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Use of an Electron Multiplier Tube as a New Technique in Disintegration Experiments

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An electron multiplier tube with 12 electrodes has been used as a detector in the bombardment of beryllium by protons of energy 239, 268, and 397 kv. The disintegration particles from the two possible reactions, ${}_4Be^9(p,\alpha){}_3Li^6$ and ${}_4Be^9(p,d){}_4Be^8$, were selected by an electrostatic analyzer which measured directly their energies. The results for each bombarding voltage are given as an energy distribution curve which shows a complete resolution of the various peaks. All the particles, except the unstable ${}_4{}^8Be$, were detected, an interesting feature being the detection of the recoil nucleus ${}_3{}^6Li$ in its three states of ionization. The perfect resolution of the peaks is due to the fact that the target used was extremely thin and that no windows were used in the complete path of the particles from the target, through the analyzer and unto the detector, since the multiplier tube works in vacuum. Thus, no straggling was observed, and the width of the peaks coincide with the values predicted by the theory of the electrostatic analyzer for the slits used in these experiments. The ratios in which the three lithium ions appear are given and the problem of the probability for capture or loss of electrons by the ions is briefly discussed, on the basis of the ratio γ of the electron orbital velocity to the velocity of the ion itself, as suggested by Bohr and used by Knipp, Teller, and Brunings in their treatment of heavy ions. The calculated values for γ under our conditions are: for the process $Li^{+++}\rightleftarrows Li^{++}$, $\gamma=1.22$, and for $Li^{++}\rightleftarrows Li^{+}$, $\gamma=1.09$, which have a net effect of favoring the doubly ionized state of lithium. The actual counting rates observed indicate, in fact, that the Li^{++} is the more abundant of the three ions.

I. INTRODUCTION

IN detecting charged particles from nuclear disintegrations the instruments generally used, such as ionization chambers or counters, depend on the ionization produced by the particles in a gas, and hence windows are necessary to separate the detector from the vacuum system. In such devices the particle loses a certain amount of energy in traversing the window, and to be detected must still retain sufficient energy to produce an appreciable ionization. Therefore, the detection of particles of very low energy is extremely difficult since it is very hard to obtain thin windows of sufficiently small stopping power which at the same time will be strong enough to be vacuum tight and to hold the difference in pressure. Even if these conditions were satisfied, for the case of very slow particles, the pulses produced might be too small and would require a high external amplification.

Studies made by several people on the ejection of secondary electrons from metals when hit by photons or particles have resulted in the multiplier tube. After a careful study of the metals and of the shape of the electrodes, J. S. Allen[1] has developed an efficient electron multiplier tube of sturdy construction and great sensitivity. Since it works in vacuum no windows are required to separate it from the rest of the system, and it can thus be used as a detector of low energy particles.

This work is primarily concerned with the use of an electron multiplier tube as a new technique in the detection of disintegration particles and in the study of nuclear processes in general. The tube used in these experiments was first carefully studied in regard to its response to different kinds of particles (alpha-particles, protons, deuterons, and electrons) under various conditions, and was then used as the detecting device in counting the particles produced in the bombardment of beryllium by protons. An electrostatic analyzer served to select the particles and measure precisely their energy before entering the multiplier tube.

There are two possible reactions when beryllium is bombarded by low energy protons, namely:

$$ {}_4Be^9+{}_1H^1\rightarrow{}_3Li^6+{}_2He^4+Q_1, \tag{1}$$

$$ {}_4Be^9+{}_1H^1\rightarrow{}_4Be^8+{}_1H^2+Q_2. \tag{2}$$

These reactions were first suggested by Oliphant, Kempton, and Rutherford,[2] who identified the alpha-particles and the deuterons as the disinte-

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[1] J. S. Allen, Phys. Rev. **55**, 336 (1939); **55**, 966 (1939).

[2] M. L. E. Oliphant, A. E. Kempton, and O. M. Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

gration particles of the two competing reactions. The alpha-particles from the first process were identified also in experiments described by Döpel,[3] Kirchner and Neuert,[4] and Zipprich.[5] Several other investigations have been subsequently made, such as those of Döpel,[6] and Kirchner and Neuert.[7] In regard to their yields there is the work of Allen,[8] who studied the range of 45- to 125-kv proton energy; Williams, Haxby, and Shepherd[9] up to 250 kv; and Hatch,[10] who extended the range to 400 kv. As for the energy release, the most precise values obtained so far are those measured by Allison[11–13] and his group of collaborators. These values, after correction,[14] are

$$Q_1=2.115\pm0.04 \text{ Mev}, \quad Q_2=0.547\pm0.006 \text{ Mev}.$$

However, in all the studies made so far it has been difficult to resolve completely the deuterons of reaction (2) from the alpha-particles of reaction (1). Allison *et al.*[12,13] were able to distinguish both particles at a bombarding voltage of 262 kv, and they measured accurately their energy from their energy limit, but the resolution was not complete.

This paper presents the successful resolution of the alpha-particles from the deuterons and the detection of the recoil nucleus Li^6 in its three stages of ionization. The energy releases Q_1 and Q_2 obtained in this investigation agree within the experimental error with the accepted values mentioned before. It will be suggested that from the ratios of the number of triply-charged lithium particles to the number of doubly- and singly-charged ions some information might be obtained in regard to the problem of capture and loss of electrons by ions.

