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$^{10}B(\alpha, {}^6Li)^8Be$ Reaction at 46 MeV and the Configuration of the ^{10}B Ground State*

B. Zeidman, H. T. Fortune,† and A. Richter‡
Argonne National Laboratory, Argonne, Illinois 60439

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Differential cross sections for the reactions $^{10}B(\alpha, {}^6Li)^8Be_{g.s.}$ and $^{10}B(\alpha, {}^6Li)^8Be_{2.9}$ have been measured in the angular range from 9 to 25° (lab system) in 1° steps at $E_\alpha = 46$ MeV. The shapes of the angular distributions are typical of a direct reaction, and the pickup processes are analyzed in distorted-wave approximations on the basis of an extreme cluster model, i.e., on the assumption that a deuteron is picked up from the target nucleus ^{10}B. Calculations using proper two-particle form factors are also performed, and the results agree with the former method. From the ratio of the experimental to the theoretical cross section, a relative spectroscopic factor (^{8}Be-core-plus-deuteron-cluster parentage) is obtained and compared with two-particle fractional-parentage coefficients calculated in intermediate coupling.

1. INTRODUCTION

The increasing evidence for the cluster structure of bound states among the light nuclei has come primarily from direct stripping and pickup reactions and from high-energy "knock-out" reactions.[1] In the present study of the $^{10}B(\alpha, {}^6Li)$ reactions to the ground state and 2.9-MeV state of ^{8}Be, the selections rules[2] on angular momentum, parity, and isospin restrict the transferred neutron-proton pair to an $S=1$, $T=0$ state. Consequently, the reaction might be viewed as deuteron transfer. In many cases, the $(\alpha, {}^6Li)$ reaction would seem to be preferable to other possible deuteron-transfer reactions such as (d, α) because of severe angular momentum mismatch in the latter. Futhermore, since the structure of ^{6}Li is to a considerable extent of the form $(\alpha + d)$, the $(\alpha, {}^6Li)$ reaction should be particularly suited to yield information about the coherent two-nucleon (i.e., deuteron) nature of the target ground state. In this context, the reaction $^{10}B + \alpha \to {}^8Be + {}^6Li$ would more graphically be written

$$({}^8Be + d) + \alpha \to {}^8Be + (\alpha + d). \qquad (1)$$

The results[3] of a plane-wave Born-approximation analysis of several $(\alpha, {}^6Li)$ angular distributions on targets of ^{12}C and ^{14}N at $E_\alpha = 42$ MeV seem to support the assumption of deuteron-cluster pickup in $(\alpha, {}^6Li)$ reactions. The other existing experimental $(\alpha, {}^6Li)$ data[4] have not been interpreted theoretically.

The principal objective of the present study is to determine whether the cross section for reaction (1) can be understood within the spirit of the various aspects of the cluster model. We have measured this reaction at an α-particle bombarding energy $E_\alpha = 46$ MeV, at which we expect the reaction to proceed predominantly via a direct-interaction mechanism. The model used to describe the process is identical to the one of Drisko Satchler, and Bassel[5] in which [in the notation of Eq. (1)] the incident α particle picks up the deuteron cluster from the target nucleus ^{10}B. Such a description, being equivalent to an extreme cluster model for the target nucleus, would be meaningful only if the deuterons were preferentially picked up from the nuclear surface. This assumption is probably reasonable because of the strong surface absorption of the α particles in the entrance channel. However, it can be checked with properly calculated two-particle form factors.[6] Finally, from the ratios of the experimental to the theoretical cross sections, one can obtain relative spectroscopic factors that reflect the ^{8}Be-core-plus-deuteron parentage in the ^{10}B ground state. In this spirit of two-nucleon parentage, the spectroscopic factors can also be compared with the two-particle fractional-parentage coefficients that Cohen and Kurath[7] calculated in intermediate coupling. In addition, attempts are being made currently to understand some of the states in ^{10}B by a refined cluster calculation[8] in which states of maximal orbital symmetry are constructed. These states correspond to the states of a ^{8}Be core and an extra deuteron (both in its triplet and singlet state).

