

The Range of Alpha-Particles in Water

HERVASIO G. DE CARVALHO* AND HERMAN YAGODA

*National Institute of Arthritis and Metabolic Diseases of the National Institute of Health, Public Health Service,
Federal Security Agency, Bethesda, Maryland*

(Received May 16, 1952)

A photographic method is described for measuring the ranges of alpha-particles in liquids whose properties are compatible with emulsion sensitivity utilizing a surface deposit of radiocolloid aggregates as point sources of alpha-radiation. The method has been applied to both water of normal isotopic composition and to heavy water containing 97 percent deuterium oxide. Using polonium radiocolloids as a source of 5.3-Mev alpha-particles ranges of 38.1 ± 0.5 and 38.0 ± 0.5 microns were measured in the respective liquids. By conducting the exposure at temperatures below the freezing point the method is also applicable to certain solid media. The ranges of RaF alpha-particles in normal and heavy ice were found to be 41.6 ± 0.5 and 41.5 ± 0.5 microns. The integral molecular stopping power of water is computed to be 1.56 ± 0.02 for an alpha-particle energy of 5.3 Mev. Similar measurements with radium sulfate radiocolloids indicates a molecular stopping power of 1.56 ± 0.02 for the alpha-particles from RaC', as compared with a computed value of 1.54 ± 0.02 . Larger estimates for this constant may originate from water-air interface effects inherent in experiments with an external detector.

I. INTRODUCTION

THE stopping power of water for alpha-particles is an important constant in the evaluation of their radiochemical action in aqueous solutions. Since living biological tissues are composed to a large extent of water the range of alpha-particles in this medium is of fundamental importance in the quantitative interpretation of the biological action of densely ionizing radiations, particularly with reference to the number of primary ionizations produced per micron of path, and in the determination of the rate of energy dissipation. The experimental measurements of the range of 5.30-Mev and 7.68-Mev alpha-particles in water employing essentially monoenergetic sources of RaF and RaC', respectively, are few in number, and the experimental values are in poor agreement with both the empirical stopping power law of Bragg-Kleeman¹ and that derived from modern stopping power theory as elaborated by Livingston and Bethe,² Cürer,³ and Webb.⁴ The early measurements were made chiefly with the aid of scintillation screens as detectors for the residual range of the alpha-particles after traversing paths of known length in water, and are therefore of low accuracy, because the microscopic detection of scintillations produced by low energy alpha-particles is subject to a large subjective error. The tendency has been, therefore, to rely on a computed value of 71 microns for the range of RaC' alpha-particles in tissue of unit density in radiobiological studies as those described by Lea.⁵

The first investigation of the range of alpha-radiations in water was reported by Michl⁶ using thin wires

coated with polonium placed in contact with photographic plates covered with water. From the geometry he derived a total range of 32 microns from the maximum width of the shadow of photographic blackening. In the course of these investigations Michl observed that "poloniumteilchen" became detached from the source and recorded individual black circular areas varying in radius between 28 to 38 microns. This phenomenon, now understood as radiocolloid aggregation, provided an alternate estimate of the range in water. Michl, however, selected 32 microns on the basis of the more reproducible shadow blackenings. Michl's methods were fundamentally sound, but the emulsions available at that early period were not of adequate sensitivity, particularly when swollen with water, for the microscopic recognition of the short tracks defining the entire path of the rays through the liquid. The few long-range tracks noted were possibly recorded shortly before development and hence escaped fading of the latent image. As seen in Sec. V his upper limit of 38 microns is identical with results of the present study.

