When the effects of the D state are included, the resulting analyzing powers agree well with the data. The agreement of the DWBA$(S+D)$ calculations with the measurements is generally best when the spin-orbit potentials make a small contribution to the tensor analyzing powers (for sub-Coulomb transition, for the $l_n=0$ transition, and for T_{21} for all transitions). This suggests that the less accurate agreement in other cases may result from the use of incorrect potentials, rather than from incorrect treatment of the D state. Other possible sources of error in the calculations arise from the neglect of tensor forces in the deuteron optical-model potential,[16] and from calculational errors resulting from the approximation method used.[9]

The authors wish to thank Dr. R. C. Johnson for making available the DWBA computer code which provided the calculations contained in this Letter.

---

*Now at Radiological Research Accelerator Facility, Brookhaven National Laboratory, Upton, N.Y. 11973.

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

[1] R. C. Johnson, Nucl. Phys. A90, 289 (1967).

[2] G. Delic and B. A. Robson, Nucl. Phys. A156, 97 (1970).

[3] See, for example, W. Haeberli, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970), p. 235.

[4] The three tensor analyzing powers describe the change in cross section which occurs when the incident deuteron beam is aligned. The deuterons are said to be aligned, or tensor polarized, when the population of the $m=0$ magnetic substate is different from $\frac{1}{3}$ for some choice of quantization axis. The analyzing powers are defined according to the Madison Convention as described in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, Wis., 1970).

[5] The experimental techniques have been described in detail by N. Rohrig and W. Haeberli, Nucl. Phys. A206, 225 (1973).

[6] R. C. Brown, A. A. Debenham, G. W. Greenlees, J. A. R. Griffith, O. Karban, D. C. Kocher, and S. Roman, Phys. Rev. Lett. 27, 1446 (1971).

[7] J. A. Thomson and H. O. Meyer, Bull. Amer. Phys. Soc. 18, 119 (1973).

[8] The quantity l_n is the orbital angular momentum transferred to the target nucleus in the reaction. The special properties of reactions with $l_n=0$ have been discussed in R. C. Johnson, Nucl. Phys. 35, 654 (1962).

[9] R. C. Johnson and F. D. Santos, Particles and Nuclei 2, 285 (1971).

[10] The parameters have the values $D_0=1.251D_0{}^0$, $D_2=0.484\ \mathrm{fm}^2$, and $\beta=1.341/\mathrm{fm}$, using the notation of Ref. 9. In the approximation used, the magnitude of the D-state effect on the tensor analyzing powers is approximately proportional to the parameter D_2. The value of D_2 used in Ref. 9 is 10% larger than the value quoted above. The value $D_2=0.484\ \mathrm{fm}^2$ was used in the present work because the nucleon-nucleon potential from which it was derived reproduces a wide range of scattering data, whereas the potential used in Ref. 9 does not. A discussion of how the parameters were calculated is rather lengthy and will be presented in a later publication.

[11] R. V. Reid, Ann. Phys. (New York) 50, 411 (1968).

[12] F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[13] J. M. Lohr and W. Haeberli, to be published.

[14] The neutron potential was taken to be a Woods-Saxon shape with a radius of $1.2A^{1/3}$ fm and diffuseness of 0.7 fm. A Thomas-type spin-orbit potential with a strength of 6 MeV was included, and the strength of the central potential was adjusted to reproduce the neutron binding energy.

[15] See, for example, D. C. Kocher and W. Haeberli, Nucl. Phys. A196, 225 (1972).

[16] G. Delic and B. A. Robson, Nucl. Phys. A127, 234 (1969).

Mass Excess and Low-Lying Level Structure of ^{14}B

G. C. Ball, G. J. Costa,* W. G. Davies, J. S. Forster, J. C. Hardy, and A. B. McDonald
Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited, Chalk River, Ontario K0J 1J0, Canada

(Received 11 June 1973)

The mass excess of ^{14}B has been measured to be 23.657± 0.030 MeV using the reaction $^{14}\mathrm{C}(^7\mathrm{Li},{}^7\mathrm{Be})^{14}\mathrm{B}$ at $E(^7\mathrm{Li})=52$ MeV; this shows that ^{14}B is bound by nearly 1 MeV against neutron emission. Five excited states were also observed at 0.74± 0.04, 1.38± 0.03, 1.82± 0.06, 2.08± 0.05, and 2.97± 0.04 MeV. The low-lying level structure of ^{14}B was found to be similar to the known negative-parity spectrum of ^{12}B.