2. EXPERIMENTAL PROCEDURE

The measurements, performed in an 18-in. scattering chamber,[9] utilized the 46-MeV α beam of the Argonne 60-in. cyclotron. The ^{10}B target (enriched to 96% in ^{10}B) was self-supporting and had an approximate thickness of 75 μg/cm^2. The detection system used is similiar to that previously developed for use in $(d, {}^3He)$ reactions.[10] Through the use of time pickoffs (modified ORTEC Model No. 260) between the detectors and associated preamplifiers, fast-logic signals (operating on the nsec time scale) are generated to gate the slower (μsec scale) electronics handling the analog signals. Inasmuch as the high capacitance of the ΔE detector resulted in unreliable operation of its pickoff unit, the usual requirement of a fast signal from ΔE was eliminated. Since a thin ΔE detector (34 μ) was used, however, this elimination caused no problem.

The detector telescope consisted of a series of totally depleted Si surface-barrier detectors of thickness 34, 300, and 500 μ as the ΔE, E, and anticoincidence (AC) detectors, respectively. The fast system generated a gate signal which opened the early linear gates in the slow system when E fired and AC did not. The appropriate product ($\propto MZ^2$) of the gated ΔE and E analog signals was formed electronically. The output of a single-channel analyzer was fed back into the fast system when the particles fell into the desired mass range. The fast system, whose logic includes pileup rejection and dead-time correction, then triggers the delayed gates of the slow system to allow both the total energy and the particle-identification signals to be recorded on the two-parameter analyzer, and thus yields an energy spectrum for each particle of interest. In the present paper only the data from the $^{10}B(\alpha, {}^6Li)$ reaction

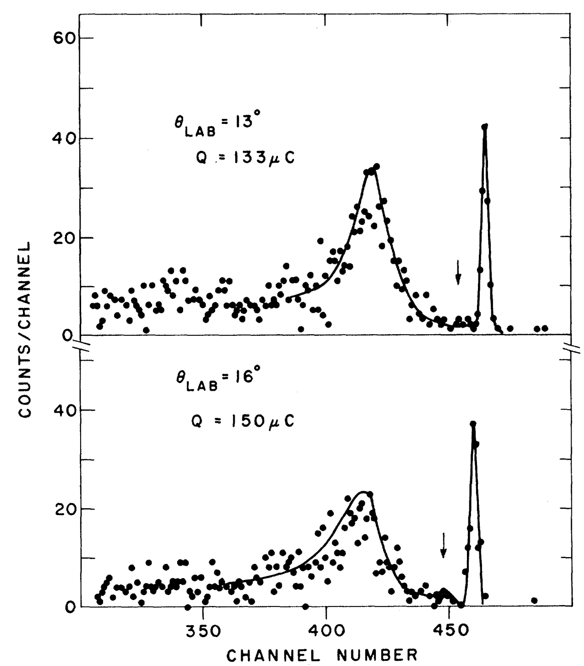

FIG. 1. ^6Li spectra from the α-particle bombardment of ^{10}B. The peaks marked by the heavy line correspond to the ground state and first excited state (2.9-MeV) transition of ^8Be. The arrow points to the location of the "ghost" state seen in various other reactions (Refs. 13–16).

are reported, since the results of the $(\alpha, {}^7Li)$ and $(\alpha, {}^7Be)$ reactions, for which data were obtained simultaneously, have already been published.[11] Typical spectra at $\theta_{lab} = 13$ and 16° are shown in Fig. 1. The ground state of ^8Be is well resolved from the broad 2.9-MeV first excited state. For the extraction of the area under the excited-state peak, a proper theoretical shape (based on the subsequent decay of that state into two α particles[12]) would normally be desirable. However, the low counting rate led us to adopt the simpler procedure of integrating the continuum yield from the onset of the apparent low-energy background up to the ground-state group. A suitable background was subtracted, and the estimated error inherent in this procedure was incorporated in the total errors. Angular distributions measured between lab angles of 9 and 25° are shown in Fig. 2. The cross section for the excited state should be considered as an upper limit and could be slightly smaller because of a possible underestimate of the unknown continuum contribution. The ±20% uncertainty in the absolute cross section is largely due to uncertainty in the target thickness. The shapes of the angular distributions are very simiiliar to each other and both are forward-peaked, characteristic of a direct process. Neither angular distribution has an apparent $L=0$ component—in agreement with theory (as discussed in Sec. 3). Several spectra, such as the one at $\theta_{lab} = 16°$ displayed at the bottom in Fig. 1, show an anomaly about 0.8 MeV above the ^8Be ground state. This anomaly could be the "ghost" of the ^8Be ground state, seen in various other reactions.[13–16] The small number of counts in the present experiment, however, does not allow us to study the behavior of this anomaly as a function of angle.

