Yield of Alpha-Particles from Lithium Films Bombarded by Protons

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(Received April 24, 1935)

The absolute yield of alpha-particles from a thick target of lithium bombarded by protons has been determined using proton energies up to a maximum of 400 kv. The values obtained for the yield in alpha-particles per 10^9 protons, at several different voltages are 16.3 at 250 kv, 33.4 at 300 kv, 58.0 at 350 kv and 92.8 at 400 kv. The yields of several thin films have been studied in considerable detail. Results show that the thin film yield increases linearly with voltage from 180 kv up to 400 kv and at the upper voltage shows no tendency to approach a constant value. The thin film yield curves were smooth, giving no evidence for the existence of resonance levels.

INTRODUCTION

MUCH work has already been done on the disintegration of lithium by high energy protons showing conclusively that a Li^7 nucleus, when disintegrated, breaks up into two alpha-particles each with a range of 8.5 cm. The yield of alpha-particles has been studied as a function of the energy of the bombarding protons using both thick and thin targets of lithium. Cockcroft and Walton[1] studied the yield of 8.5 cm alpha-particles from a thick target of metallic lithium with various values of the proton energy from about 70 kv up to a maximum of 500 kv. Using a thick target of lithium fluoride Henderson[2] determined the yield of 8.5 cm alpha-particles at six different proton energies, ranging from about 430 kv up to 1200 kv. From an analysis of his thick target data Henderson concluded that the thin film yield should reach a constant value at 400 kv. Oliphant and Rutherford[3] bombarded a thin film of lithium oxide and studied the probability of disintegration using very intense proton streams but with a maximum energy of 200 kv. They found that the probability of disintegration is still increasing at their highest voltage but from the shape of the curve they concluded that the yield of alpha-particles should reach a constant value or even decrease as the energy of the protons increases above 200 kv.

In an attempt to remove the uncertainty which still exists as to the form of the yield curve we have studied several thin films using protons with accurately determined energies from about 100 kv up to 400 kv. We have also examined the yield over the whole range of voltage available at closely spaced voltages to determine whether or not resonance levels exist for penetration of protons into the Li^7 nucleus. Another object of this research was to determine the absolute yield of a thick target of lithium prepared by evaporation under good vacuum conditions and then bombarded without being exposed to air.

APPARATUS AND METHOD

A. Production and measurement of high potential

The source of high potential is a Van de Graaff generator operating in a steel tank under moderately high air pressure. Details of the construction and operation of this apparatus will be published in *The Review of Scientific Instruments*. The maximum steady voltage obtainable is at present limited to about 400 kv by breakdowns in the accelerating tube. During a run the voltage can generally be held constant to within about one percent. A generating voltmeter similar to the type developed by Kirkpatrick and Miyake[4] has been found very satisfactory for the measurement of the voltage. This instrument was calibrated at potentials up to 40 kv by means of a bank of carefully measured high resistances. A sphere gap which had been checked with the resistance measurements at low potentials was used to extend the calibration curve up to 100 kv. The scale was found to be accurately linear in this range. Assuming linearity over the entire range the calibration curve was extrapolated up to 400 kv. This assumption of linearity was then proved valid in the following way. The molecular ions (H_2^+) and atomic ions (H_1^+) were separated by a magnetic analyzer and were brought

[1] J. D. Cockcroft and E. T. S. Walton, Proc. Roy. Soc. **A137**, 229 (1932).
[2] M. C. Henderson, Phys. Rev. **43**, 98 (1933).
[3] M. E. Oliphant and Lord Rutherford, Proc. Roy. Soc. **A141**, 259 (1933).
[4] D. Kirkpatrick and J. Miyake, Rev. Sci. Inst. **3**, 1 (1932).

