The $Li^7(p, n)Be^7$ still seems to be the preferred source for neutrons of energy from 120 kev to 640 kev. Above 640 kev (where the lithium neutrons lose their monoergic character) the $T(p, n)He^3$ and $C^{14}(p, n)N^{14}$ reactions seem promising for low voltage accelerators. The $B^{11}(p, n)C^{11}$ reaction might be useful where higher voltages are available. For neutron energies below 120 kev C^{14} and O^{18} targets would be attractive. Use of targets of higher Z is seriously limited by the very low neutron yields.

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The Disintegration of Boron by Slow Neutrons

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The total ionization produced by the Li^7 and α-particles from the $B^{10}(n, \alpha)Li^7$ reaction has been measured in an argon-boron trifluoride gas mixture, and that produced by the two particles separately with a thin boron film. Electron collection has been employed, using a fast amplifier feeding a 30-channel pulse-analyzer. The results indicate a departure from linearity in the relation between ionization and energy. Using the formula suggested by Cranshaw and Harvey in their work on natural α-emitters, values of the Q of the boron reaction have been obtained. They are 2.793 ± 0.027 Mev and 2.320 ± 0.020 Mev for the ground state and excited state transitions, in agreement with the recently published values of Tollestrup, Fowler, and Lauritsen. The branching ratio, that is the probability of the reaction going to the ground state, has been measured as 5.8 ± 0.1 percent.

I. INTRODUCTION

THIS investigation was undertaken primarily to measure the relative probabilities of the two reactions $B^{10}(n, \alpha)Li^7$ and $B^{10}(n, \alpha)Li^{7*}$. At that time (1947) the best value 1:15, due to Bøggild,[1] appeared to be limited in statistical accuracy. Moreover, the measurements on the energy release, which were summarized by Bøggild, were not in good agreement. It therefore seemed worth while to extend the scope of the experiment and make an accurate comparison of the ionizations produced by the boron reactions with that of Pu^{239} α-particles.

At first the total ionization of the Li^7 and α-particles was measured relative to that of the Pu^{239} α-particle in an ionization chamber containing boron trifluoride and argon. Later a thin boron film was used and the ionizations of the Li^7 and α-particles were measured separately, thus permitting a more reliable estimate to be made of the ionization-energy relation.

II. DESCRIPTION OF APPARATUS

The Ionization Chamber

The ionization chamber contained two plane parallel electrodes, 10 cm square and 6.6 cm apart, with a grid of parallel wires placed 1.5 cm in front of the electron collecting electrode. The wires in the grid were 0.12 mm in diameter and were spaced 0.95 mm apart. Such a grid is adequate for shielding the collector from the induced effect of the slowly moving positive ion component of the ionization.[2,3] The calibration source of Pu^{239}, deposited on a 1-cm diameter platinum disk, was mounted in the center of the negative electrode and covered with a simple collimator, a sheet of $\frac{1}{2}$-mm brass drilled with 1-mm holes. The electrodes were supported on glass insulators.

The chamber was sealed with a lead gasket so that it could be baked out (at about 200°C) in preparation for a boron trifluoride filling. The gasket was made of lead containing 1 percent of tin, an alloy which creeps much less than pure lead. High tensile steel bolts, $3\frac{1}{2}$ inches long and $\frac{1}{4}$ inch in diameter, were used to compress the gasket between heavy flanges. If short thick bolts were used the extension of the bolt for a given force on the gasket would be less, and any creep of the lead would quickly result in a loss of gasket compression.[4] A leak would then be likely to develop, particularly during the baking out procedure.

Chamber Fillings

The chamber was filled with argon (99.8 percent pure) containing 2 percent of boron trifluoride to a pressure of one atmosphere. The boron trifluoride was prepared from calcium fluoroborate by J. F. Steljes. No deteriora-

[1] J. K. Bøggild, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **23**, No. 4 (1945).

[2] Bunemann, Cranshaw, and Harvey, Can. J. Research **A27**, 191 (1949).

[3] T. E. Cranshaw and J. A. Harvey, Can. J. Research **A26**, 243 (1948).

[4] H. Carmichael, "Design of the Chalk River Ion Chambers" C.R. Tec-276 (1946).

tion in the gas filling could be detected, by change in pulse size, after standing for several months.

