PHYSICAL REVIEW C VOLUME 13, NUMBER 3 MARCH 1976

Communications

The Communications section is for brief reports on completed research. A Communication may be no longer than the equivalent of 2800 words, i.e., the length to which a **Physical Review Letter** *is limited. (See the editorial in the 21 December 1970 issue of* **Physical Review Letters.**) *Manuscripts intended for this section must be accompanied by a brief abstract for information retrieval purposes and a keyword abstract.*

Spectroscopic utility of the two-proton pickup (^{6}Li,^{8}B) reaction*

R. B. Weisenmiller, N. A. Jelley,† K. H. Wilcox, G. J. Wozniak, and Joseph Cerny
Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720
(Received 6 October 1975)

Data for the (^{6}Li, ^{8}B) reaction on targets of ^{10}B, ^{12}C, ^{13}C, and ^{16}O at 80 and 93 MeV are presented. Spectroscopic selectivity is observed and evidence for the dominance of spatially symmetric transfer of the two protons is shown. On the $T_z=0$ targets a close similarity is found to the analogous (p,t) reaction, and the ^{13}C results indicate the location of low-lying $1p$-shell states in ^{11}Be.

NUCLEAR REACTIONS ^{10}B(^{6}Li, ^{8}B), ^{12}C(^{6}Li, ^{8}B), ^{13}C(^{6}Li, ^{8}B), ^{16}O(^{6}Li, ^{8}B), E =80, 93 MeV; measured $\sigma(E_f, \theta)$; energy levels ^{8}Li, ^{10}Be, ^{11}Be, ^{14}C; assessed importance of spatially antisymmetric transfer; comparisons with two-neutron pickup reactions leading to analog states and with two-particle spectroscopic amplitudes; resolution 300 keV.

Although light-ion induced two-nucleon transfer reactions have been used extensively to study two-particle and two-hole configurations, the difficulties inherent in observing the $(n, ^3\text{He})$ reaction have hindered the study of two-proton hole states. However, the development of heavy-ion beams has made available several possible reactions capable of probing such states in neutron-excess nuclei. We wish to report on results, obtained in the first survey of a two-proton pickup reaction on $1p$-shell targets, which demonstrate the feasibility of the (^{6}Li, ^{8}B) reaction as a means of studying these configurations.

Among the two-proton pickup reactions reported[1,2] to date—(^{6}Li, ^{8}B), (^{11}B, ^{13}N), and (^{18}O, ^{20}Ne)—the first has several experimental advantages. Both ^{7}B and ^{9}B are particle-unbound, thus allowing clean separation of the ^{8}B particles from other boron isotopes by particle identification techniques with solid-state detector telescopes. Since ^{8}B has no bound excited states, its energy spectra lack the shadow peak ambiguity of the (^{18}O, ^{20}Ne) reaction, though this advantage is also shared by the (^{11}B, ^{13}N) reaction. However, the (^{6}Li, ^{8}B) reaction is the lightest of the broadly feasible two-proton pickup reactions, and the kinematic contribution to the energy resolution is therefore smaller, particularly for light targets.

This study focused on $1p$-shell targets because this region has been investigated thoroughly with other two-nucleon transfer reactions and the coefficients of fractional parentage (cfp) relevant to two-nucleon transfer have been calculated[3]; furthermore, there is an obvious symmetry in the (mirror) final states populated in the (p,t) and (^{6}Li, ^{8}B) reactions on $T_z=0$ targets and we report results from three such targets: ^{12}C, ^{16}O, and ^{10}B. The two-particle cfp[4] for $^8\text{B}(2^+) \rightarrow {}^6\text{Li}(1^+) + 2p$ show that the two protons can be transferred from a spatially symmetric (^1D) state or an antisymmetric (^3P) state relative to the ^{6}Li core. The simplest cluster transfer mechanism corresponds to an internal ^1S state [as in the (p,t) reaction] for the transferred nucleons, which for the (^{6}Li, ^{8}B) reaction can only arise from the ^1D component. However, there is a much larger amplitude for the ^3P than for the ^1D component, so if antisymmetric transfer[5] is important, the expected symmetry between the (^{6}Li, ^{8}B) and (p,t) reactions might be distorted. Although most of the established two-proton hole states in the $1p$ shell can be populated by both transfer symmetries, there are a few known levels which would be fed predominantly by spatially antisymmetric transfer,[3,5] and two examples of these are discussed below.

