coupling. Satchler[15] has given explicit formulas for this type of calculation. For the case at hand, the mixing ratio of 3 to 2 can be obtained from the $j-j$ coupling model, if one assumes that the captured proton is $d_{5/2}$. $L-S$ coupling gives the correct mixture also, if the proton makes the transition from the $^2P_{1/2}$ ground state of C^{13} to a $^3F_2$ compound state of N^{14}. Accordingly, neither model is favored for this particular example.

Isotopic spin selection rules for $E1$ transitions in self-conjugate ($T_z=0$) nuclei[16–18] restrict T to ± 1 only. Hence, provided the Coulomb interaction is sufficiently small, the 10.43-Mev level must be a $T=1$ state. This is in agreement with the nonobservance[19] of this level by inelastic scattering of 22-Mev α particles by N^{14}.

The integral $\int \sigma_{p,\gamma}(E)dE$ over the resonance gives a value of 0.033 Mev millibarn, in good agreement[20,21] with that calculated by detailed balance from the inverse reaction $N^{14}(\gamma,p)C^{13}$.

[15] G. R. Satchler, Proc. Phys. Soc. (London) **A66**, 1081 (1953).
[16] L. A. Radicati, Proc. Phys. Soc. (London) **A66**, 139 (1953).
[17] M. Gell-Mann and J. L. Telegdi, Phys. Rev. **91**, 169 (1953).
[18] L. A. Radicati, Phys. Rev. **87**, 521 (1952).
[19] Miller, Gupta, Carmichael, Rasmussen, and Sampson, Phys. Rev. **101**, 740 (1956).
[20] Wright, Morrison, Reid, and Atkinson, Proc. Phys. Soc. (London) **A69**, 77 (1956).
[21] C. B. Sargent (private communication).

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New Nuclear Reactions Induced by 2-Mev Lithium Ions; the Masses of B^{13} and C^{15}†

E. Norbeck, Jr.
Department of Physics and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
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A lithium ion source has been developed which can be used in a standard 2-Mev van de Graaff generator, producing a focussed beam of 1–2 microamperes of magnetically separated Li^7. Above 1.4 Mev the beam produced disintegration particles from lithium targets, and above 1.8 Mev disintegrations from beryllium were observed. The reaction $Li^7(Li^7,p)B^{13}$ was studied by observing the protons at 90° from the lithium beam. The Q value is 5.97 ± 0.05 Mev and the $M-A$ of B^{13} is 20.39 ± 0.05 Mev, corresponding to a physical atomic weight of 13.02190 ± 0.00005. The cross section for the ejection of B^{13} protons into unit solid angle at 90° rises monotonically and exponentially from 1.2 to 22 microbarns between 1.4 and 2.0-Mev bombarding energy.

Three groups of protons from the reaction $Li^6(Li^7,p)B^{12}$ were identified, and the two of lesser energy corresponded well with the known excited states of B^{12} at 0.950 and 1.67 Mev. The intensities of the proton groups at 2 Mev were ground:first excited:second excited = 1:1.1:0.8.

Two groups of protons were identified from the reaction $Be^9(Li^7,p)C^{15}$. The more energetic of these established the Q value of the reaction as 9.05 ± 0.05 Mev, and corresponds to an $M-A$ of C^{15} of 14.35 ± 0.05 Mev, or a physical atomic weight of 15.01541 ± 0.00005. The proton group of lesser energy is 2.1 times as intense as the ground state group at 2-Mev bombarding energy and at 90° from the beam; it corresponds to an excited state of the C^{15} nucleus lying 0.70 ± 0.05 Mev above the ground state.

I. INTRODUCTION

THE fact that Li^+ ions are emitted from hot filaments coated with certain lithium compounds has been known since 1916,[1] and this and other lithium ion sources have been subsequently described.[2–7] In 1935 some Russian investigators[8] reported seeing a homogeneous group of reaction products of range 8.5 cm when they turned a 1.2-Mev lithium beam onto a lithium target, but they said that they thought these were due to protons in the beam and were not the result of genuine Li–Li reactions.