In the second stage of the investigation, using a thin boron film, the chamber was filled with argon containing 2 percent of carbon dioxide, again to a pressure of one atmosphere. The chamber was not baked out for these measurements, simple flushing being considered adequate. No change of pulse size with age could be detected.

Measurements were made at different operating voltages up to -2.5 kv on the high tension electrode (cathode) to check that saturation had been achieved. The grid was maintained at a negative potential of about half the cathode potential to ensure that it collected no electrons.

The Boron Source

The thin boron film was deposited on the cathode. A dilute aqueous solution of boric acid was sprayed on to the highly polished front surface of the electrode using a De Vilbiss No. 40 "Nebulizer". This device produces an exceedingly fine spray, but to avoid any coagulation of the droplets the electrode was kept heated (to about 120°C) during the spraying so that evaporation of the water was almost instantaneous. It is not possible with this technique to predict how much boric acid will be deposited, and the operation is accordingly a matter of trial and error. Finally the electrode was heated to about 200°C to convert the boric acid to boric anhydride (B_2O_3). This change can be observed as a return of the electrode to an apparently more highly polished state after the slight dullness caused by the initial boric acid deposition. (If it is necessary to keep the prepared film for any time before using it should be kept in a desiccator.) Boron of natural isotopic composition was used.

With the neutron flux available an adequate counting rate was an important consideration. Accordingly the film was not covered with a collimator. The thickness of the film was estimated, from the neutron flux and the observed counting rate, to be about 2 μg of B_2O_3 per square centimeter.

The Amplifier

To ensure a good signal-to-noise ratio the head amplifier was mounted directly onto the chamber. The head amplifier employed a ring-of-three feedback circuit to give high stability of gain. Its output was fed to the main amplifier via a cathode follower. The main amplifier consisted of two further rings separated by a condenser-resistance network determining the pulse shape. The ring-of-three circuit is a slightly modified version of that used by Cranshaw and Harvey.[3]

The amplifier was normally operated with a differentiating time constant of 4 μsec. and a smoothing time constant (to limit the band width) of about 1 μsec. That the use of such short time constants was permissible was demonstrated in subsidiary experiments with lower chamber operating voltages using the same band width, and with slower amplifier responses using the same operating voltages.

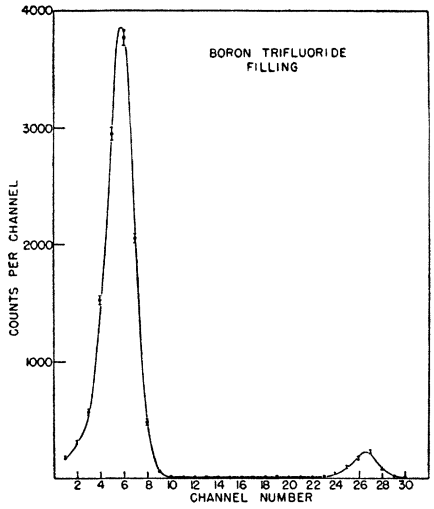

FIG. 1. Pulse height distribution from boron trifluoride showing the transitions to the ground state and excited state of the Li^7 nucleus.

Pulse Height Measurements

The spread in amplitude of the pulses was only a few percent. To obtain an accurate value for the most probable pulse height it is clearly desirable to extend this spread over several channels of the pulse-analyzer. This was accomplished by feeding the output of the main amplifier through a biased amplifier unit similar to the one described by Cranshaw and Harvey.[3]

The 30-channel pulse analyzer has been described by Westcott and Hanna.[5]

All pulse height measurements were made in terms of the output of a pulse signal generator which fed standard pulses, of adjustable amplitude, to the collecting electrode through a small (5 $\mu\mu$F) condenser.[6]

The Neutron Source

The measurements on boron trifluoride were made using a small polonium-beryllium source and a paraffin moderator. The slow neutron flux was about 10^2 neutrons/cm^2-sec. For the thin boron film work a stronger source was used to give a flux about 100 times larger. It will be noticed that the curves shown in Figs. 2 and 3 show a considerable background level at low energy. This background was due almost entirely to fast neutrons.

