Collisions of Alpha-Particles in Deuterium

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An investigation is made of the yields of deuterons emitted from deuterium under bombardment by alpha-particles from a polonium source. Three different but complementary experimental arrangements are employed: (1) The yield of deuterons projected forward is measured as a function of the alpha-particle velocity, the impinging alpha-particles being of nearly homogeneous velocity. (2) Absorption measurements are made on the deuterons projected forward by alpha-particles of all velocities up to the polonium limit. The results are found to agree with those of (1). (3) The yield of deuterons is measured as a function of the angle of projection for two different alpha-particle velocities. To permit comparisons, similar experiments were made with ordinary hydrogen. As theoretical implications of this work may be mentioned: (1) Anomalous scattering begins at greater relative alpha-particle energies for deuterium than it does for hydrogen. Thus it is found that the radius at which the deuteron field becomes non-Coulombian is smaller than the corresponding radius for the proton. (2) An irregularity found in the deuteron yield for impinging alpha-particles of 2.6 MV. is interpreted as a resonance phenomenon. (3) The angular variation in the deuteron yield is of a nature not easily explained by Taylor's theory of scattering. This matter is discussed in some detail.

THE experimental basis of our knowledge of the field of force surrounding nuclei is largely derived from observations on the scattering of charged particles by the nuclear fields. Such observations have been made on the scattering of alpha-particles by hydrogen, helium and other light elements by various workers and in each case have given information about both the nature of the scattering process and the limits of the attractive nuclear field. Experiments on the scattering of alpha-particles by deuterium are of particular interest since any differences observed from the behavior in impacts with protons must be due to the additional neutron. At the same time there may exist nuclear resonance phenomena of the type first discussed by N. F. Mott[1] which would affect the nature of the scattering.

Experiments by Rutherford and Kempton[2] indicate a general similarity between the nuclear field of the deuteron and that of the proton. These authors point out, however, the desirability of further work on the question and suggest that more detailed investigations may bring to light differences in the scattering phenomena due to protons and deuterons. The present work exhibits such differences.

The scattering of alpha-particles in hydrogen was thoroughly investigated long ago by Chadwick and Bieler.[3] They determined the angular distribution of projected protons for alpha-particles of various velocities. In this paper we present similar data for projected deuterons, investigating their behavior in greater detail. In order to provide a certain basis of comparison we have repeated in part the work of Chadwick and Bieler on hydrogen, using an automatic method of counting instead of observing scintillations. The results are in substantial agreement with theirs.

From the yield of deuterons projected in a forward direction by alpha-particles of various energies the conclusion is drawn that the deviation of the nuclear field from the Coulomb type, which in the case of the proton occurs when the alpha-particle is about 4.6×10^{-13} cm from its center, takes place for the deuteron at the smaller distance of 3.2×10^{-13} cm.

The variation of proton yield with angle of projection provides an interesting test of present hypotheses of the nucleus. Taylor[4] has worked out a theory of this variation which assumes a proton potential of the usual crater type, and applied it to the results of Chadwick and Bieler. A similar analysis will be made in this paper for the results on deuterons, and it will be shown that, while for low velocities of the bombarding alpha-particles there is no violent disagreement between the experimental results and Taylor's

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[1] N. F. Mott, Proc. Roy. Soc. **A133**, 228 (1931).
[2] Lord Rutherford and A. E. Kempton, Proc. Roy. Soc. **A143**, 724 (1934).
[3] J. Chadwick and E. S. Bieler, Phil. Mag. **42**, 923 (1921).
[4] H. M. Taylor, Proc. Roy. Soc. **A136**, 605 (1932).

theory, the simple model of the nucleus breaks down when the alpha-particles have a greater speed.

It is not implausible to suppose that an alpha-particle and a deuteron can form a combination of temporary stability in the scattering process, since this would correspond to an energy state of the known nucleus ${}_3Li^6$. A similar combination of an alpha-particle and a proton, on the other hand, seems less likely because of the very high charge-to-mass ratio of the resulting structure. This implies that an alpha-particle and a deuteron can enter into what may be called a resonance interaction. Such resonance should have a definite effect upon scattering phenomena, an effect indeed for which a qualitative theory exists.[1] Its occurrence may be quite common, but is difficult to observe if the scattering nucleus is heavy, for the effect decreases with increasing mass. The deuteron presents a favorable chance of its observation since the effect itself is large and the projected nuclei have longer ranges and can therefore be counted with relative ease. A resonance interaction of this type has been found for alpha-particle energies of 2.6 MV.

Experiments on the Forward Projection of H and D Nuclei

1. Scattering of alpha-particles by a Coulomb field

The early experiments of Rutherford showed that if alpha-particles fall on scattering nuclei of medium or high atomic number they suffer deflection according to the Rutherford-Darwin relation. This formula is derived by classical dynamics on the hypothesis that the nuclei repel the alpha-particles according to the inverse square law. The formula is unaltered if derived by wave-mechanical theory providing the field is strictly Coulombian for the energies of the alpha-particles used. Later experiments on the deflection of alpha-particles by nuclei of low charge showed that the Rutherford-Darwin law does not hold for close collisions. Thus it is concluded that for these collisions the inverse square law ceases to hold. Accordingly a determination of the least energy of alpha-particles which, for direct collisions, cease to be deflected as expected by the formula, gives some measure of the distance at which the *attractive* field of the nucleus becomes effective.

