# Studies of Alpha-Particle Emitting States of $C^{12}$ Observed in the Reactions $B^{10}(He^3, p)C^{12}(\alpha)Be^8$ and $C^{13}(He^3, \alpha)C^{12}(\alpha)Be^8$†

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## I. INTRODUCTION

The main purpose of the present experiments was to try to detect alpha-particle emission from the $C^{12}$ 15.1-MeV 1+ energy level which is well established as being the first $T=1$ state in $C^{12}$. The observation of such alpha-particle decay would be a measure of the degree of violation of the isotopic-spin selection rule according to which the decay to $Be^8$ is forbidden. It is well known[1] that, although the 15.1-MeV state is unstable against alpha-particle emission by about 8 MeV, the level decays predominantly by gamma-ray emission to the $C^{12}$ ground state with a gamma-ray branch of $\sim 3\%$ to the 4.43-MeV level. Since the spin-parity of the 15.1-MeV level is 1+ the alpha-particle decay to the 0+ ground state of $Be^8$ is forbidden by the selection rules for states of "unnatural" parity. Hence, if an isotopic-spin-violating alpha-particle branch were to occur it would presumably take place to the broad 2.9-MeV 2+ first excited state of $Be^8$.

Some of the previous attempts[1] to establish an alpha-particle branch from the 15.1-MeV state have consisted of measuring $\Gamma_\gamma/\Gamma$ in order to see if this quantity is significantly less than unity. However, for small values of $\Gamma_\alpha/\Gamma$ this method is not very sensitive. The alternate approach of searching directly for the alpha particles coming from the 15.1-MeV state is complicated by the presence of neighboring $C^{12}$ levels, all of which decay predominantly by alpha-particle emission, and in some cases by the presence of alpha-particle continua due to competing reactions. In an experiment on the $B^{10}(He^3, p)C^{12}(\alpha)Be^8$ reaction Miller, Pixley, and Segel[2] searched for $(p, \alpha)$ coincidences involving the 15.1-MeV state of $C^{12}$. Their limit of $\Gamma_\alpha/\Gamma<0.2$ appears to be the lowest obtained previously.

It was felt that a more sensitive search for alpha-particle emission from the 15.1-MeV state could be made by using techniques of two-dimensional pulse-height analysis. This paper reports the results of such searches when exciting the 15.1-MeV state in two different nuclear reactions.

## II. EXPERIMENTAL PROCEDURES AND RESULTS

In both sets of experiments use was made of a conventional bombardment chamber having a beam-collimating system, a rotatable target-mounting post at the center and two rotatable arms which hold the counter and slit assemblies. Silicon solid-state detectors were used for detecting the particles. Their outputs were amplified and fed to a TMC 128×128-channel pulse-height analyzer and also to a coincidence circuit which gated the analyzer.

As an aid in establishing the positions of peaks corresponding to the populations of the 4.43, 12.7, and 15.1-MeV gamma-ray emitting levels of $C^{12}$ (and in establishing their relative population intensities) runs were made on coincidences between the outputs of one of the particle detectors and a 5-×5-in. NaI gamma-ray counter placed on top of the chamber.

The interpretations of the various particle–particle coincidence spectra were aided by an SDS-910 computer which was programmed to calculate and display the loci of coincidence events corresponding to the population of $C^{12}$ states followed by decay to either the ground or the 2.9-MeV level of $Be^8$.

### A. The $B^{10}(He^3, p)C^{12}(\alpha)Be^8$ Reaction

This reaction was studied by using a 50-$\mu$g/cm²-thick self-supporting $B^{10}$ foil target and a $He^3$ beam energy of 2.0 MeV. The detector used for protons had a sensitive thickness of 2 mm and it was covered with an 18 mg/cm² thick Al absorber in order to exclude alpha particles. Generally the tantalum slits in front of both detectors were 3 mm wide, 9 mm high and at a distance of 1.2–1.5 cm from the target. A 1-mm-diam beam was used in all cases.

Figure 1 shows the results of a 22-h run at a beam current of 0.04 $\mu$A. The curving diagonal line at the outer limit of the coincidence distribution corresponds to the locus of $Be^8{}_{gnd}$ $(p, \alpha)$ coincidences. It is consistent in shape and position with the calculation by the SDS-

† Research carried out under the auspices of the U. S. Atomic Energy Commission.

[1] For a summary of the evidence see F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1951).

[2] G. L. Miller, R. E. Pixley, and R. E. Segel, Proc. Roy. Soc. (London) **A259**, 275 (1960).

