Results of H^3 Bombardment of Ag Leading to Pd^{109}

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H^3 has been used as the bombarding particle to effect nuclear reactions. H^3 was produced by (d, H^3) reaction in Be and Ag and immediately utilized as are neutrons in a fast neutron bombardment. The energy of the H^3 particles was about 10 Mev. The target was a stack of Ag foils in front of which different thicknesses of Be were placed and a 10-Mev deuteron beam was made to impinge on the Be. The H^3 generated within Be, produced the 13-hour Pd^{109} activity in Ag foils as confirmed by chemistry. The reaction is believed to be $Ag^{109}(H^3, He^3)Pd^{109}$. Spurious (n, p) reaction was estimated and corrected for. The observed range of H^3 in different materials is discussed. The threshold for the H^3 reaction in Ag is roughly estimated to be between 1.1 and 1.5 Mev.

I. INTRODUCTION

H^3 has been suggested by many as a very desirable bombarding particle.[1] As yet H^3 is not available to us in quantity. In order to use this isotope for bombardments, reactions were employed which produced H^3. The procedure is analogous to fast neutron bombardment. The experimental difficulties are, however, much greater than the neutron analog. The neutrons easily come out of the Li or Be targets whereas H^3 is stopped by a few mils of material.

In the present investigations, H^3 was produced and utilized from the reactions[2] $Be^9(d, H^3)Be^8$ and $Ag^{107}(d, H^3)Ag^{106}$. Presumably the quantity of H^3 obtained from the bombardment of impurities and from the $d-d$ reaction[3] may be considered very small.

Figure 1 shows a nuclear chart of the silver region where the work was carried on. Observations were made on the 13-hour Pd^{109} activity which was previously known[4] to be produced by the reaction $Ag^{109}(n, p)Pd^{109}$. Reports by others[5] that the 13-hour activity thus produced belongs to Pd^{109} and not to Pd^{107}, has been confirmed in course of the present work by noting that this activity is not produced on prolonged alpha-bombardment of ruthenium.

It is the purpose of this paper to show that the 13-hour Pd^{109} activity is produced by H^3 in considerable strength because of the reaction[6] $Ag^{109}(H^3, He^3)Pd^{109}$.

II. EXPERIMENTAL

A number of silver foils, each 0.001 inch thick, were housed in a specially designed aluminum target piece. In front of the stack of foils, a beryllium sheet was placed. The thickness of the beryllium could be varied arbitrarily from zero to 15 mils. The 10-Mev deuteron beam impinged upon the beryllium and, depending upon the thickness of the Be sheet, then penetrated up to a certain depth within silver. H^3 produced in beryllium and also in silver is stopped in the first few foils. The last foils were subjected to neutron reactions only. The duration of the bombardment was the same in each run at approximately equal beam strength. Chemistry on preliminary samples was carried out both on the silver and ruthenium activations to confirm the elements. The decay curves of the activated silver foils were followed, under identical geometrical conditions. Out of a large number of bombardments, only five will be needed to explain the essential features of the present experiments with H^3. The results of these five bombardments with beryllium thicknesses 0, 4.2, 7.5, 11.7, and 15 mils, are detailed as follows.

The decay curves of the silver foils in a

[1] M. Y. Colby and R. N. Little, Phys. Rev. **70**, 437 (1946).
[2] R. D. O'Neal and M. Goldhaber, Phys. Rev. **57**, 1086 (1940); L. W. Alvarez and R. Cornog, Phys. Rev. **58**, 197 (1940); R. S. Krishnan, Proc. Camb. Phil. Soc. **36**, 500 (1940); R. S. Krishnan and T. E. Banks, Proc. Camb. Phil. Soc. **37**, 317 (1941); D. N. Kundu and M. L. Pool, Phys. Rev. **71**, 140 (1947).
[3] L. W. Alvarez and R. Cornog, Phys. Rev. **56**, 613 (1939); **58**, 197 (1940).
[4] N. Feather and J. V. Dunworth, Proc. Roy. Soc. London **A168**, 566 (1938).
[5] W. Rall, Phys. Rev. **70**, 112 (1946).
[6] D. N. Kundu and M. L. Pool, Bull. Am. Phys. Soc. **22**, 11 (1946).

