and Lazareff[14] found the ratio to be 3.24. Aston[15] found values between 3.0 and 3.1.

Becker,[16] Hettner and Bohme,[17] and Kallman and Lazareff[14] have given evidence for the existence of Cl^{39}. On the other hand, Ashley and Jenkins,[18] and Hardy and Sutherland[19] have been unable to find Cl^{39}. From the present investigation it is concluded that Cl^{39}, if present, exists to less than 1 part in 20,000 compared to Cl^{35}.

The writers wish to express their appreciation to Professor John T. Tate for his interest and advice in connection with this experiment. The HCl gas was furnished by D. L. Fuller, C. P. Roe, and R. E. Peck of the School of Chemistry, University of Minnesota.

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[14] Kallman and Lazareff, Zeits. f. Physik **80**, 237 (1933).

[15] Aston, *Mass Spectra and Isotopes* (Longmans, Green & Co., New York).

[16] Becker, Zeits. f. Physik **59**, 583 (1930).

[17] Hettner and Bohme, Zeits. f. Physik **72**, 95 (1931).

[18] Ashley and Jenkins, Phys. Rev. **37**, 1712 (1931).

[19] Hardy and Sutherland, Phys. Rev. **41**, 471 (1932).

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Collisions of Alpha-Particles with Sulphur Nuclei*

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More than 700,000 thorium C and C′ alpha-particle tracks have been photographed with a stereoscopic camera in a Wilson chamber filled with a mixture of hydrogen sulphide and hydrogen. A range-velocity curve for sulphur recoil atoms has been constructed by plotting the measured ranges (reduced to standard air) against the calculated velocities for 60 selected alpha-particle sulphur collisions. This curve is discussed and compared with the results of other workers. A possible relationship has been noted between the range-velocity curves of atoms having similar electronic configurations. No collisions indicating possible sulphur disintegrations were observed. Several low energy collisions were noted which were apparently lacking in coplanarity, but this effect is explained as being due to small deflections suffered by the recoil nucleus shortly after the collision. The calculated distances of closest approach are compared with the radius of the sulphur nucleus as given by Pollard and Brasefield. The methods of measurement and calculation employed have been checked by applying them to collisions with protons.

I. Introduction

SINCE the pioneer experiments of Blackett and others, the Wilson cloud chamber has become of great importance in the study of nuclear reactions. No accurate interpretation of the energy changes in these reactions can be made, however, unless it is possible to deduce the velocities of the recoiling particles from their observed ranges. The relationship expressing the velocity as a function of the range of the particle cannot as yet be obtained from theory for heavy nuclei owing to the complexity of these atoms, and the construction of such a curve is of necessity an experimental problem.[1] Previous experiments by Blackett,[2] Blackett and Lees,[3] Feather,[4] and Eaton[5] have established such curves for several elements. However, it is important that such information be extended as far as possible in order that a general empirical relationship may be established which will apply to all atoms.

The element sulphur was selected in this work for the following reasons:

First, a stable gaseous compound of sulphur, hydrogen sulphide, can be obtained, enabling this element to be studied conveniently in the cloud chamber, and the form of the range-velocity curve can therefore be determined.

Second, in addition to increasing the general information on the subject of range-velocity curves the form of the sulphur curve is of particular interest in the study of the following nuclear reaction

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* Part of a dissertation presented to the Faculty of the Graduate School of Yale University in candidacy for the degree of Doctor of Philosophy.

[1] Calculations made by W. E. Duncanson, Proc. Camb. Phil. Soc. **30**, 102 (1933–34), and by G. Mano, J. de phys. et rad. [7] **5**, 628 (1934), using the theoretical expressions of Bethe and Bloch, have yielded results in good agreement with experiment for the range-velocity relations of alpha-particles and protons of moderately high energies. Unfortunately, however, the assumptions made in the derivation of these formulae preclude their application to particles having the low energies considered here.

[2] P. M. S. Blackett, Proc. Roy. Soc. **A102**, 294 (1922); **A103**, 62 (1933).