910 computer. When the yield summed across this line in the $y$, or $\alpha$ direction is plotted versus proton energy the open-circle curve in Fig. 2 results. The broad ridge in Fig. 1 roughly parallel to the ground-state line corresponds to $Be^8{}_{2.9}$. When the $\alpha$-integrated yield across it is plotted versus proton channel, the curve with solid points in Fig. 2 results One may note the short diagonal line near the origin in Fig. 1 which corresponds to $(p, p)$ coincidences resulting from the proton decay of high-lying $C^{12}$ states to $B^{11}$.

### B. The $C^{13}(He^3, \alpha)C^{12}(\alpha)Be$: Reaction

The target used for these experiments was a thin self-supporting carbon foil[3] enriched to $\sim 65\%$ $C^{13}$. No absorbers were used in front of the detectors and in this case there was the additional complication of duplicity in the coincidence pattern. A partial simplification was achieved by using one detector in relatively good geometry and the other in poor geometry so as to enhance the effect of summing in the latter detector of the alpha particle leading to the $Be^8{}_{2.9}$ state plus one of the decay particles from the breakup of the 2.9-MeV state.

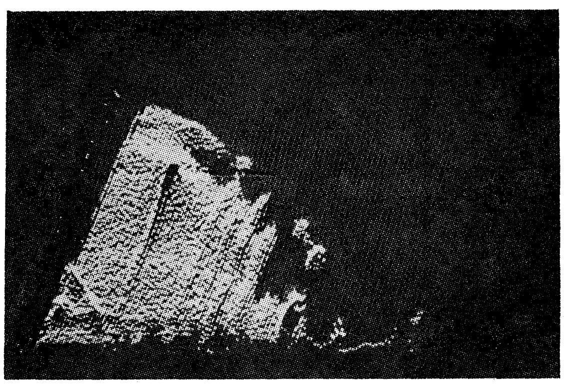

FIG. 1. Isometric display on a TMC 128×128-channel pulse-height analyzer of the reaction $B^{10}(He^3, p)C^{12}(\alpha)Be^8$ using two silicon counters to observe protons ($x$ axis) and alpha particles ($y$ axis). The origin is at the lower left corner. Dector angles were $\theta_p = 70°$ and $\theta_\alpha = -90°$.

Figure 3 shows one of the runs made on this reaction (0.01 $\mu$A for 17 h at $E_{He^3} = 3.0$ MeV). The most outstanding feature of the spectrum is the strong line parallel to the $y$ axis (its weaker complement parallel to the $x$ axis may also be seen) which corresponds to the population of the $C^{12}$ 12.7-MeV state followed by decay to $Be^8{}_{2.9}$.

A plot parallel to the $y$ axis taken at $x$-channel number 44 corresponding to the 12.7-MeV peak shows that three broad peaks are present. The middle one corresponds to the detection of alpha particles from the 12.7-MeV state populating the $Be^8{}_{2.9}$ state; the higher peak is presumably the summing of the populating alpha

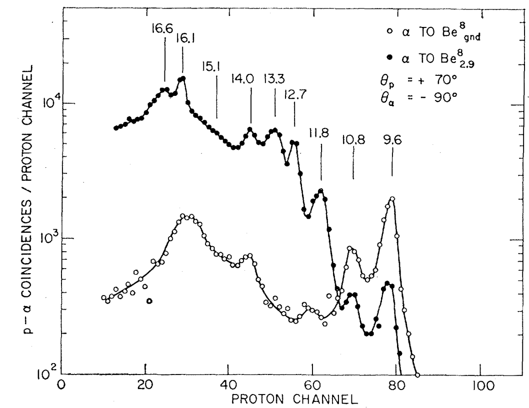


FIG. 2. Open circles—yield of $(p, \alpha)$ coincidences, from data of Fig. 1, integrated across the $Be^8{}_{gnd}$ line in the $y$, or $\alpha$ direction, and plotted against proton channel number. Solid points—yield $(p, \alpha)$ coincidences integrated across the broad $Be^8{}_{2.9}$ ridge and plotted versus proton channel number.

particles plus one of the break-up alphas from the $Be^8{}_{2.9}$ level; and the lower energy peak probably results from detection of the $Be^8{}_{2.9}$ break-up alpha alone. Gamma-ray coincidence runs showed that the 15.1/12.7 population ratio was $\sim 0.6$, allowing for the known value of $\Gamma_\alpha/\Gamma$ for the 12.7-MeV level. Plots of the data of Fig. 3 were made similar to the procedure used for Fig. 2.