The general techniques for the production of lithium beams at the Lawrence Berkeley Laboratory 88-inch cyclotron and the identification of ^{8}B reaction products have been described previously.[2] Because these reactions have highly negative Q

values, beam energies of 80 and 93 MeV were used. Two telescopes, consisting of two transmission (ΔE) detectors, typically 15 and 10 μm thick, a 200-μm E detector and a 1000-μm reject detector, were employed. Each subtended 0.29 msr; a typical energy resolution was 300 keV. Background reduction in this moderately low yield reaction (~1–15 μb/sr c.m.) was accomplished by requiring a conformity in the particle identification signals generated by each of the two ΔE detectors. Two ^{16}O targets were used: a 16% oxidized (by atom) 0.34-mg/cm^{2}Li target and a 0.21-mg/cm^2 silicon dioxide target. Other targets were 0.22-mg/cm^2 natural carbon, 0.14-mg/cm^2 ^{10}B (96%), and 0.14-mg/cm^2 ^{13}C (90%). Kinematic shifts were utilized in the analysis to discern the levels of interest from those arising from target contaminants.

A comparison between a ^{12}C(^{6}Li, ^{8}B)^{10}Be spectrum and a ^{12}C(p,t)^{10}C spectrum,[6] Figures 1(a) and 1(b), shows that a close similarity exists between these reactions. In both spectra the 0$^+$ ground state and the first excited 2$^+$ state (2_1^+) are strongly populated, in agreement with the calculated two-particle transition strengths.[3] The next higher peak, observed at 5.96 MeV in ^{10}Be, could be expected largely to consist of the 2$^+$ member of the 2$^+$, 1$^-$ doublet at this energy,[7] since lowest order shell model configurations and a simple pickup reaction mechanism prohibit forming the 1$^-$ state; indeed the angular distribution of the analog of this state in the (p,t) data[6] is consistent with $L=2$. The population of this 2_2^+ level is less than the 2_1^+ level, although transitions to the former have a much greater theoretical strength.[3] Possibly some of this missing strength is contained in the 2_3^+ level at 7.54 MeV in ^{10}Be which, although thought[8] to have a dominant sd-shell character, is observably populated. Comparison with the (p,t) data, shown in Fig. 1(b), implies that the analog of this 2_3^+ state might be the 6.6-MeV level in ^{10}C, which is again consistent with the (p,t) angular distribution.[6] Finally, evidence is seen at several angles for the weak population of a probable[7] 2$^+$ state at 9.4 MeV and a state at 11.8 MeV.

Figures 2(a) and 2(b) provide another example of the similarity between the (^{6}Li, ^{8}B) and (p,t) (Ref. 9) reactions, now employing ^{16}O targets. In both spectra, the 1p-shell two-hole states, such as the 0$^+$ ground state and the two lowest 2$^+$ states, are populated the strongest, while the non-p-shell states, such as the 1$^-$ and[8] 0$^+$ levels at 6.09 and 6.59 MeV in ^{14}C, respectively, are only weakly populated. [These 1$^-$ and 0$^+$ states are obscured in Fig. 2(a) because of a carbon contaminant peak, but were seen using the SiO$_2$ target.] The large

