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Collisions of Alpha-Particles with Neon Nuclei*

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The tracks of more than 700,000 alpha-particles from a source of thorium active deposit have been photographed in a Wilson chamber filled with a mixture of approximately 85 percent neon, 10 percent air, and 5 percent hydrogen. The collisions with nuclei have been studied by replacing the film in the camera and projecting; convenient methods for doing this are described. A range-velocity curve for neon recoil atoms has been constructed by plotting the measured ranges against the calculated velocities for 85 forks. No interactions have been observed which give any evidence of the disintegrations of nuclei, with the emission of protons or neutrons. From a particular study of six elastic, coplanar collisions in which high energies have been transferred to the recoil atoms, it is concluded that the probability of disintegrating Ne^{20} with alpha-particles of less than 6-cm range (in air) is small; from this a lower limit for the mass of Na^{23} is calculated. The methods of measurement and calculation have been thoroughly tested by applying them to collisions with other nuclei, three with hydrogen, five with "air," one with helium, and one with deuterium.

I. INTRODUCTION

THE observation of forked alpha-particle tracks in the Wilson cloud chamber has in the past led to knowledge along two general lines. Firstly, the study[1–7] of elastic collisions has provided a test of the inverse square law and of the nuclear theory of the atom, and has yielded range-velocity relations for the various recoil atoms concerned, and, secondly, the study[8, 9, 10] of the relatively few inelastic collisions observed has thrown light on the disintegration of nuclei by alpha-particles, giving an idea as to the mechanism and energy balance. It was the general idea of the present work to attempt to obtain information along both of these lines in the case of neon. In particular, the disintegration of a fluorine atom by an alpha-particle should give rise to a proton and a Ne^{22} recoil atom, as Chadwick and Constable[11] have shown, and in case such a process is ever observed in a cloud chamber—the chance is greater than for any other element besides nitrogen—the range velocity relations for neon recoil atoms may become useful. Furthermore, since a disintegration yield from neon under bombardment of alpha-particles has been observed by Rutherford and Chadwick,[12] using scintillation methods, there is a possibility, however small, that such disintegration might be observed in the cloud chamber. The recording of

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1 Blackett, Proc. Roy. Soc. **A102**, 294 (1922).
2 Blackett, Proc. Roy. Soc. **A103**, 62 (1923).
3 Akiyama, Jap. J. Phys. **2**, 279 (1923).
4 Auger and Perrin, Comptes rendus **175**, 340 (1922).
5 Harkins and Ryan, J. Am. Chem. Soc. **45**, 2095 (1923).
6 Blackett and Lees, Proc. Roy. Soc. **A134**, 658 (1932).
7 Feather, Proc. Roy. Soc. **A141**, 194 (1933).
8 Blackett, Proc. Roy. Soc. **A107**, 349 (1925).
9 Blackett and Lees, Proc. Roy. Soc. **A136**, 325 (1932).
10 Harkins, Zeits. f. Physik **50**, 97 (1928); Harkins and Schuh, Phys. Rev. **35**, 809 (1930).
11 Chadwick and Constable, Proc. Roy. Soc. **A135**, 48 (1932).
12 Rutherford and Chadwick, Proc. Phys. Soc. London **36**, 417 (1924).

such an event would be of particular interest, since up to the present time alpha-particle disintegrations of nitrogen atoms only have been observed in the cloud chamber.

II. Experimental Arrangements and Analysis of the Tracks

The Wilson cloud chamber which was used in the work has been described by F. N. D. Kurie.[13] It is of the conventional piston type, the expansions being effected by periodically connecting the space underneath the piston to an evacuated flask by means of a synchronizing mechanism. The illumination was provided by a pair of ordinary carbon arcs, through which about 30–40 amperes were passed at the moment of expansion. An attempt was made to use photoflood lamps for illumination, but experiment showed that eight ordinary photofloods grouped very closely around the chamber were insufficient to give proper contrast on the film. The addition of a 2000-watt photoflood improved the situation only slightly, so that the arcs were finally resorted to. The camera was designed and constructed by Kurie[13] and is of a very convenient type. By a system of mirrors, two photographs were taken at right angles to one another on a single 35-mm moving picture film through a single lens. The image planes were slightly inclined so that practically all regions of the chamber were in focus. An automatic motor-drive device moved the film forward between expansions, and wound up the exposed film on a reel. The shutter was a Wollensak Betax (automatic) and was operated by an electromagnetic cable release.

