Title	$^{11}B(p, a)\ ^{8}Be(a)\ ^{4}He$ Reaction at 7.3 MeV (Memorial Issue Dedicated to the Late Professor Yoshiaki Uemura)
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Citation	Bulletin of the Institute for Chemical Research, Kyoto University (1974), 52(1): 218-226
Issue Date	1974-07-25
URL	http://hdl.handle.net/2433/76526
Right	
Type	Departmental Bulletin Paper
Textversion	publisher

Bull. Inst. Chem. Res., Kyoto Univ., Vol. 52, No. 1

$^{11}B(p, \alpha)^8Be(\alpha)^4He$ Reaction at 7.3 MeV

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Received January 8, 1974

Angular distributions of the first emitted alpha particles and angular correlations between the firstand the second emitted alpha particles were measured. These angular distributions and correlations were analyzed on the basis of the compound nucleus process. The spin of 2 is assigned favorably to the compound nuclear state of ^{12}C formed in the reaction.

I. INTRODUCTION

The nuclear reaction resulting in three particles in the final state is useful to obtain informations about nuclear states and reaction mechanisms. If this reaction proceeds via a sequential breakup process, the spin and parity of the compound nuclear state formed in the first stage can be determined by measuring angular correlations between the first emitted particle and the second emitted particle.

In the present experiment, angular distributions for the $^{11}B(p, \alpha)^8Be$ reaction were measured in the first stage and then, in the second stage, angular correlations for the $^{11}B(p, \alpha)^8Be(\alpha)^4He$ reaction were measured. An ambiguity in determining the parity of the compound nuclear state remained in the first stage experiment could be removed by analyzing the data in the second stage experiment. It is also noted about deviations of obtained angular correlations from calculated ones.

II. EXPERIMENTAL PROCEDURE

The 7.3 MeV proton beam from the Kyoto University 105 cm cyclotron was brought into a scattering chamber designed for correlation experiment. A self supported target of ^{11}B of about 0.35 mg/cm^2 thick was prepared from metallic powder of 98.5% enriched ^{11}B isotope.

In the measurement of the angular distribution, a solid state detector of 100 μ thick was used to detect alpha particles from the $^{11}B(p, \alpha)^8Be$ reaction. The detection angle varied from 20° to 160° in 10° steps in the laboratory system.

In the measurement of the angular correlation, two solid state detectors were used

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to detect two alpha particles in coincidence from the $^{11}B+p\rightarrow 3\alpha$ reaction. A detector of 100 μ thick was mounted on the bow shaped arm in the scattering chamber and the detection angle was fixed at 53° or 112° in the laboratory system. These angles were 60° and 120° in the center of mass system, respectively. These angles corresponded to the first and the second maxima in the angular distribution for the $^{11}B(p, \alpha)^8Be(2.9)$ reaction, respectively. Another detector of 50 μ thick was set on the turn table and the detection angles varied in several degrees steps in the reaction plane from 60° to 148° when the fixed detector was set at 53° and from 20° to 89° when the fixed detector was set at 112°.

The electronic system was the same as reported elsewhere.[1]

III. EXPERIMENTAL RESULTS

In the first stage, the $^{11}B(p, \alpha)^8Be$ reaction was studied with the single detector method. Figure 1 shows a typical energy spectrum of alpha particles from the $^{11}B(p, \alpha)^8Be$ reaction. A sharp peak in the spectrum corresponds to the ground state of ^8Be and a broad peak corresponds to the first excited state of ^8Be. Angular distributions of alpha particles leaving ^8Be in the ground and the first excited states are shown in Figs. 2 and 3,

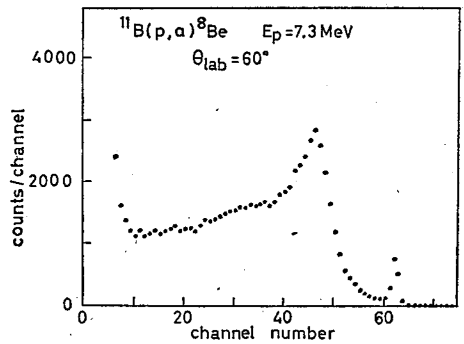

Fig. 1. Energy spectrum of alpha particles from the $^{11}B(p, \alpha)^8Be$ reaction.