[3] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. **A134**, 658 (1932).

[4] N. Feather, Proc. Roy. Soc. **A141**, 194 (1933).

[5] W. W. Eaton, Phys. Rev. **48**, 921 (1935).

$$_{15}P^{31}+{}_2He^4\rightarrow{}_{16}S^{34}+{}_1H^1$$

giving a proton and the $_{16}S^{34}$ nucleus, an isotope of $_{16}S^{32}$. This reaction has been shown to take place by counting experiments when phosphorus is bombarded with thorium C′ alpha-particles. (The range-velocity curve determined experimentally in this work is for $_{16}S^{32}$, whereas the nucleus obtained in the above reaction is $_{16}S^{34}$. However, to a first approximation this curve may be taken as representing also the range-velocity relation for any such $_{16}S^{34}$ nucleus, the actual error involved in this procedure being as yet unknown, but certainly small.)

Third, since disintegration protons are known to appear when sulphur is bombarded with thorium C′ alpha-particles, there was a small but finite probability that a disintegration of a sulphur nucleus might be observed during the course of this work. The importance of observing such an event in the cloud chamber is readily seen when we consider the fact that only with the cloud chamber can we observe all of the particles resulting from a single nuclear process of this type along with their respective ranges and directions of emission.

II. Experimental Arrangements and Analysis of the Tracks

Since the chamber was to be used primarily for the study of range-velocity relations of heavy nuclei, it was deemed advisable to make it large in diameter and capable of operation at any pressure below 76 cm. The use of a large diameter chamber and operation at a pressure sufficiently low to make the ranges of the thorium C′ alpha-particles in the chamber comparable to the diameter enables relatively long recoil tracks to be obtained. The accuracy of the measurements made upon the forks may thus be increased. This is especially important when studying the collisions of alpha-particles with heavy nuclei since the velocity which a heavy nucleus attains when struck by an alpha-particle is comparatively small, and its range in air at normal pressure and at a temperature of 15°C (hereafter designated as its reduced air range) is therefore short.

The internal diameter of the chamber was accordingly made slightly greater than 20 cm, and the chamber was so constructed as to be possible of operation at any pressure between the extreme limits of 0 and 2 atmospheres. The chamber is of the sylphon type and follows the general design of Dahl, Hafstad and Tuve.[6] The agency for producing the sudden expansion is a piston operated by compressed air. The adjustment of the expansion ratio is made by means of stops threaded on to the drive shaft connecting the piston to the sylphon. This adjustment is entirely independent of the pressure of the gas used in the chamber. Variations in atmospheric pressure do not affect either the expansion ratio or the pressure of the gas in the chamber.

The illumination is provided by a pair of carbon arcs placed on opposite sides of the chamber. The arcs are operated in series from the 220 volt d.c. line. The shorting out of a large resistance in series with the arcs at the time of the expansion permits a current of about 40 amperes to flow through the arcs for a short interval of time and produces very intense illumination.

The camera used in this work is of the Kurie type.[7] The essential features of this type of camera are briefly as follows. By means of an appropriate mirror and prism system this camera is made equivalent to two cameras taking two simultaneous pictures along lines of sight at right angles to each other. By inclining the film planes slightly to the plane of the lens (accomplished by means of a special film wedge) the mid-plane of the chamber is made conjugate to both images. Thus the whole illuminated region of the chamber may be kept in sharp focus for each image. The operation of the camera is entirely automatic, a small d.c. motor serving to drive the film forward between expansions. The lens used is a Bausch and Lomb "Micro-Tessar" of 32 mm focal length, and the shutter is a Wollensak "Betax" (automatic). A flexible cable release attached to the armature of a small electromagnet opens the shutter at the appropriate moment in each cycle of operations.

The source of alpha-particles is a small monel metal button upon which thorium active deposit has been collected. This source is mounted outside the chamber and separated from the

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[6] O. Dahl, L. R. Hafstad and M. A. Tuve, Rev. Sci. Inst. **4**, 373 (1933).