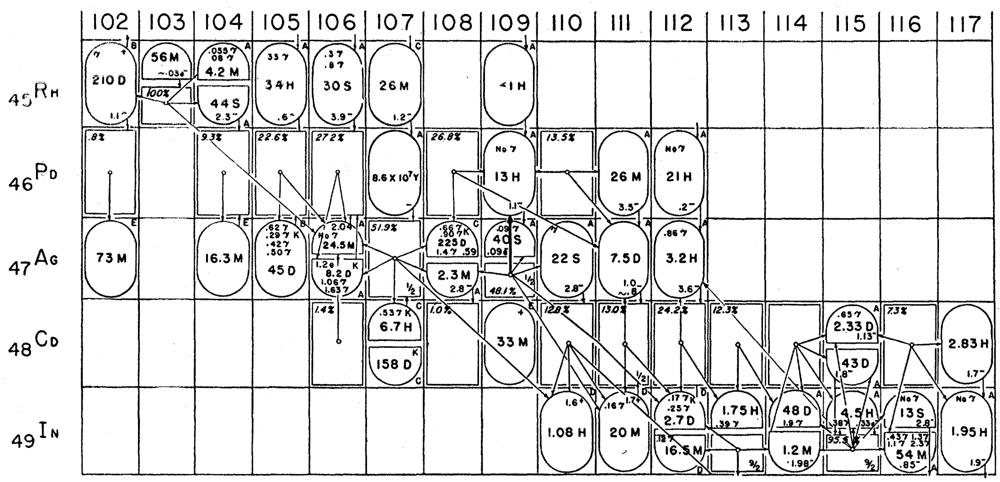

FIG. 1. Silver region in the chart of atomic nuclei. Heavy arrow indicates formation of Pd^{109} from Ag^{109} caused by H^3 bombardment.

deuteron bombardment of silver without any beryllium are shown in Fig. 2. The activities are in arbitrary units, and the numbers refer to different silver foils beginning from the front. Only that portion of the complete decay curves where the 13-hour Pd^{109} activity is predominately large has been presented on the same time scale. The activities in the front foils 1, 2, 3, and 4 are widely different, whereas those in foils 5, 6, 7, and 8, induced by neutrons, are approximately the same. A single curve has, therefore, been drawn through the points corresponding to foil

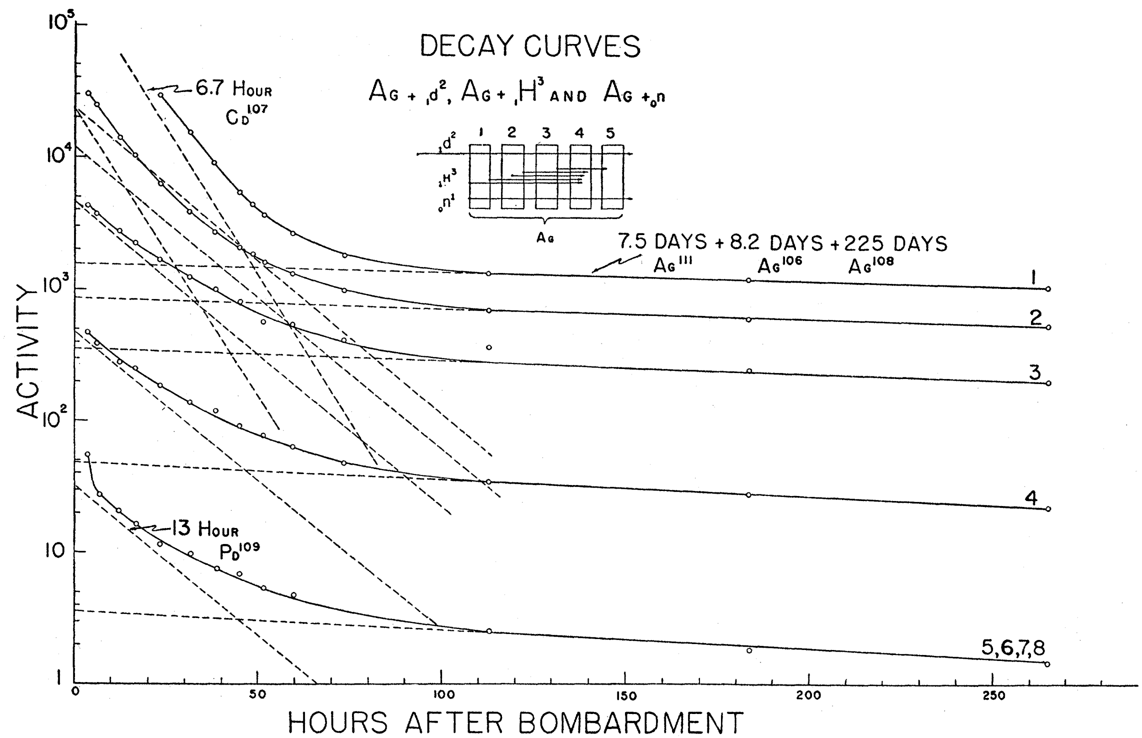

FIG. 2. Decay curves of a deuteron bombardment on Ag foils without any Be in front. The 13-hour Pd^{109} and the 6.7-hour Cd^{107} activities are shown in their relative strengths in the different foils.