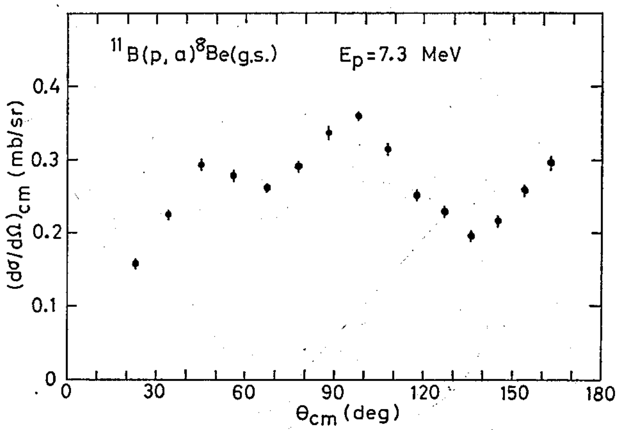

Fig. 2. Angular distribution of alpha particles from the $^{11}B(p, \alpha)^8Be$ (g.s.) reaction.

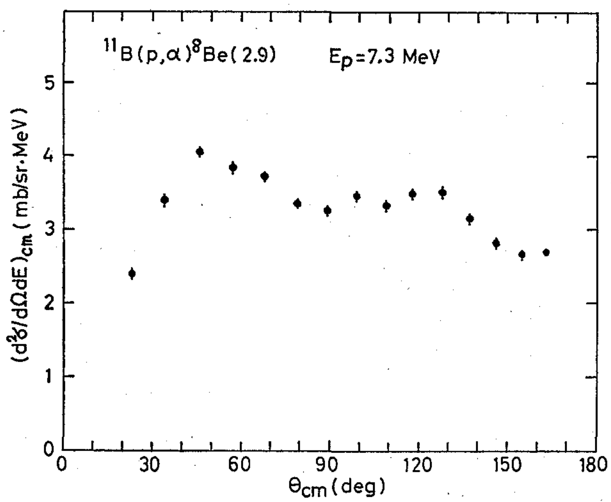

Fig. 3. Angular distribution of alpha particles from the $^{11}B(p, \alpha)^8Be$ (2.9) reaction.

respectively. The differential cross section for the first excited state of ^8Be was obtained from the yield fallen into the energy width of 0.5 MeV around the peak energy. The error bars in the figure represent statistical errors only.

In the second stage, the $^{11}B+p\rightarrow3\alpha$ reaction was studied with the $\alpha-\alpha$ coincidence method. Among two alpha particles detected in coincidence, one alpha particle detected with the fixed detector placed at the angle θ_1^{lab} is designated as α_1 and the other detected with the moving detector placed at the angle θ_2^{lab} as α_2. The third alpha particle, undetected, is designated as α_3. E_1 and E_2 are the energies of α_1 and α_2 respectively. Angles used in the present experiment are defined as shown in Fig. 4.

Figure 5 shows a typical coincidence energy spectrum of alpha particles from the $^{11}B+p\rightarrow3\alpha$ reaction together with energy spectra projected onto the E_1 and E_2 axes,

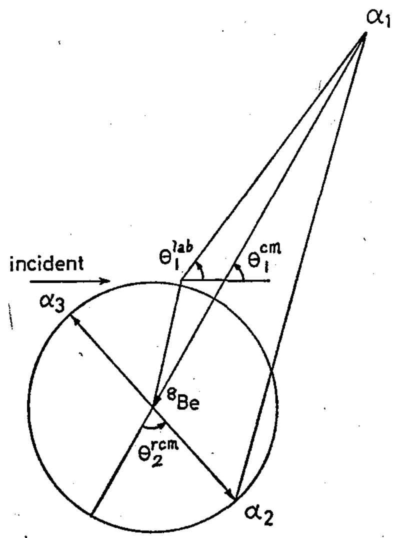

Fig. 4. Definition of angles used in the text.