In 1936 Kinsey[9] at Berkeley performed a very careful series of experiments in which he bombarded lithium and beryllium targets with 10 μa of lithium at 1 Mev. After carefully removing hydrogen both from the beam and the target he could find no neutrons or disintegration particles with a range greater than 2 cm from either target. He claimed that there was less than one disintegration per 10^{13} Li ions. The present experiments show that this conclusion was correct, and that if a few hundred electron kilovolts more beam energy had been available, reactions would have been observed.

Quite recently a group of Russians[10] accelerated lithium from a β-eucryptite source to 250 kev and used

† This work supported in part by the U. S. Atomic Energy Commission.
[1] O. W. Richardson, *The Emission of Electricity from Hot Bodies* (Longmans Green and Company, London, 1916).
[2] K. H. Kingdon, Phys. Rev. **23**, 778 (1924).
[3] R. L. Thornton and B. B. Kinsey, Phys. Rev. **46**, 324 (1934).
[4] C. A. Whitmer and M. L. Pool, Phys. Rev. **47**, 795 (1935).
[5] J. P. Blewett and E. J. Jones, Phys. Rev. **50**, 465 (1936).
[6] L. H. Rumbaugh, Phys. Rev. **49**, 882 (1936).
[7] C. A. Whitmer and M. L. Pool, Phys. Rev. **49**, 882 (1936).
[8] Petuhov, Sinelnikov, and Val'ter, Physik. Z. Sowjetunion **8**, 212 (1935).
[9] B. B. Kinsey, Phys. Rev. **50**, 386 (1936).
[10] Leviant, Korsunskii, Pivovar, and Podgornyi, Doklady Akad. Nauk S.S.S.R. **103**, 403 (1955).

the beam to determine the effective cross sections for electron loss in air for the energy range 85–250 kev.

II. APPARATUS

A. Ion Source

In designing the ion source the method of Blewett and Jones[5] was used because of the high yield and simplicity of construction. The lithium compound used was synthetic β eucryptite, made by melting an intimate mixture of powdered Li_2CO_3, Al_2O_3, and SiO_2 at 1400°C in a platinum crucible.[11] The melt was powdered and remelted, and the final melt was ground until the powder passed a 200-mesh screen. In order to apply this powder to a filament of platinum or tantalum it was suspended in amyl acetate and painted on. Emission sion of Li^+ ions occurs at temperatures near 1000°C, below the melting point of the powder. We do not have a reliable estimate of the life of such filaments, but they are capable of intermittent operation for several hours per day for several weeks. The replacement of filaments never became a major source of delay in the experimental schedule.

B. Accelerators

Two accelerators were available for this work, a 500-kev Cockcroft-Walton circuit, and a 2-Mev Van de Graaff generator constructed by the High Voltage Engineering Corporation and belonging to the Division of the Biological Sciences. We are indebted to Dr. R. E. Zirkle and Dr. W. Bloom for the loan of this machine.

Lithium ion sources were constructed for each accelerator; the one for the Cockcroft-Walton circuit will be described elsewhere.[12] For the Van de Graaff generator, the gas ion source was removed and replaced by a simple cylindrical housing, containing the coated filament and an extraction electrode. The same electrostatic beam-focussing gaps were used for Li as had been used for protons. The lithium beam, emerging vertically downward from the accelerator, was deflected into the horizontal plane by an electrostatic deflector of 36 inches radius.[13] The beam emerging from this deflector passed between two shutters connected electrically so as to supply the signal necessary to control the Van de Graaff energy through a variable corona leak.

Following the electrostatic energy selection and control, a $22\frac{1}{2}°$ magnetic deviation of the accelerated beam made it possible to direct either the Li^6 or the Li^7 constituent[14] to the target, and to remove any H^+ or H_2^+ ions if present.

[11] Initial difficulties in obtaining a melt of these materials in the proportion of 1 Li_2O:1 Al_2O_3:2 SiO_2 were resolved by adding a slight excess (5%) of SiO_2, which lowers the melting point appreciably.

[12] S. K. Allison and C. S. Littlejohn, Phys. Rev. **104**, 959 (1956).

[13] A similar device has been described by Fowler, Lauritsen, and Lauritsen, Rev. Sci. Instr. **18**, 818 (1947).