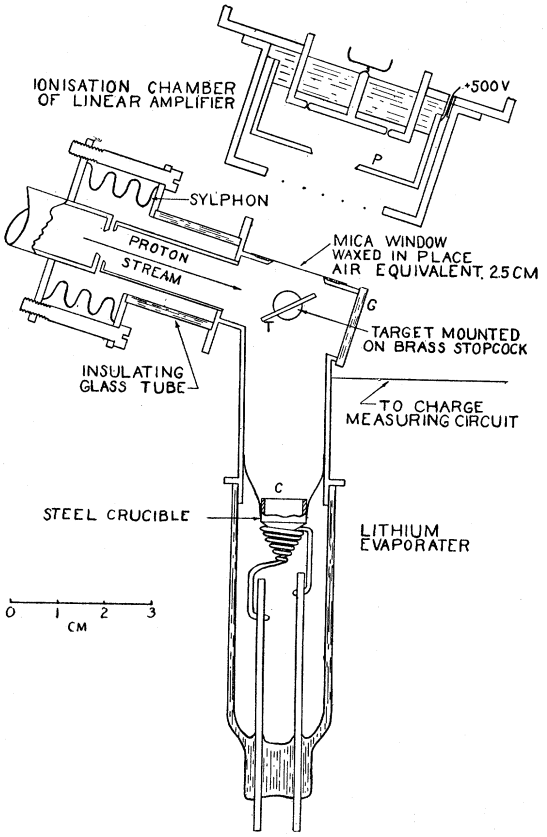

FIG. 1. Arrangement of target, counter and lithium evaporator.

alternately through a $\frac{1}{4}$-inch hole on to a glass plate G, Fig. 1, waxed to the target chamber, where they caused rather bright fluorescence. With the voltage at V_1 the molecular beam was brought to an accurately determined position M on the glass plate G. Leaving the magnetic field fixed the voltage was increased until the H_1^+ beam was at position M. If V_2 was this second voltage its value, providing the voltmeter is linear, should be given by $V_2=2V_1$. With several different voltages between 125 kv and 200 kv for V_1 the values determined for the ratio were $V_2/V_1=2\pm0.04$. A slight wavering of the fluorescent spot prevented more accurate determinations.

B. Target arrangement and counter

The target chamber with the apparatus for evaporation of lithium and for counting of alpha-particles is shown in Fig. 1. A heavy sheet of nickel T mounted on a ground brass stopcock can be turned from the outside to a horizontal position to receive a coat of lithium and then to the position shown in Fig. 1 for the bombardment with protons. Alpha-particles from the lithium pass through a mica window into the ionization chamber of a linear amplifier. The mica window was sufficiently large so that the effective solid angle was determined only by the opening in the plate P of the ionization chamber. This opening was covered by a copper screen for most of the experiments but an unscreened hole (diameter 0.953 cm) with beveled edges was used in determining the absolute yield. A large unscreened opening will cause a nonuniform field in the ionization chamber which might give an inaccurate count. To investigate this possibility a smaller opening was tried (diameter 0.418 cm). No difference in yield could be detected.

For the first part of the work on thick films a linear amplifier similar to that of Dunning[5] was used. It is equipped with a Cenco high impedance counter and a cathode-ray oscillograph. This arrangement was fairly satisfactory for counting-speeds up to 300 per minute. To permit faster counting a scale counter has been devised by one of us which counts every nth particle where n can be adjusted to any desired value. Generally n was set at about 12. Tests over a period of two months show that the scale remains sufficiently constant with time. Regularly spaced pulses generated by a thyratron circuit are accurately counted by this instrument at speeds of 120 per second. With alpha-particles it is satisfactory up to speeds of 2000 per minute. A circuit diagram and details of operation will be published in *The Review of Scientific Instruments*. As an additional check the regular "scale of one" counter was used occasionally when the absolute yield was of importance.

C. Measurement of proton current

Fig. 2 shows the general arrangement used to measure the number of protons incident on the target during a given time interval. G_1 is a Leeds and Northrup galvanometer, sensitivity 4.66 $\times10^{-10}$ amp. per millimeter. G_2 is a ballistic galvanometer, sensitivity 2.98×10^{-9} coulombs per millimeter. C_2 is a low leak condenser, capacitance 8 mfd. C_1 is a condenser with a

[5] J. R. Dunning, Rev. Sci. Inst. **5**, 137 (1934).