The source of alpha-particles was a short length of copper wire which had been allowed to collect thorium active deposit by exposure to a quantity of mesothorium and its products. It was mounted outside the chamber and separated from it by a very thin sheet of mica waxed over a slit. The beam of alpha-particles was thus collimated so that the vertical spread was about 15° and the horizontal spread about 60°. The space between the mica and the wire was in all cases evacuated. The stopping power of the mica was first determined by weighing, and was afterwards checked by measurements of the actual ranges of the particles in the chamber. The value was about 0.9 cm air equivalent, so that with the arrangements described it was possible to bombard the gas in the chamber with alpha-particles of two residual ranges, 7.7 and 3.9 cm.

Photographs were taken on 100-foot reels of supersensitive panchromatic grayback film, the development being carried out with modified Eastman D–76 fine grain developer. The individual pictures were examined visually quite conveniently by projecting them on a screen with a Leica projector. A typical stereoscopic pair is shown in Fig. 1(d) with a neon collision almost in the plane of the chamber.

In order to study the collisions which were recorded, the film was replaced in the camera in exactly the same position it occupied when a given exposure was made. It was then illuminated by a 500-watt projection lamp and a condenser system, and the two images produced by the sets of mirrors received on a specially designed movable screen. In order to find the plane of any collision relative to the camera (within limits of inclination to the horizontal of 45°–90°) it was obviously necessary only to adjust the screen so that the two images of a given fork coincided. This was true provided the collision was coplanar, and thus the act of combining the two images in this way provided a fairly sensitive test upon this point. It was found that the actual process of combining simultaneously the images of the three tracks of a given fork could be simplified to a great extent by following a definite order in manipulations of the screen. The screen used was capable of horizontal motion in all directions, vertical motion, and rotation about three axes, and experiment showed that a great deal of time could be saved by having one axis of rotation lie in the plane of the screen itself. The most expeditious procedure was then in general to combine the two images of the alpha-particle track before collision so that they coincided with the axis lying in the screen, and then by rotating about this axis, the desired plane could easily be found, since the first adjustment was not disturbed by this process. The stand was designed so that a piece of photographic paper could be held flat in the position of the white screen, and when a given fork had been combined, the adjustment was secured by clamping, and prints taken of

[13] Kurie, Rev. Sci. Inst. **3**, 655 (1932).