[14] The ratio Li^7/Li^6 was about 7/1 instead of the natural 12.3/1, showing some isotope separation by evaporation from the filament.

C. Targets

Films of lithium metal for use as targets were prepared by evaporating lithium metal from lithium carbonate held on a heated tantalum ribbon in vacuum. Thick lithium fluoride targets were made by melting the salt on iron buttons. Beryllium targets were machined out of the metal. In the present reactions where short range impinging lithium ions produced high-energy protons of relatively very long range, typical thin-target proton spectra were obtained from thick targets.

III. DETECTION METHODS

Some of the reactions induced by lithium bombardment of lithium and beryllium targets produce disintegration protons of ranges 30 to 240 cm in air. These particles are easily distinguished from the α particles, and other particles isotropic with helium which are grouped together in the shorter ranges. The first measurements have been confined to these long-range proton groups, and in general the method of measurement was to compare their ranges with ranges of protons of known energy, produced in well-known nuclear reactions. Foils of aluminum and Mylar[15] were placed in the path of the protons and the residual energy of the protons was measured as they impinged on a scintillating crystal attached to a photomultiplier tube held at a fixed distance from the bombardment chamber.

The experimental results reported here were obtained by an analysis of the electrical pulses from a thallium-activated cesium iodide crystal and photomultiplier tube combination. A slice of the CsI crystal 0.5 mm thick was held on the outer surface of the phototube window with silicone stopcock grease light being excluded by a thin sheet of aluminum foil over the crystal. With careful mounting these had a peak width at half maximum corresponding to 100 kev in proton kinetic energy.

IV. RESULTS

A. Energy Measurements on Disintegration Particles

1. Bombardment of Tritiated Zirconium Targets

Our first attempts to observe nuclear disintegrations produced by accelerated lithium ions was through bombardment of a tritiated zirconium target. The reactions $Li^6(t,d)Li^7$; $Q=0.988$ Mev $Li^6(t,d)Li^{7*}$; $Q=0.511$ Mev and $Li^6(t,p)Li^8$; $Q=0.800$ Mev, produced by a beam of accelerated tritons, have already been reported and studied by other investigators.[16] There are tritium–lithium-seven reactions, but the produced

[15] We wish to thank the Film Department of the E. I. Dupont de Nemours Company for supplying us with sheets of this extremely strong polyester film 0.00025 inch thick.

[16] Pepper, Allen, Almqvist, and Dewan, Phys. Rev. **85**, 155 (1952).

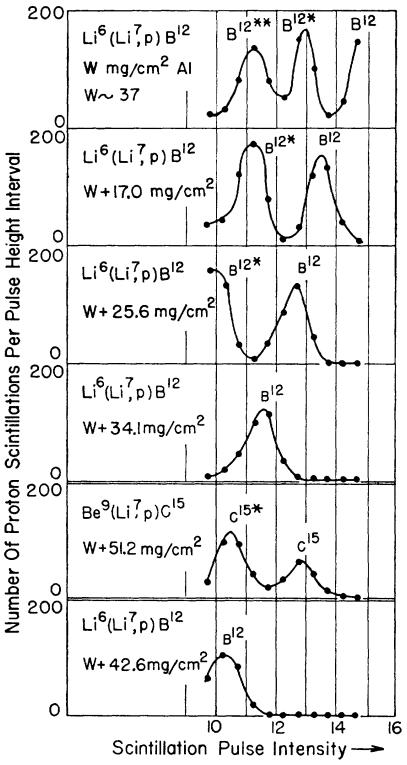

FIG. 1. Analysis of the scintillation pulse heights from a CsI(Tl) crystal struck by protons from various transmutations induced by Li^7. Aluminum stopping foils were placed in the path of the protons between target and crystal.

particles are too energetic for our energy spectrometer. The same reactions should be induced by accelerated lithium ions, except that to obtain comparable collisions in the center-of-mass system the lithium-six kinetic energy must be twice that used if tritium is accelerated. Disintegration products from the tritium target bombarded by 440-kev Li^6 and Li^7 ions were searched for, and some particles were found, but the counting rate was so low that no precise information could be obtained. The experiments were abandoned in favor of the higher beam energies obtainable from the Van de Graaff generator.