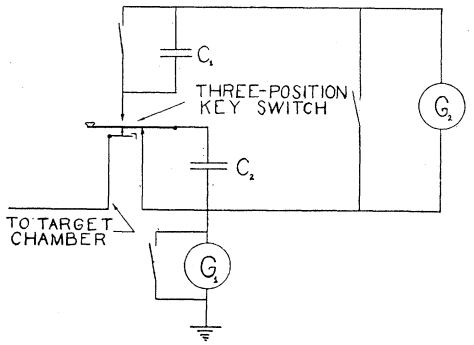

FIG. 2. Circuit for measuring the total number of protons incident on the target during a given time interval.

capacitance chosen to give suitable deflections of the ballistic galvanometer for the time interval and proton current desired. The charge and discharge key is a modification of the Kempe type.

In making a yield determination the arm of the key is depressed to its lowest position, shorting the condenser C_2 and grounding the target chamber through G_1, which now registers the proton current. At $t=0$ the first catch is released and the arm snaps up to the central position. The proton current now flows on to C_2 with G_1 still recording the magnitude of the current. At the end of the time interval the second catch is released. The arm snaps against its upper contact disconnecting the target chamber completely and discharging C_2 into C_1 through the ballistic galvanometer. If Q is the total charge originally on C_2, then the charge q sent through the ballistic galvanometer and measured is given by $q=QC_1/(C_1+C_2)$. Additional points on the key short the Cenco impulse counter except when the arm is at its central position. Thus the counter registers only those disintegrations caused by the charge accumulated on C_2. From the deflection of G_2 and the values of C_1 and C_2 the total charge is easily computed. This system is much more accurate and easier to use than a single current-reading galvanometer.

D. Evaporation of lithium

Considerable difficulty was experienced in obtaining good coats of evaporated lithium. For thick film work a piece of lithium of about $\frac{1}{4}$ cc was put in the crucible C, Fig. 1. The filament temperature was increased slowly for about two days to permit sufficient outgassing so that when evaporation started the pressure could be kept below 2×10^{-5} mm of Hg. With pressures below about 4×10^{-5} mm of Hg the lithium evaporated onto the plate T, Fig. 1 in a white matt surface. At higher pressures the film was dark and gave a lower yield when bombarded with protons. The rate of evaporation was difficult to control. Often after several hours of slow evaporation the rate suddenly rose by a large factor and the pressure became sufficiently high to give a dark colored film.

RESULTS

A. Thick films

Curve A, Fig. 3 shows the data for several runs on a thick target. The first run, shown by dots (increasing voltage) and circles (decreasing voltage) was taken a few hours after evaporation of a fresh lithium surface with good vacuum conditions. For most of these points about 10,000 alpha-particles were counted. Only two points have counts below 5000 and for many the count was above 12,000. The two sets of points check each other very well and fall on a smooth curve. Two days later another run was taken on the same surface using a proton beam with voltages from 340 kv down to 161 kv (shown by triangles). The yield was quite accurately the same as for the first run, showing that the target had not changed appreciably with time. For the lower part of the curve the molecular beam was used instead of the proton beam for the following reason. The accelerating tube depends on corona discharge for the proper potential distribution to give good focusing and does not work well below 150 kv. Since a 300-kv molecular ion consists of two protons, each with an energy of 150 kv the molecular beam can be used at high voltages to give low energy protons. The curve for the molecular ions joins onto the proton beam data satisfactorily.

At 251 kv the yield of alpha-particles per 10^9 protons for the three runs plotted is 17.0, 16.4 and 16.8. At 358 kv the two values are 62.2 and 63.0. A few days later the yield was lower and the data were inconsistent; a brown spot had developed on the target where the ion beam had hit. A fresh film was now evaporated under very good vacuum conditions. It gave a yield of 18.0

