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Collisions of Alpha-Particles with Carbon Nuclei*

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More than 750,000 thorium (C+C′) alpha-particle cloud tracks have been photographed with a stereoscopic camera using a cloud chamber filled in one series with methyl-chloride and helium, and in another with acetylene and helium. For each series a range-velocity curve for carbon has been constructed by plotting the measured ranges, reduced to standard air values, against the calculated velocities for a total of 55 selected alpha-particle-carbon collisions. These curves are used for testing the validity of the method of reducing the ranges of heavy recoil nuclei in any gas to standard air values. Partial validity of the method has been observed in the present instance. An empirical relationship between the total mean straggling (in range), the atomic numbers of the atoms comprising the absorbing medium, and the atomic number of the recoil nucleus is presented. A brief analysis of the effectiveness of certain errors on the range-velocity results is given.

INTRODUCTION

IN 1923 a method of analysis of forked cloud tracks was published by Blackett[1] who calculated range and velocity values for recoil oxygen, hydrogen, and helium nuclei. The work was considerably extended and refined by Blackett and Lees[2] who added relations for nitrogen and argon to those already mentioned. Feather[3] has obtained range and velocity values for fluorine nuclei from a cloud-chamber study of the scattering of alpha-particles in carbon tetrafluoride. He investigated at the same time the cloud tracks of eight recoil nuclei supposed to be carbon. The range-velocity relation for neon has been investigated by Eaton,[4] for sulphur by Anthony[5] and for deuterium and neon by McCarthy.[6]

The current practice in the presentation of the above information has been to reduce all range measurements to the values they would have had in dry air at 15°C and at normal atmospheric pressure, regardless of the nature of the gas in which the measurements have been made. The classical method of obtaining this reduction depends upon assumptions to which objection may be made, and has been used only because no other satisfactory method of reducing the results to this standard has been presented. One of the objects—important in itself—of the present paper is to test the validity of this procedure. Such an investigation must at present be purely

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[1] P. M. S. Blackett, Proc. Roy. Soc. **A103**, 62–78 (1923).
[2] P. M. S. Blackett and D. S. Lees, Proc. Roy. Soc. **A134**, 658–671 (1932).
[3] N. Feather, Proc. Roy. Soc. **A141**, 194–209 (1933).
[4] W. W. Eaton, Phys. Rev. **48**, 921–928 (1935).
[5] R. L. Anthony, Phys. Rev. **50**, 726–732 (1936).
[6] J. T. McCarthy, Phys. Rev. **53**, 30–34 (1938).

experimental in nature, since the dependence of the effective charge of a moving atomic nucleus on its kinetic energy cannot be obtained without experiment.

Among the lighter elements carbon has received but little attention, presumably because there appears to be small chance of observing any disintegration effects in the cloud chamber. Hence material for a range-velocity curve for carbon is still required. In part for this reason, but to a greater extent because carbon represents the best available material for accurate tests on the classical method of range reduction, it was chosen for the present work.

The range-velocity curves which have been obtained so far can be divided into two groups: one for which the method of reduction of the ranges of heavy recoil nuclei to standard air conditions is known to be reasonably valid, and the other for which the method contains an unproved assumption. The first group includes nitrogen and oxygen, as either alone approximates air in composition. Helium is included, as the reduction to standard air conditions is made by measuring the stopping power of the gas for alpha-particles. Hydrogen and deuterium are also included since experimental measurements[7] indicate that the relative atomic stopping power of a gas is the same for protons and deuterons as for alpha-particles. The second group contains fluorine, neon, argon, sulfur, and the elements studied in the present investigation, carbon and chlorine.

The method of reduction of a set of forked tracks to standard air conditions can be described as a "demagnification" of the recombination photograph of the tracks to the size where undeviated alpha-particle tracks have the length they would have had in standard air, suitable adjustments being made, if necessary, for variation in the demagnification factor (relative stopping power) with the range of the alpha-particles. The objection to this procedure is that there is no apparent reason to believe that the demagnification factor is the same for a heavy recoil nucleus as for an alpha-particle when a transfer from one gas to another is involved in standardizing the results. To provide an answer to this objection, data on the range and velocity of carbon recoil nuclei were obtained from two distinctly different gas mixtures and are compared in this paper.