[7] F. N. D. Kurie, Rev. Sci. Inst. **3**, 655 (1932).

chamber by means of a piece of mica waxed over a series of five 1-mm diameter holes. The space between the source and the mica window is evacuated in order to insure that no loss in the energy of the alpha-particles occurs before they enter the mica. The stopping power of the mica window used was 0.8 cm air equivalent (determined by weighing). Thus the residual reduced air ranges of the thorium C and C′ alpha-particles in the chamber were 3.99 cm and 7.82 cm, respectively.

The stopping power of the gas mixture in the chamber relative to standard air was computed at all times since the relative proportions of the hydrogen sulphide, hydrogen, and water vapor present in the chamber were always known. This method of determining the stopping power of the gas mixture was preferred to a direct comparison of the measured ranges in the chamber with those to be expected in standard air, since it was found that the direct comparison involved a small error as a result of the vertical spread of the beam of alpha-particles from the source. This vertical spread had the effect of making the average alpha-particle range in the chamber appear to be shorter than the true range when this average range was determined by measurements made upon any single reprojection print, the difference in stopping powers as determined by the two methods amounting to about three percent. This effect was not, however, a source of error in the measurements made upon any single collision when the collision had been properly recombined.

Photographs were taken on 100-foot reels of Eastman "Super X" panchromatic grayback film. The individual pictures were examined visually by passing the film over a specially constructed light box. Reprojection of the images is accomplished by replacing the film in the camera and illuminating the film from above. The methods and apparatus used for recombining the forks and the analysis of the reprojection prints have been thoroughly described by Eaton[5] and need not be discussed here.

III. Results

A little more than 10,000 stereoscopic pictures were taken of alpha-particle tracks in a gas mixture of hydrogen sulphide and hydrogen. A rough estimate of the average number of alpha-particle tracks on each picture yields the value of 70 tracks per expansion, making a total of 700,000 alpha-particle tracks photographed. Of this total number approximately 65 percent, or 455,000, were of the longer range type while the remaining 35 percent, or 245,000 were of the shorter range variety. Over 200 collisions of alpha-particles with sulphur nuclei were reprojected and examined. Approximately 50 of these were rejected in the measuring-up process, and from the remaining number 60 were selected as being suitable for a range-velocity curve. Fig. 1 shows the plot of the ranges of the recoil sulphur nuclei (reduced to standard air) against their computed velocities. The dotted curve, drawn in for comparison, is the range-velocity curve for argon as given by Blackett and Lees. It is seen that for ranges of the recoil nuclei greater than 1 mm the argon curve falls below the sulphur curve. This is to be expected on the basis of the formula proposed by Blackett and Lees

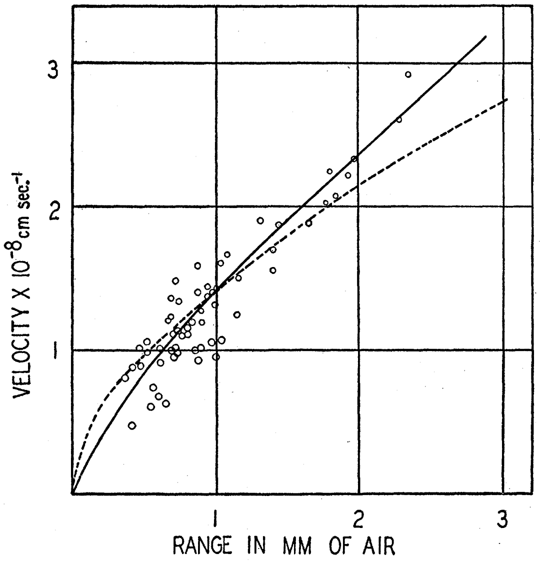

Fig. 1. Range-velocity curve for sulphur recoil atoms. Dotted curve is curve for argon atoms as given by Blackett and Lees.