3. ANALYSIS AND RESULTS

Since the ground state of ^{10}B has $J^{\pi} = 3^+$, angular momentum selection rules for two-particle pickup from ^{10}B leading to ^8Be allow $L=2$ and 4 for population of the ground state and $L=0$, 2, and 4 for population of the 2^+ first excited state of ^8Be. However, $L=4$ is not allowed if the pickup is restricted to $1p$-shell nucleons. Futhermore, microscopic calculations[7] predict that $L=0$ will not contribute to the population of the 2^+ state. Thus both states are reached via $L=2$, $S=1$, $J=3$.

The distorted-wave calculations were performed with the IBM-7094 version of the computer code JULIE.[17] The optical-model parameters in the entrance ($^{10}B+\alpha$) channel were taken from an analysis of $^{11}B(\alpha, \alpha)$ elastic scattering at the same bombarding energy.[18] These parameters have already been used successfully to approximate the

TABLE I. Optical-model parameters used in distorted-wave analysis of the $^{10}B(\alpha, ^6Li)^8Be$ reaction.

Channel	V_0 (MeV)	W (MeV)	$r_0 = r_C$ (F)	a (F)	r_0' (F)	a' (F)	V_{so}	Ref.
Transferred particle	···	0	1.26	0.60	···	···	$\lambda = 25$	
$^{10}B + \alpha$	194	24	1.38	0.60	1.60	0.60	0	a
$^6Li + ^8Be$	65	3.2	1.42	0.80	2.73	0.56	0	b
	65.5	15.5	1.48	0.41	1.43	1.48	0	b
	65.5	31	1.48	0.41	1.43	1.48	0	b,c

[a]See Ref. 18.
[b]See Ref. 20.
[c]The imaginary potential was doubled to take account of the difference in energy.

$^{10}B + \alpha$ scattering wave functions in a distorted-wave Born-approximation (DWBA) treatment of the $^{11}B(^3He, \alpha)^{10}B$ reaction.[19] For the exit-channel ($^6Li + ^8Be$) interaction, a variety of ^6Li optical-model parameters were tried. Most of these were taken from the recent work of Bethge, Fou, and Zurmühle.[20] However, all the ^6Li parameters gave uniformly poor fits to the present reaction data – even after correcting the absorption potential to allow for the higher energy in the present reaction. Table I lists the entrance-channel optical-model potential and some of the potentials that were tried for the exit channel.

For the form factor of the transferred "deuteron" cluster, two completely separate ideas were tested. First, a bound-state wave function having $L = 2$ and no nodes was calculated for the case of a cluster with $M = 2$, $Z = 1$ bound to an ^8Be core. In this calculation with the bound-state part of the code JULIE, the potential was represented by a real Woods-Saxon well and the binding energy was taken to be the energy to separate a deuteron from the ground state of ^{10}B (6.03 MeV to form the ground state of ^8Be, and 8.93 MeV to form the 2.90-MeV state of ^8Be). Such an extreme "lump" approximation is, of course, highly suspect. For this reason, a second type of form factor was obtained; the wave functions in a Woods-Saxon potential were calculated for a neutron and for a proton bound to a ^8Be core. The binding energies for the proton and neutron were taken to be identical and equal to one-half the deuteron separation energy. From these two single-particle wave functions, a "realistic" form factor (a deuteron wave function representing the c.m. motion of the two nucleons about the ^8Be core) was obtained by the procedure of Bayman.[21]