In the case of collisions with hydrogen nuclei it is very much easier to observe the projected nuclei than the deflected alpha-particles since their greater range renders them easily detectable. The theory of the projection of such nuclei has been worked out by Darwin, who shows that the number of nuclei projected per second into a given solid angle at an angle θ to the direction of the incident alpha-particle is

$$n = A/V^4(1/M+1/m)^2 \sec^3\theta. \qquad (1)$$

A is a constant for a fixed arrangement of target and source.
M, V are the mass and velocity of alpha-particle.
m is the mass of the nucleus.

It follows that the total number projected within a cone of half-angle θ about the direction of the alpha-rays is

$$F = (A\pi/V^4)(1/M+1/m)^2 \tan^2\theta. \qquad (2)$$

Then providing the angle θ does not vary, a test of this relation can be made by determining either n or F for different incident particle velocities. Both n and F should diminish rapidly with increasing velocity by reason of the $1/V^4$ factor. If we consider the *range* of the impinging particle the diminution of yield with increasing range is less rapid, being approximately proportional to $R^{-4/3}$. While in experiments on variation of yield with angle of projection, to be described later, the quantity n was observed, it is more convenient for the present purpose to determine F.

Our experimental arrangement therefore was constructed to allow a determination of the number of hydrogen or deuterium nuclei projected within a constant angle for varying ranges of the incident alpha-particle. Since the nuclei are projected approximately in the direction of the impinging alpha-particles we speak of "forwards projection."

2. Arrangement of apparatus

The general arrangement of apparatus can be seen from Fig. 1. A is the alpha-particle source, of polonium deposited on a silver disk of 1 cm diameter and of strength about 20 millicuries. A test showed that the spread of alpha-particle

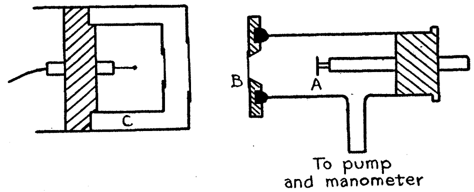

FIG. 1. Diagram of apparatus used in experiments on forward projection.

ranges did not exceed 0.3 cm. B is the target of hydrogen or deuterium. This was deposited on a foil of aluminum of air equivalent, in some cases, 0.9 cm, in others 2.2 cm, which was waxed over a number of holes situated in a circle of about 1.6 cm diameter. Both larger and smaller apertures were used, and also a small zone in which the holes were confined to the space between circles of 0.7 cm and 1.4 cm diameter. For layers of hydrogen we used either powdered $Ca(OH)_2$ deposited from an alcohol suspension or a thin film of vaseline. For deuterium we used $Ca(OD)_2$ shaken up with CCl_4 and painted over the aluminum. The $Ca(OD)_2$ proved more difficult to obtain in thin layers than the $Ca(OH)_2$—probably because of a trace of metallic calcium left in after its preparation. We found, by weighing, that the $Ca(OD)_2$ layers varied in average thickness from 0.2 cm to 0.6 cm air equivalent. The uniformity was poor but in the thinner layers the total spread in the range of the incident particles could not be very large. Since there is danger that $Ca(OD)_2$ can change into $Ca(OH)_2$ if moisture is present, we used a fresh layer every few days. That a layer is stable for a period of days was directly shown in magnetic deflection experiments. In order to prevent the $Ca(OD)_2$ powder from dropping off or being blown off while the pressure in the space AB was changed, the layer was covered with either a thin gold or aluminum leaf. Blank experiments showed that the yield of disintegration products from aluminum was negligible compared to that of the projected hydrogen nuclei.

The projected nuclei produced in the target were counted by the proportional Geiger counter C of the form described by Pollard and Eaton.[5] The aperture of C was of diameter 1 cm in some experiments and 0.6 cm in others, according to the degree of angular definition required. The distance AB was varied about 4 cm; BC about 2.5 cm. By introducing known pressures of oxygen into the space AB the range of the alpha-particles impinging on the target could be changed slowly and the corresponding yield of projected nuclei counted. The distance BC and the angle subtended by the aperture B at the counter were carefully chosen to enable the detection of the projected nuclei at as small ranges as possible. The main difficulty encountered in verifying the Rutherford-Darwin formula is in detecting the recoil nuclei at such low energies. Where the formula holds the ranges of the recoil protons or deuterons are (for forwards projection) about 6 cm and fall off rapidly in range (proportionally to $\cos^3\theta$) for angles greater than 20°. The shortest recoil range that can reach the counter is about 4 cm. If wide apertures permitting large angles between the alpha-particle and the recoil nucleus are used it is inevitable that at low alpha-particle energies a proportion of the protons or deuterons do not reach the counter. Our mean angle was in general not greater than 20°, which means that the exact shape of the curves for alpha-particle ranges less than 1.4 cm (for protons) or 1.2 cm (for deuterons) is uncertain.