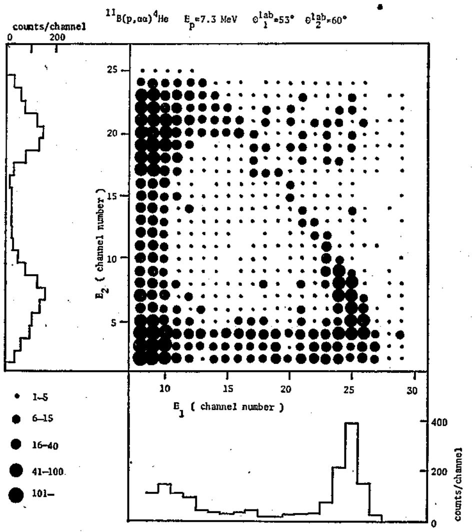

Fig. 5. Coincidence energy spectrum of alpha particles from the $^{11}B+p\rightarrow 3\alpha$ reaction. Histograms below and left represent the energy spectra projected onto the E_1 and E_2 axes.

respectively. In the projected spectra, the ordinate represents the count of events after the background subtraction. The background counts were estimated from the yield out of the locus of $\alpha-\alpha$ coincidence events. The background subtraction was necessary only in the domain where either E_1 or E_2 was lower than about 4 MeV. In the energy spectrum projected onto the E_1 axis, a peak at higher energy side corresponds to $E_{23}=3.0$ MeV and another peak at lower energy side corresponds to $E_{13}=3.0$ MeV, where E_{ij} is the relative energy between α_i and α_j.

Then, energy spectra projected onto the E_1 axis, are plotted against θ_2^{lab} for each fixed angle θ_1^{lab} as shown in Figs. 6 and 7. Figure 6 is for $\theta_1^{lab}=53°$ and Fig. 7 is for $\theta_1^{lab}=112°$. In these figures, peaks appear just on the loci corresponding to $E_{23}=$

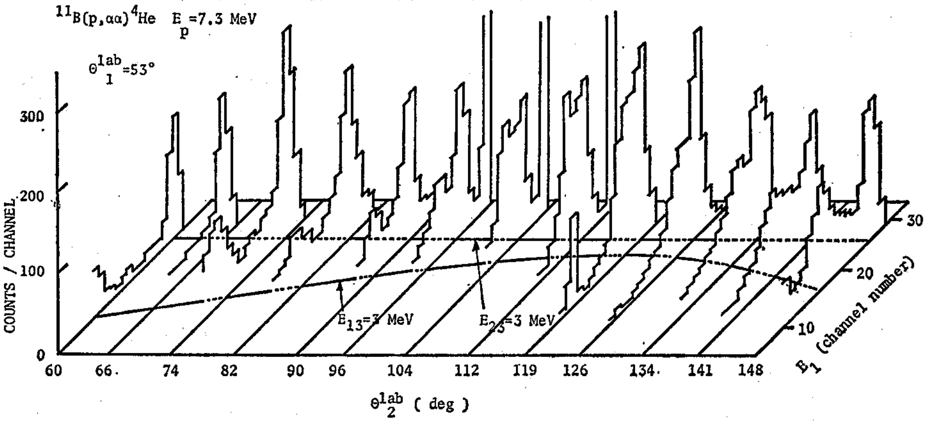

Fig. 6. Plot of coincidence energy spectra against θ_2^{lab} for $\theta_1^{lab}=53°$. The straight and curved lines represent the calculated loci corresponding $E_{23}=3.0$ MeV and $E_{13}=3.0$ MeV, respectively.

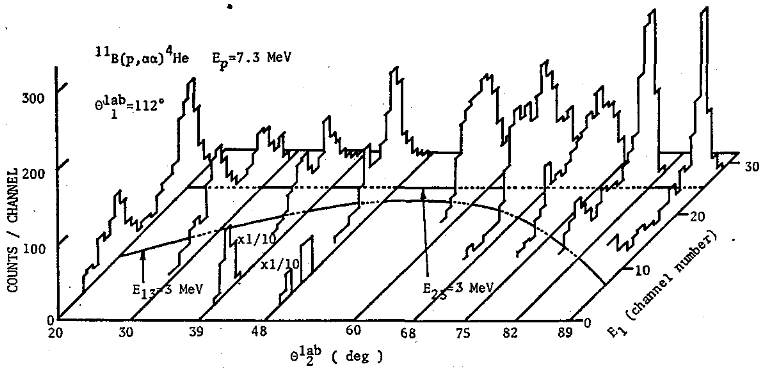

Fig. 7. Plot of coincidence energy spectra against θ_2^{lab} for $\theta_1^{lab}=112°$. The straight and curved lines represent the calculated loci corresponding $E_{23}=3.0$ MeV and $E_{13}=3.0$ MeV, respectively.