2. *Reaction* $Li^6(Li^7,p)B^{12}$

In a preliminary experiment, an unanalyzed Li^7Li^6 direct beam at 1.5 Mev from the Van de Graaff was allowed to strike a lithium metal target. It was at once apparent that yields of disintegration particles in sufficient amount for precise range measurements were being produced. Later. when the Van de Graaff energy was raised to 2.0 Mev it was seen that the lithium beam produced lesser, but still measurable, yields from beryllium metal targets.

From information available before these experiments were undertaken, it could be predicted (see Table I) that a possible new reaction to be obtained from the bombardment of a Li^6 target with a Li^7 beam is $Li^6(Li^7,p)B^{12}$. Two investigations have been made[17] from which the mass of B^{12} can be computed, and its $M-A$ is given by Ajzenberg and Lauritsen[18] as 16.912 $\pm$0.020 Mev. From these prior studies of $B^{11}(d,p)B^{12}$, excited states have been found at 0.947$\pm$0.005 and 1.674$\pm$0.011 Mev, and higher. The upper portion of Fig. 1 shows proton groups from a Li^6F target under 2.00$\pm$0.05-Mev Li^7 bombardment which clearly arise from the reaction $Li^6(Li^7,p)B^{12}$, and show the two levels mentioned. The uppermost curve shows the pulse-height analysis from the CsI(Tl) crystal when struck by protons from this reaction after they have passed through the equivalent of about 37 mg/cm² of aluminum (arising from the exit window of the target chamber, the air path, and the foil over the crystal). The figure shows how the scintillation pulse intensity decreases as increasing, and accurately measured, amounts of aluminum are placed in the path of the protons. The lower portion of Fig. 2 shows the displacement of the pulse-height maximum as a function of absorber thickness. The observed displacement of 14.5 mg/cm² Al at the same pulse height agrees well with the separation of 14 mg/cm² Al predicted in Table II.

Upon using the previous measurements of the B^{12} energy levels, it was calculated that the energies of these two excited state proton groups under the conditions of observation are 7.575$\pm$0.05 and 6.904$\pm$0.05 Mev, and these were used as reference values for the measurement of proton groups arising from reactions involving residual nuclei whose masses were unknown or more uncertain than that of B^{12}. Our estimate of the intensity ratios of the group for 2-Mev Li^7 ion bombardment is (ground):(first excited):(second excited) = 1:1.1:0.8.

TABLE I. Exothermic reactions to be expected from lithium bombardment of lithium targets.

Reaction	Q(Mev)	Reaction	Q(Mev)
	Li^7 beam, Li^7 target		
$Li^7(Li^7,p)B^{13}$	(5.97)[a]	$Li^7(Li^7,\alpha)Be^{10}$	14.77
$Li^7(Li^7,d)B^{12}$	3.31	$Li^7(Li^7,He^5)Be^9$	6.96
$Li^7(Li^7,t)B^{11}$	6.22	$Li^7(Li^7,He^6)Be^8$	7.23
	Li^7 beam, Li^6 target		
$Li^6(Li^7,p)B^{12}$	8.32	$Li^6(Li^7,He^3)Be^{10}$	1.450
$Li^6(Li^7,d)B^{11}$	7.19	$Li^6(Li^7,\alpha)Be^9$	15.21
$Li^6(Li^7,t)B^{10}$	1.99	$Li^6(Li^7,He^5)Be^8$	12.54
	Li^6 beam, Li^6 target		
$Li^6(Li^6,p)B^{11}$	12.21	$Li^6(Li^6,He^3)Be^9$	1.884
$Li^6(Li^6,d)B^{10}$	2.98	$Li^6(Li^6,\alpha)Be^8$	20.78
$Li^6(Li^6,t)B^9$	0.797	$Li^6(Li^6,He^5)Be^7$	0.898

[a] Measurement reported in this paper; other values estimated from $M-A$ values in F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955), p. 157.

[17] M. M. Elkind, Phys. Rev. **92**, 127 (1953); Buechner, Van Patter, Strait, and Sperduto, Phys. Rev. **79**, 262 (1950).