In counting the particles we used mainly a method of photographic recording of an oscillograph trace. Counting by a relay and impulse counter is somewhat uncertain for low alpha-particle energies since the particles entering the counter opening are of differing ranges and so produce deflections of differing sizes.

3. Experimental results

The first experiments were made on recoil protons and were intended to enable investigation of the range of incident alpha-particles at which the falling yield of recoil protons expected from the Rutherford-Darwin formula gives way to the rising yield due to anomalous scattering. In Fig. 2 the results of one such experiment (made with a target in the form of an annulus) are given. It will be seen that the yield curve turns upward at an alpha-particle range of 1.75 cm. This is in good agreement with the values found by Chadwick and Bieler, which do not,

[5] E. Pollard and W. W. Eaton, Phys. Rev. **47**, 597 (1935).

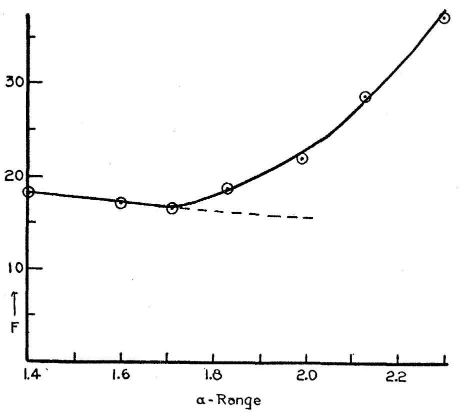

FIG. 2. Yield of protons per minute *vs.* alpha-particle range in cm air equivalent. Broken line represents classical yield (Eq. (2)).

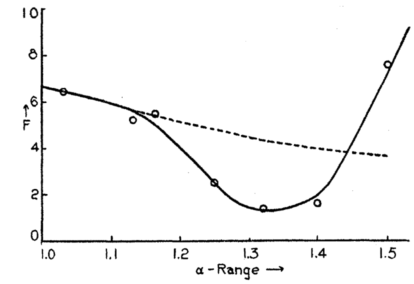

FIG. 3. Yield of deuterons per minute *vs.* alpha-particle range in cm air equivalent. Broken line represents classical yield (Eq. (2)).

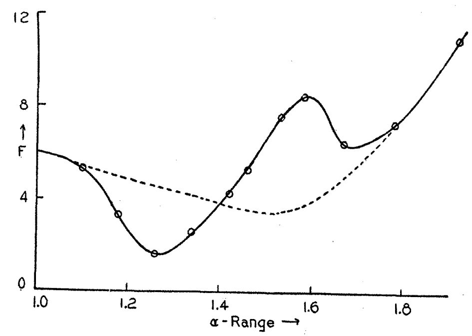

FIG. 4. Yield of deuterons per minute *vs.* alpha-particle range in cm air equivalent. Broken line represents probable trend if resonance were absent.

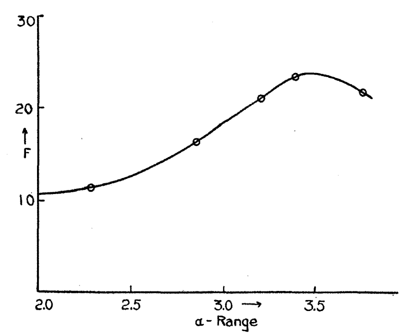

FIG. 5. Yield of deuterons per minute *vs.* alpha-particle range in cm air equivalent.

however, fix this minimum so definitely. The yield curve for low energies follows, at least approximately, the Rutherford-Darwin formula. Taylor[4] has used the results of Chadwick and Bieler to derive the radius of the potential well used to explain the anomalous scattering. His results show that this radius is very nearly equal to the distance of closest approach for which the classical theory first ceases to hold. We can make an estimate of the radius of the potential well by calculating the distance of closest approach corresponding to an alpha-particle of range 1.75 cm. The value found is 4.6×10^{-13} *cm*. The ranges are correct to 0.05 cm.

The results of a similar experiment on a layer of $Ca(OD)_2$ are shown in Fig. 3. Here the target was contained within a circular hole. It will be seen that there is a rapid drop between 1.15 and 1.35 cm followed by a rather more rapid rise than observed for protons. In this run a special attempt was made to detect the recoil deuterons of low energy: their behavior appears to be classical in the region 1.0 to 1.15 cm though we do not wish to assert this positively. The absolute value at the minimum is so low that it seems certain that there is a drop below the expected classical value before the rising yield begins. In Fig. 4 a curve is given for rather higher ranges. It gives the yield from a small central opening, and shows that the yield rises to a maximum at 1.6 cm range, falling from there to 1.7 cm and rising smoothly afterward. This curve represents the results of a total of five runs on different occasions with different layers of $Ca(OD)_2$. Because of the uncertainty in the thickness of the layer the alpha-particle ranges cannot be relied on to much better than 0.1 cm. A curve similar to this, but taken with a somewhat thicker layer and therefore less accurate, was published before.[6]

[6] A preliminary account of this experiment with this explanation has been given. Nature **135**, 393 (1935); Phys. Rev. **47**, 571 (1935).

