Nuclear Energy Levels and Mass of Nitrogen-17†*

C. S. LITTLEJOHN
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois

(Received November 7, 1958)

Energy levels and the atomic mass defect of the nucleus N^{17} have been determined by measuring the kinetic energies of proton groups produced in the reaction $B^{11}(Li^7,p)N^{17}$ on bombardment of isotopically separated B^{11} targets with 2-Mev Li^7 ions.

The protons were counted at 90°, in the laboratory system, from the forward direction of the lithium beam. The group of highest energy gave an $(M-A)$ value of 12.92 ± 0.06 Mev for the N^{17} ground state, corresponding to a physical atomic weight of 17.01388 ± 0.00006. Two completely resolved groups of lower energy showed excited states at 1.32 and 1.89 Mev. Two strong but incompletely separated peaks showed levels at 2.50 and 2.82 Mev of excitation. Incompletely resolved groups of lower energy indicated four higher states at 3.27, 3.57, 3.86, and 4.18 Mev. Due to low counting rates, intensity estimates are difficult but indicate that, at 90° and 2-Mev bombardment, the ground-state group is only $\frac{1}{4}$ as strong as the most intense groups which arise from the 2.50 and 2.82-Mev levels. The groups from the higher levels (3.3–4.2 Mev) are less intense by a factor of 0.7. A comparison is made of the spectrum of N^{17} with O^{17} and F^{17}. Coulomb corrections are applied to calculate the isotopic spin $T=\frac{3}{2}$ sequence corresponding to the above levels in O^{17}, the lowest such level being predicted at 11.04 Mev in O^{17}. A brief discussion is given of the reaction and also of the interpretation in terms of nuclear shell structure of the levels observed.

INTRODUCTION

THE use of the lithium ion beam at the 2-Mev Van de Graaff accelerator at the University of Chicago has made possible the study of the properties of various light nuclei which are relatively inaccessible through standard techniques of bombardment.[1–4] Nuclear reactions occurring during the bombardment of light elements for which the low-energy lithium projectiles can penetrate the Coulomb barrier lead to many reaction products lying on the high neutron side of the line of stable nuclides. Thus it is possible, with (Li,p) and (Li,d) reactions in particular, to investigate rather easily the energy levels of these residual nuclei having an excess of neutrons.

Very little experimental information is available to date for the nuclide N^{17}. Its beta decay has been studied by Alvarez and others[5–8]; the half-life is 4.14 ± 0.04 seconds. The beta decay is complex and proceeds to an excited state or states of O^{17} which in turn decay by neutron emission to O^{16}. The maximum energy of the beta spectrum has been given as 3.7 ± 0.2 Mev by Alvarez; the log ft value is 3.8. The evidence for the mass of N^{17} comes almost entirely from the work of Alvarez on the beta decay. It was felt that a more accurate value for the mass could be obtained from the more straightforward measurements which are possible with lithium reactions.

The reactions $C^{14}(\alpha,p)N^{17}$, $O^{17}(n,p)N^{17}$, $O^{18}(\gamma,p)N^{17}$, as well as photospallation reactions leading to N^{17}, have been reported in the literature.[9–11] No excited states of N^{17} have yet been reported.

The bombardment of a B^{11} target with the Li^7 beam leads to the formation of the nuclide N^{17} by the reaction $B^{11}(Li^7,p)N^{17}$, which is exothermic by approximately 8.4 Mev. By detecting and measuring the energy of the proton groups emitted in this two body reaction during the bombardment, excited states of N^{17} can be observed. Levels up to 9 Mev in N^{17} should be excited in this reaction; however, in actual practice, low-energy proton groups corresponding to high excitations in N^{17} are difficult to observe due to the presence of many other reaction products. The proton groups from levels up to 4.2 Mev excitation, however, may be studied in the absence of all charged nuclear particles from competing reactions by interposing 52 mg/cm² of Al between target and scintillating crystal.