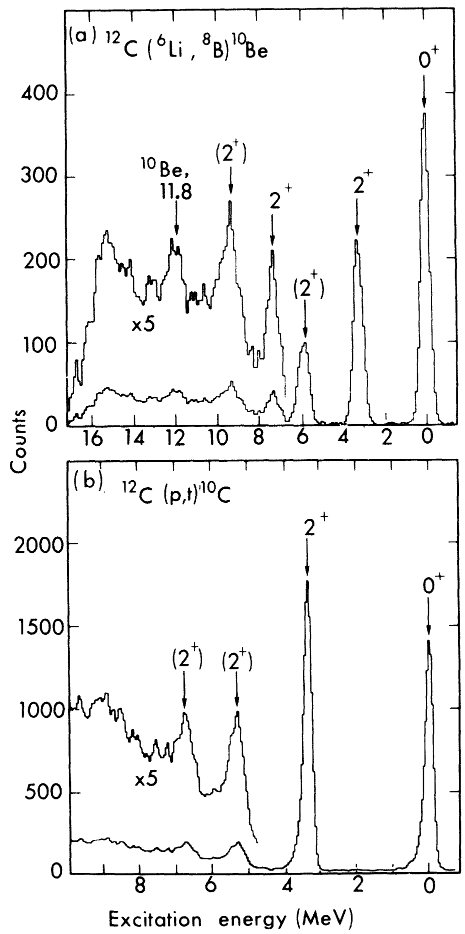

FIG. 1. (a) A composite spectrum of the ^{12}C(^{6}Li, ^{8}B)^{10}Be reaction ($E_{^6\mathrm{Li}}=80$ MeV) between $\theta_{\mathrm{lab}}=12.8°$ and 16.8° in which the data were kinematically shifted to $\theta_{\mathrm{lab}}=15.8°$. (b) The ^{12}C($p,t$)^{10}C reaction induced by 54-MeV protons at 19.5° (Ashery *et al.*, Ref. 6). (This angle lies at the first minimum in the ^{10}C g.s. angular distribution.)

theoretical spectroscopic amplitude for the 2_1^+ configuration may well be shared among the 7.01-, 8.32-, and 10.44-MeV states,[10] all of which are fed by the (^{6}Li, ^{8}B) reaction.

Another interesting comparison can be made between these two reactions induced on a ^{10}B target. In this case, Cohen and Kurath[3] predict that a low-lying excited state in the product nucleus should be populated more strongly than its ground state. This is borne out in the ^{10}B(^{6}Li, ^{8}B)^{8}Li data, shown in Fig. 3(a), and also in the ^{10}B(p,t)^{8}B data,[11] which are not shown. One sees the expected strong population of the 3$^+$ level at 2.26 MeV relative to that of the ^{8}Li 2$^+$ ground state (the known[7] ^{8}Li level at 6.53 MeV was also observed).

The weak population of two specific final states in the above data indicates that spatially antisymmetric transfer of two protons in the (^{6}Li, ^{8}B) re-

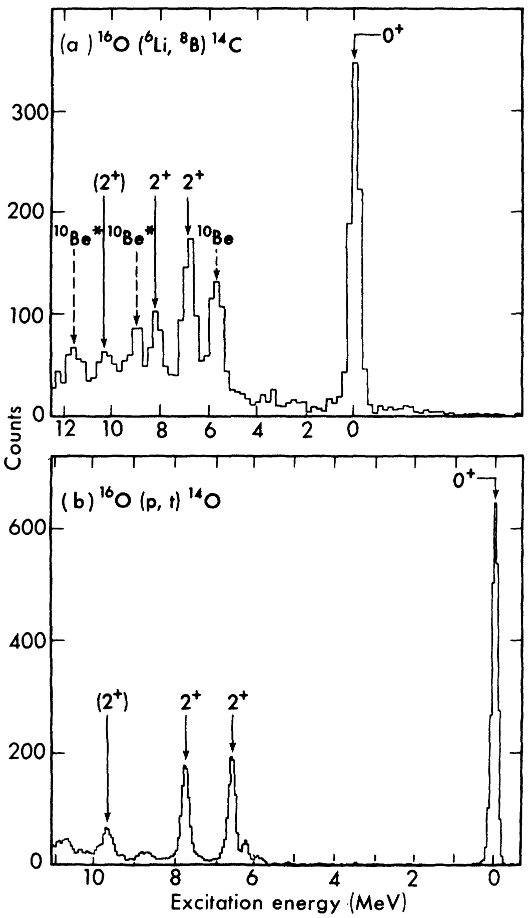

FIG. 2. (a) An energy spectrum from a partially oxidized Li target for the $^{16}O(^{6}Li, ^{8}B)^{14}C$ reaction. These data were collected at 13.5° with a 93-MeV ^{6}Li beam. Carbon contamination gave rise to the ^{10}Be states. (b) The $^{16}O(p,t)^{14}O$ reaction induced by 54.1-MeV protons at 27° (Fleming, Hardy, and Cerny, Ref. 9).

