near the high-frequency limit is very similar to that for photons well below the limit as is expected from the calculations for high-Z elements. The distribution, however, is dominated by multiple scattering to such an extent that it does not reveal very well the narrower intrinsic distribution near the threshold. No attempt is made to determine the basic angular distributions. It would be desirable to extend these measurements to include thin-target angular distributions from light as well as heavy elements.

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Gamma Rays from the $Be^9(\alpha,n_1)C^{12}$ Reaction*

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The excitation function of the 4.43-MeV gamma ray from the $Be^9(\alpha,n_1\gamma_{4.43})C^{12}$ reaction has been studied and angular distributions have been measured at 13 alpha-particle energies from 3.6 to 7.6 MeV in an effort to determine compound nucleus nature of the $Be^9+\alpha$ system. Many broad resonances are found in the energy region studied.

INTRODUCTION

The $Be^9(\alpha,n)$ reaction is of current interest to many investigators because of the possibility of a successful description of the reaction mechanism as a direct process. The applicability of a direct interaction theory depends on the amount of compound nucleus contribution in the reaction amplitude. We have studied the resonance structure of one exit channel of the $Be^9+\alpha$ system by observing the 4.43-MeV gamma ray emitted in the de-excitation of the C^{12} first excited state. This reaction has been studied extensively below 5.3 MeV,[1] and (n,γ) angular correlations have been measured at $E_\alpha=3.35$ MeV[2] and 5.35 MeV.[3] These results have yielded information about possible reaction mechanisms.

In the present work the excitation function of the 4.43-MeV gamma ray is extended to $E_\alpha=10$ MeV. The $Be^9(\alpha,n,\gamma_{4.43})C^{12}$ reaction cross section decreases rapidly above 5.5 MeV in contrast to the previously reported rise in the total neutron cross section.[4] Reactions other than those leading to C^{12*} which can contribute to the increasing neutron yield are:

$$\begin{aligned} Be^9+\alpha &\rightarrow Be^8+\alpha+n, && (1)\\ &\rightarrow Be^9+\alpha \rightarrow Be^8+n+\alpha, && (2)\\ &\rightarrow Be^8+He^5 \rightarrow Be^8+\alpha+n, && (3)\\ &\rightarrow 3\alpha+n. && (4)\end{aligned}$$

These reactions will produce a low-energy continuum of neutrons. Such a low-energy neutron group was first observed by Auger[5] in 1933 in a study of neutrons from a Po-Be source. A few years later Bjerge[6] established that these slow neutrons were not accompanied by gamma rays. The results from these experiments were questioned,[7] and only recently has the existence of the low-energy neutrons been confirmed by Romain *et al.*[8] and by the present work in conjunction with previous results. At higher bombarding energies a neutron continuum has been observed by Nilsson and Kjellman.[9]

EXPERIMENTAL PROCEDURE AND RESULTS

The alpha-particle beam[10] of the Florida State University Tandem Van de Graaff Accelerator was used to bombard a thin beryllium target prepared by vacuum

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evaporation of beryllium onto a 0.005-in.-thick gold foil. The gamma rays were detected and analyzed by means of two 3-in. by 3-in. NaI(Tl) crystals on photomultipliers and suitably amplified pulses were sorted in a 256-channel pulse-height analyzer. The crystals subtended a half angle of about 15° at the center of the target. The spectrum of the 4.43-MeV gamma ray from a Po-Be neutron source provided an energy calibration. With the tandem accelerator it is possible to obtain alpha particles with energies up to 19 MeV. However, an appreciable yield of gamma rays from the oxygen and carbon contaminants in the target and the encroachment of the neutron background on the pulse-height region of interest precluded an effective investigation of the Be^9(α,$n\gamma_{4.43}$) reaction above a bombarding energy of about 10 MeV.

The 4.43-MeV gamma-ray excitation function measured at 0° and 90° and from $E_\alpha = 3.4$ to 10.1 MeV is shown in Fig. 1. Data in the region below $E_\alpha = 5.3$ MeV were obtained previously by Bonner *et al.*[1] The two sets of data are in good relative agreement in the region of overlap. The absolute cross section indicated in Fig. 1 is that obtained by Bonner *et al.*[1] In addition to the known resonance at $E_\alpha = 3.98$ MeV, there is a very broad resonance like structure at about 5 MeV with a width of about 2 MeV. The resonances in the region of 7.9 to 10 MeV are due to inelastic scattering from the carbon contaminate in the target.[10] The yield from this reaction is too small to give observable effects below $E_\alpha = 7.7$ MeV.[10,11]

In an effort to obtain information regarding the nature of the broad structure, gamma-ray angular distributions were measured at thirteen bombarding energies (indicated by arrows in Fig. 1) between 3.3 and 7.6 MeV (Fig. 2). The data were fitted by the method of least squares to an even order Legendre polynomial series truncated at $P_4(\cos\theta)$. The least-square coefficients have been corrected for the finite detector size and are plotted as a function of bombarding energy in Fig. 3.

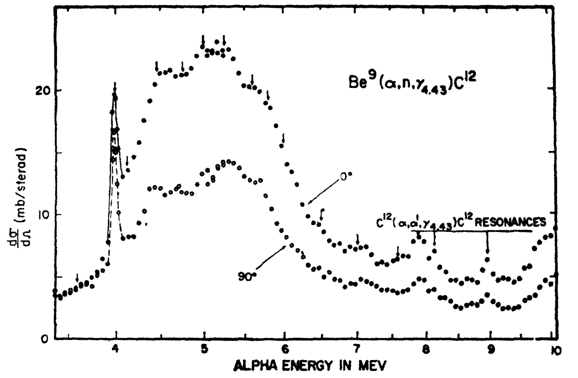

FIG. 1. Excitation curve for the Be^9(α,$n_1\gamma_{4.43}$)C^{12} reaction. The cross-section scale is that of Bonner *et al.* (see reference 1). Arrows indicate the bombarding energies at which angular distributions were measured. Above 7.3 MeV, several peaks due to a carbon contaminant are identified.