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[7] F. Kirchner and H. Neuert, Physik Zeits. **38**, 969 (1937).
[8] J. S. Allen, Phys. Rev. **51**, 182 (1937).
[9] J. H. Williams, R. O. Haxby, and W. G. Shepherd, Phys. Rev. **52**, 1031 (1937).
[10] G. T. Hatch, Phys. Rev. **54**, 165 (1938).
[11] S. K. Allison, L. S. Skaggs, and N. M. Smith, Jr., Phys. Rev. **54**, 171 (1938).
[12] S. K. Allison, E. R. Graves, L. S. Skaggs, and N. M. Smith, Jr., Phys. Rev. **55**, 107 (1939).
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[14] S. K. Allison, L. S. Skaggs, and N. M. Smith, Jr., Phys. Rev. **57**, 550 (1940).

II. EXPERIMENTAL PROCEDURE

Apparatus Used

A. The Linear Accelerator

The Cockroft-Walton voltage quadrupling circuit used before the war in this laboratory has been almost completely rebuilt. One of the main features of its reconstruction is the use of four sealed-off diodes with inverse peak rating of 250 kv instead of the older rectifiers which had to be continuously pumped. The new condensers used have larger capacities than the previous ones, and were distributed among the various stages of the circuit in such a way as to make the ripple and voltage lowering as small as possible. This 400-kv high potential source was used to accelerate protons produced by a low voltage capillary arc, which is described elsewhere.[15] Using a filament current of 24 amperes, an arc current of 0.5 amperes, and varying the probe voltage between 3000 and 6000 volts, beams as high as 80 microamperes at the target could be easily obtained. However, currents of only 10 to 20 microamperes were used in these experiments.

The accelerating voltage was measured by means of a resistance voltmeter consisting of a stack of resistor units. Each one of these units consists of 31 individual resistors of 10 megohms each, assembled helically in a frame of Lucite which insures good contacts, complete separation of each resistor, and prevents corona. A total of 21 of these units (each one of about 3.1×10^8 ohms) was screwed on top of each other and enclosed in a sealed glass cylinder with a dehydrating cap at its bottom. This high resistance stack was calibrated and found to be 6.83×10^9 ohms when 10 microamperes were passed through it. The variation of the resistance with the current was studied and the results showed, for instance, that at 30 μa the resistance dropped to 6.81×10^9 ohms, and at 55 μa it was 6.75×10^9 ohms. The current-resistance curve obtained was then used to determine the calibration curve for the high voltage.

B. The Bombarding Chamber and Target

This chamber consisted of a specially designed brass block which provided apertures for different

[15] S. K. Allison, Rev. Sci. Inst. **19**, 291 (1948).

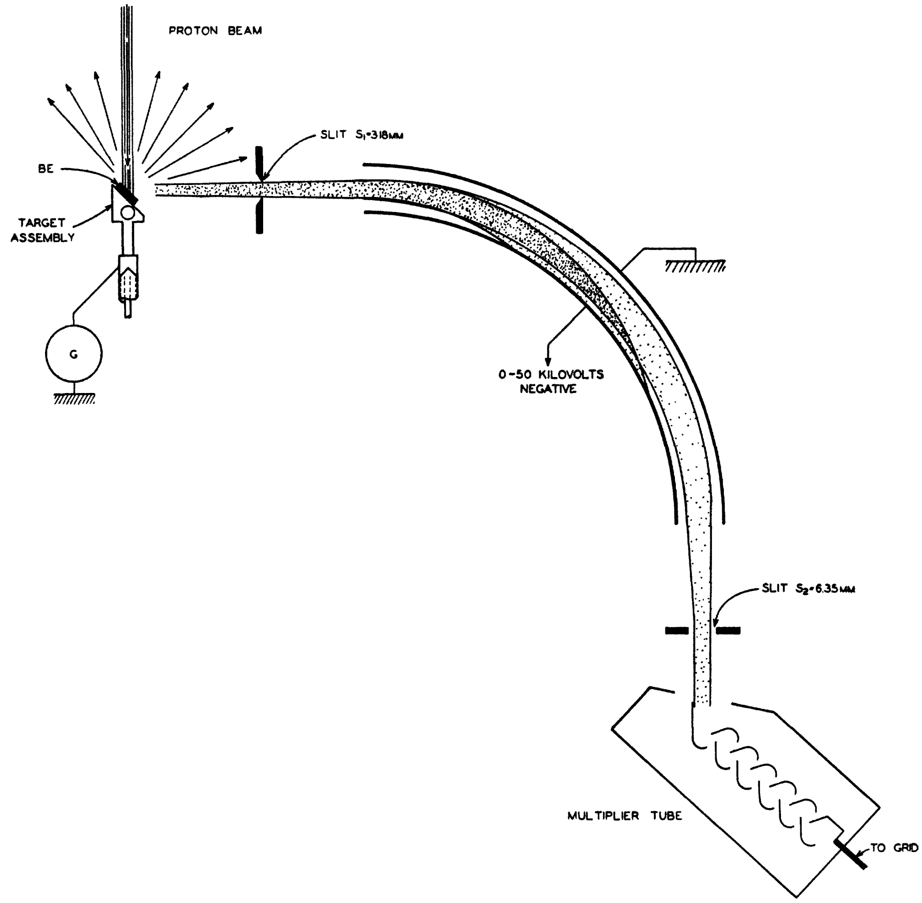


FIG. 1. Schematic arrangement of the target, electrostatic analyzer, and electron multiplier tube used as detector of disintegration particles.