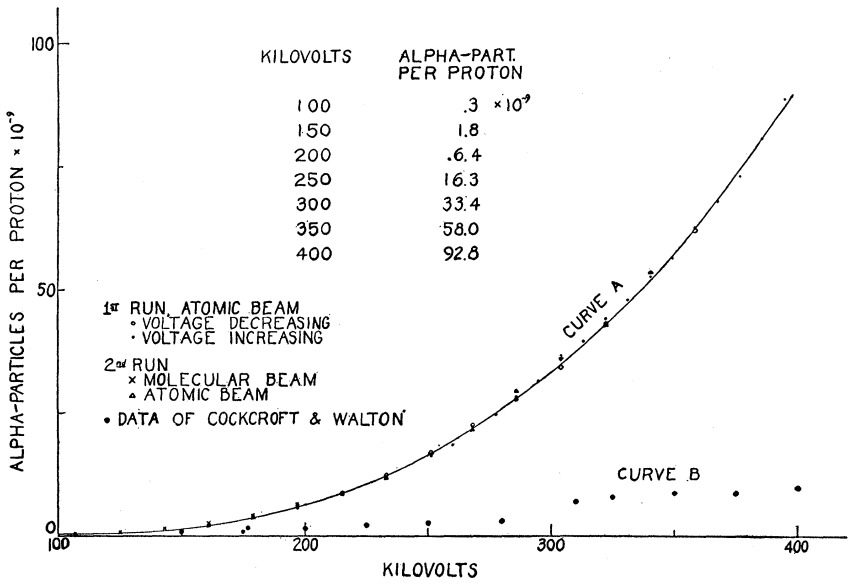

FIG. 3. Yield of alpha-particles from thick films of lithium bombarded by protons. Curve A is a plot of the data obtained at this laboratory. Curve B shows the data of Cockcroft and Walton.

at 251 kv and 62.5 at 358 kv. The increase in yield at the lower voltage may have been due to less surface contamination of the lithium target for the second film, since surface contamination is more important at low voltages. The true yield for a pure lithium film may therefore be somewhat higher at low voltages than the values indicated by the curve and table of Fig. 3. During the measurements the distance from the center of the target to the ionization chamber was 43 ± 0.7 mm. This uncertainty and the uncertain purity of the target are the most serious factors limiting the accuracy of the absolute yield determinations.

Curve B of Fig. 3 shows the yields obtained by Cockcroft and Walton with a target of lithium metal. Most of their values are smaller by a rather large factor than those obtained at this laboratory (curve A, Fig. 3). Henderson, using a target of lithium fluoride obtained values in good agreement with Cockcroft and Walton's data. This was unexpected but could be satisfactorily explained, as Henderson pointed out, by assuming that the lithium target used by Cockcroft and Walton was covered with a layer of lithium hydroxide. Lithium fluoride has 12 electrons per lithium nucleus, while pure lithium has only 3. Since fast protons lose their energy principally to the external electrons, a proton absorbed by lithium fluoride will on the average have had only $\frac{1}{4}$ as many close encounters with lithium nuclei as one absorbed in pure metal. Lithium hydroxide also has 12 external electrons per lithium nucleus and should therefore give the same yield as lithium fluoride, but $\frac{1}{4}$ the yield of pure lithium. Assuming that the target used by Cockcroft and Walton was effectively composed of lithium hydroxide, their yield values should be $\frac{1}{4}$ as large as the values obtained at this laboratory with pure lithium. A comparison of curves A and B of Fig. 3 shows this to be only approximately true.

B. Thin films

Several different geometrical arrangements were used for the thin film work. Five films were studied with the apparatus shown in Fig. 4. With this arrangement the effective solid angle subtended by the ionization chamber was sufficiently large to permit fast counting on a very thin film. A hole ($\frac{3}{8}$ in. diameter) in the end plate of the evacuated chamber is closed by a mica film waxed to the plate. The inner surface of the mica is coated with lithium by evaporation in a separate apparatus before being waxed into position. A mica film with an absorption of 2 or 3

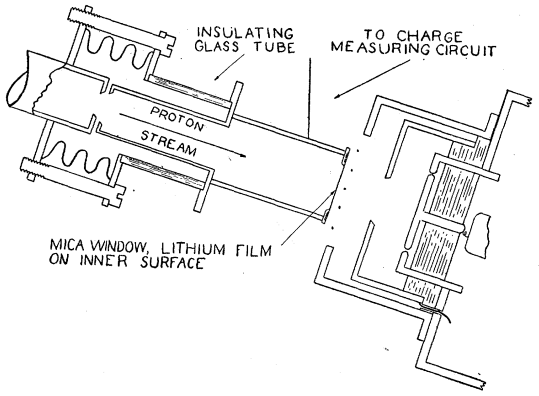

FIG. 4. Arrangement of target and counter for the study of thin films of lithium oxide on mica.

cm air equivalent is sufficiently strong to withstand the air pressure and of the right thickness to stop all protons but transmit the 8.5-cm alpha-particles. Of the five lithium films studied with this apparatus, I and II were prepared by evaporation of lithium on to bare mica. When exposed to the air the lithium quickly became oxidized and then probably changed over slowly into the hydroxide. Inconsistent yield curves from these nonconducting films and visible sparking along their surfaces indicated that charging up of the mica might have objectionable effects. To eliminate this possibility of inaccuracy films III, IV and V were first coated with a very thin semi-transparent layer of silver. For films III and IV the lithium was evaporated onto the silver surface. With film V the lithium and silver were on opposite surfaces. Both methods eliminated excessive surface charges and the yield curves obtained were similar.