The mass of ^{14}B has presented an intriguing puzzle for a number of years. In 1966, Garvey and Kelson[1] predicted ^{14}B to be nucleon stable by ~400 keV. Although they considered their result to be equivocal, a short time later the nucleus was indeed observed by Poskanzer *et al.*[2] to be bound. In that experiment, a semiconductor-counter telescope was used in conjunction with a power-law particle identifier to establish ^{14}B as one of many light nuclides produced in the spallation reaction, U + 5.3-GeV protons; its actual mass, however, remained unknown. More recently, it has been shown that the "longitudinal" mass relationship of Garvey *et al.*[3] [see their Eq. (2)] predicts ^{14}B to be *unbound* by ~400 keV[4] if current mass measurements[5] are used for neighboring nuclei. Specifically, the mass excess is given by

$$^{14}B = {}^{16}C + ({}^{13}B - {}^{17}N) + ({}^{16}N - {}^{14}C)$$

$$= 25.05 \pm 0.02 \text{ MeV},$$

or

$$^{14}B = {}^{12}Be + ({}^{15}C - {}^{11}Be) + ({}^{12}B - {}^{14}C)$$

$$= 25.00 \pm 0.10 \text{ MeV}.$$

This discrepancy between experiment and prediction is apparently characteristic[4] of $T_z = 2$ nuclei with $A = 4n + 2 \leq 26$, and may result from the incomplete cancelation of the interlevel residual neutron-proton interaction for the two odd-odd nuclei involved in each longitudinal relationship. Thus, an accurate measurement of the ^{14}B mass can help to establish the region of validity for the mass equations and eventually lead to a more precise knowledge of the nucleon drip lines among low-Z elements.

A survey of the possible reactions that could be used to measure the mass of ^{14}B shows that all have large negative Q values of ~20–25 MeV and require exotic targets and/or projectiles. We have used the reaction $^{14}C(^7Li, {}^7Be)^{14}B$ to obtain the first measurement of the mass excess of ^{14}B. The result indicates that ^{14}B is bound by nearly 1 MeV, a disagreement of ~1.4 MeV with the predictions.

A 52-MeV ^7Li beam from the upgraded Chalk River MP tandem accelerator was used to bombard a self-supporting, ~250-$\mu g/cm^2$, ^{14}C target prepared by cracking isotopically enriched (~94% ^{14}C) methyl iodide in a radio-frequency discharge.[6] A ΔE(26 μm), E(164 μm), $\overline{E}$(700 μm) solid-state counter telescope positioned at angles $\leq 20°$ was used to detect and identify the reaction products. The data were recorded event by event on magnetic tape and played back on the Chalk River PDP-10 computer using the ^7Be range-energy table of Northcliffe and Schilling[7] to describe the energy loss or each detected particle.

The $^{14}C(^7Li, {}^7Be)^{14}B$ energy spectrum obtained at $\theta_{\text{lab}} = 15°$ is shown in Fig. 1, and represents the accumulation of several shorter runs over a period of 3 days at an average beam current of 20 nA. Data from the (^7Li, ^9Be) reaction, which were obtained simultaneously in this experiment, monitored possible gain and/or zero shifts.

It is evident from Fig. 1 that the small amount of ^{12}C (8%), ^{14}N (2%), and ^{16}O (4%) in the ^{14}C target produces a significant background in the region of the ^{14}B ground state. (The iodine present does not affect the spectrum in this region.) As