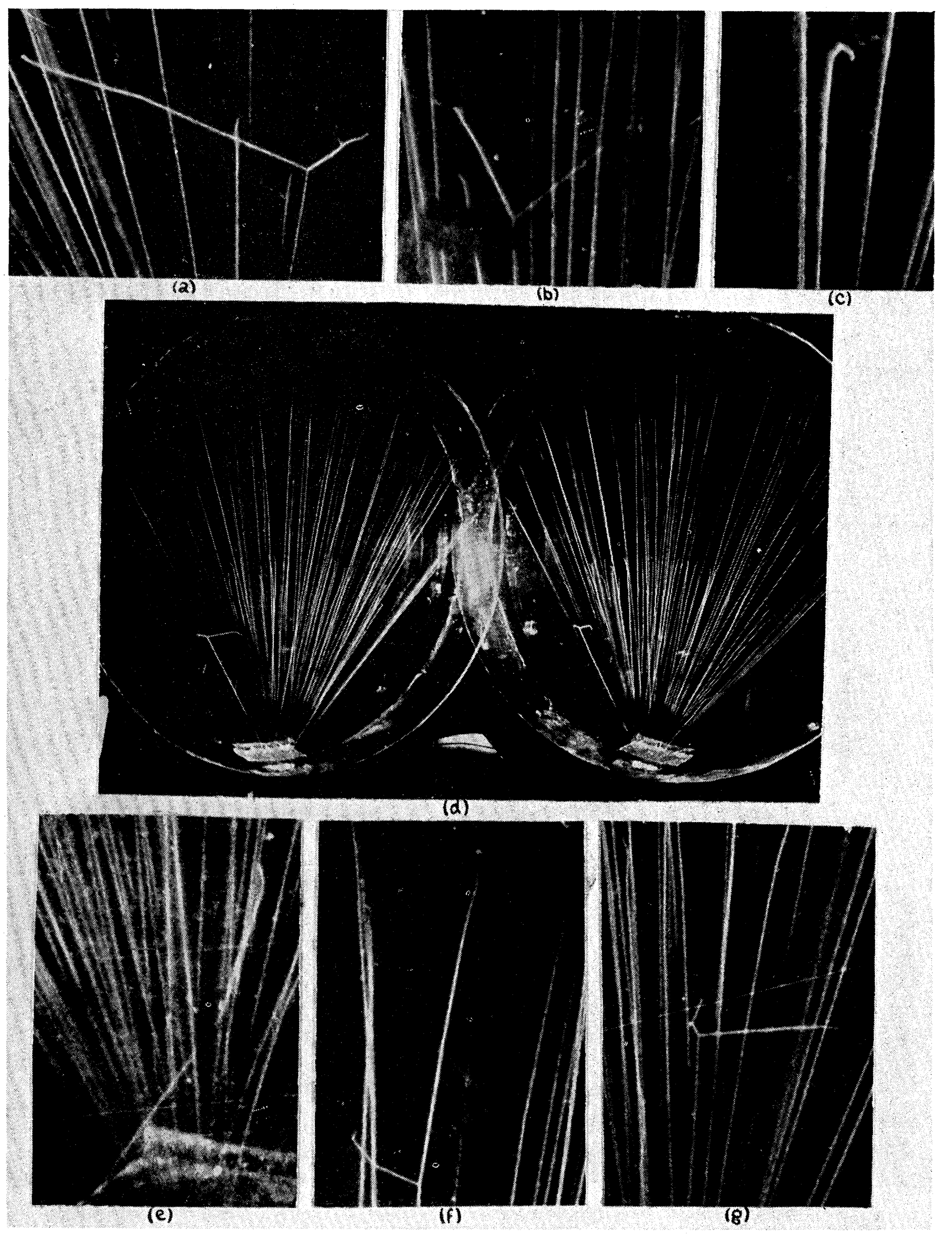

FIG. 1. (a) Alpha-particle-neon fork, with neon recoil atom making a second collision, producing a short spur: (b) Alpha-particle-deuterium fork: (c) Alpha-particle track showing approximate reversal of direction without any close collision. (No recoil track.) (d) Typical stereoscopic pair of photographs, showing collision of alpha-particle with neon atom: (e) Longest neon recoil track obtained. Reduced range of neon atom 8.4 mm (air), initial energy 1.1×10^6 electron volts: (f) Alpha-particle-hydrogen fork: (g) Alpha-particle-neon fork, with neon recoil atom making a second collision, producing a very short spur (compare (a)).

each image separately. By measuring each print independently it was thus possible to eliminate errors due to imperfect coincidence. The measurements of the two prints were usually weighted according to the orientation with respect to the camera, since at certain inclinations the errors were much larger than at others, because of the different angles at which the light struck the paper. In the case of events that took place in planes inclined at angles of from 45°–0° to the vertical (45°–90° to the plane of the chamber) it was impossible to receive two images on a screen with an opaque backing, and so an attachment was added whereby a translucent screen could be supported by its edges alone, the images being combined by observing one through the screen and one directly. The screen was then replaced by small lantern slide plates and the two exposures taken. The method of course fails at 45° to the vertical.

In order to analyze a fork, it is necessary merely to measure lengths and angles on the prints, and this was done on a drawing board using a protractor and rules. Ordinarily the measurements on a given fork were confined to the angles ϕ and θ (angles which the directions of motion after collision of the alpha-particle and the recoil atom make, respectively, with the initial direction of motion of the alpha-particle), the lengths of the recoil track and the alpha-track after collision, or, if the latter is not obtainable, the distance of the point of collision from the source. In most cases the mass ratio of the struck particle to the alpha-particle was calculated from the angles alone, by using the formula $m/M = \sin\phi/\sin(2\theta+\phi)$, where m is the mass of the struck particle and M the mass of the alpha-particle. This is of very limited value in the case of atoms as heavy as neon, however, since the angle $(2\theta+\phi)$ approaches 180° nearly enough so that small errors in the angles cause large errors in the sine function. In the case of lighter atoms, it determines with fair accuracy the mass of the struck particle and gives an idea as to the elastic character of the collision, since, if energy is not conserved, the above formula will not hold. The velocity of recoil of the struck particle was calculated in all cases, either by the formula $u = (M \sin\phi/m \sin\theta)\, v$, where u is the velocity of recoil, v the velocity of the alpha-particle after collision as estimated from its range, or, in case v could not be so determined, by the formula $u = 2V\cos\theta/(1+m/M)$, where V is the velocity of the alpha-particle before collision estimated from the distance of the point of collision to the source. In case θ is not easily measured, and the alpha-particle track is not completely observed, we may calculate v directly from V using ϕ, and then calculate u from the energy equation.