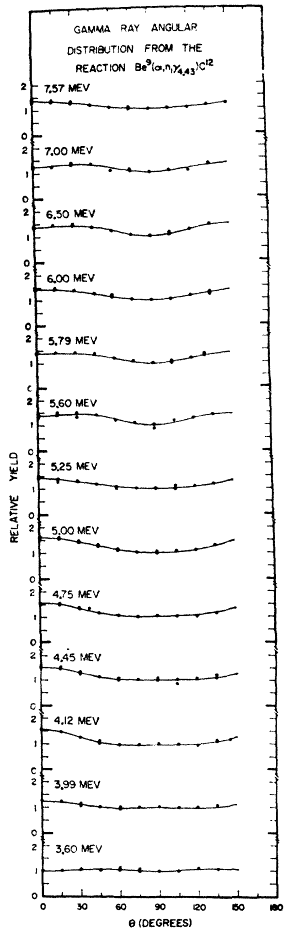

FIG. 2. Angular distributions of the 4.43-MeV gamma ray. The bombarding energies are located by the arrows in Fig. 1.

DISCUSSION

The total neutron yield from the Be^9+α reactions has been measured from $E_\alpha = 2$ to 5.3 MeV by Bonner *et al.*[1] and from 2.58 to 8.2 MeV by Gibbons and Macklin.[4] Up to about 5 MeV the neutron yield shows a close correspondence to the 4.43-MeV gamma-ray yield. Beyond this point the total neutron yield continues to increase whereas the gamma-ray yield decreases nearly monotonically up to $E_\alpha = 10$ MeV.

From early Po-Be source studies it is known that at $E_\alpha = 5.3$ MeV the Be^9(α,n)C^{12} reaction proceeds primarily through the first excited state of C^{12}. The population ratio of the first and second excited states of carbon has a nearly constant value of 10:1 between $E_\alpha = 5.5$ and 6.0 MeV.[12,13] Therefore, above $E_\alpha = 5.3$ MeV the decreasing yield of the 4.43-MeV gamma ray suggests that the increase in neutron yield is not

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associated with either the ground state or the first two excited states of C^{12}. Below a bombarding energy of about 5.7 MeV these are the only states of C^{12} which are energetically possible. Therefore, between 5.3 and 5.7 MeV the increasing neutron yield must be the result of reactions given by Eqs. (1), (2), (3), and (4).

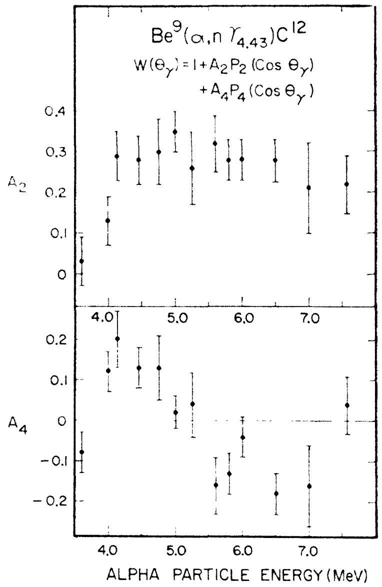

FIG. 3. A plot of the angular distribution coefficients as a function of bombarding energy.

As suggested in the interpretation of the total neutron yield of Gibbons and Macklin,[4] the region near the broad structure at 5 MeV (Fig. 1) may be interpreted as several broad overlapping resonances. Alternatively, several resonances with widths narrow compared with 2 MeV may be superimposed on one large resonance. The trend of the angular distribution coefficients, especially A_4 in Fig. 3, changes over an energy interval of several MeV, about the width of the gross structure in the excitation curve at 5 MeV. Detailed structure in the excitation curve and fluctuations in the angular distribution coefficients identify several closely spaced, possibly overlapping resonances, and, consequently, the trend in the coefficients may be either a multilevel or single level effect. All of the angular distributions of the 4.43-MeV gamma ray are symmetric about an axis 90° from the beam direction. The resonance energies as observed by several investigators and the corresponding excited state energies in C^{13} are listed in Table I.

TABLE I. Energy levels in C^{13}.

E_α (MeV)				E_{ex} (MeV)
a	b	c	d	d
3.98	4.00	4.00	3.98	13.41
4.4	4.50	4.25	4.45	13.73
5.0	5.0	4.95	5.00	14.11
		5.3	5.3	14.3
	5.75	5.7	5.7	14.6
			(7.1)	15.6
	7.8		7.7	16.0

[a] Bonner *et al.*, reference 1.
[b] Gibbons and Macklin, reference 4.
[c] Romain *et al.*, reference 8.
[d] Present work: Be$(\alpha,n_1\gamma_{4,43})$C^{12}.

In view of the complex structure of the Be$^9(\alpha,n_1)$ reaction cross section it is unlikely that a simple direct process is the dominant mode of interaction. An effective comparison between experimental gamma-ray angular distributions and the calculated distributions following compound nucleus formation is prohibited by our uncertain knowledge of the many channel spin mixtures involved and the many interfering levels.