[18] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

3. *Reaction* $Li^7(Li^7,p)B^{13}$

A measurement of the proton energy from $Li^7(Li^7,p)B^{13}$ led to a determination of the mass of B^{13} which has been briefly reported.[19] From Table I we can calculate that, at 1.61-Mev bombarding energy, the expected range for the d's at 90° in the laboratory system from $Li^6(Li^7,d)B^{11}$ is 33 cm in air, and that the range of the protons from $Li^6(Li^7,p)B^{12}$ is 82 cm. Any proton groups of intermediate range which can be demonstrated to appear in the Li^7 beam Li^7 target combination and not with a Li^7 beam and Li^6 target must leave as a residual nucleus B^{13}. (Their absence in the Li^7Li^6 combination would show that they cannot arise from $Li^6(Li^7,p)B^{12*}$.) A group with these properties was found, at 49.7 cm air range, or 73.7 mg/cm² A'. The new proton group was compared with a 58-cm proton group from $B^{10}(d,p)B^{11*}$ whose Q value has been measured by magnetic analysis.[20]

The protons in question will have an energy of 6.802±0.008 Mev at 90° in the laboratory from a 400-kev deuteron beam. The deuteron beam for this reaction was furnished by the kevatron. The photomultiplier tube was firmly clamped to the target chamber so that all parameters could be held constant even when the entire assembly was moved to a different accelerator. Great care was exercised to insure that no conditions were changed. The same cables were used, and all the relevant voltages were measured, using the same meters. The photomultiplier tube voltage was measured by an accurate electrostatic voltmeter. After taking data using both accelerators, everything was moved back to the first in order to insure that nothing changed. A comparison of the known and unknown protons is included in Fig. 2.

The identity in slope of the new curve with that of the known protons from boron shows that the new particles from lithium are protons. The two curves were displaced by 12.35±0.5 mg/cm² of aluminum, or 8.35 ±0.5 cm of air, and using the slope of the proton range-energy curve in this region we find 6.23±0.05 Mev for the energy of the new proton group. See Table II.

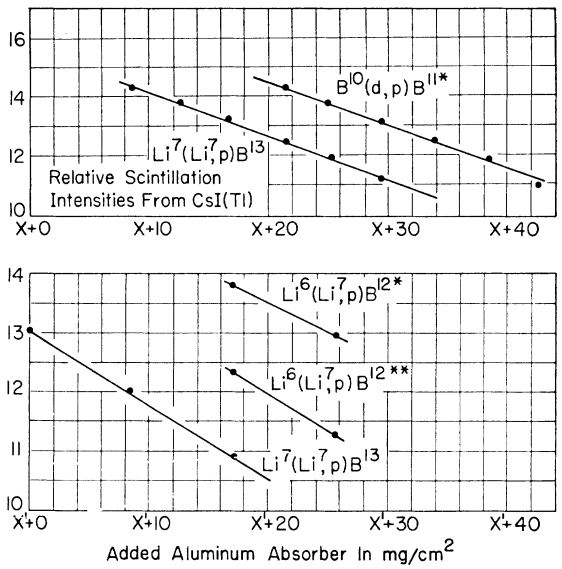

FIG. 2. Plots of maximum pulse height against absorber thickness, constructed from observations of the type shown in Fig. 1. Horizontal displacements correspond to range differences.

TABLE II. The Q-value of $Li^7(Li^7,p)B^{13}$.

Item	Source of comparison protons $B^{10}(d,p)B^{11*}$	$Li^6(Li^7,p)B^{12*}$	$Li^6(Li^7,p)B^{12**}$
Q value of ground state reaction (Mev)	9.235±0.011[a]	8.325±0.02[b]	8.325±0.02[b]
Energy of excited state (Mev)	2.138±0.009[a]	0.947±0.005[b]	1.674±0.011[b]
Bombarding energy (Mev)	0.400	2.00 ±0.05	2.00 ±0.05
Energy of comparison protons at 90° lab system (Mev)	6.802±0.008	7.575±0.05	6.904±0.05
Range of comparison protons in Al (mg/cm²)	85.8	102	88.0
Range difference B^{13}—comparison (mg/cm²)	−12.4	−25.5	−11.0
Energy of B^{13} protons (Mev)[c]	6.23 ±0.05	6.39 ±0.05	6.41 ±0.05
Q for $Li^7(Li^7,p)B^{13}$	5.97 ±0.05	5.97 ±0.05	5.99 ±0.05
$M-A$ for B^{13} (Mev)	20.39 ±0.05	20.39 ±0.05	20.37 ±0.05

