wave calculations. Perhaps the present results, showing experimentally the onset of isospin nonconservation, will be a useful guide for improving the treatment of Coulomb and Q-value effects in future reaction calculations.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1] J. Cerny and R. H. Pehl, Phys. Rev. Lett. 12, 619 (1964). (43.7-MeV protons.)

[2] J. C. Hardy, H. Brunnader, and J. Cerny, Phys. Rev. Lett. 22, 1439 (1969).

[3] D. G. Fleming, J. C. Hardy, and J. Cerny, Nucl. Phys. A162, 225 (1971). (43.7- and 54.1-MeV protons.)

[4] J. M. Nelson, N. S. Chant, and P. S. Fisher, Phys. Lett. 31B, 445 (1970). (49.5-MeV protons.)

[5] S. M. Harris, Phys. Rev. C 1, 362 (1970).

[6] B. Hird and R. W. Ollerhead, Nucl. Instrum. Methods 71, 231 (1971).

[7] M. Gaillard, R. Bouché, L. Feuvrais, P. Gaillard, A. Guichard, M. Gusakow, J. L. Leonhardt, and J. R. Pizzi, Nucl. Phys. A119, 161 (1968), and A131, 353 (1969).

[8] B. F. Bayman and A. Kallio, Phys. Rev. 156, 1121 (1967). The code DWUCK, written by P. D. Kunz (University of Colorado), was used for the distorted-wave calculations. The calculation of two-nucleon transfer by this code is discussed in detail in H. W. Baer, J. J. Kraushaar, C. E. Moss, N. S. P. King, R. E. L. Green, P. D. Kunz, and E. Rost, Ann. Phys. (New York) 76, 437 (1973). For optical-model calculations we used the parameter sets denoted $P1$-$T1$ and $P1$-$T6$ in this work and in J. R. Shepard, thesis, University of Colorado, 1972 (unpublished).

[9] Baer, Kraushaar, Moss, King, Green, Kunz, and Rost, Ref. 8.

[10] Shepard, Ref. 8.

Feasibility of α-Transfer Studies via the (α, ^{8}Be) Reaction at High Energies*

G. J. Wozniak, N. A. Jelley, and Joseph Cerny
Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94702

(Received 8 June 1973)

Using a new ^{8}Be identifier of high detection efficiency, we observed the (α, ^{8}Be) reaction on targets of ^{11}B, ^{12}C, and ^{16}O at 65 MeV. Differential cross sections (~ 1–60 μb/sr) were measured from $\theta_{\text{c.m.}} = 20°–80°$. The only states strongly populated were those predicted to have large α-structure amplitudes, implying that direct processes dominate at $E_\alpha = 65$ MeV.

Although it has been apparent for some time that the (α, ^{8}Be$_{\text{g.s.}}$) reaction is potentially one of the least controversial α-pickup reactions, the original experiments by Brown *et al.*[1] employing α-α coincidence techniques showed that at 35.5–41.9 MeV bombarding energies, nondirect processes appeared predominant. We wish both to show that direct processes appear to dominate at higher bombarding energies, and to present a new technique which greatly enhances the experimental feasibility of such studies. The large α-structure amplitude of ^{8}Be should make (α, ^{8}Be$_{\text{g.s}}$) a most useful spectroscopic reaction with which to investigate theoretical α-structure amplitudes in nuclei, such as those for the p shell given by Kurath[2] and Rotter.[3]

To study the (α, ^{8}Be) reaction, one must detect the particle-unstable ^{8}Be nucleus. Usually this is done either by coincidence techniques[1] or by the detection of both breakup α particles in a single counter telescope.[4] Since the cross section is small (~ 1–60 μb/sr) at 65 MeV, we have developed a new ^{8}Be detection technique with an appreciable probability of detecting the two breakup α particles by using a position-sensitive counter telescope with an angular acceptance larger than that of the ^{8}Be breakup cone.

Our approach is illustrated in Fig. 1(a). The ^{8}Be identifier[5] employs a circular collimator, divided into two open segments by a solid post, followed by a counter telescope consisting of a ΔE detector backed by a position-sensitive E detector (PSD).[6] As will be seen, the presence of the post can be used to select ^{8}Be events.