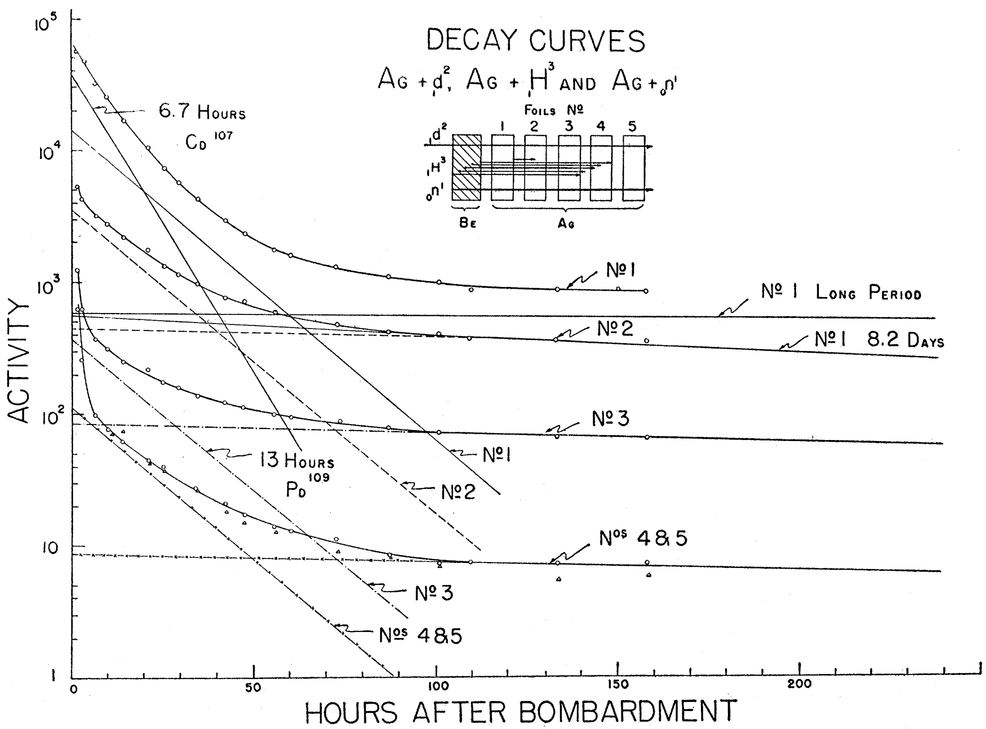

FIG. 3. Decay curves of Ag foils after bombardment by H^3 using 4.2 mils of Be. The 13-hour Pd^{109} activity caused by H^3 and neutrons is shown; that caused by neutrons only is given by curves 4 and 5.

5 alone. The 6.7-hour Cd^{107} activity which monitors the deuterons of energy up to 4.6 Mev[7] is seen in great relative strength in the first two foils only. This set of curves for the activities of the silver foils under deuteron bombardment where no beryllium had been used, served as the reference for all the other sets taken with different thicknesses of beryllium.

Figure 3 shows the results of a similar deuteron bombardment on silver with 4.2 mils of beryllium in front of the silver foils. The activities in the initial foils are still considerably different, though not quite as widely as in Fig. 2. The activities in foils 4 and 5 are the same. The spread of values is indicated but a single curve is drawn through them. The amount of the 13-hour activity in the first three foils above the neutron activation level has apparently diminished.