Theory

One of the outstanding advantages in making a cloud chamber analysis of the range and velocity of atomic nuclei is that the physical laws involved in the calculations, namely the conservation of energy and of linear momentum, are most fundamental and well established.[8] It is assumed that all of the forked tracks studied in the present paper represent nuclear collisions which are elastic* in nature. Hence Eqs. (1), (2) and (3), which follow from the laws of conservation of energy and of linear momentum, are employed in the present analysis to obtain values of the initial velocities of recoil nuclei:

$$\frac{m}{M}=\frac{\sin \Phi}{\sin (2\theta+\Phi)}, \tag{1}$$

$$u=\frac{\sin (2\theta+\Phi)}{\sin \theta}v, \tag{2}$$

$$u=\frac{2V\cos \theta}{\{1+m/M\}}. \tag{3}$$

Here M and m represent the masses of the alpha-particle and colliding nucleus, respectively. V represents the velocity of the alpha-particle just before collision, while v and u represent the respective velocities of alpha-particle and nucleus just after collision. Φ is the angle of deflection of the alpha-particle, while θ represents the angle made by the trajectory of the struck nucleus and the original, or forward, direction of the incident alpha-particle. For convenience, Φ and θ are both taken to be positive when they lie on opposite sides of the direction of the incident alpha-particle.

Experimental Procedure

The cloud chamber used in the present study is of the conventional sylphon type, following

[7] C. Gerthsen, Ann. d. Physik [5] **5**, 657–669 (1930).

[8] F. Joliot, Comptes rendus **192**, 1105–1107 (1931).

* Calculation of distances of closest approach in the collisions investigated here show that only Coulomb field scattering was effective.

closely the design published by Dahl, Hafstad and Tuve.[9] It has the outstanding advantages when used for measurements on the cloud tracks of recoil nuclei of having a large diameter and of being easily adjusted for work over a wide range of pressures. The stereoscopic camera used in conjunction with the cloud chamber has previously been described.[10]

For the present work, the cloud chamber was altered in several respects from its original form. Two aluminum wedge-shaped latches which automatically lock the cloud chamber piston at the lowest point of its expansion stroke have been installed, as well as a control system regulating the air pressure producing the cloud chamber expansion, so that all expansions were of the same magnitude. Cloud track illumination was provided by two banks of spotlights, each containing eight fifty-candlepower tungsten filament lamps arranged in such a way that light was scattered uniformly by all parts of each track to each mirror into the stereoscopic camera.

A wedge-shaped button of polished silicon steel was used as an alpha-particle source. Powdered material containing thorium was placed on a conducting plane in a closed container. Above this the wedge source was placed and maintained at a negative potential of about 300 volts relative to the plane. Due to the geometry of the wedge and plane the electric field has a maximum gradient along the sharp edge of the wedge, so that the greatest density of recoil thorium A ions is found in this region, effectively forming a strong line source of Th $(C+C')$ alpha-particles.

Cloud tracks were photographed on Agfa ultra-speed panchromatic film which is efficient under tungsten lamp illumination. D-76 fine-grain developer was used. In recombining track images, the film was replaced in the stereoscopic camera in the same position it had when the cloud chamber was photographed, and the real images of the stereoscopic pair of negatives were reprojected onto a screen placed below a thickness of glass equivalent to that in the top of the cloud chamber. If the film has been replaced correctly, the recombined images of a given track will have the same dimensions on the screen that the original track had in the cloud chamber. Forked tracks which are coplanar can be recombined in this manner by suitable orientation of the combining screen, which has one linear and two angular adjustments.

Reprojection recombinations were made directly onto the sensitive print paper by inserting a ruby light filter in the reprojection system, a flicker method of alternating the images on the screen being used. The ruby light filter was simply withdrawn when it was desired to make a reprojection print. In general the two components of a given stereoscopic combination were registered on separate prints, Eastman Kodaline extreme contrast paper being used.

Survey of Errors

The main factors which influenced the accuracy of the experimental results are as follows.