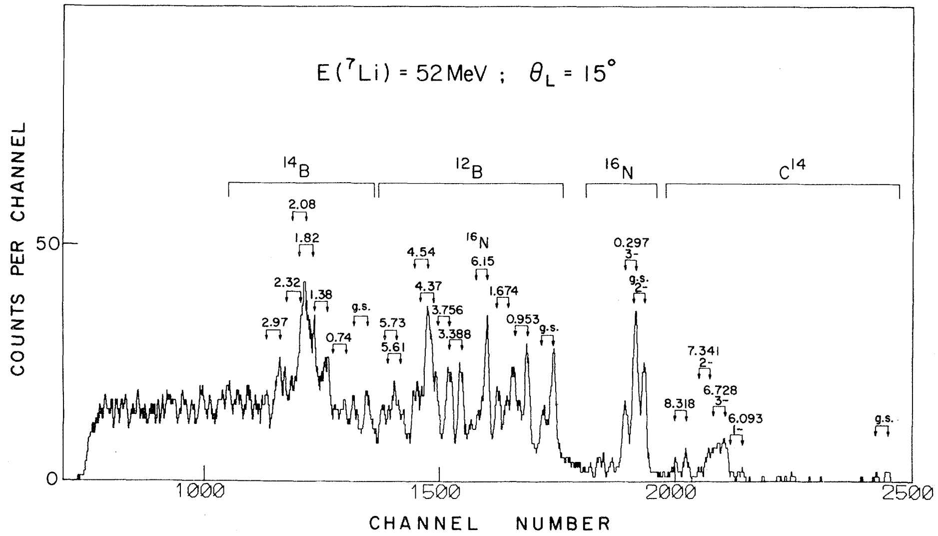

FIG. 1. An energy spectrum from the reaction $^{14}C(^7Li, {}^7Be)^{14}B$. The double arrows denote the ground and first excited (0.431 MeV) states of ^7Be. The data have been smoothed by averaging over five channels. Levels populated in the reactions $^{12}C(^7Li, {}^7Be)^{12}B$, $^{14}N(^7Li, {}^7Be)^{14}C$, and $^{16}O(^7Li, {}^7Be)^{16}N$ are also identified.

a result, it was necessary to obtain spectra for these impurities by bombarding targets of adenine ($C_5H_5N_5$), NiO, a vacuum-evaporated ^{12}C foil, and a ^{12}C film produced by cracking natural methyl iodide. A composite impurity spectrum was constructed by normalizing the individual spectra to the intensities of known[8,9] levels populated in the reactions $^{12}C(^7Li, ^7Be)^{12}B$, $^{14}N(^7Li, ^7Be)^{14}C$, and $^{16}O(^7Li, ^7Be)^{16}N$ and observed in the ^{14}B spectrum. A portion of this impurity spectrum is compared with the ^{14}B spectrum in Fig. 2. The highest-energy peak observed in the ^{14}B spectrum that could not be attributed to a known impurity level was assigned as the ground state of ^{14}B. The Q value for the reaction $^{14}C(^7Li, ^7Be)^{14}B$ was determined using the known ^{12}B, ^{14}C, and ^{16}N levels to provide an internal energy calibration of the counter-telescope system which was relatively insensitive to angle and target-thickness uncertainties. A shorter run at $\theta_{lab} = 20°$ demonstrated that the stronger peaks attributed to excited levels of ^{14}B had the expected kinematic shift.

The Q value for the reaction $^{14}C(^7Li, ^7Be)^{14}B$ was found to be -21.499 ± 0.030 MeV and corresponds to a mass excess for ^{14}B of 23.657 ± 0.030 MeV. Excited states were observed at 0.74 ± 0.04, 1.38 ± 0.03, 1.82 ± 0.06, 2.08 ± 0.05, (2.32 ± 0.04),[10] and 2.97 ± 0.04 MeV. As was found previously,[4] every level populated via the $(^7Li, ^7Be)$ reaction is observed as a doublet in the ratio $^7Be(0.431)/^7Be(g.s.) \sim 0.3$. The cross section for producing ^{14}B in its ground state was approximately 4 μb/sr.

It is well known[8] that the low-lying negative-parity levels of ^{12}B result primarily from the coupling of a $1p_{3/2}$ proton hole to a $2s_{1/2}$ or $1d_{5/2}$ neutron. In particular, the 1.674-MeV, 2^- and 2.621-MeV, 1^- levels in ^{12}B have been identified as the members of the $((p_{3/2})_\pi^{-1}, (2s_{1/2})_\nu^{1})$ multiplet, while the 3.388-MeV, 3^-, 4.37-MeV, 2^-, and 4.54-MeV, 4^- levels have been associated with the $((p_{3/2})_\pi^{-1}, (1d_{5/2})_\nu^{1})$ multiplet. Since the two extra neutrons in ^{14}B occupy the inactive $p_{1/2}$ shell, it is expected that the low-lying negative-parity spectrum of ^{14}B should be similar to that of ^{12}B.