target holders, namely, one for the beryllium target used in this work, one for a heavy ice target used in an investigation of the *D-D* reaction, and one for the polonium source mounted on a micrometer screw which was used in the initial study made of the multiplier tube. The beryllium target was prepared by evaporating the metal in vacuum onto a well polished nickel button. This was done by spot welding several pieces of beryllium on a tantalum wire which was then heated by a current in vacuum. Several nickel buttons were placed directly over this wire and the evaporated metal condensed on them. The first targets thus made were extremely thin. In fact, a test was made with two control buttons on both of which some polonium was deposited, but only one of them was placed with the other clean nickel buttons to receive the beryllium layer. The range *vs.* counting rate curve was then taken for the two polonium buttons to determine the stopping power of the beryllium layer, and it was found that the alphas from the polonium covered with Be had practically the same range as the alphas from the uncoated polonium. Thus the thickness of the beryllium layer was estimated to be equivalent to less than 1 mm of air.

This thin Be target was placed at 45° to the direction of the incoming protons and the disintegration particles entered the analyzer at 90° with the bombarding beam. To avoid the deposition of an oil film from the diffusion pumps on the target, this was heated by means of a platinum coil following the method described by Hatch.[10] The same thin target was used all throughout this investigation; it produced particles in sufficient intensities and its extreme thinness caused no straggling, as will be shown later in the discussion of the results.

C. The Electrostatic Analyzer

The description of this analyzer has appeared in previous literature,[11] and no fundamental changes have been made on the instrument. It consists of two concentric cylindrical plates made of aluminum which subtend an angle of 90° at their center of curvature. The radius of the outer plate is 25.717 cm and that of the inner one is 25.083 cm, the mean radius being 25.400 cm. The space between them is 0.635 cm and their height is 8.26 cm. Figure 1 shows the arrangement of the electrostatic analyzer, together with the bombarding chamber and the multiplier tube. The slit S_1, 0.318 cm wide, was placed at a distance of 8.90 cm from the entrance to the analyzer, which is the focal distance of the apparatus, and another slit S_2, 0.635 cm wide, was placed at the same distance from the exit. In the preliminary tests of the multiplier tube with a polonium source placed in the bombarding chamber, the slit S_1 was covered with a Nylon film 0.0002 inch thick, with a stopping power of about 0.9 cm of air. This was necessary in order to separate the vacuum system of the analyzer and multiplier tube from the air space in which the polonium alphas were slowed down. However, during the investigation of the beryllium-proton reaction there was no film on the slit S_1, the vacuum space being common for the accelerator tube, bombarding chamber, analyzer, and detector.

The voltage for the analyzer was supplied by a 50-kv source, the negative of which was connected to the inner plate of the deflector, the outer plate being grounded. This deflecting voltage was measured within 0.3 percent by an electrostatic voltmeter whose scale was calibrated and re-checked several times during the course of the experiments. For this electrostatic analyzer the relation giving the energy of a particle traveling along a circular orbit is

$$E = 20.00\,Vz, \tag{3}$$

in which E represents the particle energy in electron volts, z is its charge, and V the deflecting potential on the analyzer in volts.

D. The Electron Multiplier Detector

The multiplier tube used in this work was made in our laboratory according to a design by J. S. Allen, and under his personal guidance.** It consists of twelve multiplying stages made of

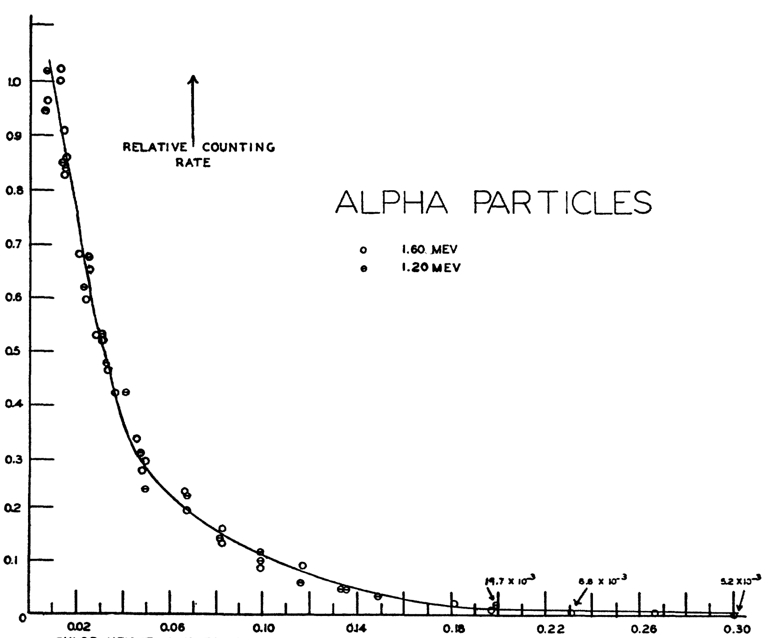


FIG. 2. Height distribution of pulses leaving the final plate of the electron multiplier tube when alpha-particles of 1.6 and 1.2 Mev are incident on the first plate.

** The preparation of these tubes was supported by the Office of Naval Research under Contract N6-ori-20, Task Order III.