An independent set of measurements for the range of RaC' alpha-particles in water has been reported by Philipp.⁷ Using scintillation screens as detectors of the residual range of the particles he measured a range of 59.5 microns in water, and one of 67 microns in water vapor. The measurement in liquid water is low compared with estimates of 77 microns deduced from the Bragg-Kleeman stopping power relationship, or the more reliable value of 68 microns computed with the aid of electronic stopping theory. The investigations of Rutherford⁸ on the sensitivity of the scintillation method show that the flash of light is discernible microscopically when the alpha-particle has a residual range in air of 3.5 mm and that the limit of visibility is reached at a residual air range of 0.2 mm. These limits would tend

* Public Health Service Research Fellow of the National Institute of Arthritis and Metabolic Diseases. Present address: Laboratorio de Producao Mineral, Rio de Janeiro, Brazil.

¹ W. H. Bragg and R. Kleeman, *Phil. Mag.* (6), **10**, 318 (1905).
² M. S. Livingston and H. A. Bethe, *Revs. Modern Phys.* **9**, 263 (1937).

³ P. Cürer, *Compt. rend.* **223**, 1121 (1946).

⁴ J. H. Webb, *Phys. Rev.* **74**, 511 (1948).

⁵ D. E. Lea, *Actions of Radiations on Living Cells* (Cambridge University Press, Cambridge, 1947) pp. 17 and 351.

⁶ W. Michl, *Sitz. Akad. Wiss. Wien* **123**, 1965 (1914).

⁷ K. Philipp, *Z. Physik* **17**, 23 (1923).

⁸ Rutherford, Chadwick, and Ellis, *Radiations from Radioactive Substances* (Cambridge University Press, Cambridge, 1930), p. 547.

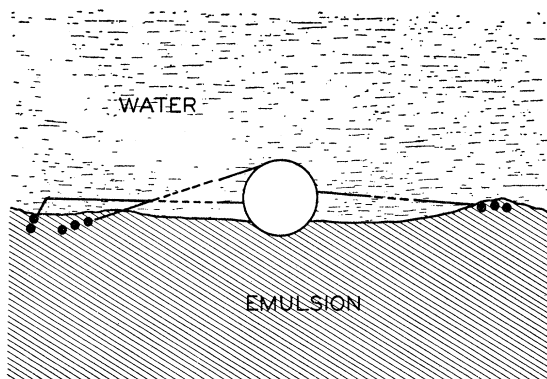


FIG. 1. Schematic representation of liquid range measurements with radiocolloid sources.

to reduce the measured range in water by about 2.3 to 0.13 microns, depending on the acuity of the observer.

The stopping power of liquid water has more recently been investigated by Appleyard⁹ by measuring with a Geiger counter the effective thickness of a deep source of polonium dispersed in water acidified with hydrochloric acid. After application of geometric and counter-window corrections his measurements yield a range of 33.2 microns, and he concludes that the stopping power of liquid water is anomalous as compared with the water vapor measurements of Philipp.

The stopping power of water is also an important factor in correlating range measurements of ionizing particles in nuclear emulsions which differ in moisture content. This subject has been investigated in detail by Wilkins,¹⁰ who concludes that the value measured by Appleyard leads to marked inconsistencies in the evaluation of the net stopping power of water-loaded emulsions. Wilkins' work indicates that ranges of 38 and 69 microns for RaF and RaC' alpha-particles, respectively, would be in best conformity with the more recent evaluation of atomic stopping numbers for hydrogen and oxygen.

A photographic method for measuring the range of alpha-particles in water utilizing radiocolloid aggregates, described briefly by one of us,¹¹ gave preliminary estimates of 39 and 67 microns for the ranges of RaF and RaC' alpha-particles in water. In view of the marked disparity between different experimental methods of liquid range measurement it is worth while to describe details of the technique and to attempt an evaluation of the factors which contribute to the spread in the values for the stopping power of water.

II. METHOD OF RANGE MEASUREMENT

The microscopic examination of nuclear type emulsions shows that the tracks of slow alpha-particles can

⁹ R. K. Appleyard, *Nature* **163**, 527 (1949); *Proc. Cambridge Phil. Soc.* **47**, part 2, 443 (1951).

¹⁰ J. J. Wilkins, Atomic Energy Research Establishment Report AERE 664 (1951) (unpublished).