The stopping power (for alpha-particles) of the gas relative to air was calculated from the known constants of the gases present in the chamber in case the composition was known, and checked by measurements of the ranges, or, when the mixture was unknown, by the latter method alone. All the ranges were reduced to standard air with the results of these measurements, and the stopping power of the gas mixture for the recoil atoms was arbitrarily taken as the same as that for fast alpha-particles.

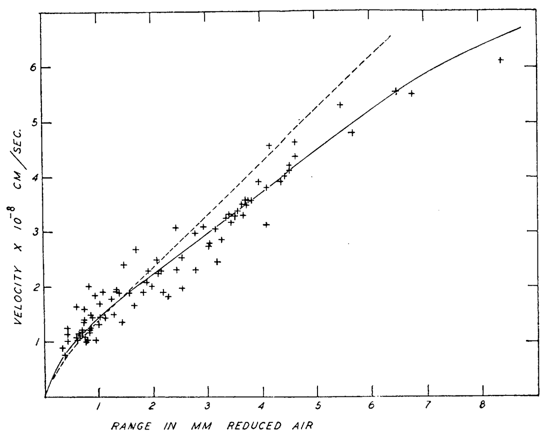

FIG. 2. Range-velocity curves for recoil atoms of neon and fluorine: Crosses and full line, present work on neon; broken line from Feather[7] on fluorine.

III. Results

Over 10,000 stereoscopic pairs of photographs were taken of the alpha-particle tracks, a portion of them being in almost pure neon gas, and the remainder in a mixture of about 85 percent neon, 10 percent air, and 5 percent hydrogen. Estimates made of the number of tracks per photograph in the case of every run showed that the total number of tracks observed was roughly 700,000; of these about 450,000 were of the long range group and 250,000 were of the short range group.

Out of about 200 collisions which were measured, about 85 were selected as being suitable for the plot of recoil velocity against recoil range, and the result of this plot is shown in Fig. 2, a similar curve for fluorine atoms due to Feather being shown for comparison. It can be seen that the neon curve falls slightly below the fluorine curve, agreeing with the general rule that the ranges of recoil atoms of the same velocity are in proportion to their masses. The fact that there is a certain amount of spread of the points on either side of the curve should not, for several reasons, appear unusual, for, added to the straggling of the recoil atoms themselves, which has been estimated by Blackett to be as much as 15 percent, there are always the inevitable errors in calculating the velocities of recoil due to the straggling of the alpha-particles, which comes into account when an alpha-particle range-velocity curve is used. Finally there are present the inherent errors of measurement, due to the method of reprojection and combination of the forks. Doubtless if stricter criteria had been used in selecting the collisions suitable for plotting the spread would have been less; on the other hand, considering the errors already present because of straggling, which probably account for most of the spread, this process could be carried to the extreme of not having enough points to determine a fairly accurate average curve.

The mass of neon was arbitrarily set at 20.2 in all the calculations. As Feather points out, a mistaken value of the mass in the case of two atoms having nearly the same weight, merely has the effect of moving a point from its position on its own range-velocity curve to a point very nearly on the range-velocity curve of the atom for which it is mistaken. Thus the curve shown may be considered correct for atoms of mass 20.2, and moreover the curves for Ne^{20} atoms or Ne^{22} atoms may easily be found merely by multiplying the velocity corresponding to any range by the ratios 20.2/20 and 20.2/22 respectively. This is a point which should not be overlooked in case the curve is ever used in the calculation of energies of Ne^{20} or Ne^{22} atoms.

It will be noticed that the two curves in Fig. 2 cross, which may seem rather odd. This, I believe, is due to a spurious effect which shows itself because of different methods of calculating stopping powers. In the present work account was taken[14] of the variation in the stopping power of neon (for alpha-particles) with velocity, whereas in Feather's calculations the relative stopping power of the gas was assumed to be constant, and was determined by measuring the ranges directly. This variation is important only for short range alpha-particles, and in the case of neon decreases with decreasing velocity. Thus for a given short range residual alpha-particle in a collision, a smaller velocity would be assigned to it than if the stopping power did not decrease in this region, therefore the calculated velocity of recoil would be low, which is what is observed. Of course, not all collisions with small recoils have small residual alpha-particle tracks, but a considerable number do, which may account for this effect.