In that account there is also given a comparison curve for ordinary hydrogen, which we are not here reproducing.

In Fig. 5 a curve for higher energies is plotted. This shows a steady rise up to 3.4 cm incident range, after which there is a fall. This maximum is not so definitely established as the earlier one. Experiments with higher energy alpha-particles will be needed to determine its precise nature.

4. Discussion of these results

If one supposes the mutual potential of the alpha-particle and the hydrogen nucleus to be of the crater type the expected features of scattering yields are as follows: first, a fall according to the classical theory for low energies, second, a rise as the intensity of the wavelet scattered from the inside of the crater increases. This supposes there are no critical energy levels. It is known, however, from experiments in which heavier nuclei are disintegrated that such critical energy levels for which the intensity of the wave function inside the nucleus is abnormally high do exist. Such levels should influence the scattering of alpha-particles even if there is no disintegration. Mott[1] has calculated the ratio of expected to classical scattering at energies near such a resonance level. He finds for this ratio, calculated for a scattering angle of 180°:

$$R=(1-\beta \sin 2P)^2+\beta^2(1-\cos 2P)^2. \qquad (3)$$

Here $\beta=137v/2Zc$ where v is the velocity of the incident alpha-particle and P is a phase angle which usually increases by π as v passes across the region of resonance. Z is the atomic number. An examination of formula (3) shows that for Z greater than about 4 and ordinary alpha-particle velocities R takes the form of a dip followed by a greater rise and a fall to unity. For aluminum, for instance, the greatest value of R is about 1.5.

In the case of very light elements formula (3) presents a different appearance. The dip is then absent, and the rise is considerably greater. The drop to unity, predicted by (3), is dependent upon the assumption that P increases to π, which means that there are no further deviations from classical behavior for greater velocities. If penetration occurs even within the resonance region, as it clearly does for elements of small atomic number, R will not return to unity but the yield will gradually merge into the general rise characteristic of anomalous scattering due to penetration. This obvious deviation from Mott's theory is also apparent in the experiments on disintegration of Be and B by resonance.

Formula (3) refers to resonance scattering by a state of zero angular momentum and does not purport to describe the general phenomenon of resonance scattering in a quantitative way, but it will serve us as a guide. The sharp drop at 1.15 cm range seen in Fig. 3 followed by the rise to a maximum at 1.6 cm seen in Fig. 4 has the general features associated with *resonance scattering*. We suggest that the region 1.15 − 1.7 cm corresponds to the band of energies grouped around an energy level of the composite nucleus $_3Li^6$. The fact that the yield does not fall to the classical value is due to the circumstance that penetration occurs independently of the resonance process as just noted.[6] The mean energy of the alpha-particles causing resonance is 2.6 MEV. In our previous publication we have stated the value 3.1 MEV. This discrepancy is due to the fact that we have there taken as the range corresponding to resonance that associated with the *maximum* of the yield curve.

The occurrence of this resonance phenomenon renders it difficult to determine the minimum at which the anomalous scattering due to the non-Coulombian field begins to be superposed on the classical scattering. If we take the minimum as experimentally found at 1.3 cm alpha-particle range, the corresponding distance of closest approach, is 3.4×10^{-13} *cm:* while if we estimate, from the trend of the rise after 1.7 cm range, that but for resonance the classical law would hold as far as 1.5 cm range we find 3.0×10^{-13} *cm.* The latter is more probably the true value. In arriving at these figures, account has been taken of the greater mass of the deuteron, in consequence of which an alpha-particle of a given energy approaches more closely to the deuteron than the proton. In either event it is seen that the radius at which normal penetration into the nucleus begins is *definitely less for deuteron-alpha-particle interaction than for proton-alpha-particle interaction.* The smaller radius for the deuteron field is more in accordance with the fields existing between heavier elements and alpha-particles. This may be linked with the fact that in heavier nuclei, as in the deuteron, there is roughly an equal number of neutrons and protons while the proton itself is in this sense abnormal. The abnormality of proton fields has been pointed out by Cockroft at the London Conference and is discussed by Pollard.[7]

Experiment on Absorption of Projected Protons

To place the position of the minima in Figs. 2, 3 and 4 beyond doubt, another independent experiment on the absorption of the projected protons was made. For this purpose the tube was filled, first with H_2, then with D_2 at atmospheric pressure, and the source was pulled back sufficiently far so that no alpha-particles would reach C. Various absorbing foils of aluminum were placed between B and C, and the number of protons or deuterons passing through was counted by the method employed before. The deuterium used in this experiment was obtained from 98 percent heavy water by the reaction: $Ca+2D_2O \rightarrow Ca(OD)_2+D_2$.