¹¹ H. G. de Carvalho, *Phys. Rev.* **78**, 330 (1950).

be discriminated from the background fog when the recorded range exceeds one micron. This suggested that under proper experimental conditions it should be possible to measure the range of alpha-particles in liquids with an accuracy of about 2 percent provided adequate sensitivity could be maintained during contact of the emulsion with the liquid. In our exploratory work efforts were made to make the emulsion surface water-repellant by application of thin films of hydrophobic materials such as zinc stearate and petroleum jelly. This approach was not successful, as films impervious to water caused absorption of the greater part of the alpha-particle energy. During these experiments it was observed that occasionally a radiocolloid aggregate would separate from the polonium source and float onto the emulsion surface, and the tracks originating from it could be discerned in the wet emulsion even after traversing the greater part of their range through water. Further exploration of the method using specially prepared dispersions of polonium and radium sulfate as point sources showed that the method gave consistent results, provided the liquid wetted the emulsion, and the radiocolloids remained fixed in position during the duration of the exposure.

The principle of the method is shown diagrammatically in Fig. 1 in which a radiocolloid aggregate (size greatly exaggerated, true dimension being less than 0.1 micron) is adsorbed on an emulsion surface covered with a thick layer of liquid. Alpha-particles directed normal to the plane of the emulsion and those ejected at small angles to its produce a black core of developed silver whose diffuse diameter varies with the activity of the radiocolloid, the energy of associated alpha-particles and the duration of the exposure. The center of this core defines the position of the point source. Particles ejected at near glancing incidence expend their energy almost entirely in the liquid and a small number of suitably oriented particles will define the range by

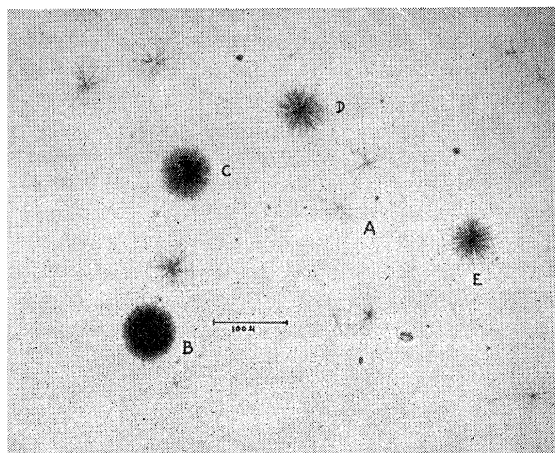


FIG. 2. Low power field of polonium radiocolloid images recorded on emulsion exposed below water.

rendering several grains developable before coming to rest in the emulsion. In so far as the radiocolloids are almost dimensionless, the method is abetted by the following considerations:

1. The emulsion surface is not a true mathematical plane, but contains an appreciable number of microscopic hills and valleys. Radiocolloids deposited on high points, such as embedded dust particles, are in a favored geometrical position for the recording of the range defining tracks.

2. Alpha-particles close to the end of their range frequently exhibit large angle scattering, so that rays ejected at near glancing incidence have an appreciable chance of being projected into the recording medium before coming to rest.

3. Because of the minute size of the radiocolloids corrections for internal absorption and geometry are negligibly small. In particular, the end point tracks are recorded at very small angles with the plane of the recording medium, and hence their horizontal projections as measured in the dry gelatin is a close approximation to their original lengths in the water-swollen emulsion.

In plates where the fog background is kept at a low level by suitable development, as little as 2 or 3 grains suffice to indicate the termination point provided they reside in an axial direction with the center of the radiocolloid. A very small part of the alpha-particle energy is expended in the activation of the end point silver halide grains. This does not introduce appreciable error in the measurement, because the emulsion is heavily loaded with water and the recorded range is rarely more than 2 percent of the entire trajectory. The distance between the last grain recorded and the center of the radiocolloid can therefore be taken as a measure of the range in the liquid. When the point sources emit several types of alpha-particles originating from radioactive series decay, such as radium, the end point tracks define the range of the most energetic member, RaC'.