III. RESULTS

A typical pulse height distribution obtained with the boron trifluoride filling is shown in Fig. 1. The two peaks

[5] C. H. Westcott and G. C. Hanna, Rev. Sci. Inst. **20**, 181 (1949).
[6] D. C. Brunton and G. C. Hanna, Can. J. Research **A28**, 190 (1950).

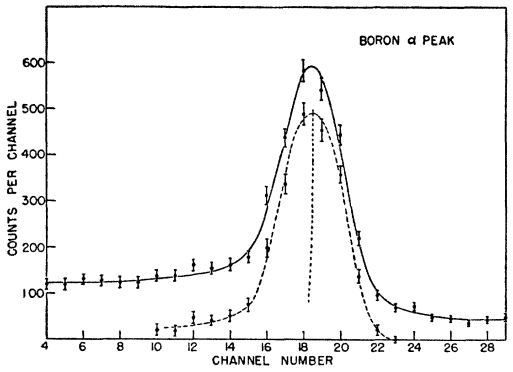

FIG. 2. Pulse height distribution of α-particles from a thin boron film.

arise from transitions to the excited state and ground state of the Li^7 nucleus. The widths of the distributions at half-maximum is 60 kev, almost all of which is due to amplifier noise, measured using the signal generator pulses.

The separate peaks due to Li^{7*} and the associated α-particle are shown in Figs. 2 and 3. The high fast-neutron background prevented measurements being made on the less probable transition to the ground state. The figures also show the peaks after the subtraction of the interpolated background level. The widths here are larger, about 80 kev, with a noticeable low energy asymmetry of the Li peak. The increase in width is due to a deterioration in the signal-to-noise ratio of the amplifier compared with the earlier runs. The asymmetry is probably due to the use of an uncollimated source. Self absorption of the oblique tracks in the source material would be more noticeable with the Li fragments because of their greater rate of loss of energy with distance penetrated. The recoil of the γ-ray, which is emitted during flight,[7] produces a total spread in energy of only 15 kev, which is not sufficient to affect the width appreciably.

Following Cranshaw and Harvey,[3] the position of the peaks was fixed by the method of drawing the central line of the distribution. The agreement between the results from boron trifluoride and the thin boron film suggest that the asymmetry does not introduce an appreciable error if the most probable pulse height is taken as the measure of the ionization.

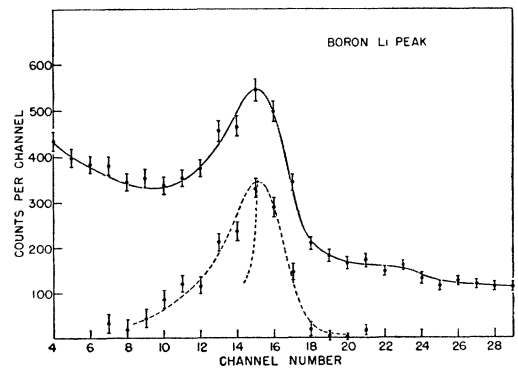

FIG. 3. Pulse height distribution of Li-particles from a thin boron film.

The results are summarized in Table I. I_1 and I_2 denote the ionizations produced by the α-particle and Li^{7*} ion respectively, when the reaction proceeds to the excited state, and I_1' and I_2' when the ground state is formed. I_3 denotes the ionization produced by the Pu^{239} α-particle.

The errors quoted are an attempt to give reasonable limits of error, the reproducibility of the measurements is considerably better.

From Table I we take a mean value of 0.431 ± 0.003 for $(I_1+I_2)/I_3$, and consequently adjust (I_1/I_3) to 0.279 ± 0.0025 and (I_2/I_3) to 0.152 ± 0.0015.

The experiments using boron trifluoride fillings gave a value of 5.8 ± 0.1 percent for the probability of the reaction going to the ground state of Li^7.

IV. EVALUATION OF ENERGIES

It will be noticed immediately that the ratio of ionizations I_2/I_1 is not equal to the energy ratio E_2/E_1, which by conservation of momentum $=4.0039/7.0182$ $=0.5705$. This is here ascribed to a difference in W, the mean energy (in electron volts) per ion pair produced, for the two particles. In fact, since $I_2/I_1=0.544\pm0.007$, $W_2/W_1=1.049\pm0.013$.