3.0 MeV and $E_{13}=3.0$ MeV. Sharp peaks corresponding to $E_{23}=0.1$ MeV or $E_{13}=0.1$ MeV also appear at angles around $\theta_2^{lab}=110°$ in Fig. 6 and around $\theta_2^{lab}=50°$ in Fig. 7. The energy states $E_{ij}=0.1$ MeV and $E_{ij}=3.0$ MeV correspond to the ground and the first excited states of ^{8}Be, respectively.

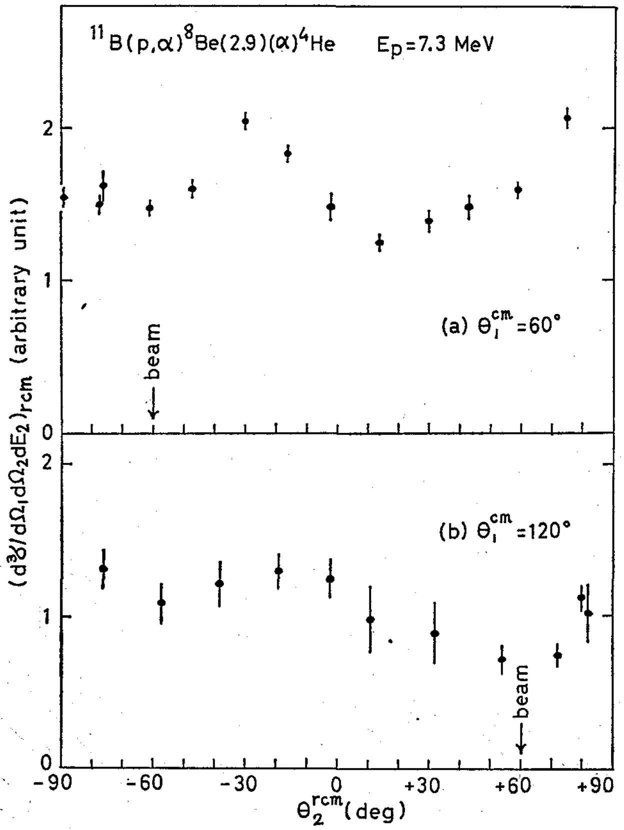

Fig. 8. Angular correlations between α_1 and α_2 for the process corresponding to $E_{23}=3.0$ MeV for $\theta_1^{cm}=60°$ (a) and $\theta_1^{cm}=120°$ (b). The abscissa θ_2^{rcm} represents the angle of emission of α_2 on the reaction plane in the recoil center of mass system. Arrows indicate the direction of the incident proton beam.

Angular correlations between α_1 and α_2 for the processes corresponding to $E_{23}=$ 3.0 MeV for $\theta_1^{cm}=60°$ and 120° are shown in Figs. 8(a) and 8(b), respectively. The abscissa θ_2^{rcm} represents the angle of emission of α_2 on the reaction plane in the recoil center of mass system. The direction $\theta_2^{rcm}=0°$ represents the direction of velocity of the composite $\alpha_2-\alpha_3$ system in the center of mass system. The differential cross sections are deduced from the yields in the energy width of 0.4 MeV around the peaks.