If now one plots the yield of particles against air equivalent of the absorption in the path of the projected protons one obtains curves which will here be called integral curves and which are related to those of Figs. 2, 3, 4 as follows: Suppose that we integrate the yield curve of Fig. 2 from right to left, beginning at some extreme value of the range R_0 and stopping at some variable smaller value R. The ordinates of the integral curve are then the areas thus obtained, subtracted from the total area to the left of R_0; the abscissae of the integral curve are the corresponding values of R_0-R, but on an extended scale. Thus there should be associated with a minimum of the previous yield curves a flattening of the integral curves.

This is seen to be the case in Fig. 6 which represents the data obtained. By extra absorption is meant the air equivalent thickness of the aluminum foils, exclusive of the absorption which occurs in the gas and in the closing foil. The flattening on the deuteron curve appears to the left of the flattening on the proton curve, which shows definitely that the deuteron minimum lies at a smaller alpha-particle range. The distance along the abscissae between the flatter portions of the two curves, $\Delta A'$ is about 1 cm.

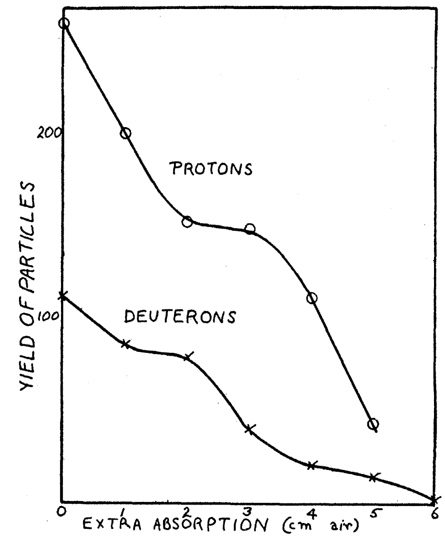

Fig. 6. Yield of particles per minute *vs.* absorption, exclusive of gas, in the path of the particles.

It is possible even to get a numerical estimate of the distance between minima on the yield curves from the quantity $\Delta A'$ as found from Fig. 6. For it can be shown (cf. Appendix) that

$$\Delta A' = 3.2R_P' - 3.6R_D' + \Delta R_0 \qquad (4)$$

approximately, where R_P' and R_D' are, respectively, the alpha-particle ranges at which the minima on the yield curves for protons and for deuterons occur; ΔR_0 is the difference of the maximum alpha-particle range in H_2 and in D_2. But Rutherford and Kempton[2] have found these to be equal, so that $\Delta R_0 = 0$. Hence, if we assume that $R_P' = 1.8$ cm, formula (4) gives for R_D' the value 1.3 cm, which is in very good agreement with our previous results.

An experiment similar to the one described in this section, but for hydrogen only, has also been reported by Pose and Diebner.[8] Instead of hydrogen gas they use a paraffin layer, which has certain advantages over the method here required for comparison with the deuterium results. They find two flat portions on the integral curve, and correspondingly deduce two minima on the yield curve. Neither of these minima agrees well with

[7] E. Pollard, Phys. Rev. **47**, 611 (1935).

[8] H. Pose and K. Diebner, Zeits. f. Physik **90**, 773 (1934); see also E. Frank, Zeits. f. Physik **90**, 764 (1934).

the one in our curves as to position on the alpha-range scale. We consider it by no means impossible that there exist irregularities in the proton yield curves at higher energies than those here investigated and are continuing our measurements in that region; but we have found no minimum at an alpha-particle range of about 2.3 cm, where one reported by Pose and Diebner should have occurred.

Experiments on the Projection at Varying Angles

A simple test of the current theory of anomalous scattering is afforded by investigating the variation of yield with the angle between the projected nucleus and the incident alpha-particle. In order to carry this out we used apparatus as illustrated in Fig. 7. This shows the view from above. A is a small brass pillar supporting the source, B is an arm rotating about a pin at C. D is the target, supported on an aluminum foil of 2.2 cm air equivalent, and kept in place by a thin aluminum leaf. E is the counter. The scale of the diagram is indicated. The rotating arm was firmly fixed to a pointer on the outside of the enclosing brass box and the angular setting could be read off on a metal scale. The opening at the target was a single hole of 0.7 cm diameter and the counter was placed 3.5 cm from the opening in most of the experiments. The pin attaching the arm to the pointer was surrounded thickly with tap grease and the enclosing box evacuated. If the pump is kept running the vacuum can be held while the arm B is rotated. The distance AC was 4.5 cm. With this arrangement our maximum angular spread was 20°, our mean spread 10°.

In order to avoid uncertainties in connection with the zero-setting of the apparatus, readings were taken alternately to the left and to the right of the zero scale position. When the readings were plotted the peak of the yield curve was slightly displaced from the scale zero. The position of the peak was then chosen as the zero angle.