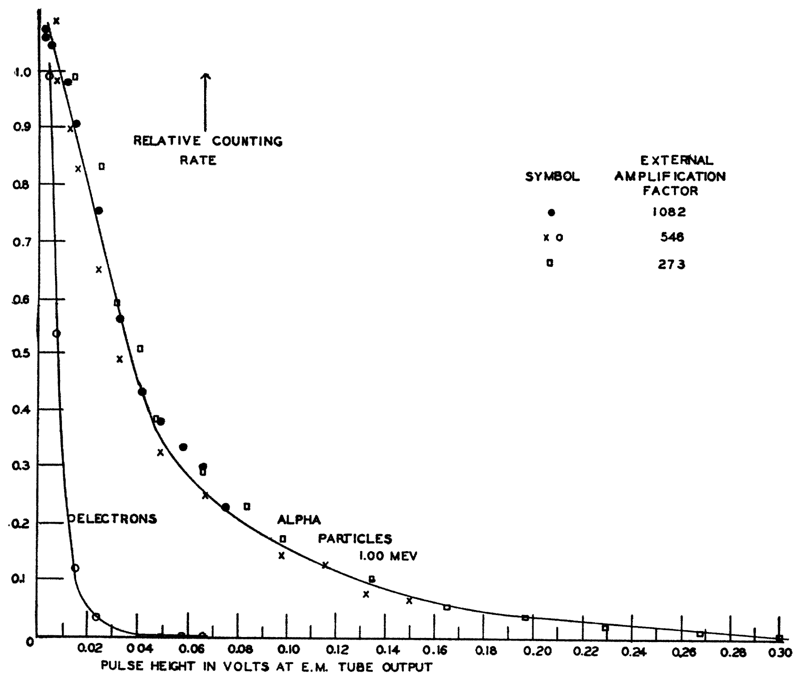


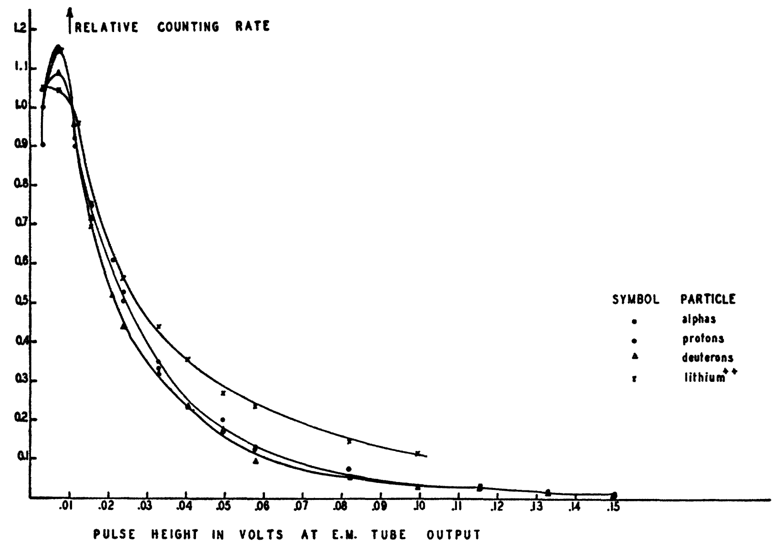
FIG. 3. Height distribution of pulses at the final plate of the electron multiplier tube due to 1-Mev alpha-particles and electrons of approximately 30 kv. The amplification of the external electronic circuit was varied in order to test the linearity of the discriminatory bias resistor on the scaling circuit.

beryllium copper. These electrodes were carefully polished and shaped by suitable presses, and held together by two Lavite plates. The whole assembly was baked in vacuum for activating the surfaces of the electrodes. It was then inserted in a tube about $7\frac{1}{2}$ inches long and 4 inches in diameter. The circular plate sealing one end of the tube had "Kovar" seal connections for the potential divider which provided the voltages between the stages. An 8000-volt supply whose output could be varied was used across the potential divider, and by studying the counting rate of the tube for Po alphas as a function of the voltage per stage, with a constant discriminator bias on the scaler, it was found that it attained a plateau at about 480 volts. We used 510 volts per stage safely during the subsequent experiments.

The first tests made showed that the multiplier required only an additional amplification of around 100. With this external gain we were able to detect alphas of less than 200-kv energy. However, it was thought to be convenient to use an amplifier giving a maximum gain of about 2160 which could be cut down in steps of one-half. The external amplification used all throughout this investigation was one-fourth of this value, i.e., 540, which proved to be sufficient and completely satisfactory. The multiplier was coupled to the amplifier through a cathode follower whose amplification was essentially equal to one. In a test made with electrons it was found that the multiplier had a multiplying factor of about 7×10^5.

The response of the tube to alphas of different energies, obtained by slowing them down in air before their admission to the electrostatic analyzer, was carefully studied. The bias curves obtained showed that the distribution of pulse heights was independent of the energy of the alphas, at least in the range studied (0.4 to 1.6 Mev), but it seemed to depend on the pressure. Figure 2 shows a curve for two different alpha-energies. For electrons it was found that the distribution was shifted toward the smaller pulse heights such that if the discriminator in the scaling circuit was set at a bias corresponding to a pulse of 0.04 volts from the multiplier tube, one could easily count alphas when electrons were present, for at this bias the number of electrons was practically zero. This is shown in Fig. 3 which gives the bias curves for electrons and for alphas of 1.0 Mev. Protons and deuterons coming from the accelerator tube and scattered by the target were also used to obtain bias curves, and the Li^{++}

FIG. 4. Bias curves for different particles. Height distributions of pulses at the final plate of the electron multiplier tube due to various ions incident on the first plate. Their energies were 0.2 Mev for the alphas, 0.22 Mev for the protons, 0.230 Mev for the deuterons, and 0.9 Mev for the lithium ions.



ion from the Be-p reaction was also selected and its bias curve obtained. Figure 4 shows these last results.