A low power view⁸ of the processed plate Fig. 2, shows a random distribution of radiocolloid images varying in blackening in proportion to the particle size of the colloids. Images produced by particles of low activity, Fig. 2, *A*, are not suitable for measurement, owing to an inadequate number of end point tracks. Images of very high activity, *B*, are not suitable for precise measurements because it is difficult to establish the exact center of the core by microscopic inspection. Range measurements were restricted to radiocolloids of intermediate size, such as, for example, *C*, *D*, and *E*. To avoid confusion of the end point tracks the concentration of the radiocolloids should be kept low, and in general measurements were taken from plates with a population about one-third that exhibited by Fig. 2. Occasionally, the radiocolloid image is produced by two closely adsorbed particles. These are readily noted by the ellipticity of the core and are not selected for measurement.

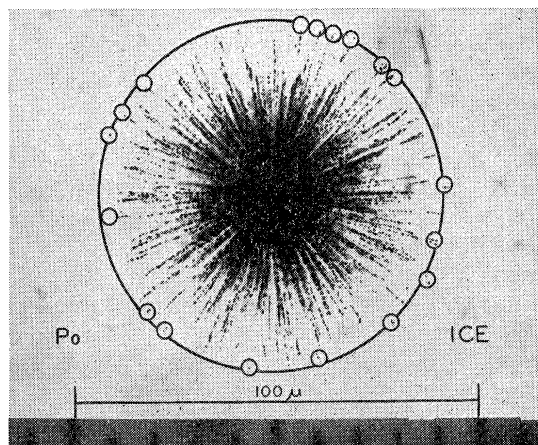


FIG. 3. Photomicrograph of a polonium radiocolloid recorded in an emulsion exposed in water frozen at -5°C . Typical end point tracks are enriched.

The average distance between the center of the radiocolloid and the periphery grains defining the range was measured with a fluorite oil immersion objective of 1.30 N.A. and a filar micrometer ocular standardized by a stage micrometer. Radiocolloid images were selected for measurement which contained at least 10 recognizable end point tracks and the average of the readings taken as a measure of the mean range for that particular point source. The center of the radiocolloid can be judged visually when the blackening of the core is not excessive. Units recording a large number of end point tracks are also of high total activity and visual judgment of the center is subject to greater error. This can be minimized by making a photomicrograph of the unit and determining the exact center on an enlargement print by drawing radial lines through the grains of the tracks, and taking the average point of intersection as the center. This method, while somewhat laborious, increases the precision because it permits a measurement of the average diameter for the zone of endpoint-tracks. A typical photomicrograph of one of the diametric measurements is exhibited in Fig. 3. In general, the photomicrographic and the visual measurements were in good agreement as noted in the tabulation:

Radiocolloid	Polonium	Radium
Photomicrographic range	$38.1 \pm 0.1 \mu$	$67.0 \pm 0.1 \mu$
Visual range	$38.1 \pm 0.5 \mu$	$67.2 \pm 0.5 \mu$

The distribution in range values for water of normal isotopic composition and a sample containing 97 percent D₂O is shown in Fig. 4.

In order to ascertain the reliability of this method of range determination a macroexposure simulating the radiocolloid method was made which would yield the range of polonium alpha-particles in air. The tip of a fine-pointed steel needle was coated with polonium electrolytically and supported about 0.3 mm above the surface of a dry Ilford C2 emulsion. The exposure of

24 hours duration was conducted in an enclosed desiccator charged with anhydrous calcium chloride at a temperature of $23 \pm 0.1^\circ\text{C}$ and 768.5 mm of Hg pressure. Microscopic examination of the developed plate revealed that the tracks of minimum discernibility resided at 37.8 mm distance from the tip of the needle. This distance, corrected for residual end point range (equivalent to 0.09 air-cm) and converted to standard conditions of 15°C and 760-mm pressure, corresponds to an air range of 3.82 ± 0.02 cm in practically perfect accord with the best ionization chamber range measurements.