The manner in which the activities in the different foils are affected by the different thicknesses of beryllium is important, for out of these variations will come the part played by H^3, if any. In Fig. 4 are shown the results of increasing the thickness of beryllium to 7.5 mils. The 13-hour activities are much lower here in all the foils. Those in the inner foils 2, 3, and 4 draw closer together and the 6.7-hour Cd is barely visible. The foils 4 and 5 show the neutron effect only, indicated by a single curve as before. In the fourth bombardment, the energy of the deuterons striking the Ag foils was so much reduced by putting in 11.7 mils of beryllium that no detectable Cd^{107} activity was produced. The results are given in Fig. 5. The 13-hour activities are much less than those in the previous experiments. The first foil is still much more active than the second. The neutron activity is seen in foils 3, 4, and 5 for which a single curve has been drawn. The points are omitted to avoid crowding in the figure. Also whatever may be the agent for the production of the Pd^{109} activity, it must have penetrated just up to the second foil, for this foil is only slightly above the neutron-activity level.

[7] L. A. Delsasso, L. N. Ridenour, R. Sherr, and W. White, Phys. Rev. 55, 113 (1939).

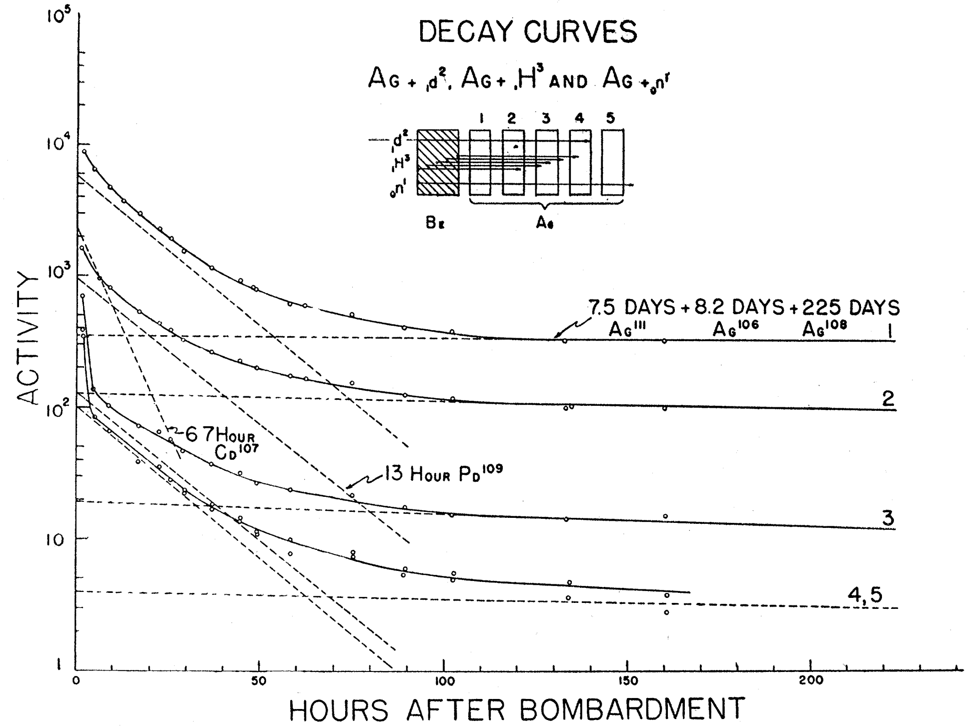

FIG. 4. Decay curves of Ag foils after bombardment by H^3 using 7.5 mils of Be. The 6.7-hour Cd^{107} is barely detectible.

