for 100 volt impacts is shown in the inset of Fig. 9. An accurate, though less detailed comparison with the theory can be made at this point. Since, for every electron scattered with a loss of V volts in addition to the ionization loss (V_i) there is an ejected electron coming away with V volts energy, we can find the theoretical curve for the sum of the incident and ejected electrons by adding to the curve in the inset of Fig. 9, its mirror image. The result, which obviously must be symmetrical about the energy $(V_c-V_i)/2$ or 37.75 volts, is given by the solid line in Fig. 9. We see that the theory predicts a minimum probability for an ionization which leaves the incident and the ejected electrons with equal energies. Furthermore, the most probable process is one in which one electron carries all but about 3.5 volts of the available energy. The experimental results which we have determined by numerical integration of the curves in Figs. 7 and 8 are given by the circles in Fig. 9. The absolute values have been multiplied by the factor 1.9 to effect a better comparison. They confirm the minimum at $(V_c-V_i)/2$ volts but show no evidence of maxima at 72 and 3.5 volts. In order to determine more accurately the shape of the curve in the regions of the predicted maxima, retarding potential increments smaller than the 2 volts used, are necessary. Intensity limitations prevented us from making the increments smaller excepting for the high energy electrons in the region of small angles. Fig. 7 shows that the small angles contribute most of the scattered electrons of high energy. Therefore one would expect to observe the higher energy maxima of Fig. 9 as a peak near 75 volts in the velocity distribution of electrons scattered at small angles. Although retarding potential increments as small as 0.2 volt were used, no such peak was found. It must be remembered that the accuracy of the theory should be better at higher incident electron energies. Consequently, it is necessary to get further experimental data before making any certain evaluation of the theory on this point.

In conclusion, the writer wishes to express his gratitude to Professor John T. Tate under whose direction the work was done. Thanks are due also to Professor E. L. Hill for helpful discussions on the theory of electron scattering.

AUGUST 15, 1937 PHYSICAL REVIEW VOLUME 52

Disintegration of Aluminum by Polonium Alpha-Particles

W. R. KANNE
Johns Hopkins University, Baltimore, Maryland
(Received June 12, 1937)

In order to investigate the discrepancies existing in the experiments of Pose and of Chadwick and Constable regarding the protons emitted by aluminum under alpha-particle bombardment, the thick target absorption curve for the protons has been repeated. The radioactive source was polonium, and an FP-54 vacuum tube electrometer was used to detect the protons. The structure of the groups observed in the present experiment agrees with the work of Chadwick and Constable, and confirms their interpretation of the results. The ranges of the principal groups are in better accord with those found by Pose. It is suggested that Pose's discrepancies were due to sources which predominantly emitted particles of shortened range, and to an insufficient number of accurate points. An increase in proton yield with the height of the resonance levels has been observed. The relative intensity of the short and long range groups is 4.0, and the difference in energy of any two corresponding groups is 2.4 Mev.

INTRODUCTION

In many respects aluminum makes an ideal target for nuclear investigations. For this reason the reaction

$$_{13}Al^{27}+{}_2He^4={}_{15}P^{*31}={}_{14}Si^{30}+{}_1H^1+Q,$$

where Q represents the energy balance, is today the most thoroughly studied of its type. In aluminum only the $_{13}Al^{27}$ nucleus is stable, so there is no confusion as to which of several isotopes might be involved in the reaction. The

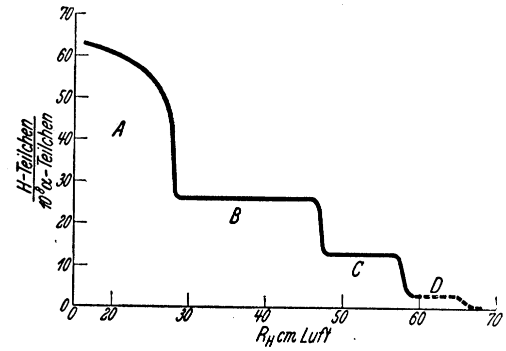

FIG. 1. Thick target absorption curve (after Diebner and Pose).

metal is chemically stable, and thin foils are easily obtainable.

The first observation of resonance in nuclear processes was made by Pose[1] in his investigation of this reaction. Chadwick and Constable[2] have confirmed the existence of resonance, but disagree regarding the shape of the absorption curve and the interpretation of the process. Pose concluded that alpha-particles of the same energy can, (a) cause resonance excitation of a proton group of definite energy, or (b) penetrate without resonance and excite a group of different energy, while Chadwick and Constable have found only resonance excitation, and have interpreted their results in terms of a system of nuclear levels.