According to the formula suggested by Blackett[2] $R \propto mZ^{-\frac{1}{2}}f(u)$, where R is the range, Z the atomic number, m the mass, and u the velocity of the recoil atom, the ratios of the ranges of recoil atoms of the same velocity should be proportional to the ratios of their masses and inversely proportional to the square roots of their atomic numbers. Comparing the present curve with that of Blackett and Lees[6] for nitrogen at a velocity of 5×10^8 cm/sec., the ratio of ranges is 1.52, whereas the formula predicts a value of 1.21. The comparison with Feather's fluorine curve shows a measured value of 1.20 as against a predicted value of 1.01. Thus whether the data are compared to nitrogen or fluorine, the range of the neon recoil atoms is greater than that predicted. This might possibly have an explanation in the electronic structure of the neon atom, or it might suggest a higher power of m in the above formula, although considering the complexity of the problem and the number of factors involved, it is probably unsafe to draw any conclusions. Besides, the above formula is known to be of rather restricted applicability.

Of particular interest are five collisions which are represented by the five highest velocity points on the curve as shown in Fig. 2, plus a sixth which was not plotted because of the fact that the recoil atom experienced a rather marked deflection which was difficult to measure accurately. Two of these collisions are shown in Fig. 1 (a) and (e). The salient features of these forks may be briefly catalogued as follows.

1. The reduced air ranges of the recoil atoms were greater than 5 mm and the distances of closest approach of the alpha-particle to the nucleus in the six cases, calculated on the inverse square law, ranged from 7.0 to 4.57×10^{-13} cm. These values, particularly the lowest, are very

[14] Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

close to the value of the nuclear radius of neon, as estimated by Pollard.[15]

2. The collisions were in all cases apparently elastic, within the limits of experimental error. There was no indication of disintegration, and the appearance of the tracks was in no case such as to indicate the passage of any other type of particle except an alpha-particle or recoil atom. The mass ratios calculated from the angles were correct to within the experimental error, although this is by no means a sensitive test for heavy atoms, as has been pointed out earlier.

3. The collisions were, as nearly as could be determined, coplanar, and since the method described by which the photographs are projected and combined provides a fairly sensitive test upon this point, the evidence is good that no neutrons or high energy gamma-rays were given off in the processes involved.

4. The angle θ had, in the six cases, the values 45°, 26°, 26°, 25°, 24°, and 13°. If the internuclear force is Coulombian it may be shown that, for a given length of recoil, the ratios of the numbers of collisions for which θ lies within the ranges 90°–60°, 60°–30°, and 30°–0° are, respectively, 1, 2, and 1. The numbers in the present case are 0, 1, and 5. It is of course obvious that not too much reliance can be placed on the analysis of such a small number of collisions; on the other hand, it is of definite significance that in five out of the six cases, small angles of deflection were observed. For this means that these collisions were practically head-on, which is improbable from the point of view of the inverse square law. Thus the conclusion is that for distances of approach as close as those in the cases considered, an anomalous region has been reached, and the inverse square law in its simple form no longer applies.

While it is not true that in the case of nuclei which disintegrate because of alpha-particle penetration, every alpha-particle which gets into the nucleus will cause a disintegration, it is safe to summarize the above study of the six collisions in which the alpha-particle approached the nucleus very closely by saying that the disintegration of neon atoms with alpha-particles of 5 or 6 cm range or less is improbable. For example, if the atoms had been nitrogen, some of the collisions of the above type would certainly have caused breakdown of the nuclei.

To go further, it is interesting to consider the composition of the neon gas from the standpoint of isotopes. It is well known that ordinary neon is a mixture of about 90 percent Ne^{20} and 10 percent Ne^{22}. It is thus not only very improbable that all the six collisions referred to are with Ne^{22} atoms, but it is on the contrary quite reasonable to assume that they are all with Ne^{20} atoms. It is thus more in accord with the observations to confine the above conclusions to the Ne^{20}. It is worth noting that by analogy with the other nuclei containing an integral number of alpha-particles (C^{12} and O^{16}), this is what would be expected.

Providing we assume that Ne^{20} does not disintegrate for alpha-particle energies corresponding to ranges less than 6 cm, then a minimum value may be assigned to the mass of Na^{23}, which is formed in the hypothetical reaction,

$$ {}_2He^4 + {}_{10}Ne^{20} = {}_{11}Na^{23} + {}_1H^1. $$

The result of such a calculation (using the latest values for the masses of alpha-particle and proton) shows that the Na^{23} nucleus must have a mass greater than 22.99945.