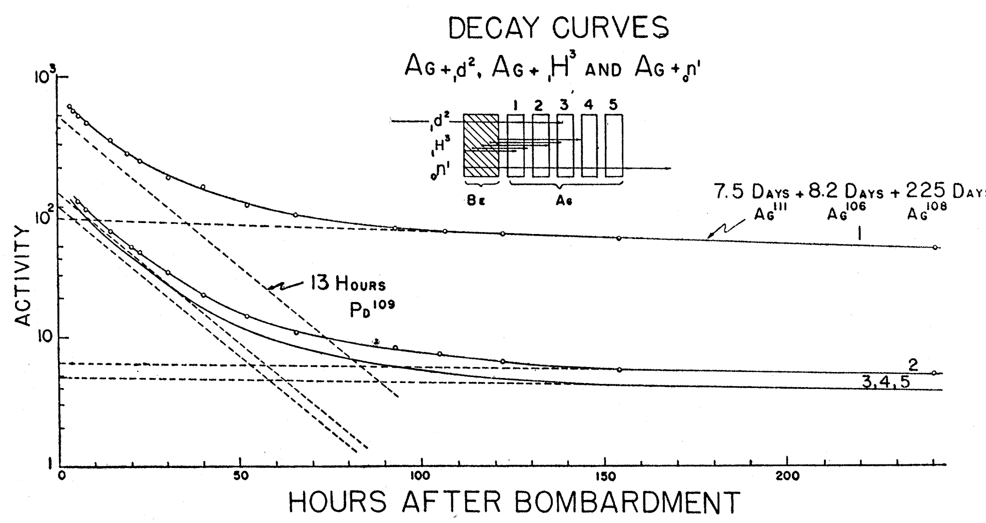

FIG. 5. Decay curves of Ag foils after bombardment by H^3 using 11.7 mils of Be. The 6.7-hour Cd^{107} is absent. The points for the bottom curves 3, 4, and 5 which represent neutron activation have been omitted to avoid crowding.

The fifth bombardment was made with 15 mils of beryllium in front of the silver foils. This thickness of beryllium just stops the deuterons. The decay curves are shown in Fig. 6. In the bottom curve which represents the neutron effect, the points for foils 2, 3, 4, and 5 are all very close together. The spread of values is indicated at a few points in the earlier part of the curve. The 13-hour activity is still present and that in the first foil is above the neutron

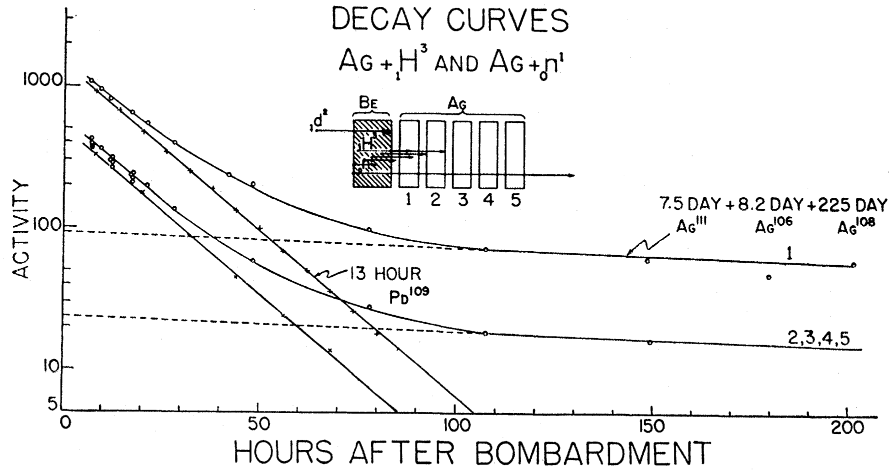

FIG. 6. Decay curves of Ag foils after bombardment by H^3 using 11.7 mils of Be. The primary deuteron beam is practically stopped within Be. A single curve has been drawn for foils 2, 3, 4, and 5 which represent neutron activities.

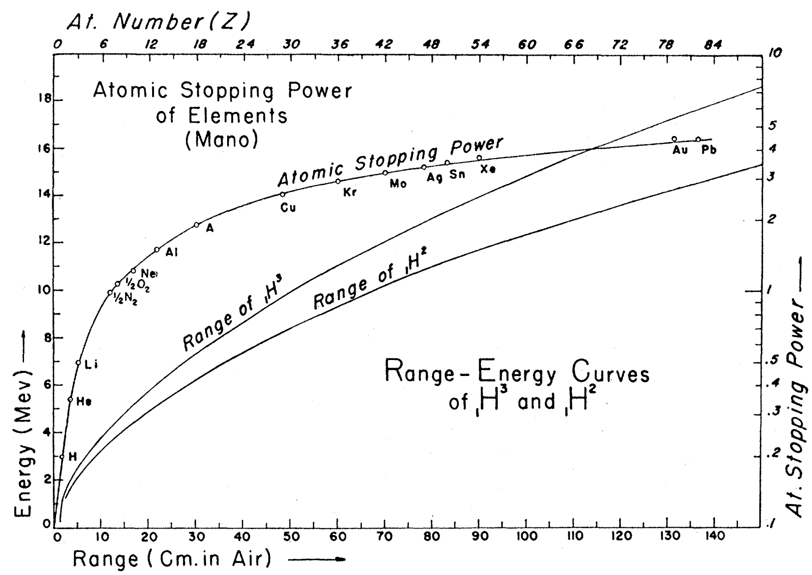

FIG. 7. Range-energy curves for H^3 and deuterons. The atomic stopping power of elements according to data by G. Mano.

activation level. It is thus suspected that some agent other than deuterons or neutrons must be operative in inducing this activity.