The background was also carefully studied, and it was found that it depended mainly on the following three factors: (a) the pressure in the tube, (b) oil from the diffusion pumps deposited on the insulators separating the plates in the electrostatic analyzer, which caused discharges when the deflecting voltage was increased, and (c) the high voltage on the analyzer when raised beyond 42 kv. The first factor was avoided by maintaining the pressure less than 5×10^{-5} mm of Hg. The oil was avoided in great part by shutting off the analyzer from the main system overnight. A weak magnet was placed around the connection between the analyzer and multiplier to deflect any secondaries still produced by discharges. With these precautions the background, even at 48 kv on the analyzer, was only slightly greater than at the lower voltages. The counts were of about one or two per second, and in two of the main experiments done it was only about 0.5 count per second, while the intensities of the disintegration particles were of the order of 50 counts per second.

III. METHOD OF TAKING OBSERVATIONS

The ion beam was magnetically analyzed before striking the target, and each peak was identified by considering the mass and charge of the ions that could be present in the beam, and the ratios of the magnet currents for the different peaks. The magnet current was then adjusted so as to select the proton beam. A second check was accomplished by adjusting the voltage V on the electrostatic analyzer so that the protons scattered by the target were detected by the multiplier. This was done using Eq. (3) and knowing the energy E_p of the bombarding protons. During a series of experiments the magnet current was readjusted either this way or by selecting one of the disintegration peaks on the analyzer, in order to insure a constant beam intensity during a given run.

The amplifier was set at an external gain of 540 and the discriminator of the scaler adjusted so that only pulses greater than 0.0124 volt, put out by the multiplier tube, could be registered. The pressure was never higher than 5×10^{-5} mm of Hg. By varying the deflecting voltage V on the electrostatic analyzer, readings were taken with a mechanical counter for 64 seconds, while the other quantities, namely, the bombarding voltage, the beam current intensity, and the magnet current, were kept as constant as possible. If discharges occurred either in the accelerating voltage or inside the analyzer, the readings were discarded and we waited until conditions were stabilized again. The data presented here is that obtained under almost perfectly steady conditions. As the analyzer voltage was increased in small steps, the counting rate showed the peaks caused by the various disintegration particles.

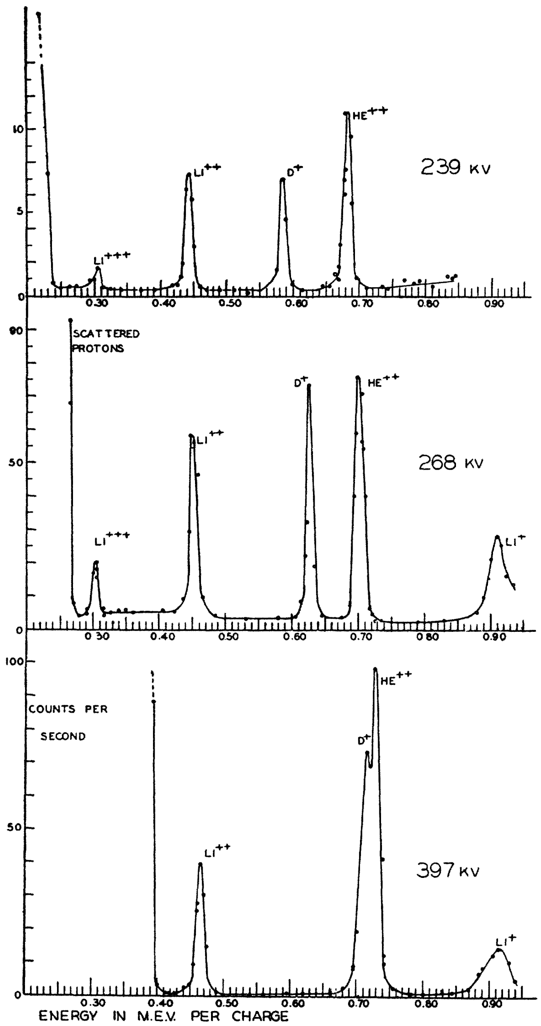


FIG. 5. Energy spectra of particles from the reactions of $_4Be^9(p,\alpha)_3Li^6$ and $_4Be^9(p,d)_4Be^8$ at various bombarding energies. The electrostatic analyzer selects groups of ions having the same energy to electronic charge ratio. The actual deflecting voltages in kilovolts may be obtained by multiplying the abscissae by 50.