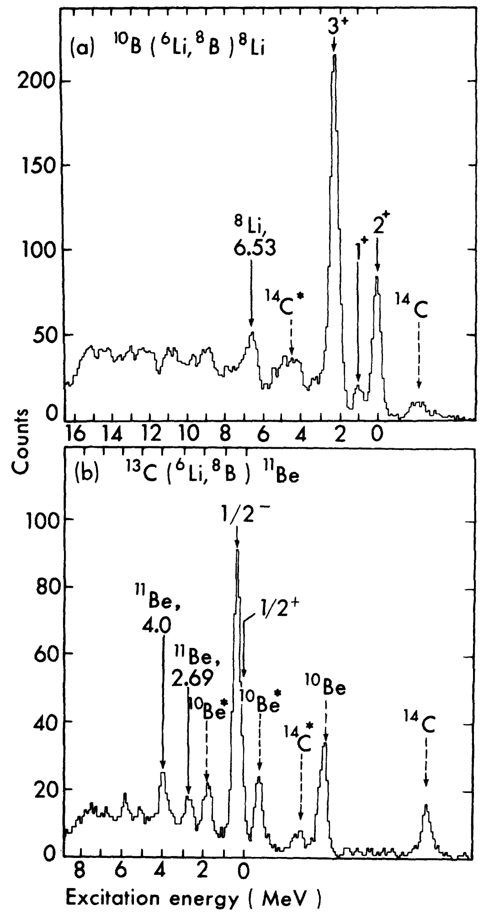

FIG. 3. (a) A composite spectrum of the $^{10}B(^{6}Li, ^{8}B)^{8}Li$ reaction ($E_{^{6}Li} = 80$ MeV) between $\theta_{lab} = 9.7°$ and 20.3° in which the data were kinematically shifted to $\theta_{lab} = 9.7°$. (b) A composite spectrum of the $^{13}C(^{6}Li, ^{8}B)^{11}Be$ reaction ($E_{^{6}Li} = 80$ MeV) between $\theta_{lab} = 9.4°$ and 20.3° for a total of 32 900 μC in which the data were kinematically shifted to $\theta_{lab} = 14.3°$. Oxygen contamination gave rise to the ^{14}C states.

action is probably not an important transfer mode. Little yield at all angles of the 1^+ level at 0.98 MeV in ^{8}Li, see Fig. 3(a), was observed; this is particularly significant since this level is essentially solely connected to the ^{10}B ground state via spatially antisymmetric transfer. Similarly, transitions from ^{16}O to the 1^+ state[10] at 11.29 MeV in ^{14}C are only possible via this transfer mode[3,5] and again are not observed [reactions on target contaminants obscure this region in Fig. 2(a), but this fact was established with the SiO_2 target]. Also noteworthy in this context is the general similarity observed in the (p,t) and $(^{6}Li, ^{8}B)$ reactions on the $T_z = 0$ targets.

The $(^{6}Li, ^{8}B)$ reaction on a ^{13}C target provides a good test of the spectroscopic selectivity of this reaction, because transitions to the ^{11}Be $\frac{1}{2}^+$ ground state[12] are forbidden in first order (see earlier $^{10}Be, 1^-$ level discussion). This unusual level ordering in ^{11}Be, consisting of an sd-shell $\frac{1}{2}^+$ ground state with the lowest $1p$-shell $\frac{1}{2}^-$ state lying at 0.32 MeV, was explained by Talmi and Unna[13] as a consequence of the differing interaction energies of the $2s_{1/2}$ and $1p_{1/2}$ neutron with the $1p_{3/2}$ protons. An energy spectrum of the $^{13}C(^{6}Li, ^{8}B)^{11}Be$ reaction is shown in Fig. 3(b). Using the energy scale readily determined from the ^{12}C contaminant, we find that the observed strength is predominantly to the $\frac{1}{2}^-$ state at 0.32 MeV, thereby additionally confirming its assignment as the lowest $1p$-shell level.[12]

Also seen in the $^{13}C(^{6}Li, ^{8}B)^{11}Be$ energy spectrum in Fig. 3(b) is a state at 2.69 MeV and a peak at ~4.0 MeV (which may contain both of the known[12] states at 3.89 and 3.96 MeV). Observation at several angles determined that the known levels at 1.79 and 3.41 MeV are populated weakly, if at all. Each of these levels was observed in the ^{9}Be(t,p)-^{11}Be reaction,[12] but it can populate both positive and negative parity states. The fact that the states at 2.69 and ~4.0 MeV were seen in the (^{6}Li,^{8}B) reaction strongly indicates that these states are $1p$-shell states and thus would have negative parity; this is consistent with the predicted[3] locations of the first three negative parity states in ^{11}Be [given a $\frac{1}{2}^-$ state at 0.32 MeV, a $\frac{3}{2}^-$ is expected at 2.6 MeV (but with a small transition strength), and a $\frac{5}{2}^-$, at 4.98 MeV].