The data obtained in a detailed study of film III (lithium hydroxide on silver) are shown in Fig. 5 by dots and crosses, where dots represent yields determined with H_1^+ ions incident on the target and crosses give yields obtained with H_2^+ ions. Two separate runs were taken for both the atomic and molecular ion data. In both cases the second run was taken at only a few voltages (those showing two dots or two crosses) as a check on the detailed data of the first runs. The excellent agreement between atomic and molecular ion data provides more evidence confirming the linearity of the voltmeter. All of the data from film III fall quite accurately onto the smooth curve which has been drawn in. Within the limits of experimental accuracy, the yield of alpha-particles is a linear function of the energy of the bombarding protons in the voltage range from 180 kv up to the maximum obtainable.

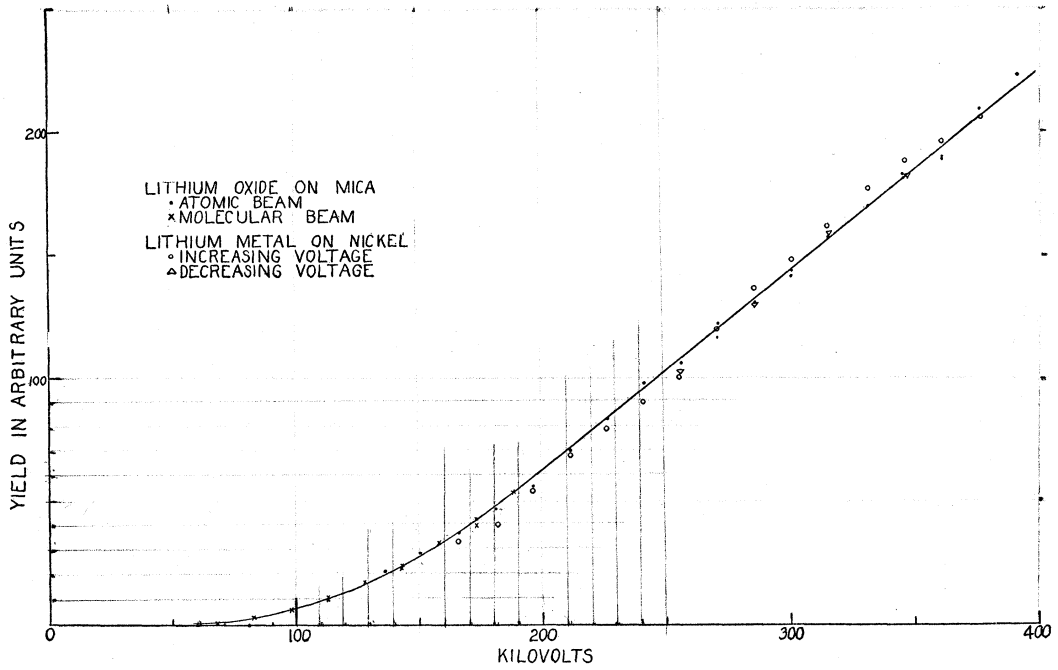

FIG. 5. Yield of alpha-particles from thin films of lithium bombarded by protons.

Above 180 kv the curve was drawn in with a straight edge. This linear increase of yield up to 400 kv indicates that the potential barrier of the lithium 7 nucleus for penetration of a proton is considerably higher than had been expected. The curve gives no evidence for the existence of resonance levels.