APPARATUS

Lithium Ion Beam

Descriptions of the production and analysis of lithium ion beams have been given in previous publications.[3,12] In the present experiment, ions from isotopically separated Li^7 β-eucryptite heated on a tungsten filament were accelerated to 2 Mev and passed through a 36-in. radius 90° electrostatic analyzer which gave an energy control of ±0.01 Mev at 2 Mev. The beam was subsequently analyzed by a $22\frac{1}{2}°$ deflection by an electromagnet to separate the Li^7 beam from any impurities present. The cross section of the beam on the target was about 0.25 cm². Beam intensities on the target of 5 μa or greater were used throughout the course of the experiments described in this paper.

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

* Submitted in partial fulfillment of the requirements for the Ph.D. degree at the University of Chicago.

1 E. Norbeck, Jr., and C. S. Littlejohn, Phys. Rev. **108**, 754 (1957).
2 Allison, Murphy, and Norbeck, Phys. Rev. **102**, 1182 (1956).
3 E. Norbeck, Jr., Phys. Rev. **105**, 204 (1957).
4 P. G. Murphy, Phys. Rev. **108**, 421 (1957).
5 L. W. Alvarez, Phys. Rev. **75**, 1127 (1949).
6 Knable, Lawrence, Leith, Meyer, and Thornton, Phys. Rev. **74**, 1217(A) (1948).
7 Stephens, Halpern, and Sher, Phys. Rev. **82**, 511 (1951).
8 E. Hayward, Phys. Rev. **75**, 917 (1949).
9 Sun, Jennings, Shoupp, and Allen, Phys. Rev. **82**, 267 (1951).
10 Charpie, Sun, Jennings, and Nechaj, Phys. Rev. **76**, 1255 (1949).
11 D. Reagan, Phys. Rev. **93**, 947(A) (1954).
12 S. K. Allison and C. S. Littlejohn, Phys. Rev. **104**, 959 (1956).

Target Chamber and Detecting Equipment

The target chamber and associated detecting equipment used in this experiment were essentially as described by Murphy.[13] An improvement consisted in the construction of a simple target holder which changes the target exposed to the beam upon 180° rotation about its axis. Thus targets may be changed immediately, and if one is chosen which gives a proton producing reaction in which all nuclei and levels concerned are well known, groups of protons for calibration purposes are available at any time. Protons from the reaction $Li^6(Li^7,p)B^{12}$ are comparable in energy to those of interest here and were used in most of the calibrations.

Reaction products emerging at 90° to the beam passed through a window of Mylar or aluminum of known stopping power and then into a cell provided with four retractable rings in which aluminum foil absorbers of various thicknesses were mounted. From here the particles passed into a methane-filled proportional counter and finally lodged in a CsI(Tl) scintillating crystal fixed to a quartz light pipe, which is in optical contact with a Dumont 6292 photomultiplier tube. The function of the proportional counter in this experiment is to discriminate against gamma rays and beta particles which would otherwise be counted, but it has also been employed successfully in conjunction with a single-channel analyzer to select particles within a certain range of values of dE/dx, that is to say, effectively to separate protons from deuterons, tritons, alpha particles, and heavier fragments.[14] The proportional counter was operated with a steady flow of methane at a pressure of 4 cm, regulated by a manostat. The 0.005-in. diam. tungsten wire electrode was operated within the proportional region at 1420 v. The thallium-activated cesium iodide scintillating crystal was cut from a larger block with a jeweler's saw to dimensions 3 cm by 1 cm by a thickness of 1 mm, and was subsequently carefully polished with rouge and xylene, and fixed permanently to a quartz window with a clear Shawinigan resin.[15] The over-all energy resolution of the equipment during the runs was 13% for comparison protons of 5 Mev remnant energy after having passed through 75 mg/cm² of aluminum absorber.

Electronics

The electronic circuits and the pulse-height analyzer were as described by Murphy.[13] The experiments were characterized by low counting rates, and reduction of the number of spurious counts was most important. It was found that disturbances from occasional sparks in the electrostatic deflector or the Van de Graaff were not picked up by the proportional counter circuit. Thus by connecting a spark antenna to the input of the amplifier the spark counts could all be thrown into the highest channel along with rejected β- and γ-ray pulses. The remnant background count totaled five to ten counts over all channels during several hours running.