In Fig. 8 the yield of deuterons is plotted against θ, the angle which the projected deuterons make with the direction of the incident alpha-particles. The upper curve refers to an energy of 5.2 MEV. corresponding to a residual alpha-range of 3.7 cm. Beyond 25° the yield drops strongly. We feel that from there on the experimental points are somewhat uncertain because of the spread in θ. For the range of the deuterons decreases with increasing θ, and at a mean angle of 25° the particles projected at extreme angles begin to stop short of the counter. A reasonable correction based on the geometry of the apparatus would raise the points, but not enough to justify the supposition that the curve swings into a classical course at this angle. For the lower curve of Fig. 8 the alpha-particle energy is 3.3 MEV, the range 1.9 cm. Here, also, we have taken observations with the same apparatus on protons, but for only one energy, and the yield curve is reproduced in the figure.

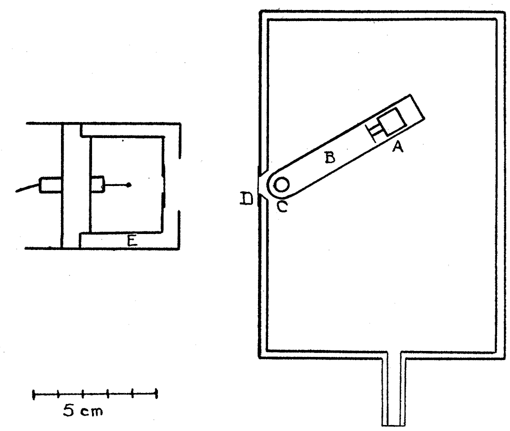

Fig. 7. Diagram of apparatus used in experiments on projection at different angles.

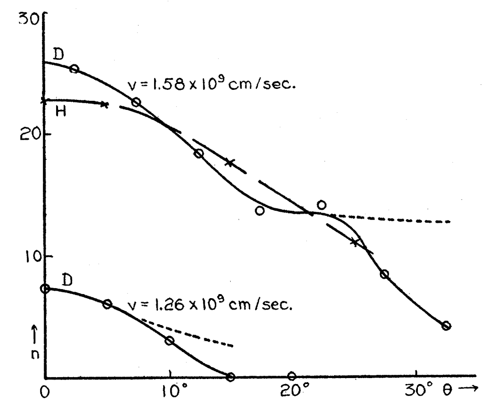

Fig. 8. Yield of deuterons (continuous), or protons (broken line), per minute *vs.* average angle of projection. v refers to velocity of alpha-particles. Dashed lines represent estimates of true curves, allowing for stoppage at extreme angles.

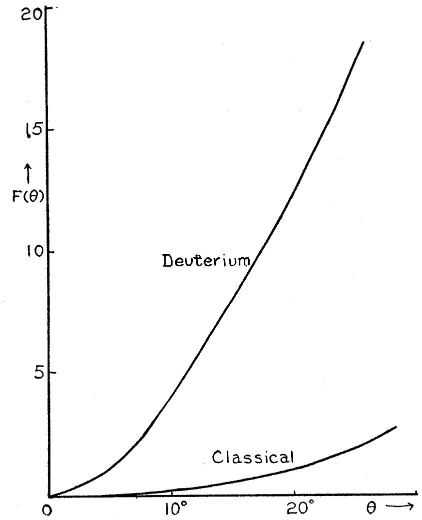

FIG. 9. Yield of deuterons projected into a cone of half-angle θ *vs.* θ. Lower curve is the classical yield.

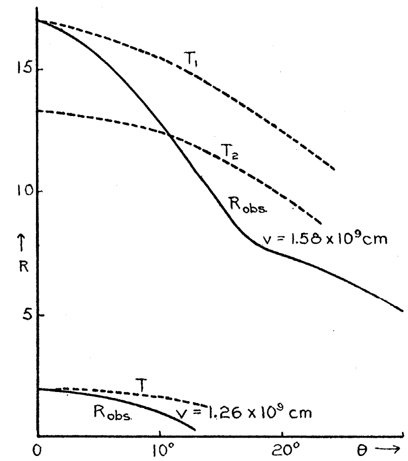

FIG. 10. Ratio of observed to classical yield *vs.* angle of projection. T_1 and T_2 are curves based on Taylor's theory.

To facilitate the comparison of our results with those of Chadwick and Bieler we have plotted their function $F(\theta)$, based on the present data, against θ in Fig. 9. $F(\theta)$ is the number of particles projected into a cone of half-angle θ about the direction of the alpha-particles. Since no great care was taken in determining the thickness of the films, no attempt is made to evaluate $F(\theta)$ per alpha-particle per cm of deuterium; it is plotted in arbitrary units. But the classical curve has been adjusted to the same scale as the deuterium curve. The hydrogen curve on this diagram is almost indistinguishable from the deuterium curve and has not been drawn.[9] It is in good agreement with Chadwick and Bieler's data, falling, as it does, somewhere between their 2.9 cm and 4.3 cm alpha-range curve.