Figure 1 shows the thick target absorption curve obtained by Diebner and Pose.[3] The energy of group A is, within experimental error, equal to that of the alpha-particles producing it. Due to the fact that they found this group to be produced by slow as well as fast alpha-particles, but with greater efficiency by the latter, it was attributed to alpha-particles which penetrate the potential barrier without resonance. They assumed that when this group is produced the alpha-particle does not remain with the nucleus, but that it transfers its entire kinetic energy to the proton. Groups B and C were found to be due to a resonance of alpha-particles of 2.2 cm and 3.2 cm range, respectively, the energy of each group being 2.5 Mev greater than that of the alpha-particle producing it. The existence of group D was barely observed in Fig. 1, and this group did not enter the investigation of resonance. Pose[4] attributed it to the beginning of nonresonance disintegration at alpha-ranges just below 4 cm—the energy change being the same as that for the resonance groups.

[1] Pose, Zeits. f. Physik **64**, 1 (1930).
[2] Chadwick and Constable, Proc. Roy. Soc. **A135**, 48 (1932).
[3] Diebner and Pose, Zeits. f. Physik **75**, 753 (1932).

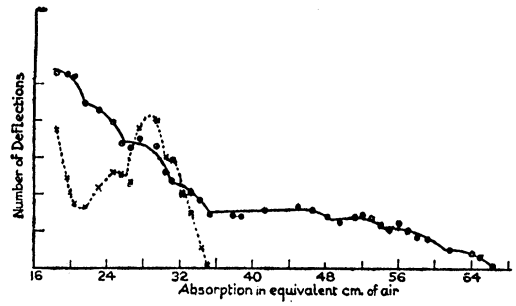

FIG. 2. Thick target absorption curve (after Chadwick and Constable).

Chadwick and Constable obtained the absorption curve shown in Fig. 2, where the dotted curve refers to a count of protons near the ends of their ranges. Altogether, eight groups are present. Pose's short range group is observed as four separate groups, and there are four groups, instead of two, having ranges greater than 40 cm. The analysis showed that corresponding high intensity (short range) and low intensity (long range) groups appear and disappear together as the energy of the alpha-particle is changed. For example, the first and fifth groups are produced together and are due to the same alpha-particle resonance.

These results led Chadwick and Constable to the conclusion that there are four resonance levels of the combined nucleus into which the alpha-particle and the aluminum nucleus may unite. Each of these states may then disintegrate so as to leave the final $_{14}Si^{30}$ nucleus in either its ground state or an excited state, giving rise to the four sets of corresponding groups. The transition from the excited state of silicon to the normal state takes place with the emission of a gamma-ray, whose energy is the difference between the energies of any corresponding long and short range groups.

EXPERIMENT

A repetition of the thick target absorption curve was chosen as the simplest test between

[4] Pose, Zeits. f. Physik **95**, 84 (1935).

the two experiments. The procedure used in the present experiment was similar to that described by Hafstad.[5] The detecting apparatus was an FP-54 vacuum tube electrometer, which was operated at a sensitivity of 35,000 mm per volt in a circuit of the simple nonbalancing type described by Kanne and Bearden.[6] The alpha-particles from a polonium source were absorbed in an aluminum target 5 mm in diameter and of 4.2 cm air equivalent. The protons emitted in this foil passed through calibrated mica absorbing screens into an ionization chamber which was made of steel and contained air at atmospheric pressure. It was conical in shape, with a central electrode, and was 1.5 cm deep. The aperture admitting the protons to the chamber, like both the source and the target, was 5 mm in diameter, and the centers of all three were in line.

The distance from the source to the target was 7.5 mm, and that from the target to the detector was 16.7 mm. If ϵ is the half-angle subtended by the target at the source, α the half-angle subtended by the detector at the target, and θ the largest angle possible between the incident alpha-particle and an emitted proton which can reach the ionization chamber, then

$$\epsilon=\tan^{-1}(2.5/7.5)=18°\ 30',$$
$$\alpha=\tan^{-1}(2.5/16.7)=8°\ 30',\text{ and}$$
$$\theta=\tan^{-1}(5/7.5)+\tan^{-1}(5/16.7)=51°.$$

The straggling of the proton groups should cover 3 or 4 cm. The total intensity factor introduced by solid angle in this arrangement is 1.57×10^{-4}.