Target Preparation

Preliminary survey work was done with a boron target of the natural isotopic mixture (81.2% B^{11}), using a B^{10} target for a subtraction in order to obtain the B^{11} contribution. The results presented here have all been obtained using pure B^{11} targets, which were prepared from boron powder isotopically separated by Oak Ridge and specified as 98.5% B^{11} and 1.5% B^{10} with only small iron impurities. The targets were prepared by compressing to 40 or 50 tons per square inch in a powder briquetting die and sintering at 800° centigrade in an inert helium atmosphere.[16] Thick targets were used in this experiment. This is not a serious disadvantage as the reaction yield falls off very rapidly below 2 Mev; in addition, the change in energy of the protons with the lithium beam energy is small as a result of the large Q-value involved. Furthermore, the total range of the impinging lithium ions in the boron is very small, so that it is effectively thin for the escape of protons. Thus a layer of B^{11} 0.16 mg/cm² thick will reduce the energy of the 2-Mev Li^7 beam to 1.5 Mev, but will only remove 0.007 Mev from a 9-Mev proton. Systematic errors arising from the use of thick targets have been taken into consideration in the evaluation of the data, and uncertainties arising from this source are included in the tabulated experimental errors.

PROCEDURE AND RESULTS

Measurement of the Energies of the Proton Groups

Figure 1 shows the result of a short run in which the 9.02 Mev (ground state) proton group, and the groups at 7.77 and 7.24 Mev can be located on the pulse-height analyzer scale with varying amounts of aluminum absorber in the proton path between the target and the scintillating crystal. The relative intensities of the groups roughly estimated later in this report come from the improved statistics gained by collective evaluation of many such runs. Immediately before and after such a run, the target was rotated 180° and a comparison spectrum obtained by bombarding, for instance, $Li_2{}^6SO_4$ with the Li^7 beam to obtain proton groups from $Li^6(Li^7,p)B^{12}$ reaction, which has $Q=8.325$ Mev[17]

[13] See Fig. 1 of reference 4.

[14] This technique was used in a study of the excited states of B^{13} which is being carried out by the author in collaboration with G. C. Morrison.

[15] "Gelva V-2½" from Shawinigan Products Corp., Empire State Building, New York 1, New York.

[16] The author is grateful to E. Warzynski of the Institute for the Study of Metals of the University of Chicago for assistance in the preparation of boron targets and β-eucryptite.

[17] Q-values are calculated using the tabulated atomic mass defects in: F. Ajzenberg and T. Lauritzen, Revs. Modern Phys. **27**, 1, 77–166 (1955). Energy levels are also quoted from this source.

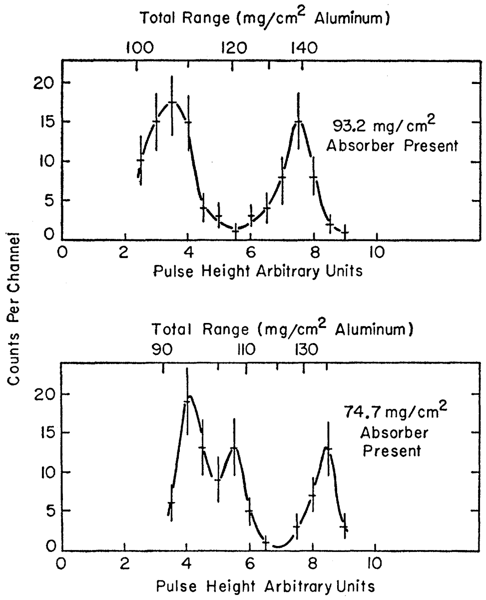

FIG. 1. Identification of pulse heights appropriate to the 7.24, 7.77, and 9.02 Mev (ground state) proton groups with two different absorber thicknesses.

and well-known levels in B^{12}. Sometimes the ground-state protons from $Li^7(Li^7,p)B^{13}$ were used in this way. With the four foils available in addition to a base foil, it was possible with suitable choices of aluminum absorber to reduce the groups being studied and the comparison peaks to low and comparable energies so that a sensitive measurement of the range difference between unknown and comparison groups was possible. Direct superposition of the unknown peaks by peaks from known proton groups was in most cases effected; when interpolation was used it was possible, because of the differential linearity of the crystal response, to obtain the energy of the unknown peaks.