This result is in conflict with the measurements in air by Fünfer,[8] and in helium by Bower, Bretscher, and Gilbert,[9] who obtained respectively values of 0.77 and 0.82 for W_2/W_1. It may be remarked that such a large change as this in W is most unexpected in view of its relative constancy, pointed out for example by Gray,[10] for all other particles. If W increases as the velocity of the ionizing particle decreases one would expect a larger value of W for the more slowly moving Li-particle, that is $W_2/W_1>1$.

Cranshaw and Harvey[3] from their measurements on the natural α-emitters proposed a formula $W=27.5+1.9E^{-\frac{1}{2}}$ for α-particles in argon, where W is in electron volts/ion pair and E in Mev. Accepting this formula, then

$$W_1=27.5+1.9E_1^{-\frac{1}{2}}$$

and $$W_3=27.5+1.9E_3^{-\frac{1}{2}}=28.34 \text{ ev/ion pair.}$$

The ionization measurements give

$$I_1/I_3=(W_3/W_1)(E_1/E_3)=0.279\pm0.002_5.$$

Solving these equations by successive approximations we have, taking[3] $E_3=5.159$ Mev,

$$E_1=1.477\pm0.013 \text{ Mev, with } W_1=29.06.$$

[7] L. G. Elliott and R. E. Bell, Phys. Rev. **74**, 1869 (1948).

[8] E. Fünfer, Ann. Phys. Leipzig **29**, 1 (1937).

[9] Bower, Bretscher, and Gilbert, Proc. Camb. Phil. Soc. **34**, 290 (1938).

[10] L. H. Gray, Proc. Camb. Phil. Soc. **40**, 72 (1944).

TABLE I. Ionization of the Li^7 and α-particles from the $B^{10}(n, \alpha)Li^7$ reaction.

Experiment	$(I_1'+I_2')/(I_1+I_2)$	$(I_1+I_2)/I_3$	I_1/I_3	I_2/I_3	I_2/I_1
BF_3	1.211±0.006	0.433±0.004	—	—	—
Thin B film	—	0.429±0.004	0.278 ±0.0025	0.151 ±0.0015	0.544 ±0.007

Now $E_2/E_1=0.5705$ (conservation of momentum) and we have immediately

$$E_2=0.843\pm0.007 \text{ Mev},$$
and $$Q=E_1+E_2=2.320\pm0.020 \text{ Mev}.$$

In order to analyze the ionization data in the case in which the boron reaction proceeds to the ground state it is necessary to make some assumptions about W for the Li-particle, since the ionization of the α-particle alone was not measured. We shall assume, somewhat arbitrarily but plausibly enough, that a Li-particle has the same value of W as an α-particle of the same velocity. If we evaluate E_2 from I_2/I_3 on this basis we obtain $E_2=0.837\pm0.008$ Mev, with $W_2=30.24$ (which is the value for an α-particle of energy 0.57×0.837 Mev). The agreement between this value of E_2 and that obtained from E_1 above is not to be taken as a complete justification of our assumption regarding W_2, and clearly the experimental errors permit some latitude. However it seems reasonable to make the same assumption in the analysis of the disintegration to the ground state.

Using the Q value $E_1+E_2=2.320\pm0.020$ Mev above, we obtain from $(I_1'+I_2')/(I_1+I_2)=1.211\pm0.006$, $Q'=E_1'+E_2'=2.793\pm0.027$ Mev, with $E_1'=1.778$ Mev, $W_1'=28.92$, $E_2'=1.015$ Mev, and $W_2'=30.00$.

If, on the other hand, W were assumed to be the same for all the particles involved (including the Pu^{239} α-particle) we should obtain $Q=2.224\pm0.019$ and $Q'=2.693\pm0.024$ Mev.

These values for Q and Q' should be compared with those obtained by Chao, Lauritsen, and Tollestrup[11] in magnetic deflection experiments: 2.316 ± 0.006 and 2.794 ± 0.006 Mev. In a later publication Tollestrup, Fowler, and Lauritsen[12] give "adopted" values of 2.313 and 2.791 Mev.