In order to see that this agent is the H^3 produced in silver and in beryllium and to follow the finer details of these curves relative to each other, it is necessary to find out how H^3 is expected to behave if it is produced in the circumstances of the present experiments.

III. RANGE OF H^3

With 10-Mev deuterons, the maximum energy of the H^3 particles produced is about 10.5 Mev from a consideration of the Q's of the reactions involved. From well-known[8] range-energy formulae, the range of a particle of energy E, charge Z, and mass M can be obtained from a known range-energy curve of another particle of the same charge Z and mass M_0. The range of the particle in question of energy E is equal to M/M_0 times the range of the known particle of energy $(M_0/M)E$. For example, the range of 10-Mev H^3 particles is equal to $\frac{3}{2}$ times the range of deuterons of energy 6.6 Mev. If the range of

[8] H. A. Bethe and M. S. Livingstone, Rev. Mod. Phys. **9**, 271 (1937).

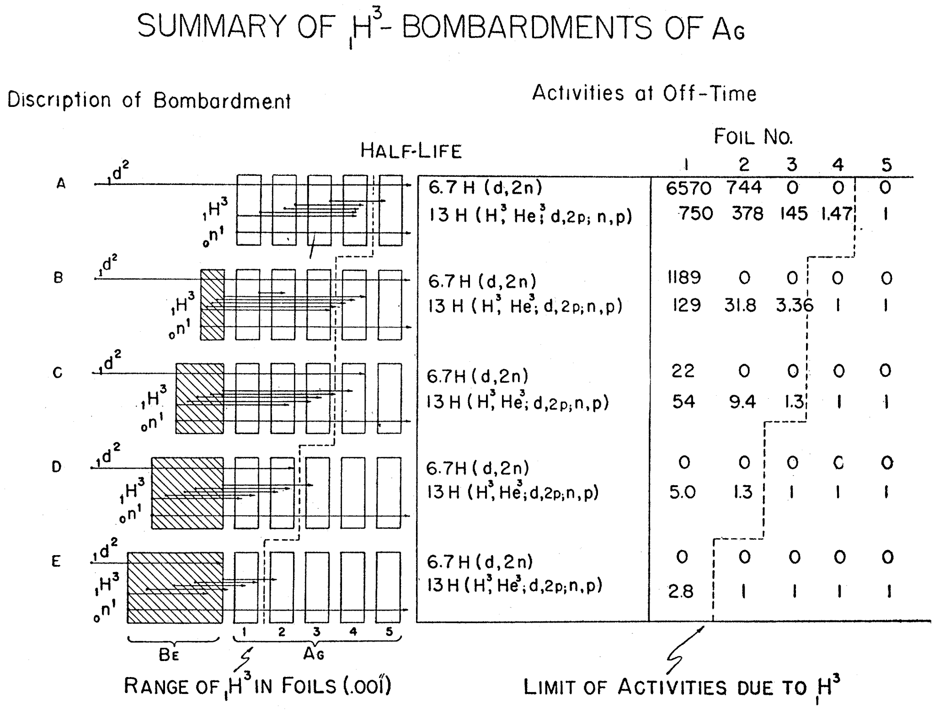

FIG. 8. Summary of results of H^3 bombardment on Ag. The description of the target and the bombarding particle is given on the left, and the activities obtained in different foils on the right. Numerical values of the activities are relative, taking neutron activity as unity.

6.6-Mev deuterons be taken as 33 cm in air, then the range of 10-Mev H^3 is approximately 49.5 cm.

The range-energy curve for H^3 is constructed in this way from the deuteron data as shown in Fig. 7. In the present experiments it is of interest to know how far the H^3 produced would penetrate through beryllium into silver and to compare it with observations. For 10.5-Mev H^3, the calculated range is 55 cm. This value is, however, subject to some uncertainty arising largely from the uncertainty in the deuteron range. The relative stopping power of silver[9] was taken to be 2.72 mg/cm^2 as equivalent to 1 cm of air. To get the relative stopping power of beryllium Mano's data[10] for the atomic stopping power of beryllium were plotted against atomic number giving a smooth curve also shown in Fig. 7 and the calculated relative stopping power, from the atomic stopping power of beryllium obtained by interpolation, is 1.18 mg/cm^2. The length of an arrow representing H^3 through beryllium and silver was thus calculated after reducing the amount of beryllium used to its equivalent silver thickness. These arrows are drawn through the foil scheme of each experiment in Figs. 2 to 7.