Results on the energies of the proton groups and the energies of the excited states of N^{17} deduced from them are shown in Table I. The evidence that the particles being measured are actually protons is that they exhibit the expected ranges and energy losses in aluminum, using the accepted values of dE/dx for protons. One may question whether any peaks come from other sources than the Li^7-B^{11} reaction. Because of the effect of the rising Coulomb barrier, nuclear reactions of the lithium beam with any nuclei of higher Z present in the target are very strongly reduced, and for the case of small target contamination this background may be ignored completely. (The low yield in the case of carbon was verified in a separate experiment.) In view of the very low cross sections in lithium-boron reactions, a further possibility was investigated. After long bombardments one might expect to obtain reactions of the beam with lithium from the beam deposited on the target. In previous work at this laboratory,[1] such an effect was seen after a 50-minute 2900-microcoulomb bombardment of a clean SiO_2 target with Li^6. The most energetic proton group from $Li^7(Li^7,p)B^{13}$ has 6.40-Mev kinetic energy under the present experimental conditions, and thus is capable of interfering with the 6.35-Mev group from $Li^7(B^{11},p)N^{17*}$. The 6.35-Mev group, however, appeared at once from a fresh boron target and the counts in the appropriate channel of the pulse-height analyzer increased linearly with time.

As is seen from Table I, groups differing in energy by 0.30 Mev were incompletely resolved, and the possibility always exists that under significantly higher resolution, further structure might be revealed. There are theoretical indications that the group from the 1.89-Mev level might be a doublet of 230-kev separation (see later in this report). Although several runs were made on this peak with the possibility in mind, clear evidence of doublet structure was not obtained.

In addition to the possibility of unresolved doublets in the observed spectrum, there also remains the possibility of peaks of yield sufficiently low that they are obscured by adjacent higher intensity levels. There is no evidence for any such level in the first 2.2 Mev of excitation in N^{17}, but it is possible that a level of half the intensity of the ground state or less might be completely obscured in the poorly resolved region of higher excitation. It should be kept in mind, also, that only groups which have sufficient intensity at 90° in the laboratory system were seen.

Errors in the determination of the energies of the proton groups will be discussed in connection with the energy measurement of the ground-state group (see Fig. 1). The half-width of the peak is approximately 300 kev, but it should be possible to locate the center of the peak to perhaps $\frac{1}{6}$ of this. At the remnant energy of the peak of 4.75 Mev, $dE/dx=0.061$ Mev/mg/cm^2; therefore this corresponds to an uncertainty of 0.8 mg/cm^2, or, at the full energy of the group, an uncertainty of 0.03 Mev.[18] A further source of errors arises

TABLE I. Proton groups observed in the reaction $B^{11}(Li^7,p)N^{17}$ and corresponding energy levels in the nuclide N^{17}.

Proton range (mg/cm² Al)	Proton kinetic energy (Mev)	N^{17} excitation (Mev)
A. Completely resolved groups		
139.8	9.02±0.05	0
107.0	7.77±0.06	1.32±0.08
95.1	7.24±0.06	1.89±0.08
B. Two isolated but incompletely resolved groups		
82.6	6.66±0.06	2.50±0.08
76.3	6.35±0.06	2.82±0.08
C. Groups estimated as maxima in an incompletely resolved band		
67.7	5.93±0.07	3.27±0.09
62.6	5.65±0.07	3.57±0.09
57.4	5.37±0.07	3.86±0.09
52.0	5.07±0.07	4.18±0.09

[18] Ranges are quoted from the range-energy curves of Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU-663 (unpublished).

in the superposition of the group with a comparison peak. For example, the ground state group in Fig. 1 was compared with the ground-state protons from the Li^7-Li^6 reaction with Al thicknesses of 74.7 mg/cm^2, 77.9 mg/cm^2, and 80.0 mg/cm^2, the group almost superposing with the intermediate foil setting. It was clear that a difference of 1.0 mg/cm^2 was easy to distinguish and that the error in the peak superposition was less than 0.03 Mev. The uncertainty in the absolute energy of the comparison peaks, as mentioned previously, is ± 0.02 Mev. The error arising from the use of thick targets was probably of the order of 0.01 Mev, not greater than 0.02 Mev. Finally, the uncertainty in the aluminum foils used in measuring the range difference is quite small, perhaps ± 0.03 mg/cm^2. From these errors one derives an over-all expected error of ± 0.05 Mev. Similar considerations apply to the other observed peaks.