$$R = kmZ^{-\frac{1}{2}}f(v).$$

Here R is the range of the recoil atom, m its mass, Z its atomic number, and v its velocity. $f(v)$ is a function of the velocity alone, and k is a constant. If this formula applies we see that for the case of argon and sulphur nuclei of the same velocity we should have

$$R_S/R_A=(m_S/m_A)(Z_A/Z_S)^{\frac{1}{2}}$$

where R_S, m_S and Z_S are the range, mass, and atomic number respectively of the sulphur atom, and R_A, m_A, and Z_A are the corresponding quantities for the argon atom. Since $m_S=32$, $m_A=39.9$, $Z_S=16$, and $z_A=18$ we have

$$R_S/R_A=0.85.$$

Hence, for the same velocity the sulphur atom should have a shorter reduced air range than the argon atom, and the sulphur range-velocity curve should lie above the argon curve. The fact that the two curves cross at about 1 mm range may have no real significance. Blackett and Lees had available Gurney's data[8] on the variation of the stopping power of argon with the range of the alpha-particles and were therefore able to correct the reduced air ranges of the recoil argon nuclei in the short range region. Since no data exist on this variation in hydrogen sulphide or even in sulphur, it could only be hoped that these variations in the case of hydrogen and sulphur (assumed to be opposite in direction) would partially balance out. The form of the sulphur curve below 1 mm range may, therefore, be slightly incorrect. However, exactly the same effect was noted by Eaton when he compared his neon curve with Feather's fluorine curve, the two curves crossing in the low range region.

If we compare the ratios of the ranges as measured from the curves in Fig. 1 for four selected values of the velocity we obtain Table I. The value of the ratio is seen to decrease steadily as higher velocity points are selected, whereas the formula predicts a value of 0.85 for all cases. Since the two curves are obviously not similar, this discrepancy between the measured ratios and the predicted value might have been expected.

TABLE I.

Velocity (10^{-8} cm/sec.)	1.6	2.0	2.4	2.6
Ratio R_S/R_A	0.95	0.90	0.85	0.80

TABLE II.

Velocity (10^{-8} cm/sec.)	1.0	1.5	2.0	3.0
Ratio R_S/R_O	1.18	1.14	1.16	1.16

TABLE III.

Velocity (10^{-8} cm/sec.)	1.0	1.5	2.0	2.5
Ratio R_A/R_{Ne}	1.07	1.07	1.07	1.07

If we compare the sulphur curve with the oxygen curve of Blackett and Lees (not shown), a marked similarity between the forms of the two curves is noted. Comparing the ratios of the ranges for four selected velocity points we obtain Table II. The ratio is seen to remain constant within the limits of measurement showing that for this case, at least, $R_S=K_Sf(v)$ and $R_O=K_Of(v)$ where the K's are undetermined constants. That is, the unknown function of the velocity is the same for each curve. Here the formula of Blackett and Lees predicts a value of 1.41 for the ratio of R_S to R_O, and this is definitely too high. The constancy of this ratio in the case of sulphur and oxygen suggested the possibility that the unknown function of the velocity upon which the range of the recoil atom depends might be the same for atoms of similar electronic configurations, for elements in the same column in the periodic table. Eaton's neon curve was accordingly compared with the argon curve of Blackett and Lees. Again, a decided similarity between the forms of the two curves was noted. For four different velocity points the following ratios in Table III were obtained. The ratio is seen to remain constant here also. For this case the predicted value is 1.35 and is again too high. In each of these two cases the comparison of the two curves was somewhat rough, and the agreement of the range ratios for the case of argon and neon may not be quite as good as that given above. The curves for argon and neon were also compared with the helium curve (alpha-particle range-velocity curve). In general, the range ratios were not as constant as in the preceding two examples. However, for ranges greater than 1 mm the agreement between the individual ratios was fair.