The experiment was performed with two different sources, both of which were prepared by chemical deposition on silver.[7, 8] The results of the experiment are based on the data obtained with the second source, but those obtained with the first source are included in the report because they lend weight to the results and suggest a possible origin of the conflict. At the end of the experiment the particles emitted by the second source were counted by a linear amplifier and it was found to have been 1.4 mc in strength originally. Particles of ranges from 3.0 cm to 3.9 cm were present, and the decrease in number

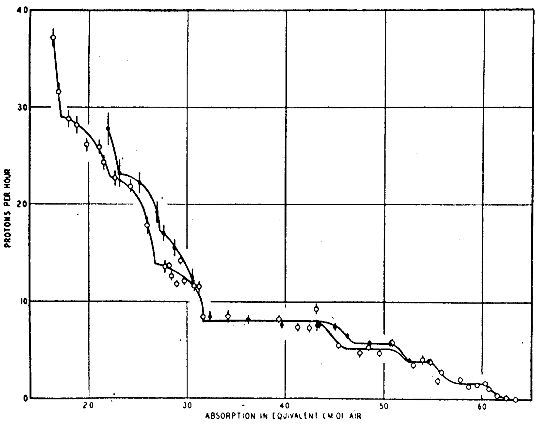

FIG. 3. Thick target absorption curve, using FP-54.

between these two ranges was linear. On the basis of a comparison of the proton yields obtained with the two sources, the first source was calculated to have been 1.1 mc originally. Since this source was weaker, it is reasonable to assume that it emitted alpha-particles of more uniform range.

In the interpretation of an absorption curve the protons which come to the ends of their ranges are of interest. These ranges were obtained by determining the stopping power of the mica in the following manner. As a first approximation 1.43 mg per sq. cm of mica was taken as equivalent to one cm of air, and the air equivalent of the absorption at each experimental point calculated on this basis. The velocity of a proton having such a range was taken from Duncanson's data,[9] and an accurate value for the stopping power of the mica, considering the integrated velocity, was obtained from Mano's stopping power-velocity tables.[10]

Discussion of Results

In Fig. 3 is shown the absorption curve for the protons emitted by a thick aluminum target, obtained with the FP-54 pliotron. The group structure described by Chadwick and Constable is present, and comparisons with Figs. 1 and 2 show the agreement with their work in preference to that of Pose. This agreement, and a partial explanation of Pose's results, support the interpretation given by Chadwick and Constable.

[5] Hafstad, Phys. Rev. **44**, 201 (1933).
[6] Kanne and Bearden, Phys. Rev. **50**, 935 (1936).
[7] I. Curie, J. Chem. Phys. **22**, 471 (1925).
[8] Hafstad, J. Frank. Inst. **221**, 191 (1936).
[9] Duncanson, Proc. Camb. Phil. Soc. **30**, 102 (1934).
[10] Mano, J. de phys. **5**, 628 (1934).

The experimental points indicated by solid circles were obtained from the first source and were multiplied by a constant factor for purposes of comparison with the data obtained from the second source, indicated by open circles. The yield scale refers to the latter data.

The only important discrepancy between this work and that of Chadwick and Constable is that the ranges found here are consistently several centimeters shorter. The group of shortest range, if present, was masked by the intense recoil protons from the source. But if the onset of the rise just above 17 cm is considered to be due to this group, rather than to the recoil protons, the difference between its energy and that of the related 45.5 cm group is found to agree with the energy differences of the other short and long range groups.

The origin of this discrepancy is not clear from the experiments, but a criticism of Chadwick and Constable's evidence for this group shows that it is not impossible that it may have been confused with the natural protons. The dotted curve in Fig. 2, which represents a count of the protons near the ends of their ranges, shows no tendency to form a maximum corresponding to this group. The same is true in the differential count obtained in the analysis of the groups, where only this group and its companion appear (Chadwick and Constable, Fig. 7). This would indicate that the absorption curve should have a large, rather than very small slope in the region between 17 and 20 cm. It is suggested as a possibility that Chadwick and Constable's entire curve may need to be shifted slightly toward smaller absorptions. The two curves obtained in the present experiment are entirely consistent with each other, their differences being traceable to the different range distributions of the two sources.

It is much to be regretted that experimenters who have used natural radioactive sources have not made statements regarding their range distributions. Chadwick and Constable have mentioned that the source with which they investigated resonance was only slightly tarnished, which from experiences in this laboratory would indicate a very nearly uniform range distribution. They make no statement, however, regarding the source with which they obtained the absorption curve.

Pose's sources were presumably prepared in Vienna, and he neither describes the method by which they were prepared nor gives their range distributions. Lacking the latter information, one can only surmise the reasons for his failure to observe the more complicated group structure. First, the fact that his group D, of longest range, was observed only with very small intensity would indicate that his source was almost lacking in high energy alpha-particles. A group of corresponding range has been observed with considerable intensity by both Chadwick and Constable and the author. The absence of a short range group due to alpha-particles of the same energy would account for the fact that he found the "range" of group A to be 27 cm, rather than 32 or 34 cm. A range of 27 cm is in good agreement with that of the next group observed in this work. His failure to observe the break in the absorption curve at 22 cm is probably due to an insufficiency of points, to an insufficiency of counts at each point, and to the failure of his apparatus to count all the protons. The latter is indicated by the fact that the rise at low absorptions is much greater than his curve shows. The groups at 52.5 and 57 cm are very close together, so that it is probable that Pose's "group" C corresponds to these two groups unresolved. And finally, his group B may be identified with the 45.5 cm group.