In view of the fact that some mention has been made in the past of collisions apparently not coplanar (Akiyama,[3] Auger and Perrin,[4] Feather[7]) it is worth mentioning the observations made during this work. It is true that there were a few forks observed, the three tines of which did not combine simultaneously on the screen. This type of collision was always rejected for measurement, and was considered of small importance on the following general reasoning:

1. Observations of a great many of the recoil tracks show that, in general, the recoil atom is peculiarly subject to deflections, particularly during the last few millimeters of its path. In some cases the recoil tracks are far from being straight, and a great many times they are curved so much towards the ends that accurate measurement of their lengths is impossible.

2. All of the collisions observed in which there was apparently lack of coplanarity were those in which the length of recoil was small. In the case of all the longer recoil forks, it was possible to combine the three tines simultaneously, referring of course to the parts of the tracks near the point of collision.

3. Only a relatively small percentage of even the shorter recoil forks, about 10 percent, exhibited this property.

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

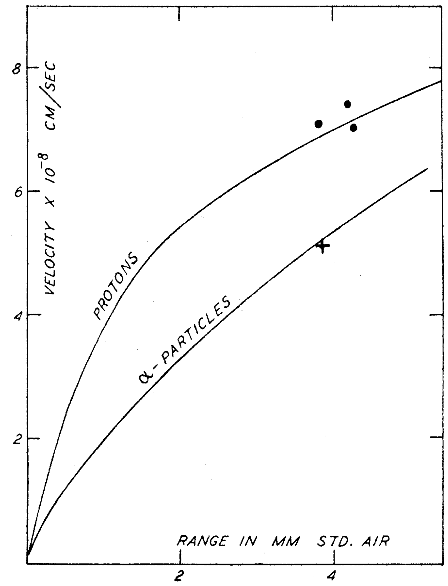

FIG. 3. Range-velocity curves for recoil atoms: of hydrogen (protons) and helium (alpha-particles). Full lines from Blackett and Lees,[6] dots and cross, collisions assigned to hydrogen and helium in present work.

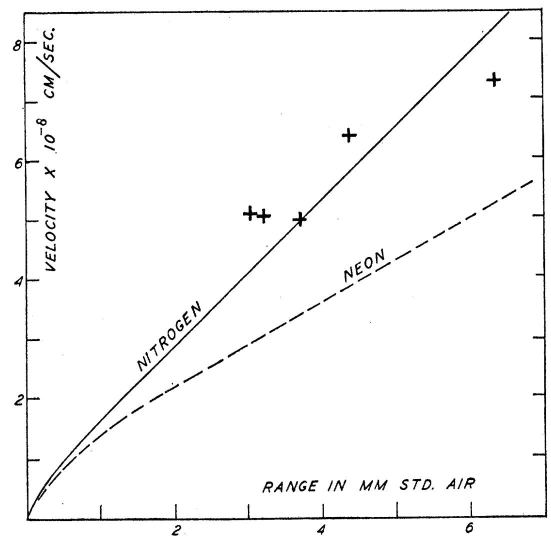

FIG. 4. Range-velocity curves for recoil atoms of nitrogen and neon. Full line from Blackett and Lees[6] on nitrogen; crosses, collisions assigned to air in present work; broken line, neon, from Fig. 2.

Thus a reasonable explanation of these apparently anomalous collisions seems to be that the recoil atom suffered a small deflection soon after collision. This would account for the facts in a very simple and direct way without injecting any hypotheses about gamma-rays or other losses of energy.[16] It may be that this explanation could be applied successfully to the collisions of this type reported by others.

During the greater part of the work, when there were present in the chamber other gases besides neon, there was of course a chance of striking these atoms. There were six collisions with hydrogen observed, of which three were suitable for measurement, and one with helium, which was doubtless present in the neon as an impurity. One of the hydrogen forks is shown in Fig. 1(f). The mass ratios in the three hydrogen forks were calculated to be 0.260, 0.238, and 0.242, in good agreement with 0.25, the correct value. In the case of the helium collision, the mass ratio came out to be 1.05, and the value of $\phi+\theta$ was measured as $90°\pm0.5°$. In Fig. 3 the calculated velocities have been plotted against the measured ranges in these cases, and the proton and alpha-particle range-velocity curves of Blackett and Lees have been drawn in for comparison. The fact that all three of the measurable hydrogen collisions had about the same velocity and range is unfortunate, but the agreement is excellent, as is that for helium.