The reduced air ranges of the recoil sulphur nuclei in the four highest energy collisions obtained were 2.35, 2.28, 1.97, and 1.93 mm respectively, while the corresponding velocities were 2.92, 2.61, 2.32, and 2.22×10^8 cm/sec. It is interesting to note that the angle ϕ for the recoil alpha-particle in each of these four cases was appreciably greater than 90°, the four values being 117.5°, 109.0°, 126.9° and 100.4°.

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[8] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

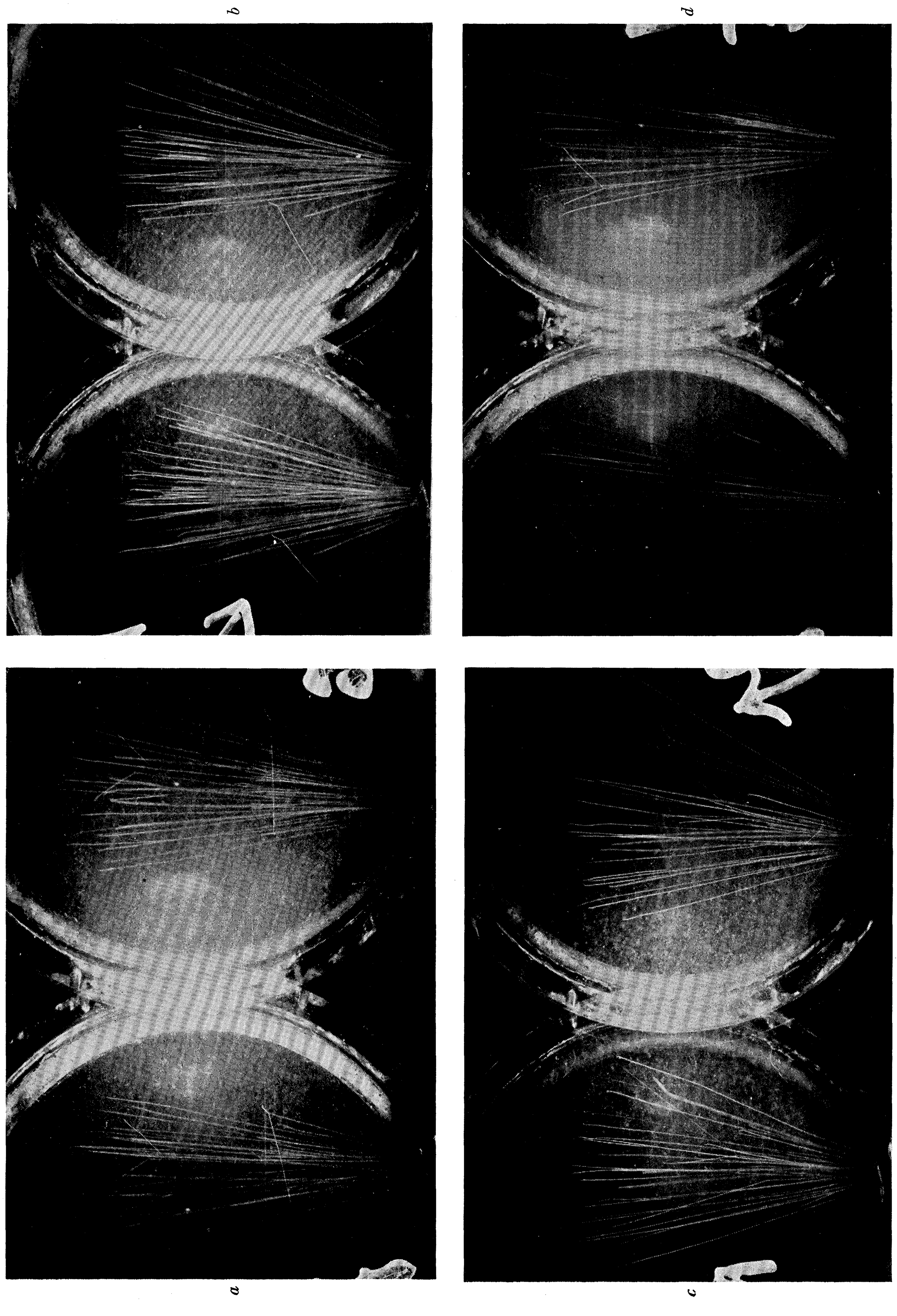

FIG. 2. *a*, *b*, Cloud chamber photographs of collisions between α-particles and sulphur nuclei. *c*, *d*, Typical photographs of collisions between α-particles and protons.