Our results may be considered in the light of Taylor's[4] theory of scattering. He shows that if one assumes the alpha-particle wave scattered by the anomalous field of the nucleus to be spherical, the yield of protons can be expressed in terms of a quantity K_0 which, physically, refers to the phase by which the wave in a Coulomb field must be displaced toward the origin of the field in order to fit it smoothly to the wave inside the well. The assumption of a spherical wave is largely justified for the example at hand since even with the highest alpha-particle energy here used the nuclear obstacle is considerably smaller than the length of the incident alpha-waves. The former is about 3×10^{-13} cm, the latter 18.5×10^{-13} cm.

For the ratio R of observed to classical yields at various angles of projection θ Taylor finds

$$R = \left| e^{(-i/\gamma)\log\cos^2\theta} + i\gamma\cos^2\theta\,(e^{2iK_0}-1)\right|^2, \quad \text{where } \gamma = hv/4\pi e^2. \qquad (5)$$

Given a nuclear model, K_0 is a calculable function of the alpha-particle velocity v, but not of θ.

To find R from the experimental data the classical yield under the same conditions had to be determined. This was done by measuring the yield, at one particular angle and with the same arrangement, for alpha-particle energies low enough so that the scattering would be classical. Then, to compute the variation in angle of classical scattering Eq. (1) was used. The resulting R is plotted in Fig. 10.

If K_0 in (5) is adjusted so that R agrees with our data at $\theta = 0°$, the value of K_0 is 41.5°. For greater angles, the theory then predicts the dotted curve T_1. This does not drop sharply enough to be in accord with experiment. Adjustment at $\theta = 0$ can also be made by choosing K_0 to be $-26°$, but then the theoretical curve drops even less sharply. There are no other values of K_0

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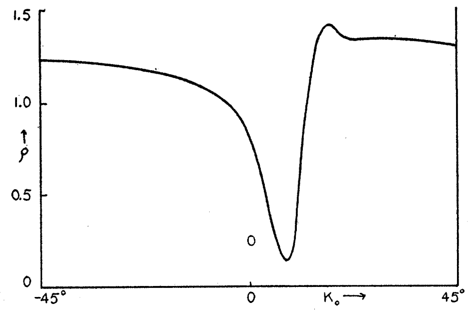
[9] It is evident that this way of plotting the data obscures the detailed character of the yield curves at small angles. Conversely, if yield curves are to be derived from Fig. 9, the procedure would entail very considerable uncertainties.



FIF. 11. $\rho = R(0°)/R(20°)$ from Taylor's theory for different values of K_0. v is taken to be 1.58×10^9 cm/sec. to agree with the experimental case.

which produce a fit at 0°. Attempts of fitting the curves at other angles (curve T_2) do not improve matters. The lower curve is explained somewhat better by Taylor's theory, but again the theoretical curve T falls less rapidly than the experimental one. In this case, $K_0 \sim 37.5°$. Agreement becomes better for smaller alpha-particle energies, as might be expected.

This test of the theory may not be entirely conclusive, since it depends quite essentially upon an accurate knowledge of the classical yield under the same circumstances, which, because of experimental difficulties, is known less well than the actual yield. To avoid this uncertainty we may proceed as follows.

The ratio R_0/R_{20}, where R_0 is observed divided by classical yield at $\theta = 0$ and R_{20} the same quantity for $\theta = 20°$, is independent of the classical yield except for a factor in θ. It is known from our experiments with considerable accuracy and has the value 2.2 for an alpha-particle velocity $v = 1.58 \times 10^9$ cm/sec. If we calculate R_0/R_{20} from Taylor's theory for this velocity but varying K_0, we obtain a function which is graphically shown in Fig. 11. Between 45° and 135° there is a monotone decrease in the ratio which causes the ends of the curve shown to join. It will be seen that R_0/R_{20} is confined to values lower than 1.5, and hence can never reach the experimental value. We feel this to be a rather definite contradiction between Taylor's theory and our data, and one which is not likely to be removed by merely including parameters K_1, K_2, etc., to take account of waves of finite angular momentum, but still maintaining a spherically symmetrical potential distribution. We regard it as more probable that the model of a fixed potential hole is at fault. Margenau,[10] and Breit and Yost[11] have discussed similar instances of failure of such models. It is well also to remember in this connection that, as a result of the spin and the magnetic moment of the deuteron, its field may not be spherically symmetrical. The range of the asymmetries would undoubtedly be greater than the extent of the usual nuclear hole. In that case the neglect of scattered waves of greater angular momentum would constitute a serious error and the theory in its simple form could not be expected to hold. It can be seen from Fig. 8 that Taylor's theory is in better agreement with the results for hydrogen, although the value of R_0/R_{20} is still somewhat outside the theoretical limit.

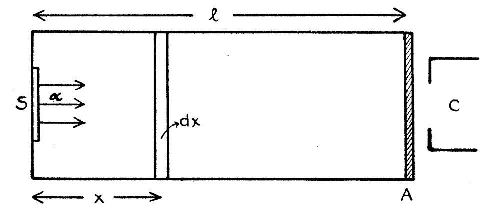


FIG. 12. Arrangement of source of particles, absorbing material and counting device.