Our results are based on a value of 5.159 Mev for the Pu^{239} α-particle energy. Actually the collimator covering the Pu^{239} source was somewhat thicker than desirable; it consisted of 1 mm diameter holes in a plate $\frac{1}{2}$-mm thick. The collecting field will be weakened inside the collimator holes, and some loss of ionization by recombination will result. The correction is not easy to determine but it is estimated to be not more than 0.5 percent. If applied—which has not been done—the correction would reduce the energies given above by 0.5 percent—a difference less than the experimental error.

The results derived above are summarized in Tables II and III.

[11] Chao, Lauritsen, and Tollestrup, Phys. Rev. **76**, 586 (1949).
[12] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).

V. THE RELATIONSHIP BETWEEN IONIZATION AND ENERGY

The agreement between our Q values and those of Chao, Lauritsen, and Tollestrup suggests that the empirical relation between W and E obtained by Cranshaw and Harvey from data at higher energies is valid in the low energy region also, and further that Li-particles spend much the same energy in creating one ion pair as do α-particles of the same velocity. Our data however are not sufficiently accurate to establish this relation uniquely. What is clear is that W is not constant in our experiments. This point will be further emphasized in this section in a more direct way.

In the previous section we were concerned with $W=E/I$, the mean value of the energy loss per ion pair over the whole range of a particle of initial energy E. Here we consider $W^*=dE/dI$, its instantaneous value at the energy E.

The theory (see for example Bohr's monograph[13]) indicates that the relative probability of excitation and of lightly-ionizing collisions (in which the energy losses are of the order of the ionization potential) is practically independent of the nature and velocity of the ionizing particle, provided its velocity is comfortably greater than that of the atomic electrons. Williams[14] has pointed out that although the number of violent collisions does depend on the velocity of the primary particle this is not important because nearly all of the energy is ultimately dissipated in subsequent lightly-ionizing collisions. This theoretical constancy of W^* at high energy is confirmed by the work of Cranshaw and Harvey and others, on α-particles, who found that the differences of the ionization produced are very closely proportional to the differences in energy.

At high energy then, greater than 4 Mev say, $W^*=dE/dI$ is constant. That is, $E=W^*I+\epsilon_0$, where ϵ_0

TABLE II. Final Q-values for the reaction $B^{10}(n, \alpha)Li^7$.

Particle		Energy, Mev	W, ev/ion pair
α	E_1	1.477±0.013, from I_1	29.06
Li*	E_2	0.843±0.007, from E_1 0.837±0.008, from I_2	30.24
α+Li*	$Q=E_1+E_2$	2.320±0.020, from E_1	(29.48)
α	E_1'	1.778±0.017	28.92
Li	E_2'	1.015±0.010 from Q'	30.00
α+Li	$Q'=E_1'+E_2'$	2.793±0.027, from Q and $(I_1'+I_2')/(I_1+I_2)$	(29.31)

TABLE III. Comparison of results for the energy values.

Experiment		Q	Q'	E_γ
Chao, Lauritsen, and Tollestrup		(2.316±0.006)	2.794±0.006	(0.478±0.001)
This work	W as above	2.320±0.020	2.793±0.027	0.473±0.013
	W constant	2.224±0.019	2.693±0.023	0.469±0.013

[13] N. Bohr, Kgl. Danske Vid. Sels. Math.-Fys. Medd. **18**, No. 8 (1948).
[14] E. J. Williams, Proc. Roy. Soc. **A135**, 108 (1932).

is a constant of integration. At intermediate energies, where W^* is not constant, we can still write $E=W^*I+\epsilon_\alpha$, where ϵ_α is a small energy (less than 100 kev) which diminishes as E gets less. This has a physical interpretation. Below a certain minimum energy the α-particle will produce no ionization, expending its energy in elastic collisions, so that $I=0$ and $\epsilon_\alpha=E$. At higher energies ionization becomes a progressively more probable event (ϵ_α increasing with, but not as fast as, E) until finally, at a sufficiently high energy which is here taken as 4 Mev, the fraction of energy absorbed in ionization attains a constant value, and ϵ_α also reaches its maximum and constant value ϵ_0.