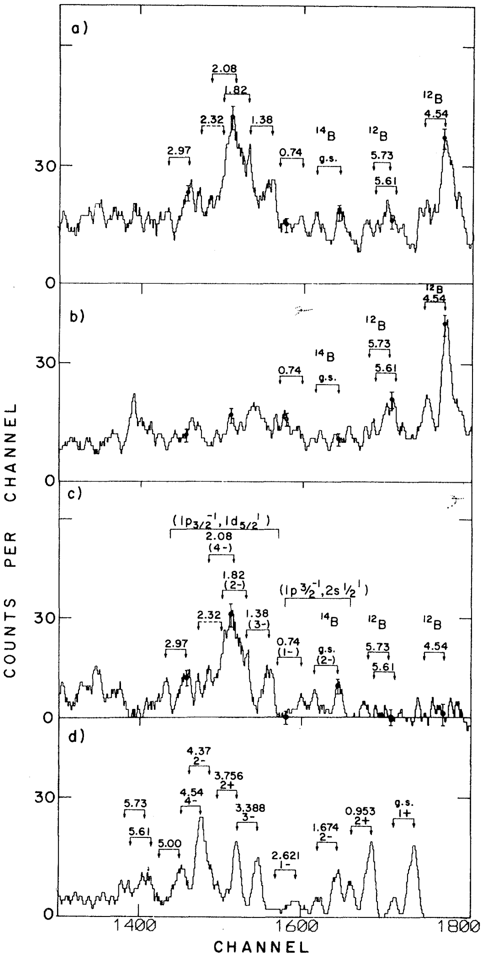

FIG. 2. (a) A portion of the ^{14}B energy spectrum shown in Fig. 1. (b) A composite (^{12}C, ^{14}N, ^{16}O) impurity spectrum. (c) ^{14}B spectrum with impurities subtracted. (d) An energy spectrum from the reaction $^{12}C(^7Li, ^7Be)^{12}B$ which has been shifted in order to compare the negative-parity states populated in ^{12}B and ^{14}B.

A comparison of the energy spectra obtained at $\theta_{lab} = 15°$ for the reactions $^{14}C(^7Li, ^7Be)^{14}B$ and $^{12}C(^7Li, ^7Be)^{12}B$ is shown in Figs. 2(c) and 2(d); a summary of excitation energies and relative intensities is given in Table I. It is apparent from these data that (1) all known negative-parity levels of ^{12}B are populated in the $(^7Li, ^7Be)$ reaction with relative intensities which differ from one another by at most an order of magnitude; and (2) a one-to-one correspondence can be established between the known negative-parity levels of ^{12}B and the ground and first four excited states of ^{14}B. These observations lead to tentative spin assignments of 2^-, 1^-, 3^-, 2^-, and 4^- for the ground state, 0.74, 1.38, 1.82, and 2.08 MeV levels of ^{14}B, respectively.

The 1.4-MeV disagreement between our measured mass of ^{14}B and that predicted by the longitudinal mass relationship suggests that formula to be inapplicable to light odd-odd nuclei with $T_z = 2$. Whether the "transverse" relationship of Garvey *et al.* [Eq. (1) of Ref. 3] should fare any better when it involves odd-odd nuclei in this

TABLE I. A comparison of the negative-parity levels populated in the reactions $^{14}C(^7Li, ^7Be)^{14}B$ and $^{12}C(^7Li, ^7Be)^{12}B$.

^{14}B			^{12}B					
Level energy (MeV± keV)	Relative intensity ^7Be(g.s.)	(0.431)	Level[a] energy (MeV)	Relative energy (MeV)	Relative intensity ^7Be(g.s.)	(0.431)	$J^{\pi\,a}$	Dominant configuration
0	1.0	0.6	1.674	0	1.0	0.4	2^-	$(1p_{3/2}^{-1}, 2s_{1/2}^{1})$
0.74± 40	0.3	<0.1	2.621	0.95	0.3	<0.1	1^-	$(1p_{3/2}^{-1}, 2s_{1/2}^{1})$
1.38± 20	1.5	b	3.388	1.71	1.4	b	3^-	$(1p_{3/2}^{-1}, 1d_{5/2}^{1})$
1.82± 60	1.6[b,c]	b	4.37	2.70	0.8	≤ 0.3	2^-	$(1p_{3/2}^{-1}, 1d_{5/2}^{1})$
2.08± 50	3.8	1.0	4.54	2.87	2.1	≤ 0.9[b]	4^-	$(1p_{3/2}^{-1}, 1d_{5/2}^{1})$

[a] See Ref. 8.