Consider two α particles from the decay of a ^{8}Be$_{\text{g.s.}}$ passing through the divided collimator on either side of the post, as shown in Fig. 1(a). These traverse the ΔE detector and stop in the E detector. In a PSD both an energy signal (E) and a signal proportional to the distance of the detected particle from the grounded end times the energy of the particle (XE) are generated. Since the center-of-mass breakup energy of the two α particles is small (92 keV) compared to

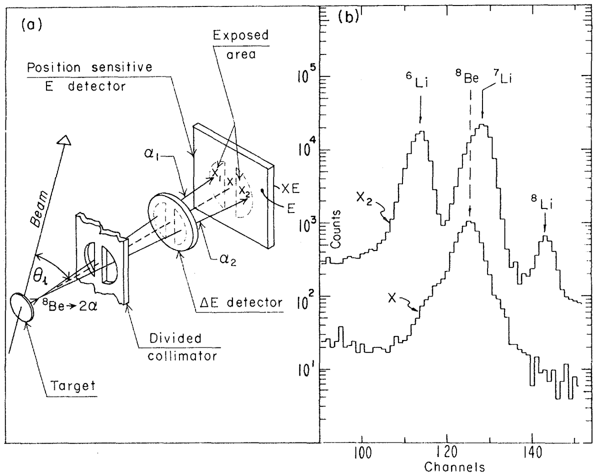

FIG. 1. (a) Schematic diagram of the ^{8}Be identifier. (b) Two-particle identifier spectra of the reaction products arising from 65-MeV ^{4}He on ^{11}B gated by position signals X or X_2 as described in the text. The position gate for the lower curve was set for $\theta_{\rm lab} = 15.0°$; the upper, $\theta_{\rm lab} = 16.5°$.

our typical ^{8}Be energies of 45 MeV, the two α's have equal energy to a good[5] approximation. One α particle therefore gives a signal $X_1E/2$; the other, $X_2E/2$. As both α's arrive within a fraction of a nanosecond of each other, the signals are automatically summed and the resultant position signal (X) obtained by dividing out the energy gives their average position. Since this position signal corresponds to a region of the PSD that is masked by the post, gating the energy by such position signals (X) selects ^{8}Be events and eliminates particle-stable nuclei. Because the position signal also establishes the original direction of the ^{8}Be, reasonable energy resolution can be obtained even though the divided collimator subtends a large angle (6.0°).

In Fig. 1(b) particle identification (PI) spectra are shown. The upper curve arises from events giving position signals (X_2) from part of the exposed area of the PSD and the lower, from events giving rise to position signals (X) corresponding to the region behind the post. A peak due to ^{8}Be events appears in the latter. Its position is slightly below the ^{7}Li peak, as predicted[4] from range-energy data for two similar-energy coincident α particles. All of the background[7] observed in the lower curve results from chance coincident particles; minimal background in the ^{8}Be energy spectra is obtained by gating on this ^{8}Be PI peak.

Use of the post to divide the circular collimator removes the central portion of the breakup cone (which has a typical solid angle of 6.4 msr) and also reduces the solid angle subtended by the collimator (in our particular case from 8.5 to 4.9 msr). However, because the ^{8}Be breakup distribution is strongly peaked at the edge of the cone, the introduction of the post only reduces the efficiency[5] from 40% to 21% for detecting both breakup α particles from a 45-MeV ^{8}Be nucleus emitted within ± 0.5° of the center of the post.

In these initial experiments we studied the (α, ^{8}Be) reaction on several p-shell targets. A 65-MeV α beam from the Lawrence Berkeley Laboratory 88-in. cyclotron was used to irradiate targets of ^{11}B (enriched to 98%), ^{12}C, and SiO_2 (as an oxygen target)[8] of thicknesses 210, 60, and 255 μg/cm^2, respectively. A 125-μm ΔE detector (1 cm in diameter) and a 300-μm E (PSD)[9] fed three high-rate amplifier systems and a pile-up rejector which rejected events arising from different beam bursts. The amplifiers fed both a divider circuit, to obtain the position signal, and a particle identifier. Energy spectra gated by position and PI were collected on a Nuclear Data 4096-channel analyzer.