1. Limits of accuracy imposed by the apparatus

A study of the geometry of the alpha-particle source and of the characteristics of the cloud-chamber expansion stroke indicated that, due to an induced straggling effect, the measurement of the relative stopping power has been indefinite to the extent of about ± 6 percent, in addition to statistical straggling effects, in the work done by Anthony and McCarthy. It has also been estimated that corrective alterations have reduced this extra straggling effect to about ± 1 percent in the present work.

While obtaining a precise measurement of the relative stopping power is ideal in the type of analysis presented here, it is worthy of note that even an approximate measurement of this quantity yields relatively accurate results on a range-velocity curve. In support of this statement, it is found by inspection that practically all the alpha-particle spurs involved in the analysis have standard air ranges which are between 1.0 and 3.0 cm in length. Graphical differentiation of the standard range-velocity curve for alpha-particles shows that the ratio of the fractional errors in measured values of alpha-particle velocity U and range R, that is:

$$f_U/f_R = (R/U)(dU/dR) \tag{4}$$

[9] O. Dahl, L. R. Hafstad and M. A. Tuve, Rev. Sci. Inst. **4**, 373–378 (1933).

[10] F. N. D. Kurie, Rev. Sci. Inst. **3**, 655–667 (1932).

is nearly constant for this region of range values, having the value 0.40 ± 0.06. It is understood here that either U or R is a measured value from which the other is obtained by reference to the standard range-velocity curve.

If we suppose that the measured value of the relative stopping power is N (percent) too large, due to induced range-straggling, then the measured standard air length r of the track caused by the heavy recoil nucleus will also be N too large. By Eq. (4), the recoil velocity of the alpha-particle involved in the collision will be 0.4 N too large due to this cause, since its standard air range will be N too large. As u is a linear function of v or V by Eq. (2) or (3), it will be 0.4 N too large due to the induced range-straggling error, as U can represent either velocity v or V. Hence the range and velocity errors for the recoil nucleus tend to cancel each other to an important degree in the method of analysis employed here.

As errors in the measurement of the relative stopping power follow a Gaussian distribution function, the probability of making a 6 percent error in the work of Anthony or of McCarthy would be small. These considerations indicate that the range-velocity curves presented by these workers can be considered to be reasonably reliable, insofar as the error due to induced straggling is concerned.

To study the accuracy of the stereoscopic camera in photography and reprojection, a flat white card on which a set of concentric circles and radial lines were drawn was photographed in positions representative of all possible forked tracks, and the recombination prints were compared with the original card. From these it was found that:

(a) The images registered on the print paper were 0.8 percent smaller than the original object, probably due in part to shrinkage of the photographic emulsions involved.

(b) The fidelity of reprojection of the pattern was greatly improved by storing the exposed and developed film prior to reprojection in rolls with the emulsion outside rather than inside.

(c) An impartial assignment of the relative weight of pairs of prints in various orientations was obtained from the ratio of the mean error in length and angle measurements in the corresponding orientations in the test series.

2. Limits of accuracy imposed by observational errors

In order to estimate the magnitudes of this type of error, two completely separate analyses were carried out on a number of the collision tracks involving chlorine. Comparison of these two analyses yielded the following information:

Observable	Φ	S	r
Mean variation in measurement, percent	± 0.8	± 1.0	± 3.0

where S represents the relative stopping power of the cloud chamber gas. Recoil spur length r was measured by an eyepiece micrometer (fixed scale type). The average fractional error in measuring r for chlorine nuclei will be greater than for carbon, since the latter produces longer recoil spurs on the average.

3. Limits of accuracy imposed by indefiniteness in auxiliary data used

As no experimental information on the variation of the relative atomic stopping power of chlorine for alpha-particles is available, this relation was interpolated from Mano's[11] calculations. The magnitude and variation of the stopping power of carbon was similarly obtained, and was found to agree reasonably well with the experimental relation published by Livingston and Bethe,[12] thus providing a check on the validity of the interpolation method.

With this information a gas and vapor mixture, containing in volume percent, 52 CH_3Cl, 26 He, 16 C_2H_5OH, 6 H_2O, was employed, the relative atomic stopping power of which should vary with velocity by less than 2 percent over the range of alpha-particle velocities used. In agreement with this calculation, it was found that the stopping power of this mixture had the same value when calculated from measured values of the ranges of Th C and Th C′ alpha-particle groups in the gas. Hence no correction for variation in stopping power of the gas with alpha-particle velocity was felt to be necessary.