The distances of closest approach of the alpha-particles to the sulphur nuclei were calculated for these four collisions, on the assumption that the inverse square law of force held, and were found to range from 11.9 to 22.6×10^{-13} cm. It is of interest to compare these values with the value 5.4×10^{-13} cm for the radius of the sulphur nucleus as given by Pollard and Brasefield.[9] The two highest energy collisions observed with sulphur nuclei are shown in Fig. 2 (*a*) and (*b*).

No disintegrations of sulphur nuclei were observed. Several low energy collisions were noted which were apparently not coplanar, but these were collisions in which the ranges of the recoil sulphur nuclei were so short that very little reliance could be placed in the measurements made upon them. In the examination of a large number of collisions the same effect previously noted by Eaton[5] was frequently observed, namely, that when near the end of the range the recoil atom frequently gives rise to a track showing a decided curvature due to a series of small collisions. It therefore seems probable that the apparent lack of coplanarity in a small number of low energy collisions was due to this cause, the "curving" of the recoil atom out of the plane of the collision making a complete recombination of the fork impossible.

Since the chamber was filled with a mixture of hydrogen sulphide and hydrogen an appreciable fraction of the collisions observed were with protons, the majority of these being examined merely to insure that the proton tracks could not be the result of sulphur disintegrations. However, measurements were made upon several of these and the results were compared with the proton range-velocity curve of Blackett and Lees as a check upon the accuracy of the methods of measurement employed in this work. This plot is shown in Fig. 3. Examples of two typical proton collisions are shown in Fig. 2 (*c*) and (*d*). Fig. 2 (*c*) shows a proton being ejected out of the chamber as a result of a collision with an alpha-particle.

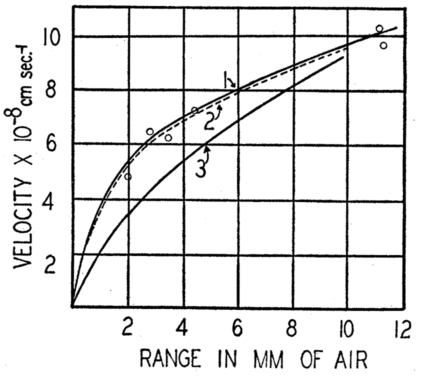

FIG. 3. Range-velocity curves for protons. Curve 1, protons in 50 percent H_2+50 percent air; curve 2, protons in air; curve 3, α-particles in air.

IV. Discussion and Conclusion

In the comparison and use of range-velocity curves in their present form, it is well to bear in mind the following points.

First, in obtaining the reduced air ranges of the recoil nuclei the assumption is made that the stopping power of the gas mixture is the same for the recoil atom as for the alpha-particle. This is, at best, a somewhat doubtful procedure, although for higher energies than those considered here this assumption is valid as has been shown by the theoretical work of Bethe and Bloch.

Second, the assumption is made that the variation of the stopping power with the range of the particle is the same for both the alpha-particle and the recoil atom. There is no more justification for this assumption than for the first.

Third, the possible small variations in the form of the range-velocity curve for a given type of atom in different gas mixtures containing different elements are not usually considered.

Finally, attention should be called to the spread of the experimental points from which any range-velocity curve is obtained. The straggling of the alpha-particles introduces a small error into the determination of the velocities of the recoil atoms. Also, the straggling of the recoil atoms, which according to Blackett's estimate may be as high as 15 percent, introduces an appreciable error into the determination of the ranges of the recoil atoms. These two combined effects of straggling, according to Eaton, probably account for the greater portion of the spread of the points on most range-velocity curves, the remaining errors being errors inherent in the methods of analysis used.