IV. DISCUSSION OF RESULTS

The results of the previous experiments are graphically summarized in Fig. 8 for convenience of discussion. On the left-hand side, a schematic diagram of the target is given and arrows representing deuterons, H^3, and neutrons are drawn through those foils which these particles may be expected to traverse. All the possibilities in which the 13-hour Pd^{109} activity may ordinarily be imagined to be produced from silver, are shown on the right-hand side. These are (n, p), (H^3, He^3) and $(d, 2p)$. The activities shown are those at the termination time of the bombardment. The residual activity in the back foils was taken as unity. The 6.7-hour Cd^{107} activity induced by $Ag^{107}(d, 2n)Cd^{107}$ is also indicated for conveniently tracing the course and energy of the deuterons through silver. The 6.7-hour activity was not observed until the energy of the

[9] Reference 8, 272 (1937).
[10] G. Mano, Ann. de physique 1, 407 (1934); J. de phys. et rad. 5, 628 (1934).

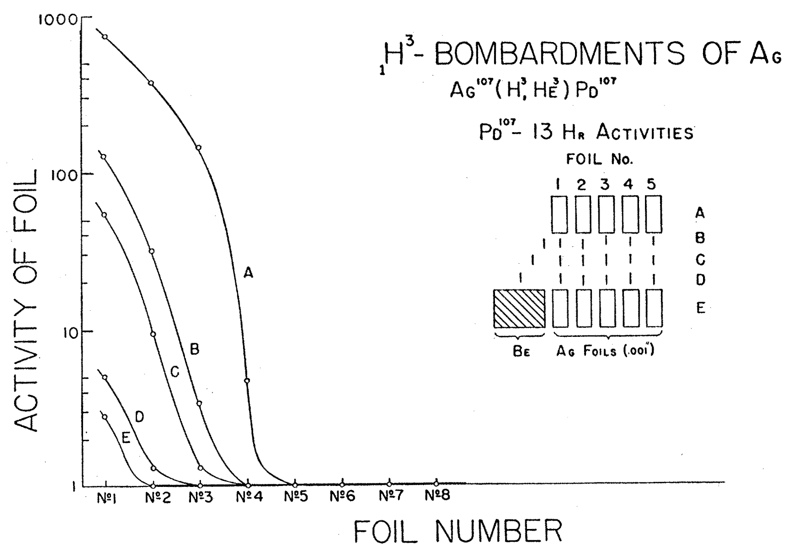

FIG. 9. The 13-hour Pd^{109} activity induced by H^3 in different foils and in different bombardments after subtracting the neutron activation. The foils are shown schematically.

deuterons was about 5.5 Mev. As the thickness of beryllium is increased, the tip of the deuteron arrow shrinks back towards the front foils. The deuteron range, which was larger than that of H^3 in the first set, has gradually fallen behind the path limit of the H^3 particles. Finally in the last set, though the deuterons have been stopped within the beryllium, the H^3 that was produced near the end of the deuteron range has still enough energy to affect at least the first Ag foil. This is possible only because the reaction with beryllium is exoenergetic. The dotted line in Fig. 8 on the left between silver foils approximately indicated the depth up to which H^3 will be available. The dotted line on the right demarcates the region of the increased 13-hour activity above that of the neutron activation. The two dotted lines agree very well in position amongst foil schemes and the corresponding activities. This makes it plausible that the H^3 might be responsible for the peculiar behavior of the 13-hour activity.

Figure 9 is obtained by plotting the above 13-hour activities against foil number. It is observed that with increasing thickness of Be, represented by the sequence *A*, *B*, *C*, *D*, *E*, the 13-hour activity on any particular foil is diminishing in amount. The limit of this activation above the neutron base line is receding towards the front foils. This is to be expected because the number and energy of H^3 on that particular foil are being reduced by absorption and scattering within the beryllium in front.

The way in which the activities at a particular depth in mg/cm^2 within the silver increases by simply increasing the amount of H^3 under identical deuteron conditions is shown in Fig. 10. The 13-hour activity plotted here is that obtained after subtracting the amount of neutron activation. The abscissae represent the thickness of Be in mils used in the different experiments. As the thickness of beryllium increases, the activity at the same equivalent depth in silver rises steeply. This indicates that apart from the neutrons and the deuterons some other agent is definitely acting on the silver to produce the 13-hour Pd^{109} activity. The part played by beryllium to augment the effect, and the close agreement of the estimated ranges of H^3 with those observed in these experiments lead to the conclusion that the new agent is the H^3 particle. The progressive diminution of activity with depth is caused by the loss of energy of the H^3 particles in the initial foils.