A study of the yield of a thin film of lithium should determine the probability of disintegration of lithium nuclei as a function of the energy of the protons causing disintegration. If the film being studied is sufficiently thick to decrease the energy of 300 kv protons to 250 kv, then protons in the entire range from 300 kv to 250 kv are causing disintegration and the yield obtained will determine only an average disintegration probability for proton energies in this range. For determining the true probability of disintegration as a function of the energy of the protons a film should be only infinitesimally thick. The yield which would be obtained from such a film will be called the true thin film yield. To find whether or not the lithium oxide film used gave accurate values for the true thin film yield, its stopping power for protons was determined in the following manner. At 256 kv this film gave an absolute yield of 0.35 (yields given in units of "alpha-particles per 10^9 protons"). The thick film yield at this voltage is 17.5 and the voltage giving a thick film yield of $17.5-0.35$ is 254.7 kv. Protons with an energy of 254.7 kv will penetrate a distance d into a thick target of lithium before being stopped and will give a yield of $17.5-0.35=17.15$. Protons with an energy of 256 kv will have their energy decreased to 254.7 kv in going through a film of thickness x and from there on will go the same distance d and give the same yield as the 254.7 kv protons. The increase in yield of 0.35 is therefore due to a film of thickness x sufficient to decrease the energy of 256 kv protons to 254.7 kv. A thin film of lithium giving a yield of 0.35 at 256 kv will therefore decrease the energy of 256 kv protons by 1.3 kv. Since for a given yield lithium hydroxide has four times the stopping power of pure lithium the film used for the data of Fig. 5 decreased the energy of 256 kv protons by 5.2 kv. This film was therefore sufficiently thin to give accurate values for the true thin film yield.

A thin film of lithium metal, coated by evaporation onto a nickel sheet, was studied with the apparatus shown in Fig. 1. Determinations of the absolute yield of this film showed that it was sufficiently thick to decrease the energy of 256 kv protons by 9 kv. The data obtained from two runs on this film are shown in Fig. 5 by circles and triangles. Further considerations such as those of the last paragraph show that two films may be sufficiently different in stopping power to give quite different absolute yields but nevertheless the curves showing yield as a function of voltage would be of practically the same form for both. Thus if the yields obtained from the lithium film on nickel are multiplied by a properly chosen constant factor the curve obtained for yield as a function of voltage should coincide with the curve determined by the lithium hydroxide film data. An inspection of Fig. 5 shows that within the limit of accuracy of the measurements the data from these two thin films give identical yield curves. Over the straight part of the yield curve (above 180 kv) the rate of increase of yield with voltage can be specified by the ratio $Y_{250}/Y_{200}=1.64$, where Y_{250} and Y_{200} are the yields at 250 kv and 200 kv respectively, determined from the curve of Fig. 5.

A thin film yield curve has been determined from the thick target data of curve A, Fig. 3 assuming the law $R=KV^{\frac{3}{2}}$ for the range of protons in lithium where R is the range and V the energy of the protons. Let Y_v be the thick film yield at voltage V determined from curve A, Fig. 3. The differences $Y_{130}-Y_{110}$, $Y_{150}-Y_{130}$, $\cdots Y_{410}-Y_{390}$ were determined from the curve. Each difference $Y_{v2}-Y_{v1}$ gives the yield of a lithium film of sufficient thickness T_{v2v1}, to decrease the energy of the protons by 20 kv. Using the law $R=KV^{\frac{3}{2}}$ this film thickness is given by $T_{v2v1}=K(V_2^{\frac{3}{2}}-V_1^{\frac{3}{2}})$. If each difference of yield $Y_{v2}-Y_{v1}$ is divided by a value T_{v2v1} proportional to the thickness of lithium effective, the thin film yields over the entire voltage range will be reduced to the yields which would be obtained from a film of constant thickness. The values $Y_{v2}-Y_{v1}/V_2^{\frac{3}{2}}-V_1^{\frac{3}{2}}$ are shown plotted in Fig. 6 (large dots) as the thin film yields for the voltages $(V_2+V_1)/2$. The continuous line drawn in is the experimentally determined thin film curve of Fig. 5 transferred to Fig. 6 for comparison. At 340 kv the derived yield value