IV. RESULTS AND DISCUSSION

Three different bombarding energies were used: 239, 268, and 397 kv. Although the resistance voltmeter described in the previous section is intrinsically accurate enough to measure the high voltage on the accelerator tube, the electronic meter used to measure the current through the high resistance was later found to be unreliable. So, for these experiments we relied on the electrostatic analyzer for the measurement of the energy of the bombarding protons. This was done by selecting through the analyzer the protons scattered by the beryllium-nickel target, and the energy at the upper limit, as given by the analyzer, was corrected for the limit of resolution of the instrument (2.5 percent), for the increase in potential in entering the analyzer ($\sim$1 percent),[14] and, of course, for the loss of energy in scattering from nickel at 90°. In this way the bombarding energies turned out to be 239, 268, and 397 kv, as indicated above. The results for each one of these bombardments are shown in Fig. 5. The abscissae represent the energy of the particle in Mev per charge, obtained from Eq. (3), and the ordinates are the counting rates in counts per second. For the two lower bombarding energies, the resolution of the various peaks is complete. When the bombarding energy was increased to 397 kv the deuterons blend with the alphas, since the rate of energy increase of the particle with respect to the increase in proton energy is higher for the deuteron than for the alpha, as will be seen from the energy relations given below.

The detection of the recoil nucleus Li^6 is an interesting feature in these results. It was possible to detect this particle in its three ionized states for a proton energy of 268 kv. For the lower voltage of 239 kv the intensities were low and there was no reliable evidence of the Li^+ ion, although the Li^{+++} and the Li^{++} were present. For the higher proton energy, 397 kv, the Li^{++} and the Li^+ were detected, but the Li^{+++} was hidden by the screen of scattered protons. In other words, the energy of the lithium nucleus being about 0.921 Mev, we see from Eq. (3) that the analyzer voltage V required to deflect the triply-charged ion would have been 15.4 kv, but since the upper limit of the energy of the scattered protons was around 0.390 Mev, they were detected in great intensities at V less than 19.5 kv. Thus, these protons covered the Li^{+++} ion, which therefore could not be detected.

From the three curves of Fig. 5 the energies of the various particles are obtained and summarized in Table I.

To obtain these energies the abscissa was read at each peak value, i.e., at the midpoint of the width at half-maximum in each case. This is justified by the fact that for our electrostatic analyzer the limit of resolution, set by the geometry of the instrument, is 2.5 percent, and from the curves we obtain, for instance, that for the alpha-peak at $E_p=268$ kv, the half-width divided by the peak value is $0.036/1.392=2.58$ percent. Thus, the width of these peaks is very close to that expected from the theory of the analyzer for the slit widths used in these experiments. The energy E, read at the ordinate of the maximum point of each peak, was then corrected for the difference of potential between the grounded target and that of the calculated radius of the orbit through the electrostatic analyzer, the correction being taken approximately as $-0.01\ E$. The numbers in parentheses are not very accurate due to uncertainty in the position of the peaks because of low intensity, as in the case of Li^{+++} at 239 kv, or because of increased background at the higher analyzer voltage needed to detect the Li^{+} for 268 and 397 kv.

The perfect resolution is due to the fact that since there are no windows in the path of the particles from the instant of their emission to the time of their detection, and since the beryllium target is so thin, practically no straggling occurs, and hence the sharpness of the peaks.

The shifting of the various peaks as the bombarding energy is increased is also clearly seen in Fig. 5. This can be checked with the energy equations. Thus, for the beryllium-proton reactions the well-known relations from the conservation of momentum and energy for ejection at 90° reduce to

$$E_\alpha=0.5E_p+0.6Q_1, \quad (4)$$

$$E_{\mathrm{Li}}=0.3E_p+0.4Q_1, \quad (5)$$

$$E_d=0.7E_p+0.8Q_2, \quad (6)$$

where the first two equations are for reaction (1) and the third for reaction (2).*** E_α is the energy of the alpha-particle, E_p the energy of the bombarding protons, E_{Li} the energy of the recoil lithium nucleus, E_d the energy of the deuteron, and Q_1 and Q_2 the energy releases in the corresponding reactions. From Eqs. (4) and (6) we see, for instance, that the deuteron energy is more sensitive to the bombarding energy than the alpha-energy. Hence the overlapping of the deuterons with the alphas when the voltage was

*** Exact masses from Mattauch's Nuclear Physics Tables were first used, but the differences in the results for Q_1 and Q_2 were much too small compared to the experimental error in measuring the energies of the particles, hence mass numbers are used in these equations.

TABLE I. Energies of the disintegration particles from ${}_4Be^9(p,\alpha){}_3Li^6$ and ${}_4Be^9(p,d){}_4Be^8$.

Proton energy (kv)	Alpha-energy (Mev)	Lithium energy Li^{+++} (Mev)	Li^{++} (Mev)	Li^{+} (Mev)	Deuteron energy (Mev)
239	1.352	(0.909)	0.876		0.579
268	1.392	0.900	0.895	(0.903)	0.621
397	1.440		0.921	(0.907)	0.708

raised to 397 kv. The increase in energy for the alpha and for the deuteron as obtained from Eqs. (4) and (6) are:

$$\Delta E_\alpha/\Delta E_p=0.5,$$
$$\Delta E_d/\Delta E_p=0.7.$$

Thus, when the proton energy is increased from 239 kv to 397 kv, the deuterons should increase their energy by 110 kv, while the alphas receive an increase of only 79 kv. Experimentally, using the data in Table I we find, for the deuterons, an increase of 129 kv, and for the alphas, an increase of 88 kv for that change in proton energy.