The differential cross sections for these (^{6}Li,^{8}B) reactions decrease monotonically with angle. This is consistent with what one might expect for a high-energy heavy-ion reaction on light targets when one is far from the grazing angle. Typical cross sections ($\theta_{c.m.} \sim 20°$) for the dominant transitions were ~15 μb/sr c.m. for reactions on ^{10}B, ^{12}C, and ^{16}O targets and ~2 μb/sr on the ^{13}C target. The highly negative Q values of these reactions cause a mismatch of the dynamic properties of the ^{6}Li and ^{8}B nuclei, which contributes to the small cross sections observed.

While it may be difficult to extract quantitative spectroscopic information from this reaction owing to the large kinematic mismatch (even if the relevant optical model parameters existed), considerable qualitative information has been gained. Furthermore, no evidence for the spatially antisymmetric transfer of the two protons in this heavy-ion reaction was observed. Although the (^{6}Li,^{8}B) reaction has other possible complications compared with the counterpart (p,t) reaction, it clearly offers excellent possibilities for the spectroscopic study of two-proton hole states in neutron-excess nuclei.

We would like to acknowledge our gratitude to Dr. D. Kurath for providing some two-nucleon fractional parentage coefficients and for some useful discussions on antisymmetric transfer, to Dr. D. Ashery for help with some of the experiments, and to Dr. D. K. Scott and Dr. M. S. Zisman for some valuable discussions.

---

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

†Present address: Nuclear Physics Laboratory, University of Oxford, England.

[1]R. H. Siemssen, C. L. Fink, L. R. Greenwood, and H. J. Körner, Phys. Rev. Lett. 28, 626 (1972); P. R. Christensen, V. I. Manko, F. D. Becchetti, and R. J. Nickles, Nucl. Phys. A207, 33 (1973); D. K. Scott, B. G. Harvey, D. L. Hendrie, L. Kraus, C. F. Maguire, J. Mahoney, Y. Terrien, and K. Yagi, Phys. Rev. Lett. 33, 1343 (1974).

[2]N. A. Jelley, K. H. Wilcox, R. B. Weisenmiller, G. J. Wozniak, and J. Cerny, Phys. Rev. C 9, 2067 (1974).

[3]S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

[4]D. Kurath (private communication).

[5]D. Kurath, Comments Nucl. Part. Phys. V2, 55 (1972); O. Lkhagva and I. Rotter, Yad. Fiz. 11, 1037 (1970) [Sov. J. Nucl. Phys. 11, 576 (1970)].

[6]D. Ashery, M. S. Zisman, G. Goth, G. J. Wozniak, R. B. Weisenmiller, and J. Cerny, unpublished data; see also W. Benenson, G. M. Crawley, J. D. Dreisbach, and W. P. Johnson, Nucl. Phys. A97, 510 (1967).

[7]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A227, 1 (1974) and references therein.

[8]D. E. Alburger, E. K. Warburton, A. Gallmann, and D. H. Wilkinson, Phys. Rev. 185, 1242 (1969).

[9]D. G. Fleming, J. C. Hardy, and J. Cerny, Nucl. Phys. A162, 225 (1971); and unpublished data.

[10]G. Kaschl, G. Mairle, H. Mackh, D. Hartwig, and U. Schwinn, Nucl. Phys. A178, 275 (1971).

[11]G. T. A. Squier, A. R. Johnston, E. W. Spiers, S. A. Harbison, and N. M. Stewart, Nucl. Phys. A141, 158 (1970).

[12]F. Ajzenberg-Selove, Nucl. Phys. A248, 1 (1975).

[13]I. Talmi and I. Unna, Phys. Rev. Lett. 4, 469 (1960).