## ANALYSIS AND DISCUSSION

An inspection of Fig. 2 shows that the $Be^8{}_{gnd}$ spectrum contains peaks corresponding to the 9.63-, 10.8-, and 14.1-MeV levels $C^{12}$. The broad peak centered at channel 30 may result from the reaction $B^{10}(He^3, \alpha)B^9(p)Be^8$ but the origin of the weak peak at channel 60 is not known. Peaks in the $Be^8{}_{2.9}$ spectrum correspond to the 11.8-, 12.7-, 13.3-, 14.1-, 16.1, and 16.6-MeV $C^{12}$ states. The 9.63 and 10.8-MeV peaks in the latter spec-

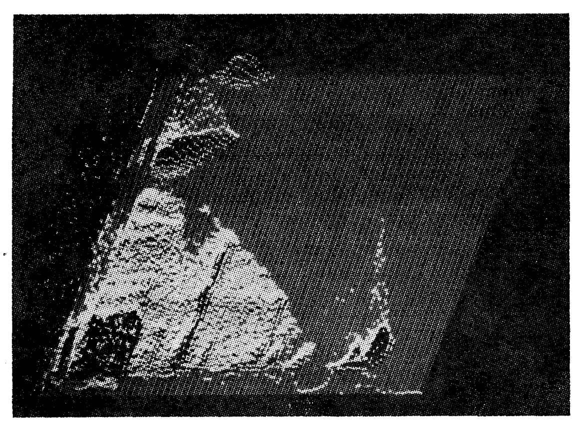

FIG. 3. Isometric display on the TMC analyzer of the reaction $C^{13}(He^3, \alpha)C^{12}(\alpha)Be^8$ using two silicon detectors. The $x$-axis counter was at 60° with a 3-mm-wide slit at 2.0 cm from the target and the $y$-axis counter was at 90° with a 5-mm-wide slit at 1.0 cm from the target.

[3] The authors are indebted to L. F. Chase, Jr., for providing the target material.

trum are due mainly to random coincidences. One may deduce from these data that the 9.63, 10.8, and 14.1-MeV states must have "natural" parity since they decay to the $Be^8_{gnd}$ state and that "unnatural" parity is indicated for the 11.8, 12.7, and 13.3-MeV states since the latter show no evidence for alpha decay to the $Be^8_{gnd}$ state.

On the $Be^8_{2.9}$ curve in Fig. 2 the region corresponding to the 15.1-MeV $C^{12}$ level shows no evidence for a peak. Based on the population intensity, as obtained from $(p, \gamma)$ coincidence runs, the upper limit on a peak in Fig. 2 corresponds to the limit $\Gamma_\alpha/\Gamma<0.05$ for the 15.1-MeV level.

Similar analyses of two runs at different angles on the $C^{13}+He^3$ reaction also lead to $\Gamma_\alpha/\Gamma<0.05$ for the 15.1-MeV state.

The experiments which we have carried out have not been sensitive enough to find the isotopic-spin-violating alpha-particle decay of the 15.1-MeV of $C^{12}$, although our limit on this decay mode is sharper than any previously reported.

## Discussion

DONOVAN: I would just like to point out that this experiment measures not only the isotopic spin purtiy of the 15.1 state in carbon, but also the isotopic spin purity of the region of $Be^8$ that it might decay to. Since the transition has not been seen, the width of that level for alpha decay is much less than the gamma width, or at most a few volts. This certainly indicates an extreme isotopic spin purity in the region of the 2+ level of $Be^8$, which was a point of earlier contention.

HOLMGREN: Your comment that the broad peak on the $Be^8$ ground-state kinematic curve might be due to the $B^{10}(He, \alpha)B^9$ reaction is indeed correct. The reaction proceeds through the 2.8-MeV state of $B^9$. This state appears to decay primarily by proton emission to the ground state of $Be^8$; whereas, the narrower state at 2.34-MeV decays primarily by alpha emission to the ground state of $Li^5$. Evidence for these decay modes can be seen in the figures of the paper by Etter *et al.* (p. 444).

ALBURGER: We did confirm that that broad bump didn't have anything to do with $C^{12}$ levels, because it didn't move in the right way.

HOLMGREN: We have looked at it in detail and it does shift as a level of $B^9$.