The energy releases Q_1 and Q_2 were calculated by substitution in Eqs. (4)–(6) and the data from Table I. Using the corrected energy of the alpha-particles to calculate Q_1, the values 2.056, 2.097, and 2.069 Mev result from the three values given. The best estimate from these results is 2.074 ± 0.03 Mev. On attempting to calculate the same Q_1 from the corrected energies of the Li^{++} particles, one obtains 2.011, 2.039, and 2.005 Mev, a slightly lower value. The value deduced from the alpha-particles seems preferable, since the discrepancy could be accounted for by the loss of 20 kev by the relatively short range Li^{++} particles in leaving the target.

Calculation of the energy release in the reaction ${}_4Be^9(p,d){}_4Be^8$ from the corrected deuteron energies leads to the values 0.516, 0.543, and 0.539 Mev, of which the first seems definitely too low. Inspection of the curve in Fig. 5 for 239-kilovolts bombarding energy indicates that the actual deuteron peak was not located. Disregarding this low result we obtain 0.541 ± 0.003 Mev as the energy release.

As to the relative numbers of deuterons and alpha-particles, the curves are not inconsistent with the findings of other investigators that the cross sections for the two competing reactions are

TABLE II. Relative numbers of Li^+, Li^{++}, and Li^{+++} ions.

Bombarding energy	Li^{++}/Li^{+++}	Li^{++}/Li^+
239 kv	5.9	
268	3.5	1.8
397		2.9

approximately equal in this range of bombarding energies. It was difficult to hold the high voltages on the accelerating tube and on the electrostatic analyzer sufficiently steady to locate precisely the maximum ordinate of the sharp peaks.

For the same reason only rough estimates can be given, at the present stage of our experiments, for the relative numbers of lithium ions of various charges. The values of Table II are the maxima of the peaks of Fig. 5. It was shown by running bias curves on the Li^{++} and Li^{+++} peaks that there was no appreciable difference in pulse height distributions produced by the electron multiplier tube from these two ion beams of the same energy (see Fig. 4). In the estimation of the value of the Li^{++}/Li^+ ratio we have assumed, without the equivalent experiment having been performed, that the pulse height distributions for Li^+ are not widely different from those of Li^{++} and Li^{+++}.

A theoretical attempt to explain these lithium ion ratios would be a part of the general problem of the capture and loss of electrons by moving ions. Knipp and Teller[16] have treated the problem for protons, alpha-particles, and intermediate and heavy ions produced in the fission process. They were primarily interested in considering the energy loss, which is due to collisions with electrons and with nuclei, the former being essentially determined by the ionic charge, which in turn depends on the ratio γ of the velocity of the outermost electron v_e, within the ion, to the velocity v_i of the ion itself. Bohr,[17] in considering the slowing down of a heavy ion, assumes that along its path the ion will lose those electrons whose orbital velocities are smaller than the velocity of the ion, while all the electrons for which $v_e > v_i$, the probability for loss is smaller than the probability for capture. There will be a value of γ, let us say γ_0, at which there will be equal probabilities for capture and loss, and γ_0 should be close to unity. Knipp and Teller have used the experimental data of Rüchardt,[18] Bartels,[19] and Rutherford[20] to estimate γ_0. They find that $\gamma_0 = 0.8 \pm 0.1$ for hydrogen-like ions, as follows:

for $H \rightleftarrows H^+$ $\quad \gamma_0 = 0.7$ in H_2; 0.8 in N_2 and O_2,
$He^+ \rightleftarrows He^{++}$ $\quad \gamma_0 = 0.8$ in mica.

In our experiments the process $Li^{+++} \rightleftarrows Li^{++}$ represents the capture or loss of a hydrogen-like electron, and might be expected to have a γ_0 of 0.8 ± 0.1.

The process $Li^{++} \rightleftarrows Li^+$ is not hydrogen-like, and there is less available evidence on which to predict γ_0. Knipp and Teller find that in the analogous process $He \rightleftarrows He^+$, the value of γ_0 is 1.6.

Calculations by Brunings, Knipp, and Teller[21] for the electron velocity v_e have been used by them to give values of γ_0 for atomic number $Z = 6$ to $Z = 55$. It is indicated that γ_0 increases from 1.3 to 1.8 when Z increases from 6 to 55, if the electron considered is the most easily removable one. However, if v_e is to be taken as the velocity of the outermost electron, they calculate that γ_0 decreases from 0.6 to 0.35 as Z increases through this range.

Since in our present case Z is 3 for lithium, we cannot use their curves to determine v_e. We shall therefore estimate only roughly what the value γ is, deriving the electron velocity from ionization potential data. Thus for the three lithium ions produced at $E_p = 268$ kv we see from Table I that their energy is about 0.900 Mev, and from Table II that their relative numbers are $Li^{++}/Li^{+++} = 3.53$ and $Li^{++}/Li^+ = 1.83$. We assume that the different ionized states are produced in traveling through the beryllium layer, since the space in the system is a vacuum. Consider the process $Li^{+++} \rightleftarrows Li^{++}$: the orbital velocity of the electron in Li^{++}, which is a hydrogen-like atom, is obtained from the energy:

$$E_e = \tfrac{1}{2} m_e v_e^2 = (9)\ (13.53)\ \text{ev},$$

[16] J. Knipp, and E. Teller, Phys. Rev. **59**, 659 (1941).
[17] N. Bohr, Phys. Rev. **58**, 654 (1940); Phys. Rev. **59**, 270 (1941).
[18] E. Rüchardt, Ann. d. Physik **71**, 377 (1923).
[19] H. Bartels, Ann. d. Physik **6**, 957 (1930); **13**, 373 (1932).
[20] E. Rutherford, Phil. Mag. **47**, 277 (1924).
[21] J. H. M. Brunings, J. K. Knipp, and E. Teller, Phys. Rev. **60**, 657 (1941).