Figure 2 presents representative spectra of the reactions ^{11}B(α, ^{7}Li)^{8}Be and ^{11}B(α, ^{8}Be)^{7}Li as well as the (α, ^{8}Be) reaction on ^{16}O (each acquired in about 2 h). One can clearly see from comparing Fig. 2(a) with 2(b) that there is total discrimination in the (α, ^{8}Be) data against ^{7}Li events. Our experimental ^{8}Be energy resolution of ~ 450 keV was principally determined by the width of the position gate (≅ 1.0°). The background observed above the ^{7}Li and ^{12}C ground state peaks is indicative of the contribution of α-α pileup events to the ^{8}Be spectra. Since the detection efficiency for $^8Be_{2.9}{}^*$ was estimated to be $\frac{1}{50}$ of that for the $^8Be_{g.s.}$, no contribution was observed[10] from the (α, $^8Be_{2.9}{}^*$) reaction.

In the reaction ^{16}O(α, ^{8}Be)^{12}C only the 0^+ ground and 2^+ first excited states of ^{12}C are observed to be strongly populated, as shown in Fig. 2(c). Transitions to the (4^+) 14.08-MeV[11] and 3^- 9.64-MeV states are weakly seen though the (4^+) level at back angles was observed strongly. There was no evidence of any significant excitation of the 2^- unnatural parity state at 11.83 MeV nor the 0^+ level at 7.65 MeV. These observations are in qualitative agreement with expectation based on the predictions[2,3] of α-structure amplitudes for ^{16}O and differ from the earlier work on the reaction ^{16}O(α, ^{8}Be)^{12}C at $E_\alpha = 41.9$ MeV. In that experiment[1] there was some evidence for excitation of the 0^+ state at 7.65 MeV and the aver-

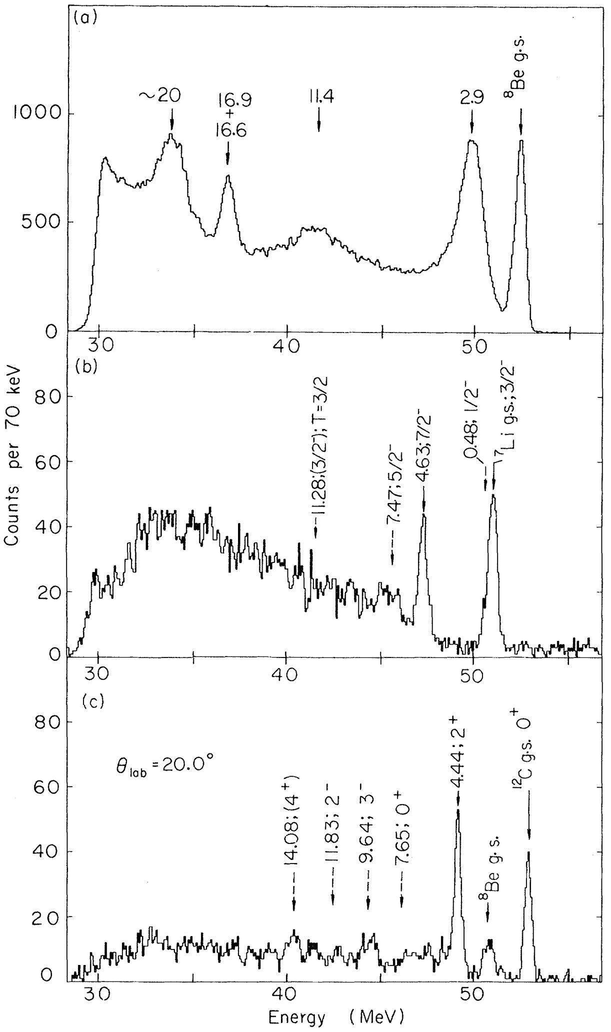

FIG. 2. Energy spectra taken at 65-MeV bombarding energy. (a), (b) ^{7}Li and ^{8}Be energy spectra, obtained concurrently by setting appropriate PI and position gates, from the reactions ^{11}B(α, ^{7}Li)^{8}Be and ^{11}B(α, ^{8}Be)^{7}Li, respectively, after 1111 μC. (c) ^{8}Be energy spectrum from the reaction ^{16}O(α, ^{8}Be)^{12}C for 1300 μC. At this angle the ground state is relatively strongly populated.