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[11] G. Mano, J. de phys. et rad. [7] **5**, 628–634 (1934).
[12] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 246–390 (1937).

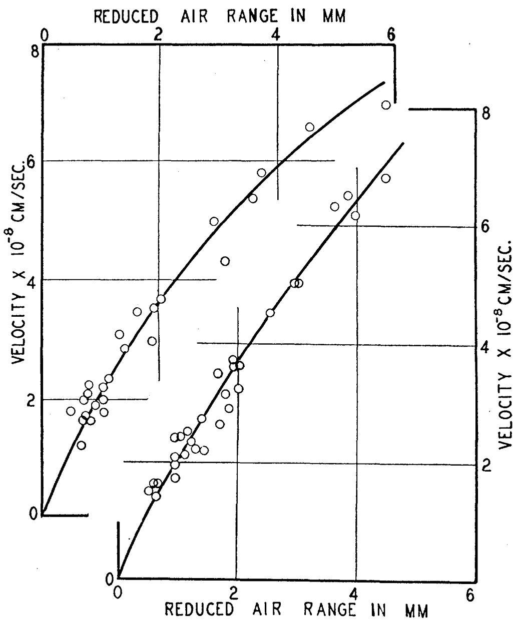

FIG. 1. Range-velocity curve for carbon recoil atoms in methyl-chloride and helium (upper curve) and in acetylene and helium (lower curve).

In the work with acetylene the following gas mixture was used: 49 C_2H_2, 40 He, 8 C_2H_5OH, 3 H_2O. It was necessary in this case to make correction for the variation in stopping power with velocity. This was calculated from experimental data[12,13] and checked against the variation in stopping power values as found from measuring the ranges of the Th C and Th C′ alpha-particle groups in the gas. These were found to agree reasonably well, and hence an average value of the two variations was employed.

Results

The cloud tracks of approximately 750,000 alpha-particles have been photographed in about 12,000 exposures. Of these, approximately two-thirds are caused by the long-range Th C′ alpha-particles, the remainder being due to Th C. In Fig. 1 are shown range-velocity curves for carbon from methyl-chloride and from acetylene, the experimental points of which have been obtained by the general method previously outlined.

The relatively few forked tracks used in constructing these curves have been selected from a much larger number available, the criterion for selection being that all or most parts of a collision fork must be clearly visible. In the work with methyl-chloride a considerably larger number of experimental points for chlorine than for carbon were obtained. This is to be expected when the alpha-particles do not approach nearer to the nucleus than distances at which only Coulomb fields of force are effective, for then the collision cross section for chlorine will be $\{17/6\}^2 \doteq 8$ times as large as that for carbon nuclei.

However, as a much larger fraction of the kinetic energy of an alpha-particle can be transferred to a carbon nucleus than to one of chlorine, a larger fraction of the collisions with carbon will produce measurable spurs, than in the case of chlorine, as was found to be the case in this work.

Discussion and Conclusions

The degree of equivalence between the range-velocity curves for recoil carbon nuclei in methyl-chloride-helium and acetylene-helium gas mixtures is seen by comparison of the curves in Fig. 1. There appears to be a definite coincidence in the location of the two curves only for standard air ranges of less than 3 mm, beyond which point there is an increasing divergence. No conclusion of general applicability can be drawn from this divergence concerning the degree of validity of the method used in reducing ranges of heavy recoil nuclei to standard air values from measurements in gases other than air. However, in the case of the carbon-containing gases used here, and probably in others, the use of the current method of applying range-velocity data obtained in one gas mixture to collisions in another gas will induce a characteristic error when high energy recoil nuclei are being studied.

It was found that the range-velocity curves for carbon, obtained from those already published for nitrogen and for alpha-particles by use of Blackett and Lees[2] relation $r \propto mZ^{-1/3}f(u)$, where m is the mass of the recoil nucleus and Z its atomic number, disagreed both in shape and in placement with the curves presented in this paper. Feather's[3] experimental curve for recoil nuclei believed to be carbon, very nearly coincides with the upper part of Fig. 1, falling between the two curves for carbon.