In conclusion we desire to express our thanks to Dr. L. R. Hafstad for preparing the Po-source used in these experiments, and to Dr. Burnam and Dr. West for providing the radon tubes from which the source was made. We also benefited by the continued interest shown by Professor Kovarik in this work.

APPENDIX

Derivation of formula

Let the source of alpha-particles be at S. (cf. Fig. 12.) The particles projected forward have their origins throughout the gas between S and A, A being the absorbing foil. (We shall consider only particles which are projected forward.) The question is: How many particles will be measured by the counting device C as the absorbing thickness A is varied?

Let $f(R)$ be the number of particles shot forth from a slab of gas of thickness 1 cm air equivalent, by alpha-particles of residual range R cm. The range of the projected particles is nearly proportional to R; we shall suppose it to be KR. The number of particles dN which originate in the layer dx will be $dN' = f(R_0 - x)dx$, if R_0 is the total range of the alpha-particles. They will be measured if $K(R_0 - x) > l - x + A$, otherwise not. Hence the number of particles

[10] H. Margenau, Phys. Rev. **46**, 613 (1934).
[11] G. Breit and F. L. Yost, Phys. Rev. **47**, 508 (1935).

originating in dx which will be counted is

$$dN=f(R_0-x)\lambda(x)dx$$

where the discontinuous factor

$$\lambda(x)=\begin{cases}1 \text{ if } x<(KR_0-l-A)/(K-1)\\ 0 \text{ if } x\geqq(KR_0-l-A)/(K-1).\end{cases}$$

The total number counted is then

$$N=\int_0^l f(R_0-x)\lambda(x)dx=\int_0^{(KR_0-l-A)/(K-1)} f(R_0-x)dx.$$

From this expression it follows at once that

$$dN/dA=-f\left[\frac{(l+A-R_0)}{(K-1)}\right]\bigg/(K-1).$$

This expression is a maximum when f is a minimum, let us say for the value $f(R')$. R' is the value of the range at which the yield curve has a minimum, i.e., the value which was determined previously (cf. Fig. 2 for protons and Figs. 3–5 for deuterons). We see, therefore, that the value of A for which the integral curve is flattest, A', is related to R' by

$$f\left(\frac{l+A'-R_0}{K-1}\right)=f(R'), \quad \text{or} \quad \frac{l+A'-R_0}{K-1}=R'.$$

Now the value of K for protons, K_P, is approximately 4.2, while that for deuterons, K_D, is about 4.6, as may be computed by using the facts that momentum is conserved in the alpha-particle impact and that, for equal energies, a deuteron has nearly twice the range of a proton. We are thus led to the formula

$$\Delta A'\equiv A_p'-A_D'=(K_p-1)R_p'-(K_D-1)R_D'+\Delta R_0$$

which was used in the text of this paper.

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Spectral Characteristics of Electrically Exploded Mercury

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The spectrum obtained by sending 300 amp. from a 150-volt generator through a small stream of mercury is found to be characterized by great broadening of many of the lines, and by a strong continuous background. In the region between 2537 and 1950A, the continuous emission is strong enough, and sufficiently clear of emission lines, to be useful for absorption experiments. The continuous emission is ascribed to recombinations in which the kinetic energy plays a part, and the broadening of lines is ascribed to the strong electric fields of ions near the emitting atom.

INTRODUCTION

THE spectra obtained by allowing a condenser charged to a high potential to discharge through fine wires were studied by Anderson[1, 2] and his colleagues. They obtained spectra characteristic of metallic vapors at very high temperatures. The character of the spectrum was observed to change quickly from continuous emission, to the spark spectrum, and then the arc spectrum of the metal. By confining the explosion to a small volume, the absorption spectrum of the metal was obtained. The spectra, both emission and absorption, extended far into the ultraviolet, because of the high temperatures developed.

A modified form of this source of light was adopted by Mott-Smith and Locher[3] to illuminate a Wilson cloud chamber, taking advantage of the high intrinsic brilliancy and the short duration of the light; however, instead of employing a high voltage condenser discharge, they used a very high current obtained by connecting a 150-volt storage battery of very low internal resistance directly across a tiny stream of mercury which served instead of a fine wire. A commutator arrangement was used to permit the current to flow for a very short time at the instant when the photograph of the cloud chamber tracks was desired.[4]

The present investigation was undertaken to see whether the spectrum obtained by the "explosion" of mercury includes a region of continuous emission suitable for use in absorption experiments, with particular reference to the region between 2500 and 1850A, in which quartz prisms provide good dispersion.

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[1] J. A. Anderson, Astrophys. J. **51**, 37 (1920).
[2] Anderson and Smith, Astrophys. J. **64**, 295 (1926).
[3] Mott-Smith and Locher, Phys. Rev. **38**, 1399 (1931).

[4] The authors acknowledge with thanks the information and suggestions given them by Dr. Locher personally.