IV. DISCUSSION

(1) Angular Distribution for the $^{11}B(p, \alpha)^{8}$ Be(2.9) Reaction

The angular distribution of alpha particles from the $^{11}B(p, \alpha)^{8}Be(2.9)$ reaction shows a feature nearly symmetric about 90° with a minimum at 90° and two maxima, one at about 60° and the other at about 120° in the center of mass system. The angular distribution obtained is fitted with the Legendre polynomials $\Sigma_k A_k P_k(\cos\theta)$. The numerical result is of the form $d\sigma/d\Omega \propto 1.00+0.055P_1-0.21P_2-0.11P_3-0.31P_4$ and is shown in Fig. 9 with a solid line. Also is shown the curve obtained as the sum of even-order terms only, $d\sigma/d\Omega \propto 1.00-0.21P_2-0.31P_4$, with a dashed line. It is found that the angular distribution of alpha particles is represented for the most part by the even-order Legendre polynomials up to 4. It is most probable that a process through a compound nuclear state of ^{12}C prevails in the $^{11}B(p, \alpha)^{8}Be(2.9)$ reaction.

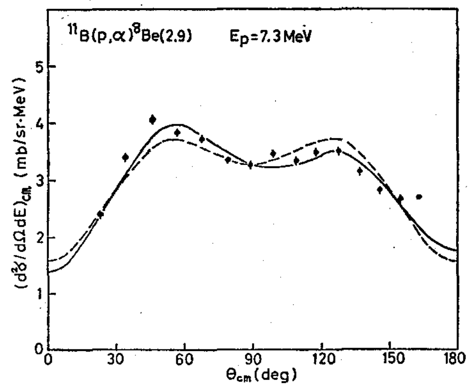

Fig. 9. Legendre polynomials fit to the angular distribution for the $^{11}B(p, \alpha)^{8}Be$ (2.9) reaction. Solid line represents $d\sigma/d\Omega \propto 1.00 +0.055P_1-0.21P_2-0.11P_3-0.31P_4$ and dashed line $d\sigma/d\Omega \propto 1.00-0.21P_2-0.31P_4$.

If the reaction proceeds via a compound nuclear state, the angular distribution is expressed as [2]

$$d\sigma/d\Omega \propto \Sigma_k(-)^{j_0-j_1}\bar{Z}(l_0Jl_0J;j_0k)\bar{Z}(l_1Jl_1J;j_1k)P_k(\cos\theta), \qquad (1)$$

where j_0 is the channel spin of the initial state ($p+{}^{11}B$(g.s.)), j_1 that of the final state ($\alpha+{}^{8}Be(2.9)$), and l_0 and l_1 are the orbital angular momenta of the incident and emergent particles, respectively. In the present case, the value of j_0 is 1 or 2 and the value of j_1 is 2. J is the spin of the compound nuclear state. There are restrictions on k defined as

$$k_{max} \leq \text{minimum}(2l_0, 2l_1, 2J).$$

On the basis of the experimental result that $k_{max}=4$, several combinations of l_0, l_1 and J^π are allowed and the values of J^π are $2^\pm$, $3^\pm$ and $4^\pm$.

The angular distributions are calculated from Eq. (1) for each allowed combination of l_0, l_1, and J^π. Two combinations are favorable to reproduce the experimental result, that is, one $l_0=3$, $l_1=2$, and $J^\pi=2^+$ and the other $l_0=2$, $l_1=3$, and $J^\pi=2^-$. Calculations for any other combination give wrong sign $P_2(\cos\theta)$ component in contrast to the experimental result. In Fig. 10, the calculated curves corresponding to $J^\pi=2^+$ and 2^- are shown with the solid and dashed lines, respectively. These curves indicate the function $d\sigma/d\Omega \propto d\sigma/d\Omega(j_0=2)+\alpha d\sigma/d\Omega(j_0=1)$, where $\alpha=0.3$ for $J^\pi=2^+$ and $\alpha=0.2$ for $J^\pi=2^-$. Values of α are chosen to give a good fit. The angular distribution is essentially reproduced with the function $d\sigma/d\Omega(j_0=2)$, which has a minimum at 0°. The function $d\sigma/d\Omega(j_0=1)$, which has a maximum at 0°, is required to fit details of the angular distribution.