[16] Smekal, Physik. Zeits. **27**, 383 (1926).

The chance of colliding with an "air" atom was estimated from a rough knowledge of the composition of the gas in the chamber to be about one in fifteen. Since it was generally impossible to distinguish between a neon and an air collision, due to the inherent difficulties in applying the mass ratio formula which have already been discussed, the admittedly arbitrary criterion was decided upon that a mass value would be determined, above which all atoms would be classed as neon when calculated by the formula, and below which they would be classed as air, that value being chosen which would give the proper ratio of number of neon collisions to number of air collisions. No doubt a few points on the neon curve really represent air collisions, and *vice versa*, but this has a negligible effect on either curve as explained before. The ranges and velocities of those recoils, which were arbitrarily called air, have been plotted in Fig. 4, and the nitrogen curve of Blackett and Lees is drawn in for comparison, as is the present neon curve. The significance of this plot, considering the arbitrary way in which the points have been classed as air, is doubtful, and it would perhaps have been just as well to assign all of these doubtful collisions to neon, and plot them on the other curve.

In addition to the tracks photographed in neon, one run of about 600 pictures was taken with a mixture of about 30 percent deuterium and 70 percent air. In this series one collision with deuterium was observed, which is reproduced in Fig. 1(b). Unfortunately the complete track of the deuteron (right-hand tine of fork) after collision was not observed. It is interesting to note that this fork may be immediately recognized as a collision with a deuterium atom for the following reasons: The angle of deflection of the alpha-particle, ϕ, is about 25°, therefore it cannot have struck hydrogen since the maximum value of ϕ in hydrogen collisions is 14.5°; the value of ϕ is less than 30°, the maximum for deuterium collisions, so it is consistent with this explanation; the track of the struck particle is finer, showing less ionization, and has the appearance of a proton or deuteron track, and, finally, the value of m/M is calculated to be 0.57, in agreement with 0.5 for a deuteron collision.

In Fig. 1(g) is shown an unusual type of fork, the recoil atom of neon experiencing a marked deflection, producing a second small recoil. Fig. 1(c) shows a photograph of an unusual type of alpha-particle track. Because of a series of small deflections producing negligible recoil spurs, the atom has experienced a net deflection of about 180°, producing a curiously shaped track.

In conclusion, it is a pleasure to thank Professor A. F. Kovarik for constant advice and encouragement throughout the course of the work, Dr. Ernest Pollard for many helpful discussions, and Professor L. W. McKeehan for numerous suggestions regarding the composition.

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Anomalous Diffraction Gratings

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Gratings similar to those described and studied by the author in 1907 and 1912 have been more fully investigated. They show narrow bright and dark bands in the continuous spectrum of a white source. Classical theory has never accounted for these anomalies, though tentative efforts were made at the time by Lord Rayleigh. The present work was done with a chromium plated echelette grating of 7200 lines to the inch ruled on copper, and one of 15,000 lines ruled by Dr. Babcock on an aluminum film on glass. The behavior of the bands as the incidence angle is altered has been very completely recorded by photography and the energy missing in the grating spectra has been found in excess in the spectrum of the central image. The dark bands appear to be due to the circumstance that diffracted wavelets from the lines are inhibited by the collective effects from neighboring lines, i.e., there is a sort of destructive interference along the plane of the grating. This obtains, however, only when the grating space is equal to an integral multiple of λ (for normal incidence) which means that the dark bands correspond to λ values which are passing off the grating on both sides at grazing emergence. The spectra formed by the Al grating are completely plane polarized, because of the circumstance that the width of the scratches is considerably less than the wave-length of the light. The dynamical action of the gratings is discussed, and the anomalous behavior is shown to be due to the presence of exceedingly narrow diffracting elements, which may be present even in the case of rather coarse rulings.

As is well known the distribution of intensity in the spectra formed by gratings varies in the different orders, some being bright in the red, others in the violet, and these variations are easily accounted for by elementary theory.

It is possible, however, to rule gratings showing bright and dark bands in very restricted spectral regions, and these anomalies have never been accounted for.