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# Direct Three-Body Decay $^{12}C\rightarrow 3\alpha$ in the Reaction $^{11}B(p, \alpha)2\alpha$ at the 163-keV Resonance

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It has been shown, that in the plane perpendicular to the proton beam the $\alpha$-particle spectrum and the $\alpha$–$\alpha$ coincidence spectra reveal a strong anomaly at the well-known 163-keV resonance of the reaction $^{11}B(p, \alpha)$.[1] Therefore a detailed study of the reaction was felt necessary, especially to look for the dependence of the observed anomaly on the incident proton energy.

The 200-keV Cockcroft–Walton accelerator of the Physikalisches Institut der Universitaet Marburg was used. At proton energies of less than 200 keV, the reaction $^{11}B(p, \alpha)$ can proceed via three reaction channels:

$$\begin{aligned} &\qquad\qquad \alpha_0+Be^8(\text{g.s.})\rightarrow\alpha_0+\alpha_{01}+\alpha_{02} && \text{(I)}\\ &\qquad\quad\nearrow\\ &{}^{11}B+p\rightarrow{}^{12}C^*\rightarrow\alpha_1+Be^{8*}(2.9\text{ MeV})\rightarrow\alpha_1+\alpha_{11}+\alpha_{12} && \text{(II)}\\ &\qquad\quad\searrow\\ &\qquad\qquad 3\alpha. && \text{(III)}\end{aligned}$$

The total cross section for the $(p, \alpha)$ reaction in the energy range below 200 keV has the following shape. Superimposed to the tails of two higher resonances at 675 keV ($\Gamma=295$ keV) and at 1388 keV ($\Gamma=1160$ keV) is the sharp resonance at 163 keV ($\Gamma=5.8$ keV). These three resonances indicate states in $^{12}C$ at excitation energies of 16.1 MeV ($J^\pi=2^+$, $T=1$), 16.57 MeV ($J^\pi=2^-$, $T=1$), and of 17.23 MeV ($J^\pi=1$, $T=1$). Because the 163-keV resonance is very sharp, the cross section below 150 keV and above 190 keV can be attributed almost completely to the tails of the other two resonances. Using a very thin target (in which 200-keV protons lose about 4 keV), one is able to reduce the contribution of the higher resonances at 163 keV to about 15%. On the other hand, taking the same target at 200 keV one may reduce the contribution of the 163-keV resonance to about 10%. Below the resonance a target of 50-keV thickness has been used, thus integrating the tails of the cross sections of the 675-keV and the 1388-keV resonances.

Five surface-barrier detectors have been used.[2] One of these counters could be moved to any point of a

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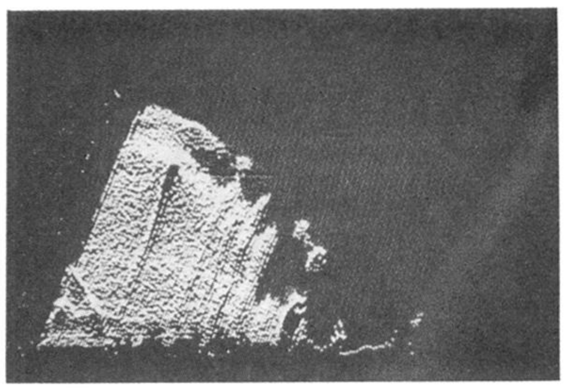
[1] D. Dehnhard, D. Kamke, and P. Kramer, *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Birks (Heywood and Company, Ltd. London, 1961), p. 821; Phys. Letters **3**, 52 (1962); Ann. Physik **14**, 201 (1964).

[2] D. Dehnhard and P. Kramer, Nucl. Instr. Methods **26**, 337 (1964).



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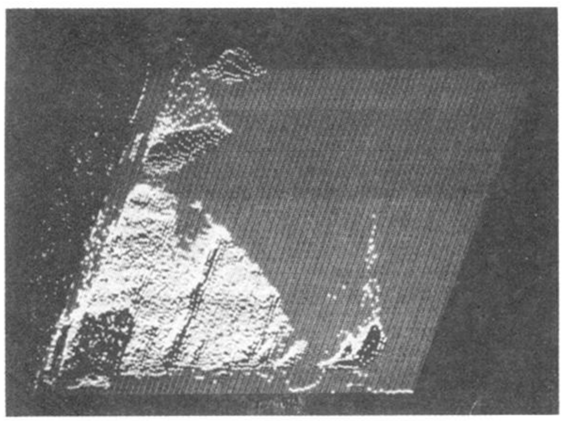

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