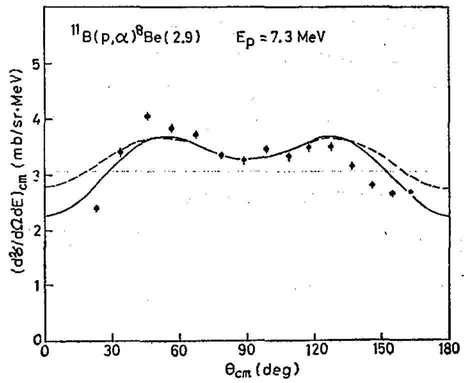

Fig. 10. Angular distributions calculated from Eq. (1) in the text. Curves indicate $d\sigma/d\Omega \propto d\sigma/d\Omega(j_0=2)+\alpha d\sigma/d\Omega(j_0=1)$. Solid line corresponds to $J^\pi=2^+(\alpha=0.3)$ and dashed line $J^\pi=2^-$ $(\alpha=0.2)$.

From the analysis of the angular distribution based on the compound nucleus process, it is concluded that the spin of 2 is assigned favorably to the compound nuclear state of ^{12}C formed in the $^{11}B(p, \alpha)^8Be(2.9)$ reaction at $E_p=7.3$ MeV. There is, however, an uncertainty in determining the parity of this state, because the function $d\sigma/d\Omega(j_0=2)$ which dominates the angular distribution gives the same distribution for $J^\pi=2^+$ as for $J^\pi=2^-$.

(2) $\alpha-\alpha$ Angular Correlation for the $^{11}B(p, \alpha)^8$ Be Be(2.9)$(\alpha)^4$ He Reaction

If the $^{11}B(p, \alpha)^8Be(2.9)$ reaction proceeds through a compound nuclear state, the angular correlation between α_1 and α_2 is expressed as[3)]

$$W(\theta_1\theta_2\phi)=\Sigma_\nu A_{\nu_0\nu_1\nu_2}P_{\nu_0\nu_1\nu_2}(\theta_1\theta_2\phi), \tag{2}$$

where

$$A_{\nu_0\nu_1\nu_2}=(-)^{j_0-j_1}\frac{1}{2J+1}\bar{Z}(l_0Jl_0J;j_0\nu_0)$$
$$\times\bar{Z}(l_2\bar{J}l_2\bar{J};j_2\nu_2)a_{\nu_1}(l_1l_1)$$
$$\times G_\gamma\left\{\begin{matrix}\bar{J} & l_1 & J\\ \bar{J} & l_1 & J\\ \nu_2 & \nu_1 & \nu_0\end{matrix}\right\}.$$

The angles θ_1 and θ_2 correspond to the directions of emission of the first emitted alpha particle and the second emitted one respectively, with respect to the direction of incident proton beams. In the present case $\phi=0$. In addition to the notations defined previously, $\bar{J}$ is the spin of the recoiled ^8Be nucleus, j_2 the channel spin of the final $\alpha+\alpha$ system produced from the breakup of ^8Be and l_2 the orbital angular momentum of α_2. From the properties of $\bar{Z}$ coefficients and G_γ coefficients involved in Eq. (2), the values of ν are even and limited as $\nu_0\leq$minimum$(2J, 2l_0)$, $\nu_1\leq 2l_1$, and $\nu_2\leq$minimum$(2\bar{J}, 2l_2)$.

The angular correlations of two alpha particles are calculated from Eq. (2). In the calculations are used two combinations of l_0, l_1, and J, that is, $l_0=3$, $l_1=2$, and $J^\pi=2^+$, and $l_0=2$, $l_1=3$, and $J^\pi=2^-$, which are selected in the analysis of the angular distribution for the $^{11}B(p, \alpha)^8Be(2.9)$ reaction. $l_2=2$ is uniquely determined for the breakup of the recoiled $^8Be(2.9)$ nucleus into two alpha particles. In Fig. 11 are shown the calculated curves corresponding to $J^\pi=2^+$ and $J^\pi=2^-$ with the solid and the dashed lines, respectively, for $\theta_2^{cm}=60°$. These curves indicate the function $W\propto W(j_0=2)+\alpha W(j_0=1)$, where $\alpha=0.3$ for $J^\pi=2^+$ and $\alpha=0.2$ for $J^\pi=2^-$. There, are used the same values of α as chosen in the analysis of the angular distribution. The calculated curves corresponding to $J^\pi=2^+$ and $J^\pi=2^-$ are out of phase with each other. This fact is useful to decide the parity of the compound state. As seen from the figure, the positive