[a] Van Patter, Buechner, and Sperduto, reference 20.
[b] Buechner, Van Patter, Strait, and Sperduto, reference 17.
[c] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663, May 28, 1951 (unpublished).

[19] Allison, Murphy, and Norbeck, Phys. Rev. **102**, 1882 (1956).
[20] Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).

If we use the published mass values and a lithium beam energy of 1.61 Mev, it follows from the conservation of energy and momentum at 90° that the Q value of the new $Li^7(Li^7,p)B^{13}$ reaction is 5.97±0.05 Mev, giving B^{13}, presumably in its ground state, a value of $(M-A)$ equal to 20.39±0.05 Mev, or a physical atomic weight of 13.02190±0.00005. This agrees with the value of 19±2 Mev for $(M-A)$ predicted by Barkas.[21]

The mass of B^{13} was subsequently remeasured by using the same $Li^7(Li^7,p)B^{13}$ proton group but different standards of reference, namely the proton groups from the first two excited states of B^{12} in $Li^6(Li^7,p)B^{12}$ as previously discussed. The comparison is shown in the lower part of Fig. 2. Using this comparison makes it unnecessary to transport all the equipment to another accelerator. The result agreed closely with that obtained from the $B^{10}(d,p)B^{11}$ comparison protons (see Table II).

4. *Reactions* $Be^9(Li^7,p)C^{15}$ *and* $Be^9(Li^7,p)C^{15*}$

With the Van de Graaff operating at 2 Mev, it was possible to penetrate the Coulomb barrier of beryllium sufficiently to obtain small but measurable yields of protons from $Be^9(Li^7,p)C^{15}$. The yield of protons per steradian per microcoulomb of Li^7 was roughly 1/300 of that from the B^{13} reaction. As shown in the pulse height analysis in Fig. 1, two groups of protons were

[21] W. H. Barkas, Phys. Rev. **55**, 691 (1939).

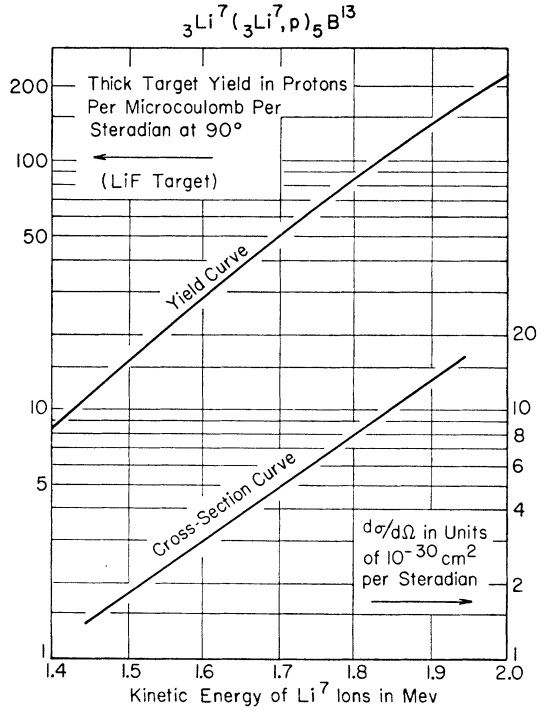

FIG. 3. Yield of 50-cm protons from a LiF target bombarded with Li^7 ions, and the cross section of Li^7 for the reaction $Li^7(Li^7,p)B^{13}$.

found, and were compared with the protons from $Li^6(Li^7,p)B^{12}$, according to Table III. There is of course, always the question as to whether the most energetic group of protons observed represents a transition to the ground state. A search for higher energy proton groups from $Be^9(Li^7,p)C^{15}$ however showed that if this is not really the ground state, the protons from the real ground state would be at least 100 times fewer in number than those from our alleged ground state. Such a strong selection rule seems unlikely. Table III shows that the proton group of lesser energy is 2.1 times as intense as the ground state group and may be interpreted as arising from a C^{15} excited state at 0.70 Mev.