Yields and Cross Sections

Only very rough estimates of the relative strengths of the proton groups could be made due to the small number of counts which it was possible to collect in a run of several hours. Such estimates are given in Table II. Relative values may be in error by 25%, and the estimated differential cross sections, being based on other poorly known quantities such as the slope of the yield curve and the stopping power of the target for lithium ions may be wrong by a factor of 2.

DISCUSSION OF RESULTS

The N^{17} Mass

Alvarez[5] found that N^{17} is a delayed neutron emitter, decaying with a β half-life of 4.14 sec to a state or states of O^{17} which in turn decay to O^{16} by neutron emission. The peak of the neutron distribution was found to lie at 0.92 ± 0.07 Mev, and the upper limit of the β-rays at 3.7 ± 0.2 Mev. The estimate of the energy difference $N^{17}-(O^{16}+n)$ was made by addition of these values, and this is given in the Ajzenberg-Lauritzen compilation[17] as 4.7 Mev, leading to an $(M-A)$ of 13.0 ± 0.2 Mev for N^{17}.

Further evidence for the N^{17} mass value comes from the $O^{18}(\gamma,p)N^{17}$ reaction. Stephens, Halpern, and Sher[7] have irradiated water samples with a betatron and observed the delayed neutrons arising from this reaction. The threshold was observed at 16.35 ± 0.2 Mev. This is higher than the value expected from the work of Alvarez by 0.34 Mev. The observed threshold would be expected to be higher than the value calculated from the masses involved by the effective barrier height, and calculations performed by these authors justify a mass value in the region observed.

In the present work the determination of the $(M-A)$ of N^{17} depends on only one measurement, that of the energy of the most energetic of the proton groups. Through several independent runs, this has been determined to be 9.02 ± 0.06 Mev. This leads to a reaction Q-value of 8.38 ± 0.06 Mev. The $(M-A)$ value for N^{17} is thus determined to be 12.92 ± 0.06 Mev. This is 0.08 Mev lower than the best previous value of 13.0 ± 0.2 Mev, and is certainly more accurate. The mass of N^{17} corresponding to the new $(M-A)$ value is 17.01388 ± 0.00006 amu.

TABLE II. Yields and cross sections for proton groups from the reaction $B^{11}(Li^7,p)N^{17}$. The tabulated values have a relative accuracy of approximately $\pm 25\%$ and an absolute accuracy of approximately a factor of two.

Proton energy (Mev)	Yield (in counts per μcoul per steradian at 90° to beam)	Cross section (in 10^{-32} cm^2 per steradian at 90° to beam)
9.02	0.08	0.32
7.77	0.10	0.41
7.24	0.17	0.74
6.66	0.33	1.40
6.35	0.29	1.25
5.93	0.14	0.59
5.65	0.19	0.81
5.37	0.19	0.81
5.07	0.19	0.81
Totals	1.7 counts per μ coul per sterad	7.1×10^{-32} cm^2/sterad

Isotopic Spin Multiplets and Coulomb Correction

N^{17} in its ground state is a member of an isotopic spin multiplet with $T=\frac{3}{2}$. It has $T_z=\frac{3}{2}$; other known members are O^{17} and F^{17} with $T_z=\frac{1}{2}$ and $-\frac{1}{2}$, respectively.

It is of interest to attempt to identify the sequence of $T=\frac{3}{2}$ states in the spectra of O^{17} and F^{17}. The spectrum of N^{17} after suitable corrections for Coulomb effects should be a guide toward this identification.