A rough estimate of the threshold energy for the production of Pd^{109} from silver can be made. To produce the 13-hour activity in the fourth foil in set A, the H^3 had at most an energy of $8\times 0.66/3.66=1.45$ Mev. Also β-ray characteristics of Pd^{109} set the lower limit to at least 1.1 Mev. Thus the threshold energy for the production of Pd^{109} in the above circumstances is between 1.1 and 1.5 Mev. It may be noted that in set E of Fig. 8, the energy of the deuterons, if any succeed in reaching the first foil because of the slight uncertainty in the value of the calculated range within beryllium, will be less than 0.8 Mev. This energy is too small to lead to any $(d, 2p)$ reaction. The H^3 particles have, however, about 3 Mev of energy which is above the observed threshold value for the H^3 reaction. Thus the 13-hour activity is produced by H^3 in small amount in the first foil in set E.

V. CONCLUSION

The observations in connection with Fig. 2 that the 13-hour Pd^{109} activity is produced from silver in an ordinary deuteron bombardment have recently been confirmed at 20-Mev deuterons by others[11] and ascribed to the reaction $Ag^{109}(d, 2p)Pd^{109}$. But the whole series of observations reported in the present investigations cannot be explained on the basis of deuteron reactions only. Because H^3 is found to explain the observations so well and also because a large amount of H^3 will be produced in the bombardment of silver with 20-Mev deuterons, it may be that a large part or even all of the 13-hour activity, supposed to be caused by $(d, 2p)$ reaction, is caused by H^3 reaction. At least with 10-Mev deuterons in present experimental set-up, the $(d, 2p)$ reaction does not play the main role. This is so because readily measurable amounts of Pd^{109} activity above the (n, p) activation are found in the foils which lie deeper than the limit of the depth up to which the deuterons may be effective. Moreover, as the H^3 is increased at any depth, the Pd^{109} activity rises sharply. Energy considerations also favor the H^3 viewpoint.

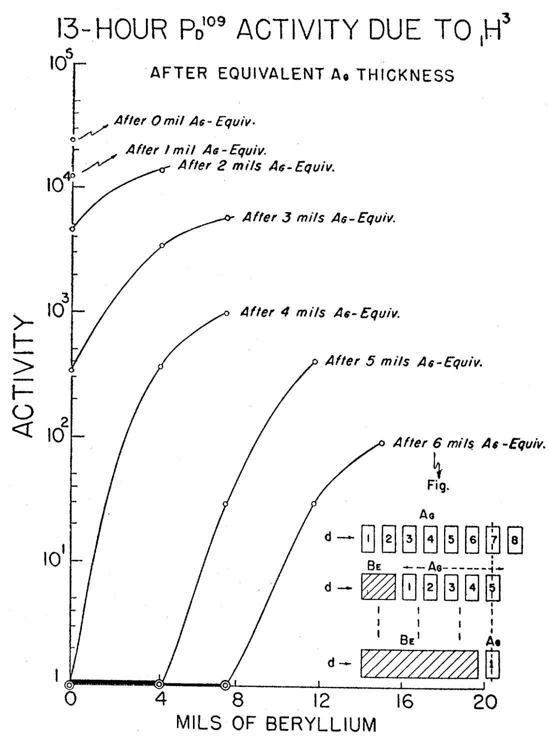

FIG. 10. The increase of the 13-hour Pd^{109} activity induced by H^3 at any depth within Ag is shown with Be thickness.

With arrangements of using H^3 as reported here, since deuterons are being used as the primary bombarding particles and since deuterons have a larger range than H^3, the course of the deuterons within the target has to be properly traced to avoid the possibility of spurious deuteron reactions. Also neutron reactions, when any are present, have to be estimated and corrected for separately in each individual run, because change in the amount of beryllium changes the number of neutrons also. The question whether the reaction is $Ag(H^3, n2p)$ or $Ag(H^3, He^3)$ is undecided except for the fact that energy considerations favor the latter view to the extent of the binding energy of the He^3 nucleus.

It is expected that the reactions (H^3, p) and (H^3, d) will also proceed with ease.

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[11] A. C. Helmholz, Phys. Rev. **70**, 982 (1946).