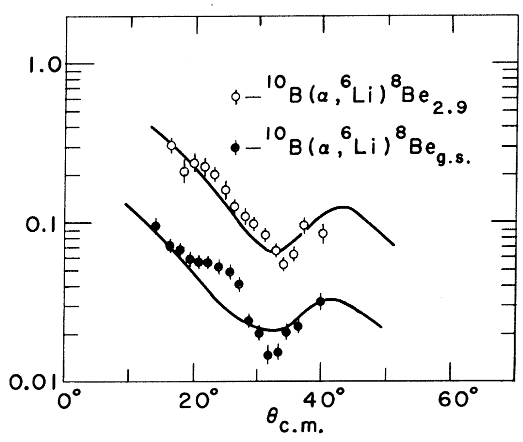

FIG. 2. Angular distributions for the $^{10}B(\alpha, ^6Li)$ reaction leading to the ground state and first excited state of ^8Be. The error bars include only the errors due to statistics and background subtraction. The curves are the results of DWBA calculations as discussed in the text.

The particular choice of identical neutron and proton binding energies (with a total B. E. equal to the "deuteron" binding energy) had the effect of making the "realistic" and "lump" form factors identical in shape in the external region. As an independent check on the recoupling procedure, it was noted that the relative magnitudes of the two types of form factors were identical for the two states of ^8Be. Of course, in neither case does the absolute magnitude have any meaning for an (α, ^6Li) reaction.

The results of the form-factor calculations are displayed in Fig. 3. The "realistic" form factor has been normalized to the JULIE form factor at large distances. It can be seen that the "lump" form factor is much more localized in the interior of the nucleus. This is understandable, since this form factor corresponds not only to a more massive particle, but also has twice the binding energy of each of the individual nucleon form factors. From the large value of the "lump" form factor in the interior region, it is obvious that the interior will make an unnaturally large contribution to the cross section if no lower cutoff is used in the radial integration. Thus, for this form factor a lower cutoff radius of 4 F was used in the

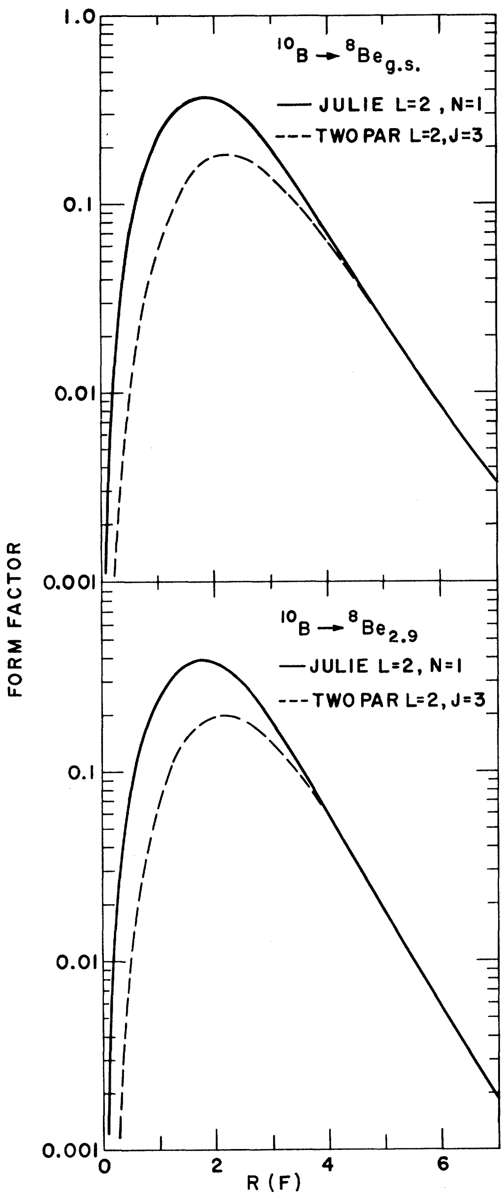

FIG. 3. Form factors for the pickup of two nucleons from ^{10}B to form the ground state and first excited state of ^8Be. The significance of the two types of form factors is discussed in the text.

radial integrals. This completely eliminates the interior of the nucleus. Outside this radius the two form factors are virtually identical. Test calculations with the "realistic" form factor gave very nearly identical results for lower cutoffs at 0 and 4 F. Thus, in this case at least, using a "lump" form factor and a large cutoff radius has much the same effect as using a realistic form factor and no cutoff.