The Coulomb correction for neighboring isobars in light nuclei has been discussed by several authors. Peaslee[19] has given a quantum-mechanical treatment from which he finds quite generally that the Coulomb energy difference between isobars may be written as the sum of two terms:

$$E_c(Z+1,Z)=a\left(\frac{Z+\frac{1}{2}}{A^{\frac{1}{3}}}\right)+b,$$

where b is an exchange term. In this formula, E_c is the beta decay energy corrected for the neutron-proton mass difference (and positron formation in the case of positron decay), Z and A are the charge and mass numbers for the nuclide in question, and a and b are constants. Peaslee finds that the constants a and b differ somewhat for nuclei according to whether $A=4n$, $4n+1$, $4n+2$, or $4n+3$, and he makes a least-squares fit to the experimental data accordingly. For the present case, where $A=4n+1$, he finds the data best fitted by the values $a=1.48$ and $b=-1.27$, with the standard deviation of the fit being 0.12 Mev.

[19] D. C. Peaslee, Phys. Rev. 95, 717 (1954).

Kofoed-Hansen[20] has done a more detailed calculation of the Coulomb energy difference using independent-particle model eigenfunctions corresponding to the cases of the infinite square well and the simple harmonic oscillator. His graphs for the Coulomb correction according to these two models, plotted as a function of $(Z+\frac{1}{2})/A^{\frac{1}{3}}$, show an almost linear behavior within a shell, but exhibit distinct breaks between shells. Thus the constants in the above equation would be expected to have different values within different shells.

A graph of observed Coulomb corrections, plotted as a function of $(Z+\frac{1}{2})/A^{\frac{1}{3}}$ and fitted by straight lines, has been given by Murphy[4] for nuclides in this region.

N^{17} presents an anomalous case in that in its proton structure it has not yet completed the p shell, whereas its neutron shells are filled through the p shell and two further neutrons are present in the next shell. There is, therefore, some doubt as to what Coulomb correction is to be expected for this nuclide. Interpolation on the graph just described from the line for $A=4n+1$ for nuclides within the p shell yields a value of 3.34 Mev at the appropriate $(Z+\frac{1}{2})/A^{\frac{1}{3}}$ value, while extrapolation down from the d and s shell line gives a value of 2.92 Mev. The average of these is 3.13 Mev, with a displacement of 0.21 Mev to either line. Taking into account the fact that N^{17} and O^{17} are not mirror nuclei, and following the procedure described by Kofoed-Hansen on the graph relative to the $(O^{17}-F^{17})$ point, gives a value for the Coulomb correction of 3.16 Mev. On the other hand, a calculation from Peaslee's optimal mean-squares fit to the available data for $A=4n+1$ gives a value of 3.06 Mev. A value of 3.12 Mev will be assumed for the $N^{17}-O^{17}$ Coulomb correction.

Upon using the best value for the mass of N^{17} obtained from this experiment, the N^{17} ground state appears 8.70 Mev above the O^{17} ground states. Applying the Coulomb correction of 3.12 Mev, and correcting for the neutron-proton mass differences, one obtains a prediction for the lowest $T=\frac{3}{2}$ state in O^{17} at 11.04 Mev, with perhaps an uncertainty of 0.12 Mev. One would also expect higher $T=\frac{3}{2}$ states in O^{17} at energies approximately 12.4, 12.9, 13.5, 13.9, 14.3, 14.6, 14.9, and 15.2 mev corresponding to the excited states of N^{17} which were seen in this experiment.

Unfortunately, at the present time our knowledge of O^{17} levels above 9.06 Mev excitation has been obtained through reactions which, according to isotopic spin conservation, should not be able to excite $T=\frac{3}{2}$ levels in O^{17}. These reactions are $C^{13}(\alpha,n)O^{16}$ and $O^{16}(n,n)O^{16}$.

One would similarly expect that $T=\frac{3}{2}$ levels for F^{17} would begin around 11 Mev of excitation. Unfortunately, levels in F^{17} are known experimentally only up to 7.4 Mev.

[20] O. Kofoed-Hansen, Nuclear Phys. **2**, 441 (1956).