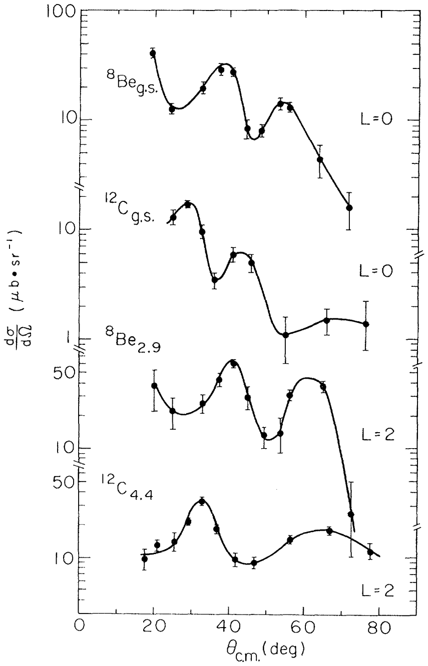

FIG. 3. Absolute differential cross sections for the strong transitions from the (α, ^{8}Be) reaction on ^{12}C and ^{16}O targets. The absolute cross sections could be uniformly in error by as much as 20%. The curves drawn are meant to guide the eye.

age yield to the 3^- state was roughly equal to that to the ground state at the angles studied. At 65 MeV, the ratio of the integrated cross sections $\sigma(3^-)/\sigma(\text{g.s.})$ is less than 0.3.

The reaction ^{11}B(α, ^{8}Be) selectively populates the $\frac{3}{2}^-$ ground state and $\frac{7}{2}^-$ 4.63-MeV second excited state of ^{7}Li and shows only a weak transition to the $\frac{5}{2}^-$ 7.47-MeV level, predicted to be *S* hindered in an *LS* coupling basis in direct transfer.[12] There was no indication of transitions to the $T=\frac{3}{2}$ state at 11.28 MeV, which would be isospin forbidden. Also, we can place a limit of 15% of the ground-state strength on the population of the $\frac{1}{2}^-$ 0.48-MeV state. This weak strength to the $\frac{1}{2}^-$ and $\frac{5}{2}^-$ levels and the strong transitions to the $\frac{3}{2}^-$ and $\frac{7}{2}^-$ levels are consistent with the calculated α-structure amplitudes[2,3] for ^{11}B. Similar agreement with theory is obtained for the reaction on ^{12}C (for which no spectrum is shown) in which only the 0^+ ground and 2^+ first excited states in ^{8}Be are clearly populated. Transitions to the 4^+ level at 11.4 MeV in ^{8}Be might be expected,[2,3] but its broad width[11] would make it difficult to observe. No population of the 2^+ (mixed isospin) states at ~16 MeV was seen, consistent with the small calculated[2] α-structure amplitude in ^{12}C.

Angular distributions for (α, ^{8}Be) reactions on ^{12}C and ^{16}O are shown in Fig. 3. Somewhat similar oscillatory behavior is seen for the two $L=0$ transfers to the ^{8}Be and ^{12}C ground states and a notably stronger strength at back angles occurs for the $L=2$ transfers. Forward-angle measurements at 70 MeV on these targets produced quite similar differential cross sections, also indicating a dominant direct reaction mechanism. The ^{11}B(α, ^{8}Be)^{7}Li data (not shown) possessed relatively structureless angular distributions for the transitions to the ground and 4.63-MeV levels of ^{7}Li, which is probably due to mixed-L transfers.