B. Yields and Cross Sections

The yield of protons from the B^{13} reaction has been measured as a function of bombarding energy of the Li^7 beam. The target was a thick deposit of natural LiF and the measurements were made into a solid angle of approximately 0.05 steradian at 90° from the lithium beam. The results are exhibited in Fig. 3.

The thick target yield curve was converted into a cross-section curve by the conventional calculation, which results in the formula

$$\frac{d\sigma}{d\Omega}=-\frac{1}{N_pN_T}\left(\frac{dY}{dE}\right)\left(\frac{dE}{dx}\right),$$

in which $d\sigma/d\Omega$ is the cross section for disintegration protons into unit solid angle at 90° in the laboratory, N_p is the number of Li^7 ions striking the target per microcoulomb, N_T is the number of Li^7 nuclei per cm^3 in the target, dY/dE is the slope of the yield-energy curve (Y in protons per steradian per microcoulomb; E in Mev), and dE/dx is the stopping power of the target material for the beam ions in Mev per centimeter.

The stopping power of LiF for 1.61-Mev Li^7 ions was estimated to be 5.7×10^3 Mev/cm, by using data on the stopping power for helium and lithium ions obtained in this laboratory and as yet unpublished. $N_p=6.2\times10^{12}$; $N_T=4.7\times10^{22}$. Values of dY/dE were obtained from the yield curves. The resultant cross sections, which vary from 1.2 to 19 microbarns per steradian as the Li^7 energy rises from 1.4 to 1.95 Mev, are exhibited in Fig. 3. The excitation curve shows no resonances and is undoubtedly determined almost entirely by the Coulomb potential barrier.

V. DISCUSSION OF RESULTS

A. B^{13}

It has been anticipated that the nuclear species B^{18} would be stable with respect to disintegration into other heavy particles. Using the mass found in this investigation, this prediction is verified. The least endothermic heavy-particle breakup would be $B^{13}\rightarrow B^{12}+n$; $Q=-4.88$ Mev. B^{13} is undoubtedly a β emitter; the full energy available for the transition to the ground state of C^{13} is 13.43 Mev. β emission from Li^7 targets bombarded by a Li^7 beam, decreasing markedly in $\sim$0.1 sec after shutting off the beam, has been demonstrated. Unfortunately the 0.022-sec B^{12}, with β rays of approximately the same energy, is also produced and further experiments will be necessary to eliminate the interference. Some other reaction might be used to produce B^{13} without the B^{12} interference although all other reactions leading to B^{13} are endothermic.

Considerable interest has been shown in the nuclide B^{13} because it was suspected of being a delayed neutron emitter.[22] These delayed neutrons have been searched for in fission and spallation fragments with negative results.[23,24] The argument suggesting the delayed neutron activity postulates an analogy between B^{13} and N^{17}. It is observed that O^{17} with one neutron added to a very stable nucleus emits a neutron when it is produced in an excited state from the β decay of N^{17}. Similarly C^{13} arising from the β decay of B^{13} has just one neutron added to a very stable nucleus. The shell model now shows that the analogy is really very poor. The ground state spin of N^{17} is $1/2^-$ which is discouraged from decaying to the $5/2^+$ ground state of O^{17} by the selection rules. It therefore goes mostly to excited states, some of which have enough energy to emit neutrons. The ground state of B^{13} would be expected to be a $3/2^-$

[22] A. H. Snell, Science **108**, 172 (1948).
[23] Hubbard, Ruby, and Stubbins, Phys. Rev. **92**, 1494 (1953).
[24] R. K. Sheline, Phys. Rev. **87**, 557 (1952).

state which would go almost entirely to the $1/2^-$ ground state of C^{13}. From a study of the energy levels for C^{13} it can be seen that the branching ratio for decay of B^{13} into neutron producing levels would be completely negligible.