It is hardly wise to attempt to draw any conconclusions from the above two comparisons, that

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[9] C. J. Brasefield and E. C. Pollard, Phys. Rev. **50**, 296 (1936).

of sulphur with oxygen, and argon with neon. However, if any significance can be attached to them, it would seem that a satisfactory range-velocity relation must take into consideration the electronic configuration of the recoiling atom, at least in the low energy regions where we cannot consider the recoil particle to be a nucleus stripped of all outer electrons. If this be true, it should lead to a regularity in the forms of the range-velocity curves for the various atoms corresponding to their positions in the periodic table, as has been suggested by Feather. In any event, the simple empirical formula of Blackett and Lees has been shown definitely to be invalid, not only in this work but also in the earlier work of Feather and of Eaton.

In conclusion, it is a pleasure to thank Professor A. F. Kovarik for his constant advice and encouragement throughout the course of this work, Dr. F. N. D. Kurie for the camera castings and a blue-print of his latest design, and Dr. E. C. Pollard for much helpful advice.

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The Relative Abundance of the Isotopes in Mn, Cb, Pd, Pt, Ir, Rh and Co

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Using a new type of ion source, the abundances of the isotopes of Pd, Ir and Pt were measured and the atomic weights deduced from these values. The atomic weight of Ir was found to be quite different from the chemical value. The analysis of Mn and Cb confirmed the simple nature of these elements to a higher degree than known before. Evidence for the existence of Rh^{101} present to one part in 1300 of Rh^{103} was obtained. Likewise Co^{57}, present to one part in 600 of Co^{59}, was found.

Introduction

It is only recently that the isotopic analysis of the last few remaining elements has been determined. Dempster[1] has given some results on Pt, Ir, Rh and Pd but has made no quantitative measurements of abundances. A more thorough search for isotopes of rhodium is of particular interest in view of the fact that it emits β-rays of two periods (44 sec. and 3.9 min., half lives) on irradiation with slow neutrons.[2] Since a knowledge of the relative abundances of isotopes in many other elements is desirable in view of the intensive study now in vogue of nuclear disintegration by various bombarding particles, it seemed worth while to re-examine some of the elements which may be studied by our method.

Apparatus

The apparatus used was the 180° permanent magnet mass spectrograph described in a previous paper.[3] The arrangement was the same except for the ion source, which is shown in Fig. 1. The substance to be analyzed was vaporized from a furnace of tungsten foil W. The ions were produced in the molecular jet by collisions with electrons entering from the opposite side of G_2. G_2 is made of tantalum, the top and bottom being covered with platinum gauze. A small potential of about 1 volt was applied between G_2 and S_1 to draw the ions out. S_1 is a double slit, the two being placed 5 mm apart to prevent the high field between S_1 and S_2 from reaching into the ionization space and producing a velocity spread of the ion beam. The same system of focusing and deflecting the ion beam onto the entrance slit of the mass spectrograph was again applied. The electrons were emitted from a 7.5-mil tungsten filament F. A potential of 45 volts was applied between F and G_1 and a variable potential between G_1 and G_2. For the production of multiply charged ions the total electron accelerating voltage was about 300 volts. The furnace W was made of 1-mil tungsten or tantalum foil, folded into a V shape. The ends of the foil were spot welded to heavy nickel leads. R is a tantalum radiation

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[1] Dempster, Proc. Am. Phil. Soc. **75**, 755 (1935); Nature **136**, 909 (1935).

[2] Fermi *et al.*, Proc. Roy. Soc. **A146**, 483 (1934).

[3] Sampson and Bleakney, Phys. Rev. **50**, 456 (1936).