This concordance does not imply a similar degree of accuracy in the range measurements of liquids, as the end point-tracks in the wet emulsion are not as clearly defined. Also the errors of microscopic measurement in a length of 38 microns are about twice as large as in the macroscopic measurement of the 38-mm air range.

III. PREPARATION OF RADIOCOLLOIDS AND DEVELOPMENT

For the preparation of radium radiocolloids a solution composed of 10 micrograms of radium and 2 mg of barium chloride per liter was saturated with sodium sulfate crystals. After aging for several days, the solution was diluted about 100-fold. No visible precipitate or turbidity forms at this concentration, but as indicated by photographic exposure, the bulk of the radium activity is concentrated in colloiddally dispersed particles, presumably a mixture of barium and radium sulfates. It is important that the preparation contain a minimum of ionically dispersed radium, as the decay of isolated atoms gives rise to the well-known alpha-stars, and a large population of these structures interferes with the recognition of the short end point-tracks. Aging of the stock dispersion increases the ratio of radiocolloids to stars.

The polonium chloride employed in these experiments

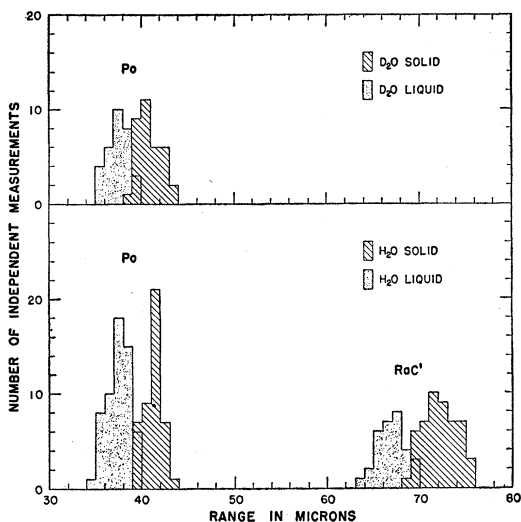


FIG. 4. Histogram of radiocolloid range measurements in water at 5°C and ice at -5°C .

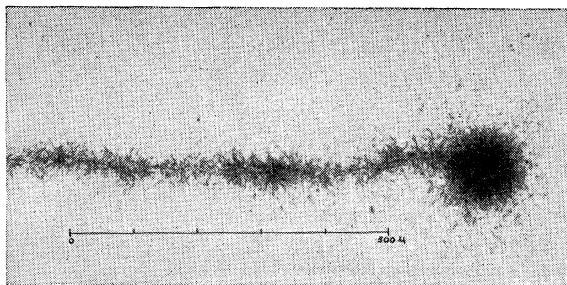


FIG. 5. Path of a radium sulfate radiocolloid recorded on surface of emulsion. The colloidal particle moved a distance of 3 mm before becoming permanently fixed to the gelatin. The test plate contained several similar tracks, and it is possible that the linear movement originated from vibrations initiated by the starting and stopping of the refrigeration mechanism. The lateral small angle scatter may represent the Brownian movement of the colloidal particle.

was a slightly acid solution having an activity of roughly 0.1 microcurie per ml at the time of the investigations. It was prepared about 3 years prior to the tests and the bulk of the activity was found to be concentrated in radiocolloids. We, therefore, have no recipe to offer, but it would appear that in starting with a fresh solution the desired degree of aggregation could be accelerated by rendering the solution faintly ammoniacal.

The slides were prepared by spreading several drops of the dispersions over the center area of 1×3 in. Eastman NTA plates (devoid of a gelatin T-coat). After several minutes the plates were rinsed with distilled water to remove excess electrolytes (Na_2SO_4 , HCl) and placed in a paraffined paper box containing a layer of water about 5 mm deep. Most of the colloidal particles are strongly adsorbed to the gelatin surface, and even persist in the gelatin after photographic processing. This can be demonstrated by making an autoradiograph of the processed slide. We have, however, observed occasional instances where some of the particles migrate slowly over the surface of the emulsion for several millimeters before coming to rest. A striking example of this unusual behavior is shown in Fig. 5. The path of dislocation is clearly delineated by recorded alpha-particle tracks and the sinuous, monopole-like trajectory is suggestive of the Brownian movement of a colloidal particle.