N^{17} Levels According to the Shell Model

The nuclide N^{17} contains seven protons and ten neutrons; hence it has one proton ($p_{\frac{1}{2}}$) hole in the proton shell which closes at O^{16}, and has two neutrons outside of the corresponding neutron shell. The ground state is expected to correspond to the jj coupling of a $p_{\frac{1}{2}}$ hole with two $d_{\frac{5}{2}}$ neutrons. These neutrons can couple to states of spin and parity 0+, 2+, and 4+, odd-spin states being forbidden by the Pauli principle. The order of the states is probably as designated, the 0+ state being lowest in energy. (This is corroborated by the order of levels observed in O^{18}, the ground state being 0+.)[21] Thus one expects the ground state of N^{17} to have spin and parity $\frac{1}{2}-$.

Excited states in N^{17} at reasonably low energies may be expected to arise from excitations of the protons and neutrons within their respective shells, although core excitation of the neutrons and excitations of protons out of the p shell may also occur and give rise to states of positive parity. The fact that the first excited states of N^{15} and O^{15} are found at 5.3 Mev would suggest that single-particle states in N^{17} arising from proton excitation may not be prominent in the region of excitation studied.

The shell occupied by the last two neutrons in N^{17} corresponds to single-particle states $d_{\frac{5}{2}}$, $2s_{\frac{1}{2}}$, and $d_{\frac{3}{2}}$. Lowest neutron excitations may be expected to arise from $(d_{\frac{5}{2}})^2$, $(s_{\frac{1}{2}})^2$, and $(d_{\frac{5}{2}}s_{\frac{1}{2}})$ configurations. The states obtained by coupling the two extra neutrons should be split into doublets by coupling to the $p_{\frac{1}{2}}$ proton hole, except in the case of $J=0$ states. The configuration of two $d_{\frac{5}{2}}$ neutrons, as mentioned previously, couples to states of positive parity and spin 0, 2, and 4. The $(s_{\frac{1}{2}})^2$ coupling will give only one state of spin and parity 0+, which in turn will lead to one state of spin and parity $\frac{1}{2}-$ when coupled to the $p_{\frac{1}{2}}$ hole. The $d_{\frac{5}{2}}s_{\frac{1}{2}}$ couplings should lead to states of positive parity and $J=2$ and 3, each of which should give rise to a doublet.

A consideration of the level structure of neighboring nuclides gives the order of magnitude of energies concerned. The levels arising from the coupling of two neutrons may be observed in the level scheme of O^{18}. A 2+ state is observed at 1.98 Mev.[21]

In the levels of N^{17} such a neutron configuration should give rise to two low-lying states of spin and parity $\frac{3}{2}-$ and $\frac{5}{2}-$. The splitting to be expected may be estimated from the low-lying levels of N^{16}, where we see that the ground and first three excited states (at 0.12, 0.29, and 0.39 Mev, respectively) arise from the coupling of a proton hole in the $p_{\frac{1}{2}}$ shell with a single neutron in the $d_{\frac{5}{2}}$ and $s_{\frac{1}{2}}$ levels, the spin up–spin down splittings being approximately 280 kev. Thus a splitting of the $\frac{3}{2}$ and $\frac{5}{2}$ states of perhaps a few hundred kilovolts would be expected. A more detailed calculation based on the center-of-gravity theorem predicts the

[21] H. E. Gove and A. E. Litherland, Bull. Am. Phys. Soc. Ser. II, **3**, 199 (1958).

$\frac{3}{2}$ level at 1.85 Mev and the $\frac{5}{2}$ level at 2.08 Mev.[22] A level at 1.89 Mev was observed experimentally and the possibility of it being a somewhat closer doublet has not been ruled out.

Further excited states have been reported in O^{18} at 3.5 Mev, 3.9 Mev, 5.0 Mev, and higher.[23] The level at 3.5 Mev has been identified by Gove and Litherland as 4+. Thus a doublet may be expected in N^{17} in the vicinity of 3.5 Mev. Calculations predict that the $\frac{7}{2}$ level should lie at 3.34 Mev and the 9/2 level should lie at 3.77 Mev.[22]

The 3.9-Mev state in O^{18} probably arises from a $(d_{\frac{5}{2}}s_{\frac{1}{2}})$ configuration and may be the $J=2$ member. This configuration again should give rise to a doublet in N^{17}.