The interpretation of experimental results in terms of this ϵ_α, which appears as a slowly varying correction term, has much to recommend it. In a number of published researches conclusions have been based on the assumption of a constant W with neglect of ϵ_α. With a knowledge of the magnitude of the latter the energy error introduced by this procedure can be appreciated immediately. Data from which the magnitude of ϵ_α (and the corresponding correction energies ϵ_A for ions of character A) can be evaluated are at present scarce and not very continuous. It therefore seems worth while to present the experimental results reported above in terms of ϵ_α and ϵ_{Li}, which can be done if it is assumed that the energies determined by Chao, Lauritsen, and Tollestrup by a quite independent method are correct. (Actually we shall take here the "adopted" Q value of $2.791-0.478=2.313$ Mev.)

We write then for the Pu α-particle, and the α-particle and Li-particle from the excited-state disintegration, respectively,

$$\left.\begin{aligned} W^*I_3&=E_3-\epsilon_\alpha-\Delta\epsilon_\alpha \\ W^*I_1&=E_1-\epsilon_\alpha \end{aligned}\right\}.$$

and

$$W^*I_2=E_2-\epsilon_{\mathrm{Li}}$$

As explained above, we expect $\Delta\epsilon_\alpha$, which is here indeterminate but positive, to be considerably smaller than ϵ_α.

The solution of these equations, using Tollestrup, Fowler, and Lauritsen's values of $E_1=1.473$ Mev, $E_2=0.840$ Mev, and Cranshaw and Harvey's value of $E_3=5.159$ Mev, with $I_1/I_3=0.279\pm0.002_5$ and $I_2/I_3=0.152\pm0.001_5$, gives

$$\epsilon_\alpha=47+0.39\Delta\epsilon_\alpha\pm17 \text{ kev}$$

and

$$\epsilon_{\mathrm{Li}}=65+0.20\Delta\epsilon_\alpha\pm10 \text{ kev}.$$

While it is possible to derive a further value for $(\epsilon_\alpha+\epsilon_{\mathrm{Li}})$ from the measured value of $(I_1'+I_2')/(I_1+I_2)$ the experimental errors deprive it of any significance. (The points are too close together to give adequate information on the slope of the $I:E$ curve.)

Since $\Delta\epsilon_\alpha$ is positive, ϵ_α and ϵ_{Li} cannot be zero, that is W is not constant. If $\Delta\epsilon_\alpha$ is set equal to zero, we have $\epsilon_{\mathrm{Li}}/\epsilon_\alpha=65/47=1.4\pm0.5$. On simple theory we would expect $\epsilon_{\mathrm{Li}}/\epsilon_\alpha\approx M_{\mathrm{Li}}/M_\alpha=1.75$.

The results of these ionization measurements are significantly different from those obtained by Jesse, Forstat, and Sadauskis[15] in argon containing 0.1 percent of boron trifluoride, and our conclusions regarding the relationship between ionization and energy are in conflict with their general thesis of constancy of W in pure argon.

An explanation of this discrepancy may lie of course in the purity of the gases used. The argon used by Cranshaw and Harvey, whose results we confirm, was not of spectroscopic purity; it was cylinder argon nominally 99.8 percent pure. But then, if this were an important factor, the argon containing 0.1 percent of boron trifluoride used by Jesse, Forstat, and Sadauskis would be expected to behave differently.

Along with Cranshaw and Harvey we are measuring only the immediately available electronic component of the ionization. Jesse, Forstat, and Sadauskis, using a slow recorder, measure the total ionization. It is possible that in pure argon atoms in metastable states of excitation can release delayed secondary electrons from the electrodes of the ionization chamber, an effect which might not unreasonably be expected to increase in relative importance for slower ionizing particles. Such secondaries would be missed if fast electron collection were employed. The magnitude of such an effect would however seem to be too small.

The author wishes to thank Mr. J. F. Steljes for his help with boron trifluoride and Mr. N. Moss who made the plutonium source. He is especially grateful to Mr. J. Emerson for the initial construction of the ionization chamber and much assistance in the early stages, and to Drs. W. B. Lewis, B. W. Sargent and W. N. English for helpful discussions.

[15] Jesse, Forstat, and Sadauskis, Phys. Rev. 77, 782 (1950).