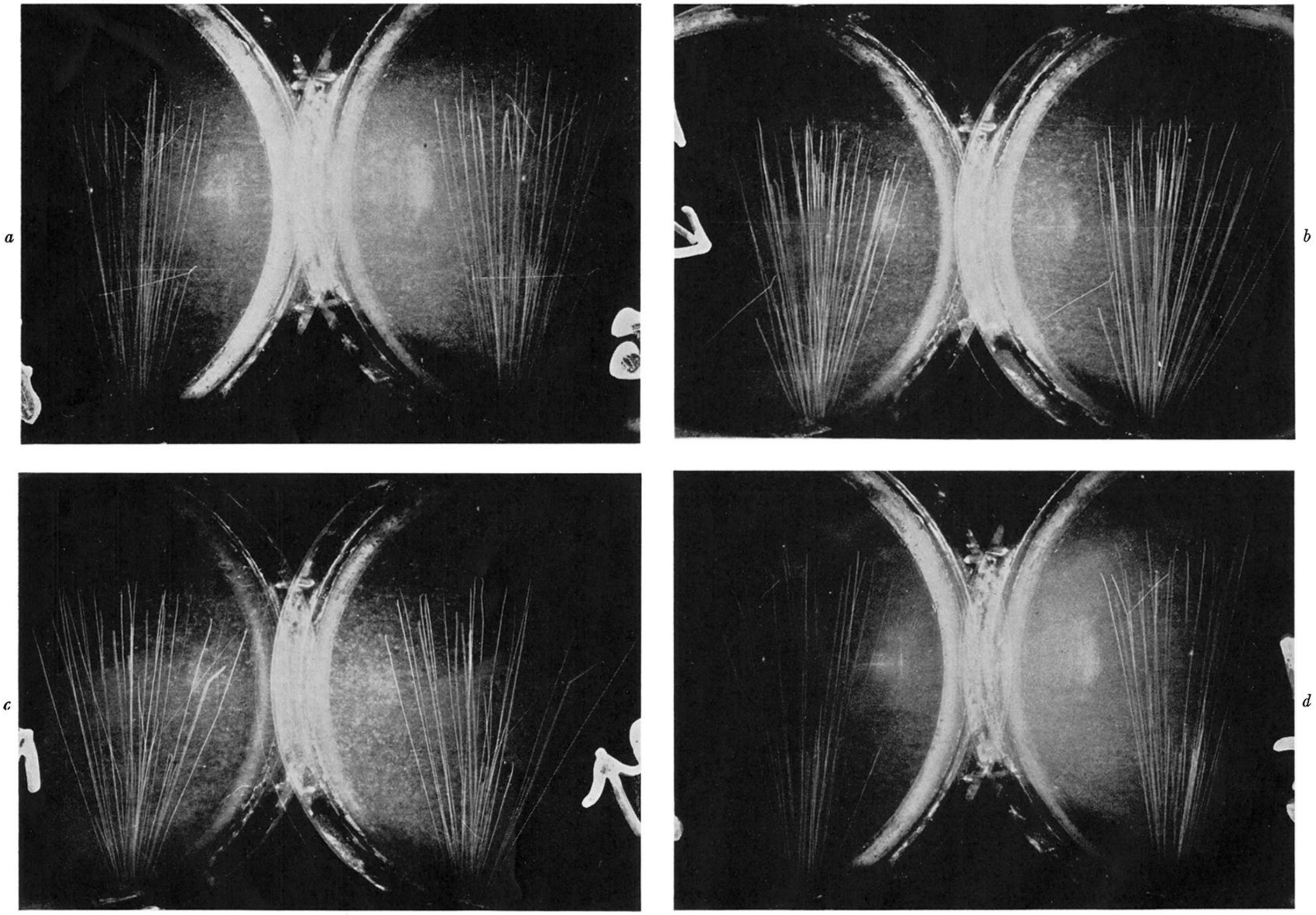

FIG. 2. *a*, *b*, Cloud chamber photographs of collisions between α-particles and sulphur nuclei. *c*, *d*, Typical photographs of collisions between α-particles and protons.