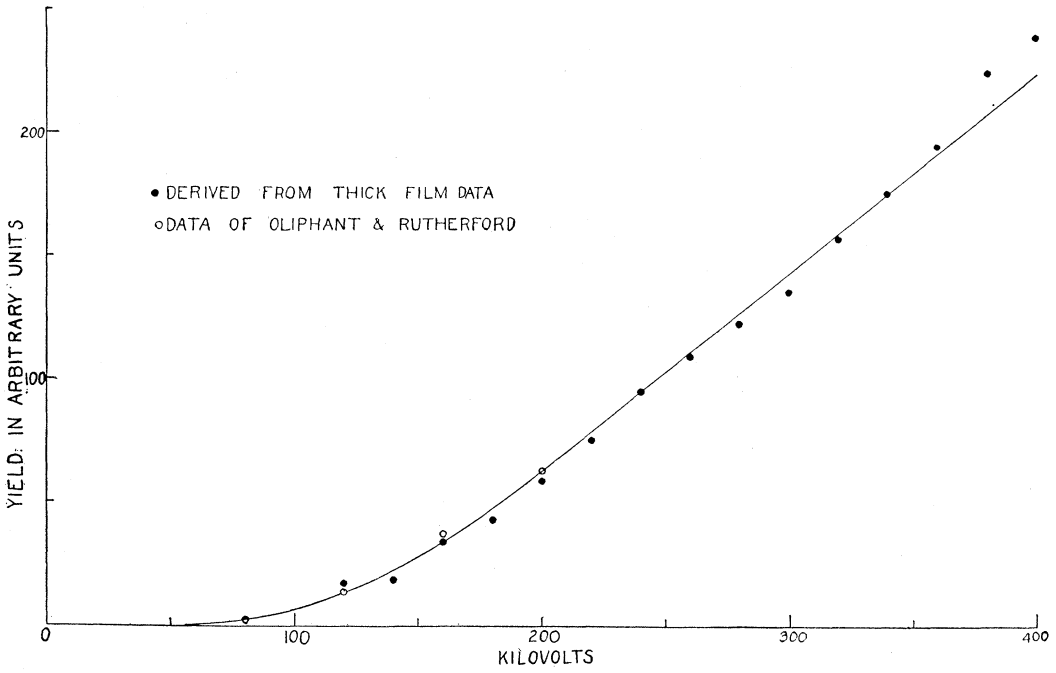

FIG. 6. Yield of alpha-particles from thin films of lithium. The large dots show data derived from the thick film yield curve of Fig. 3. The curve drawn in is the direct experimental curve of Fig. 5 transferred to this figure for comparison.

was made to fall on the experimental curve by multiplying all derived values by a suitable constant. In obtaining the yield values of Fig. 6 from the thick film curve of Fig. 3 slight inaccuracies in measuring the differences $Y_{v2} - Y_{v1}$ caused the rather large irregularities observed in the yield values given by large dots. If these irregularities are neglected the curve determined by the derived data falls quite accurately on the curve drawn in, which is the thin film curve determined by direct experiment. This excellent agreement of the data derived from a thick film curve with the experimentally determined thin film curve is a very satisfactory check on the accuracy of the yield measurements on both the thick and thin lithium films.

The circles of Fig. 6 show yield values determined from a curve obtained by Oliphant and Rutherford on a thin film of lithium oxide. If their curve is assumed to be a straight line at high voltages and is extrapolated up to 250 kv, the rate of increase of yield with voltage determined from their curve is given by $Y_{250}/Y_{200}=1.51$. The value obtained for this ratio from the curve of Fig. 5 and Fig. 6 is 1.64. Thus the thin film yields determined at this laboratory show a more rapid rise with voltage than the yields given by Oliphant and Rutherford.

CONCLUSION

Although our measurement of the absolute yield of alpha-particles from a thick target of lithium bombarded by protons seems fairly satisfactory we hope to check the results soon with a new target chamber and a different sample of lithium.

Our work on thin targets is quite conclusive in showing an increasing yield up to 400 kv. All of our data indicate that above 180 kv the yield is quite accurately a linear function of voltage with a rate of increase which can be specified by giving the yield ratio found, $Y_{250}/Y_{200}=1.64$. Within our limits of accuracy no resonance levels could be detected.

We wish to express our indebtedness to Professor C. E. Mendenhall who directed this research and to Professor G. Breit for much valuable advice. We also wish to thank Mr. E. J. Bernet for his work on the linear amplifier and Mr. G. R. Sears for advice and helpful discussions. One of us (R. G. H.) wishes to acknowledge the generous grant of a fellowship from the Wisconsin Alumni Research Foundation.