while the ion energy is

$$E_i = \tfrac{1}{2} m_i v_i^2 = 0.900 \times 10^6 \text{ ev.}$$

Hence:

$$\frac{v_e^2}{v_i^2} = \frac{(121.77)(1840)(6)}{(0.900)(10^6)(1)},$$

$$\frac{v_e^2}{v_i^2} = 1.49,$$

and

$$\gamma_1 = \frac{v_e}{v_i} = 1.22.$$

This value shows that, since $v_e > v_i$, the probability for Li^{+++} to capture an electron and become Li^{++} is greater than the reverse process, or that Li^{++} tries to retain its electron rather than lose it. Hence the process $Li^{+++} \rightarrow Li^{++}$ is more probable than $Li^{++} \rightarrow Li^{+++}$. For the case $Li^{++} \rightleftarrows Li^{+}$, the orbital velocity of either electron is obtained by adding the second ionization potential for lithium, which is 75.28 ev to 121.77 ev of the hydrogen-like atom and dividing by 2. That is, if 75.28 ev is the energy required to remove either of the two electrons in Li^{+} and 121.77 ev the energy needed to remove the remaining electron in Li^{++}, their sum, 197 ev, would represent the total energy of the original Li^{+}, which in absolute value is equal to the kinetic energy of both electrons in Li^{+}. Hence, for one electron only, its kinetic energy is $\frac{1}{2}$ (197) or 98.5 ev. Since the ion velocity is the same as in the preceding case, we have

$$\frac{v_e^2}{v_i^2} = \frac{(98.5)(1840)(6)}{(0.900)(10^6)(1)},$$

$$v_e^2/v_i^2 = 1.2,$$

and

$$\gamma_2 = v_e/v_i = 1.09.$$

If 1.6 is the value of γ_0 in this helium-like process, then for our conditions, where $\gamma_2 = 1.09$, the process $Li^{+} \rightarrow Li^{++}$ should be favored. These values of γ_1 and γ_2 seem to indicate that the net advantage is for the state Li^{++}. Hence the doubly ionized state should be more densely populated than either the singly- or the triply-ionized states. This is, in fact, verified by our data as given in Table II, the ratios Li^{++}/Li^{+++} and Li^{++}/Li^{+} indicating that the Li^{++} ion is always favored.

These elementary considerations indicate that the ionic ratios of lithium should not depend on the bombarding energy as they apparently do in Table II. The variation in the kinetic energy of the lithium ions with proton energy, though observable because the experimental arrangement is adapted to energy rather than intensity measurements, is so small that no appreciable change in γ should occur. Until more careful intensity measurements are made it cannot be said that the apparent effect is real.

The detection of the alpha-particles from the splitting of the recoil nucleus Be^8 was also attempted in this investigation without success. The first effort made was in connection with the characteristic bias curves for alphas and for protons obtained with the multiplier tube. Since the alphas from Be^8 have a very low energy, it was calculated that the deflecting voltage on the analyzer had to be lower than the voltage required to detect the scattered protons from the bombarding beam. However, the intensity of these protons was very high across a wide range of analyzer voltages, hence the first hope to detect the Be^8 alphas was based on a different distribution of pulses produced in the multiplier tube by the alphas as compared to that produced by the protons. Unfortunately, the bias curves obtained (see Fig. 4) showed that the distributions were the same, and therefore the protons could not be discriminated against in order to count only alphas.

The second attempt was made to see if any of the Be^8 disintegration products could be detected as singly-charge helium ions. It was hoped that the analyzer voltage V required to detect such ions would be greater than that which selected the high energy edge of the scattered protons. In this experiment the analyzer voltage was lowered to a point beyond which the intensities of the disintegration particles would become too small. At 239 kv a careful investigation of the region between the proton limit and the Li^{+++} peak was made, but no particles were detected. We may summarize the experiments by stating that no doubly-charged alpha-particles of energy greater than 480 kev, from the break-up of Be^8, could be found, and no singly-charged helium ions appeared in the energy range above 240 kev.

V. CONCLUSIONS

The results of this investigation show that the electron multiplier tube can be used successfully as an efficient and reliable detector of particles from nuclear disintegrations. Most of the disadvantages of other types of detectors are eliminated, such as the use of windows, the need of high amplification of pulses, and the troublesome microphonics present in devices like ionization chambers. It is most valuable for the detection of low energy particles and can be used to count either photons, betas, or heavier particles.

In regard to the detection of an atom in its different states of ionization, by using the multiplier tube in combination with the electrostatic analyzer, this investigation points out the possibility of studying the rather complicated problem of the capture and loss of electrons by ions, of which there is not as yet a well established theory. The results reported here, on the relative probabilities of the appearance of singly-, doubly-, and triply-charged ions in a beam of lithium nuclei of 0.900-Mev kinetic energy, support the view that the significant parameter is the ratio of the orbital electronic velocity to the ionic velocity. It is hoped that further experiments of this type will provide more reliable data on this capture and loss phenomenon.

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