All of the calculated angular distributions that possessed appreciable structure were out of phase with the data. It was not felt worthwhile (or meaningful) to spend much time varying the ^6Li optical-model parameters in order to fit the data. Figure 2 displays the data for the two final states of ^8Be studied, together with typical results of DWBA calculations. It can be seen that the calculations reproduce the general trend of the data and indicate that the process is one of direct pickup. Furthermore, it is of interest to compare the extracted "spectroscopic factors" with theoretical expectations. Even though the ratio of experimental to theoretical values varied considerably for different ^6Li potentials, the ratio of the ratios

$$R = \frac{(\sigma_{\exp}/\sigma_{\rm th})_{\rm g.s.}}{(\sigma_{\exp}/\sigma_{\rm th})_{2.90}}$$

was relatively insensitive to the details of the calculations. The extracted value was $R = 0.24$. This is to be compared with the ratio $R_{\rm th} = 0.324$ between the theoretical two-particle spectroscopic factors Cohen and Kurath[7] calculated for these two states. Considering the crudeness of the model presently available for the analysis of $(\alpha, {}^6Li)$ reactions together with the restricted range of the measured angular distributions, these two numbers are in virtual agreement. Therefore, the results of the present experiment agree with Cohen and Kurath's description of the two-particle configuration of the ground state of ^{10}B.

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†Present address: University of Pennsylvania, Philadelphia, Pennsylvania 19104.

‡On leave of absence from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

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Determination of the Relative Electron Density at the Be Nucleus in Different Chemical Combinations, Measured as Changes in the Electron-Capture Half-Life of ^{7}Be

H. W. Johlige, D. C. Aumann, and H.-J. Born

Institut für Radiochemie, Technische Hochschule München, 8046 Garching b. München/Germany

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Differences in the decay constant of ^{7}Be in various states of chemical combination were measured using the differential-ionization-chamber technique. The results are:

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{BeF_2})_{\mathrm{amorph}}=(1.130\pm0.058)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{Be_4O(CH_3COO)_6})=(-0.724\pm0.057)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{BeBr_2})=(1.472\pm0.063)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{Be_4O(CH_3COO)_6})-\lambda(\mathrm{BeF_2})_{\mathrm{amorph}}=(1.852\pm0.082)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{Be(C_5H_5)_2})=(0.795\pm0.074)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{BeO})-\lambda(\mathrm{Be^{2+}(OH_2)_4})=(-0.374\pm0.077)\times10^{-3}\lambda(\mathrm{Be})\,,$$

$$\lambda(\mathrm{Be(C_5H_5)_2}-\lambda(\mathrm{Be^{2+}(OH_2)_4})=(-1.169\pm0.106)\times10^{-3}\lambda(\mathrm{Be})\,.$$

The decay constant of ^{7}Be is proportional to the electron density at the nucleus. These results can therefore be used to establish a scale for the relative electron density at the Be nucleus in different chemical combinations.

I. INTRODUCTION

^{7}Be undergoes orbital-electron capture with a half-life of 53 days. The capture probability, and hence the decay constant of ^{7}Be is proportional to the electron density at the nucleus and varies with the chemical state of the atom. Experiments to determine the difference in the decay rate in Be, BeO, and BeF_2 have been performed by groups in Berkeley,[1,2] Brookhaven,[3] and France.[4] The results of these experiments are listed in Table I, together with the results of our measurements.

The measurements presented in this paper were undertaken to learn more about the influence of electron rearrangement by bonding on the decay constant of ^{7}Be. The method might be useful in giving some insight into the electron density at the Be nucleus in different chemical surroundings. The