A low-lying level in N^{17} corresponding to the 1.32-Mev state observed might arise from the coupling of the two extra neutrons in $s_{\frac{1}{2}}$ states to a resultant 0+. A level corresponding to this configuration in O^{18} would have escaped observation in the $C^{14}(\alpha,\gamma)O^{18}$ experiments of Gove and Litherland, since gamma transitions from this state to the 0+ ground state of O^{18} would be forbidden and gamma transitions from other states to a 0+ state would go preferentially to ground. Also it might have escaped observation in stripping experiments since it is a two-particle excitation. The low energies of the states arising from a single $s_{\frac{1}{2}}$ neutron in N^{16} and O^{17} suggest that such a state would be at a fairly low energy. Such a state in O^{18} has been predicted by Elliott and Flowers at 2.8 Mev.[24] Calculations based on this value indicate that this configuration could give rise to a state in N^{17} at 1.4 Mev.[22] The existence of a state in N^{17} at 1.32 Mev suggests that the presence of such a level in O^{18} should be investigated experimentally.

Cross Sections

The height of the potential barrier between a lithium and a boron nucleus is in the range 3.5–4.2 Mev, if the constant used for computing the nuclear radius is taken to lie in the interval 1.25×10^{-13} to 1.5×10^{-13} cm. To bring this much kinetic energy into the collision, the lithium would have to have 6.2 to 7.3 Mev kinetic energy in the laboratory system. The excitation of the compound nucleus O^{18} is 25.6 Mev for 2-Mev Li^7 ions. The cross section for the proton-producing reaction is held down by the Coulomb barrier and the large number of channels through which it is energetically possible for the intermediate nucleus to decay. The calculated values of the partial-wave cross sections for formation of the compound nucleus, using the tables of Feshbach, Shapiro, and Weisskopf for barrier penetrability[25], are shown in Table III.

TABLE III. Theoretical partial wave capture cross sections in the bombardment of B^{11} with 2-Mev Li^7. The cross section is given by $\sigma_l=(2l+1)\pi\lambda\!\!\!^{-2}T$, where $\lambda\!\!\!^{-}$ is the de Broglie wavelength of the relative motion, divided by 2π, and is equal to 2×10^{-13} cm; l is the orbital angular momentum quantum number; and T_l is the penetrability of the Coulomb barrier.

l	T_l	σ_l (units 10^{-29} cm^2)
0	1.27×10^{-4}	1.60
1	6.83×10^{-5}	2.57
2	1.91×10^{-5}	1.20
3	3.12×10^{-6}	0.27
4	3.08×10^{-7}	0.03
5	2.05×10^{-8}	0.003
		Total: 5.67

A comparison of the differential cross sections for the various proton groups observed with the calculated total reaction cross section (Table III) shows that the former are quite low relative to the latter. Assumption of isotropy in the angular distribution for the sake of comparison leads to a ratio of approximately 60 to 1 for the total predicted capture cross section to the summed observed cross section for the proton groups. This rather large factor may be accounted for, at least in part, by the presence of the many other competing reactions which may proceed during this bombardment.

ACKNOWLEDGMENTS

This work was carried out under the sponsorship of Professor S. K. Allison, to whom I am grateful for advice and encouragement throughout the experiment. I wish to thank Dr. G. C. Morrison for many helpful discussions of the experiment, and Dr. R. Lawson for discussion of the interpretation and theoretical calculations of the levels. I wish to thank J. Erwood, L. Herzenberg, and M. Kamegai for their active interest and support throughout the work in dependable operation of the accelerator, maintenance of the electronic equipment, and general assistance in the laboratory.

[22] I am very grateful to Dr. R. Lawson of the Enrico Fermi Institute for Nuclear Studies of the University of Chicago for helpful discussion of the theoretical interpretation of the levels and for his calculation of the location of the energy levels in N^{17}.

[23] N. Jarmie, Phys. Rev. **104**, 1683 (1956).

[24] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).

[25] Feshbach, Shapiro, and Weisskopf, Atomic Energy Commission Report NYO-3077 (unpublished).