^{12})/\eta(\alpha)$, which was taken to be 2.7 ± 0.5 from analysis of the relative stopping of boron nuclei and alpha particles in air and emulsions.[42]

As noted previously, $x_{\beta\alpha}$ is the branching fraction for the $\beta-\alpha$ decays through the 7.653-Mev excited state of C^{12}, relative to all β-decay processes from B^{12}. The C^{12*} state may also decay by gamma-ray emission directly to the ground state (0^+) or by a 3.22-Mev and 4.43-Mev gamma-ray cascade through the $J=2^+$ first excited state of C^{12}. According to Beghian *et al.*,[17] the cascade decay is observed in $Be^9(\alpha,n)C^{12}$, while the direct transition to the ground state is at least 100 times less probable. Independent limits for these modes may be derived from recent studies of the B^{12} decay by Kavanagh[43] who finds, from $\beta\gamma$-coincidence measurements, that $\gamma(7.65)/\beta(\text{total})<10^{-4}$, $\gamma(4.43)/\beta(\text{total})=0.013\pm0.004$ and, from $\gamma\gamma$-coincidence studies, that $\gamma(3.22)/\gamma(4.43)<10^{-2}$. These results are consistent with those of Tanner,[31] Bent *et al.*,[28] Rasmussen *et al.*,[24] and Hornyak.[29] Thus the observed 4.43-Mev gamma rays result almost entirely from direct β transitions to the first excited state of C^{12} and the 3.22-Mev and 7.65-Mev gamma rays occur in at most 10^{-4} of the β decays. For

[42] A. B. Lillie, Phys. Rev. **87**, 716 (1952); D. L. Livesey, Can. J. Phys. **34**, 203 (1956); P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. (London) **A134**, 658 (1932).
[43] R. W. Kavanagh, thesis, California Institute of Technology, 1956 (unpublished) and private communication.

the de-excitation of the 7.653-Mev state in C^{12}, we thus have $\gamma(3.22\text{ Mev})/\alpha \lesssim 10^{-2}$ and $\gamma(7.65\text{ Mev})/\alpha \lesssim 10^{-2}$. Thus, to a good approximation, $x_{\beta\alpha}$ is just the branching ratio of all β decays to the 7.653-Mev state. Using $W_\beta(\max) = E_\beta(\max) + m_0c^2 = 13.376 + 0.511 - 7.653 = 6.234$ Mev and $t_{\frac{1}{2}} = 0.206/0.013 = 1.58$ sec for the effective half-life, one obtains $\log ft = 4.2$ for this transition, placing it clearly in the class of allowed transitions. The corresponding values for the transitions to the ground state and to C^{12*}(4.43 Mev) are $\log ft = 4.1$ and 5.1 respectively. The transition to the ground state is definitely allowed and that to the 4.43-Mev state would seem to be allowed but unfavored or perhaps first-forbidden, but certainly not second-forbidden. The allowed transition to the 0^+ ground state of C^{12} requires that B^{12} have spin and parity 1^+, since a 0^+ to 0^+ transition would violate the isotopic-spin selection rule. The allowed nature of the transition to the 7.653-Mev state then indicates 0^+ or 2^+ for its spin and parity, the 1^+ possibility being ruled out by our observation of the α decay.

The fact that the γ-ray transitions from the 7.653-Mev state are at most 1% of the alpha-particle transitions makes possible a fairly definite choice between the 0^+ and 2^+ assignments for this state. In Table I we list the partial widths expected for the alpha and gamma transitions in the two cases. In these calculations we have taken $R(Be^8+He^4) = 5.3\times10^{-13}$ cm. The maximum widths are given for alpha particles in terms of θ_α^2, the dimensionless reduced width in units of $3\hbar^2/2MR^2$, and for gamma rays in terms of the single-particle values,[44] (sp). The upper limit for θ_α^2 according to Wigner is unity, and a reasonable estimate for the present case is $\theta_\alpha^2 \sim 0.1$. For $M1$ gamma transitions in light nuclei, Wilkinson[45] finds an average of 15% of the single-particle value. The $E2$ transitions can actually be enhanced over the single-particle estimates in the collective nuclear model. However, for the $0^+ \rightarrow 2^+$, 3.22-Mev transition, Ferrell[46] calculates $\Gamma_\gamma = 0.0014$ ev with an error of the order of a factor of two.

Table I shows that for the 0^+ assignment for C^{12*} (7.65), it is reasonable that α decay should exceed either γ decay by a factor of at least 100, whereas for the 2^+ assignment, we would expect the alpha decay and the two γ-ray transitions to be comparable in magnitude. Although $\gamma/\alpha \sim 0.01$ cannot be entirely ruled out for this assignment, still we feel that the evidence rather strongly favors the 0^+ assignment. The fact that the 7.65-Mev radiation has not been observed in other reactions resulting in the production of C^{12*} (7.65 Mev) is strong confirming evidence.

The experiments discussed here have not established definitely that the 7.653-Mev state in C^{12} decays by gamma radiation. This decay has been reported by other workers, however. The inelastic scattering of electrons by C^{12} leading to this state shows that in any case nuclear electron-positron pair emission will transform C^{12*} into C^{12}. As noted above, evidence for these pairs has been reported. The recent failure of Kruse *et al.*[47] to observe pairs is not disturbing since their upper limit is not inconsistent with the decay widths presented in Table I.

CONCLUSION

It has been shown that the second excited state of C^{12} decays into three alpha particles through an intermediate stage involving He^4 and the ground state of Be^8. The general reversibility of nuclear reactions thus leads us to expect C^{12} to be produced in the Salpeter processes:

$$2He^4 \rightleftharpoons Be^8; \quad Be^8(\alpha,\gamma \text{ or } e^\pm)C^{12}.$$

The experiments reported here show that the excitation energy of C^{12*} is 7.653 ± 0.008 Mev, that $Q(C^{12*}-Be^8-He^4) = 278\pm4$ kev, $Q(C^{12*}-3He^4) = 372 \pm 4$ kev, and that the most probable spin and parity assignments for this state are $J = 0^+$. It would thus appear that this state does indeed play a dominant role in the synthesis of elements from helium as predicted by Hoyle. The reaction rate of the conversion of helium into carbon is

$$p = 2.37\times10^{-4}(\rho x_\alpha)^2 \frac{\Gamma_\gamma}{T_8{}^3} \exp\left(-\frac{43.2}{T_8}\right) \text{sec}^{-1},$$

where $\Gamma_\gamma \sim 0.0014$ ev. If the gamma radiation is highly forbidden, then Γ_γ must be replaced by $\Gamma_{\pm e} \sim 5\times10^{-5}$ ev. Further examination of the implications for astrophysics are made in the following article by Salpeter.

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[44] S. A. Moszkowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955).

[45] D. H. Wilkinson, Atomic Energy of Canada Limited Report PD-260, Chalk River, Canada, 1955 (unpublished).

[46] R. A. Ferrell (private communication).

[47] Kruse, Bent, and Eklund, Bull. Am. Phys. Soc. Ser. II, **2**, 29 (1957).

[48] Fowler, Cook, Lauritsen, Lauritsen, and Mozer, Bull. Am. Phys. Soc. Ser. II, **1**, 191 (1956).