At the bottom of Fig. 1, Spectrogram 9, we have a photograph of the spectrum of a Mazda lamp filament taken with such a grating extending from the extreme red (at the right) to the violet. The black bands are very sharply

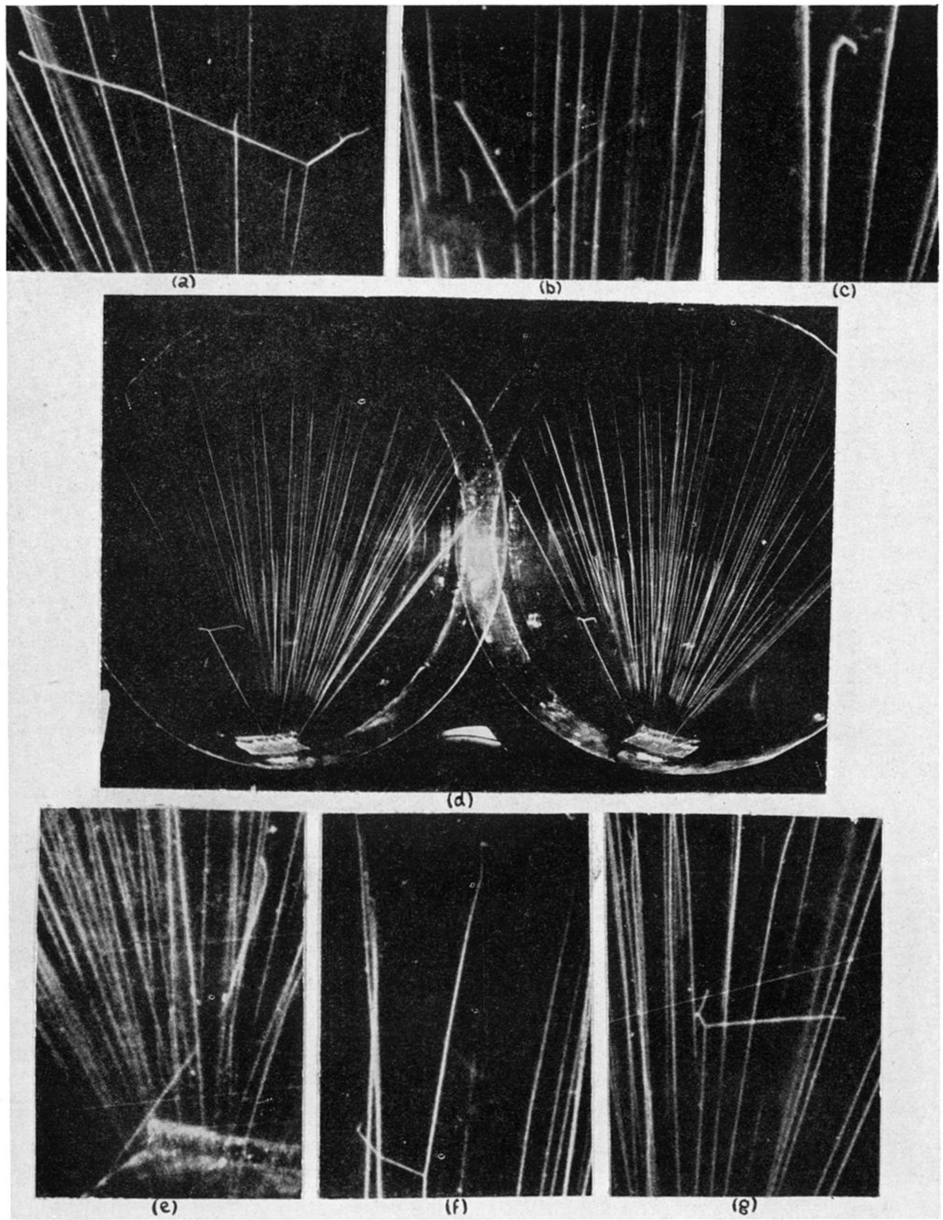

FIG. 1. (a) Alpha-particle-neon fork, with neon recoil atom making a second collision, producing a short spur: (b) Alpha-particle-deuterium fork: (c) Alpha-particle track showing approximate reversal of direction without any close collision. (No recoil track.) (d) Typical stereoscopic pair of photographs, showing collision of alpha-particle with neon atom: (e) Longest neon recoil track obtained. Reduced range of neon atom 8.4 mm (air), initial energy 1.1×10^6 electron volts: (f) Alpha-particle-hydrogen fork: (g) Alpha-particle-neon fork, with neon recoil atom making a second collision, producing a very short spur (compare (a)).