It should be mentioned that the appearance in the curves published by Diebner and Pose of only a small indication of a short range group

TABLE I. *Energies of proton groups from Al. Their differences (γ-rays) and intensity ratios are also given.*

RANGE cm	ENERGY Mev	RANGE cm	ENERGY Mev	γ-RAY Mev	RELATIVE INTENSITY
17.2	3.4	45.5 (47)	5.9 (6.1)	2.5	
22 (23)	3.9 (4.0)	52 (52.5)	6.4 (6.45)	2.5 (2.45)	4.0
27 (27.7)	4.4 (4.5)	57	6.75	2.35	4.1
32 (32)	4.8 (4.8)	62.5	7.2	2.4	4.0

TABLE II. *Proton yields for resonance levels. Average α-particle ranges and the ranges of the protons ejected are given.*

AVERAGE R_α	R_p	YIELD
2.95	22 cm and 52.5 cm	2.65×10^{-7}
3.3	27 cm and 57 cm	7.7×10^{-7}
3.75	32 cm and 62.5 cm	19×10^{-7}

when the 46 cm group is excited, supports the present findings that this first group, if present, is very close to the natural protons.

The data on corresponding proton groups are given in Table I, where the numbers in brackets refer to the data indicated by solid circles in Fig. 3. Since the relative intensities of the short and long range proton groups do not change, the silicon potential barrier has no effect on protons emitted with energies greater than 3.9 Mev.

Only a tentative determination of the proton yields may be made from the present experiment, since the range of the resonant alpha-particles is necessary in order to find the number of particles emitted by the source that can be effective in producing the particular mode of disintegration. Chadwick and Constable give as the values of the maximum ranges of the resonant alpha-particles: 2.7, 3.1, 3.45, and 3.9 cm. They have observed that the resonances are about 300,000 volts wide, so that the average ranges of the alpha-particles would be 2.55, 2.95, 3.3, and 3.75 cm. Then considering the number of effective alpha-particles emitted by the source, the total proton yields for each resonance level may be calculated. (Table II.)

If the 17.2 cm group had four times the intensity of the 45.5 cm group, the yield for this pair would be 3.8×10^{-7}. Chadwick and Constable give 3.5×10^{-7} as the yield for each resonance level.

A summary of work of this type up to 1935 on the several light elements has been given by Pollard.[11] Experiments on aluminum with the higher energy particles from Th C′ and Ra C′ have been performed by Haxel[12, 13] and by Duncanson and Miller.[14] The results of these experiments are in agreement with the interpretation that is accepted here. They have found that the high energy projectiles are able to give enough energy to the combined ${}_{15}P^{31}$ nucleus so that the ${}_{14}Si^{30}$ nucleus may be left in either its normal state or any of three excited states, with enough energy left to the proton for it to be observable. Duncanson and Miller have observed two additional resonance levels at 4.25 cm and 5.25 cm. In all, six resonance levels of the combined nucleus, and four states of the final nucleus have been observed.

Recent work by Waring and Chang,[15] in agreement with the Bohr concepts of nuclei and of nuclear reactions, has shown that resonance is closely associated with the emitted particle. Further work by Chang and Szalay[16] has led to similar results. They have suggested that the potential barrier of a nucleus does not exhibit resonance levels, as Chadwick and Constable had described, but that the maxima in the yield of protons are due to pronounced changes in the probability of the "transition" in which a proton is emitted.

The writer wishes to acknowledge his indebtedness to Professor J. A. Bearden, under whose direction this work was done, for his continued advice and encouragement. He also wishes to thank Dr. L. R. Hafstad for valuable discussions regarding the problem. The radioactive sources used in the present experiment were prepared from a Ra D +E+F solution extracted by L. R. Hafstad from old radon bulbs generously supplied by Drs. C. F. Burnham and F. West, of the Kelly Hospital, Baltimore, Maryland.

[11] Pollard, Phys. Rev. **47**, 611 (1935).
[12] Haxel, Zeits. f. Physik **88**, 346 (1934).
[13] Haxel, Zeits. f. Physik **90**, 373 (1934).
[14] Duncanson and Miller, Proc. Roy. Soc. **A146**, 396 (1934).
[15] Waring and Chang, Proc. Roy. Soc. **A157**, 652 (1936).
[16] Chang and Szalay, Proc. Roy. Soc. **A159**, 72 (1937).