[13] R. W. Gurney, Proc. Roy. Soc. **A107**, 340–349 (1925).

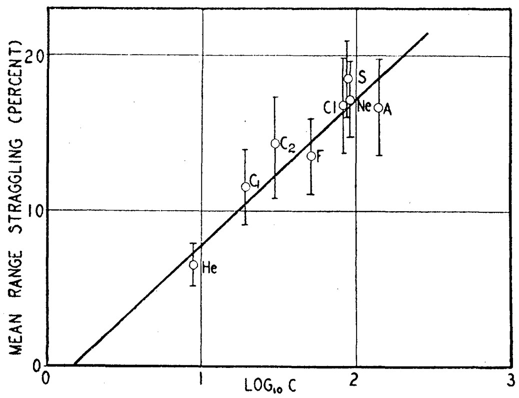

FIG. 2. Empirical relation between atomic numbers of recoil atom and absorbing medium, and the average range straggling of experimental points.

It has been found that the fractional error involved in the measurement of cloud track lengths is of the order of ± 3 percent for short tracks, and the probable error in the measurement of the recoil velocity u is approximately ± 2 percent. Yet measurement shows that the average total range-straggling of experimental points from the experimental curve has a value of more than 10 percent for each of the range-velocity curves of heavy recoil nuclei for which a sufficient number of experimental points have been obtained with which to make an analysis.

It is customary to attribute the additional range-straggling to statistical variations in the interaction of the recoil nucleus and its remaining orbital electrons with the atoms of the medium through which the nucleus passes. If the interaction is entirely between orbital electrons, the degree of straggling should be a function of the product of the effective nuclear charge of the recoil atom (equal to the number of removed electrons) with the effective atomic number* B of the absorbing atoms. If, however, there is a considerable probability of slight direct interactions of the recoil nucleus with nuclei of the absorbing medium, the amount of straggling would be a function of the product (C) of the atomic number of the recoil atom with B.

* If the medium is composed of atoms having atomic numbers $A_1, A_2, \cdots A_n$, and relative abundances $f_1, f_2, \cdots f_n$, respectively, the effective atomic number of the atoms in the medium is taken here to be

$$B = \sum_{s=1}^{s=n} A_s f_s \quad \text{where} \quad \sum_{s=1}^{s=n} f_s = 1.$$

In order to investigate the possibilities of such relations, the average of the total fractional range-straggling for all ranges having standard air values between 0.5 and 2.0 mm was measured for each of the published range-velocity curves for He, F, Ne, S, A, Cl, and the two curves for carbon presented in this paper. Equivalent range sections of each range-velocity curve were chosen so that the average number of absorbing atoms encountered by a recoil nucleus would be the same for all nuclei. The section of the curves selected was that which was most richly populated with experimental points.

It proved impossible with the very rough information available to indicate what the predominating cause of straggling among the heavy recoil nuclei might be. However, an interesting empirical relation between the product C and the total range straggling was obtained and is shown in Fig. 2. It indicates that the practice of mixing a heavy gas with a light one merely to increase the relative stopping power of the latter[6] is a less desirable condition than using the lighter gas at a pressure sufficiently great to give a relative stopping power equivalent to that of the mixture.

In addition to many examples of secondary branches and deflections in the tracks of recoil nuclei published by other authors, notably those of Joliot,[14] a series of such branched tracks has been observed by the writer. These indicate that a considerable nuclear collision cross section exists for heavy recoil atomic nuclei in a medium containing heavy atomic nuclei. Estimation of the expected frequency of slight collisions between such heavy nuclei, from observation of the distribution of points on range-velocity curves and also from the theory of Coulomb field scattering, indicates that such encounters occur with a frequency such that they cannot be neglected in an explanation of the large straggling effect noted above.

It is a pleasure for the writer to thank Professor A. F. Kovarik for his continued advice and encouragement throughout the course of this work. He wishes also to acknowledge the valuable assistance given by Mr. W. L. Davidson, Jr., in checking calculations.

[14] F. Joliot, J. de phys. et rad. [7] 5, 219–225 (1934).