[b] These transitions were obscured by other levels.

[c] Calculated assuming $^7Be(0.43)/^7Be(g.s.) = 0.3$ for the 1.38-MeV level.

mass region must then be doubted as well. Interesting test cases could be provided by ^{13}Be and ^{15}B whose masses can be predicted with the transverse mass equation now that the ^{14}B mass is known. These masses can also be predicted, though, without using the mass of any odd-odd nucleus by combining both the longitudinal and transverse expressions. For ^{15}B the results are

$$^{15}B = {}^{14}B + {}^{16}C - {}^{14}C - {}^{16}N + {}^{15}N$$

$$= 28.75 \pm 0.03 \text{ MeV (transverse)},$$

$$^{15}B = {}^{13}B + 2({}^{16}C - {}^{14}C) - {}^{17}N + {}^{15}N$$

$$= 30.14 \pm 0.04 \text{ MeV (combination)}.$$

In either case, ^{15}B is bound by more than 1.5 MeV, and a direct mass measurement could easily distinguish between the two predictions. For ^{13}Be the comparable predictions are 35.34 ± 0.11 MeV and 36.68 ± 0.20 MeV, both indicating it to be unbound to neutron emission by at least 2 MeV.

The properties of all members of the mass-14 $T = 2$ multiplet can now be evaluated. The mass excess of ^{14}F is predicted [from Eq. (3) of Kelson and Garvey[11]] to be 33.38 MeV, which shows the nucleus to be unstable by ~3 MeV to proton decay. An estimate of the excitation energy of the lowest $T = 2$ levels in ^{14}C, ^{14}N, and ^{14}O can be made from the mass of ^{14}B using experimental Coulomb energy differences; values of 22.5, 24.8, and 22.5 MeV are obtained for ^{14}C, ^{14}N, and ^{14}O, respectively. As a result, these levels should be stable to allowed neutron decay by ~0.7 MeV and unstable to proton decay by <3.0 MeV. Boron-14 itself is expected to have a half-life of less than 50 msec with several (probably weak) β-delayed neutron branches.

---

*Attached staff from Laboratories des Basses Enérgies, Centre de Recherche Nucléaire et Université Louis Pasteur, Strasbourg/3, France.

[1] G. T. Garvey and I. Kelson, Phys. Rev. Lett. 16, 197 (1966).

[2] A. M. Poskanzer, S. W. Cosper, E. K. Hyde, and J. Cerny, Phys. Rev. Lett. 17, 1271 (1966).

[3] G. T. Garvey, W. J. Gerace, R. L. Jaffe, I. Talmi, and I. Kelson, Rev. Mod. Phys. 41, S1 (1969).

[4] G. C. Ball, W. G. Davies, J. S. Forster, and J. C. Hardy, Phys. Rev. Lett. 28, 1069, 1497 (1972).

[5] A. H. Wapstra and N. B. Gove, Nucl. Data 9, 267 (1971); H. H. Howard, R. H. Stokes, and B. H. Erkkila, Phys. Rev. Lett. 27, 1086 (1971).

[6] J. L. Gallant, Nucl. Instrum. Methods 102, 477 (1972).

[7] L. C. Northcliffe and R. F. Schilling, Nucl. Data, Sect. A 7, 233 (1970).

[8] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 114, 1 (1968); F. P. Mooring, J. E. Monahan, and R. E. Segel, Phys. Rev. 178, 1612 (1969); H. T. Fortune and C. M. Vincent, Phys. Rev. 185, 1401 (1970); R. O. Lane, C. E. Nelson, J. L. Adams, J. E. Monahan, A. J. Elwyn, F. P. Mooring, and A. Langsdorf, Phys. Rev. C 2, 2097 (1970); J. E. Monahan, H. T. Fortune, C. M. Vincent, and R. E. Segel, Phys. Rev. C 3, 2192 (1971).

[9] F. Ajzenberg-Selove, Nucl. Phys. A152, 1 (1970), and A166, 1 (1971).

[10] Brackets indicate that the existence of this level is uncertain.

[11] I. Kelson and G. T. Garvey, Phys. Lett. 23, 689 (1966).