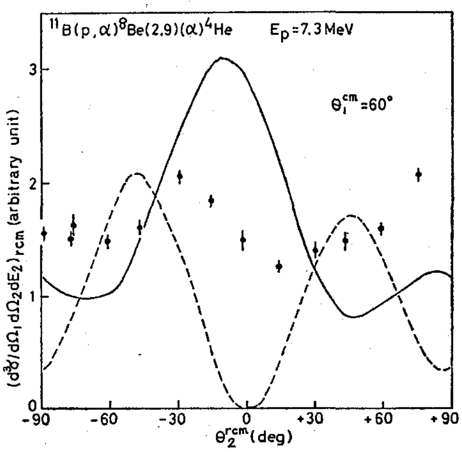

Fig. 11. Angular correlation functions calculated from Eq. (2) in the text. Curves indicate $W\propto W(j_0=2)+\alpha W(j_0=1)$. Solid line corresponds to $J^\pi=2^+$ ($\alpha=0.3$) and dashed line corresponds to $J^\pi=2^-$ ($\alpha=0.2$).

parity can rather be chosen than the negative parity. But the detailed fit cannot be obtained as far as the values of α mentioned above are used.

From the analyses of the angular distribution and the angular correlations, it is concluded that the $^{11}B(p, \alpha)^8Be(2.9)(\alpha)^4He$ reaction at $E_p=7.3$ MeV proceeds via a sequential process through the $J=2$ state of ^{12}C. In the excitation functions of the $^{11}B(p, \alpha)^8Be(2.9)$ reaction a broad resonance was reported at $E_p=7.18$ MeV.[4] The proton energy of 7.3 MeV in the present experiment corresponds to the side of this resonance peak and then this resonance seems to be the $J=2$ state.

There are some problems to be noted; (1) In the angular distribution of alpha particles from the $^{11}B(p, \alpha)^8Be(2.9)$ reaction, there are small odd-order components as seen in Fig. 9. On the basis of the compound nucleus process, these odd-order components can be explained in terms of the interference between two processes via compound nuclear states of parities different with each other. (2) The mean life time of the compound nuclear state formed in the $^{11}B(p, \alpha)^8Be(2.9)$ reaction is of about 2×10^{-21} sec because the energy width is of about 0.34 MeV.[4] This value of life time seems too short for the reaction to be considered strictly as a compound nucleus process. Moreover, the mean life time of $^8Be(2.9)$ is of about 4.5×10^{-22} sec. In this time interval, the first emitted particle does not fly so far from the recoiled $^8Be(2.9)$ nucleus. Then the breakup of $^8Be(2.9)$ cannot be considered as the one of the isolated system. From these facts mentioned above, it is expected that the shape of angular correlation deviates from the pattern calculated on the basis of the sequential breakup process. (3) At angles $\theta_2^{rcm}\simeq\pm70°$, the first emitted alpha particle and one of the component alpha particles of $^8Be(2.9)$ compose kinematically the 4^+ state of ^8Be and, then, the interference between two $^{11}B+p\rightarrow3\alpha$ processes through the 2^+ and 4^+ states of ^8Be can occur. If it is the case the angular correlation of alpha particles from the $^{11}B(p, \alpha)^8Be(2.9)(\alpha)^4He$ reaction can be distorted by the effect of interference around $\theta_2^{rcm}\simeq\pm70°$.

ACKNOWLEDGMENTS

The authors would like to acknowledge the late Professor Y. UEMURA for his advices and encouragements. They also thank Dr. S. MATSUKI for his helpful co-operations. Their thanks are also due to the members of the cyclotron crew for their patient co-operations.

REFERENCES

(1) N. Fujiwara, *J. Phys. Soc. Japan*, **27**, 1380 (1969).
(2) H. Feshbach, "Nuclear Spectroscopy Part B", F. Ajzenberg-Selove Ed., Academic Press, New York and London, 1960, p. 625.
(3) L. C. Biedenharn, *ibid.*, p. 732.
(4) L. Marquez, J. P. Laugier, R. Ballini, C. Lemeille, N. Saunier, et J. Rey, *Nucl. Phys.*, **A97**, 321 (1967).