B. C^{15}

β rays of mean life 2.4±0.3 seconds, presumably arising from the decay of C^{15}, have been observed by Hudspeth, Swann, and Heydenburg.[25] They bombarded a $BaCO_3$ target containing 40% C^{14} with 2.4-Mev deuterons, the reaction being $C^{14}(d,p)C^{15}$. They estimated that the maximum energy of the β-ray spectrum is 8.8±0.5 Mev. Later, Rickard, Hudspeth, and Clendenin[26] studied the excitation curve for the production of the 2.4-second activity from C^{14}, and from theoretical analysis of the excitation curve concluded that Q for the (d,p) reaction lies between 0 and 0.3 Mev, most probably at 0.15±0.15 Mev, placing the $M-A$ of C^{15} at 13.1 Mev, and predicted that the observed β spectrum upper limit would be 8.6 Mev.

In experiments at the University of Wisconsin, Douglas, Broer, and Chiba[27] failed to confirm the small, possibly positive Q-value for $C^{14}(d,p)C^{15}$ and found $Q=-0.96$ Mev. They confirmed the 2.4-second life of C^{15}, but found no β radiation as energetic as 5–10 Mev, concluding that most (if not all) of the β transitions are to excited states of N^{15}.

After further work Bostrom, Hudspeth, and Morgan[28] found that their weak activity from C^{15} had been mixed with activity resulting from deuteron bombardment of O^{18}. Proper allowance for this puts the earlier work from their group[26] into agreement with the Wisconsin value.

Our value of $M-A$ for C^{15} is 14.35±0.05 Mev, which predicts that Q for $C^{14}(d,p)C^{15}$ is −1.06 Mev. The bombardment threshold in the laboratory system should then be 1.22 Mev. Thus our results confirm the Wisconsin measurement of the ground state of C^{15} and add to this the discovery of an excited state of this nucleus at 0.70 Mev.

TABLE III. Q values of $Be^9(Li^7,p)C^{15}$ and $Be^9(Li^7,p)C^{15*}$. (Disintegration protons observed at 90° from a 2.00±0.05 Mev lithium beam.)

Source of comparison protons	$Li^6(Li^7,p)B^{12}$; $Q=8.325$ Mev	
Energy of comparison protons	8.45±0.02 Mev	
Range of comparison protons in Al	124.5 mg/cm²	
Item	$Be^9(Li^7,p)C^{15}$	$Be^9(Li^7,p)C^{15*}$
Range difference C^{15}—comparison (mg/cm² Al)	+27.31±0.7	+9.63±0.7
Energy of C^{15} protons (Mev)	9.48±0.05	8.82±0.05
Q value (Mev)	9.05±0.05	8.35±0.05
Excitation energy (Mev)	0	0.70±0.05
$(M-A)C^{15}$ (Mev)	14.35±0.05	...
Physical atomic weight	15.01541±0.00005	...
Intensity of group/intensity of ground state	...	2.1

It has been suggested[29] that the ground state of C^{15} has a spin of $\frac{1}{2}^+$, and that the analog level with $T=\frac{3}{2}$ in N^{15} has been observed from $C^{14}(p,\gamma)N^{15}$ at 11.61 Mev which is reasonably close to the expected value of 11.9 Mev, obtained after correcting the 9.8-Mev $C^{15}-N^{15}$ difference for Coulomb energy. If this is the case, the 0.70-Mev C^{15*} level probably has $J=5/2^+$, but the expected similarity of C^{15} to O^{17} with its $J=5/2^+$ ground state and 0.98-Mev $J=1/2^+$ state is some evidence for a similar assignment to the C^{15} ground and first excited state.

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[25] Hudspeth, Swann, and Heydenburg, Phys. Rev. **77**, 736 (1950).
[26] Rickard, Hudspeth, and Clendenin, Phys. Rev. **96**, 1272 (1954).
[27] Douglas, Broer, and Chiba, Phys. Rev. **100**, 1253 (1955).
[28] Bostrom, Hudspeth, and Morgan, Bull. Am. Phys. Soc. Ser. II, **1**, 94 (1956).
[29] Bartholomew, Litherland, Paul, and Gove, Can. J. Phys. **34**, 147 (1956); see also Can J. Phys. **33**, 441 (1955).