To extract spectroscopic factors which can be quantitatively compared to theoretical predictions, one must account for kinematic effects which might affect the relative excitation of states. As a crude preliminary approximation one can neglect these effects and look at the ratio of yields at the first maximum. [A fairly extensive attempt was made to fit these data via the zero-range distorted-wave Born approximation (DWBA) assuming an α-cluster transfer. Unfortunately, only poor fits were obtained, although at 65 MeV the angular momenta in the entrance and exit channels are well matched. This failure may be due to the fact that the ^{8}Be optical potential is unknown; in addition neglect of finite-range effects may contribute.] At the first maximum, the experimental ratios of the differential cross sections of the first excited to ground states of both ^{12}C and ^{8}Be are closely equal to 2, while the corresponding ratios of spectroscopic factors[2,3] are 5.5 and 1.3, respectively.

While it may require detailed excitation function studies to conclusively determine the direct nature of the (α,^{8}Be) reaction at 65 MeV, the strong population of only those states which are predicted to have significant α-structure amplitudes implies a dominant direct reaction mechanism. Hopefully, a description of this α-transfer process by an exact DWBA approach will enable quantitative tests to be made of spectroscopic predictions. Furthermore, using this relatively simple ^{8}Be identifier, extensive comparisons with other α-pickup reactions like (d,^{6}Li) and (^{3}He,^{7}Be) will be made possible.

We would like to thank Dr. F. D. Becchetti for useful discussions on direct reaction theory.

---

*Work performed under the auspices of the U.S. Atomic Energy Commission.

[1] R. E. Brown, J. S. Blair, D. Bodansky, N. Cue, and C. D. Kavaloski, Phys. Rev. 138, B1394 (1965).

[2] D. Kurath, Phys. Rev. C 7, 1390 (1973).

[3] I. Rotter, Fortschr. Phys. 16, 195 (1968).

[4] G. J. Wozniak, H. L. Harney, K. H. Wilcox, and J. Cerny, Phys. Rev. Lett. 28, 1278 (1972).

[5] G. J. Wozniak, N. A. Jelley, and J. Cerny, unpublished.

[6] *Guide to the Selection and Use of Position Sensitive Detectors*, edited by W. W. Daehnick (Nuclear Diodes, Prairieview, Ill., 1969).

[7] A substantial portion of these chance coincidence events are caused by high-energy particles which traverse the counter telescope and could be eliminated by adding a reject detector.

[8] A Si target was irradiated at $\theta_{\rm lab} = 20.0°$ to understand the small background in the SiO$_2$ data arising from ^{24}Mg states populated by (α, ^{8}Be) on ^{28}Si.

[9] Our PSD was obtained from Edax International Inc.

[10] Events from the (α, ^{8}Be$_{2.9}$*) reaction on light targets, if two-body, would have ~ 500 keV higher energy than those from (α, ^{8}Be$_{\rm g.s.}$) transitions to the same final states, as a result of a kinematic effect.

[11] All excitation energies and spin and parity assignments quoted are from F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A114, 1 (1968), and A78, 1 (1966), except for the J^π assignments for levels of ^{7}Li, which are from R. J. Spiger and T. A. Tombrello, Phys. Rev. 163, 964 (1967).

[12] A. N. Boyarkina, Izv. Akad. Nauk SSSR, Ser. Fiz. 28, 337 (1964) [Bull. Acad. Sci. USSR, Phys. Ser. 28, 255 (1964)].

Theory of the Pion-Nucleus Optical Potential with Crossing*

J. Barry Cammarata and M. K. Banerjee
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

(Received 16 July 1973)

A theory of the π-nucleus optical potential is developed from the exact propagator of a pion in the presence of a nucleus. The crossed π-nucleus diagrams, absent in previous work, are shown to have significant effect on the cross sections and the elastic-scattering wave functions of low-energy pions.

There have recently appeared in the literature a number of papers discussing ways to improve the π-nucleus optical potential.[1] Although we find that most of these efforts have been primarily concerned with the description of the basic πN interaction, there is an additional feature of π-nucleus scattering which is physically significant and should be included in the construction of