In order to avoid dislocation of the particles during exposure and to minimize fading of the latent image the preparations were kept in a refrigerator at a temperature of $5 \pm 1^\circ\text{C}$. For measurements in the solid state, the slide was prepared in a similar fashion, leaving about 1 mm of the liquid on the surface, and the tray was left inside the freezing compartment (about -5°C) for the duration of the exposure.

Slides were developed after periods of 1 to 10 days, by a brief immersion in 1:20 Eastman D-19 solution. The success of the method is dependent on the ability to develop the end point grains with the production of a minimum of random fog grains. The tracks of interest

TABLE I. Range measurements.

Molecule	State	Density g cm ⁻²	α -particle energy, Mev	Range in microns		
				Meas.	Calc.	Diff.
H ₂ O	liquid	1.000	5.30	38.1±0.5	37.4	+0.7
	solid	0.917	5.30	41.6±0.5	40.7	+0.9
	liquid	1.000	7.68	67.2±0.5	68.0	-0.8
	solid	0.917	7.68	72.8±0.5	74.3	-1.5
D ₂ O	liquid	1.104	5.30	38.0±0.5	37.6	+0.4
	solid	1.017	5.30	41.5±0.5	40.9	+0.6

reside at depths of less than 2 microns; hence no effort was made to secure uniform depth development. The process was usually terminated soon after the appearance of surface abrasion marks by immersing the plate in a 1 percent acetic acid stop bath.

IV. PURIFICATION OF TEST LIQUIDS

The range measurements were made on freshly distilled air-free water. The sample of heavy water was observed to contain peroxides. This was removed by acidifying 25 ml of the preparation with 0.1 ml of sulfuric acid and adding crystals of potassium permanganate until in excess as evidenced by the formation of a stable pink coloration. The mixture was distilled, giving a distillate of specific gravity 1.104 at 25°C indicating a D₂O content of 97 percent. Most commercial samples of heavy water contain peroxides, which probably originate during the electrolytic decomposition of the water employed in the concentration process. The peroxides have a destructive action on the latent image of nuclear particle tracks¹² and purification of the heavy water is essential when making exposures of long duration.

While purified liquids were brought in contact with the emulsion, some contamination doubtlessly occurred during the course of the exposure as a result of the extraction of water soluble components from the emulsion layer. In manufacture, small amounts of glycerine and potassium bromide are incorporated in the sensitive material.¹³ Measurements of the water extractable components in the plates showed the presence of 2.3 mg of solubles per cm² of a 100-micron thick emulsion. The diffusion of these constituents into the test liquid does not affect the range measurements materially, as a large part of the surface water solubles are removed in the operations of applying the radiocolloids to the emulsion. In the early stages of the exposure the alpha-particles traverse pure test fluid. At later stages a maximum concentration of about 2 percent solute may possibly be built up at the emulsion-liquid interface. Calculations based on glycerine as the principal contaminant indicate that the incorporation of this solute would tend to diminish the range in water by about 0.6 percent. Since the range is established by the most remote

¹² H. Yagoda and N. Kaplan, Phys. Rev. **73**, 634 (1948).

¹³ H. Yagoda, *Radioactive Measurements with Nuclear Emulsions* (John Wiley and Sons, Inc., New York, 1949), p. 128.

end point tracks, contamination tends to diminish their number without influence on the path length. In range measurements in the solid state, a layer of pure liquid is frozen and subsequent contamination is inhibited. In so far as the molecular stopping power of water deduced from the measurements appears to be independent of the state, the contamination of the test liquids was probably inappreciable.

V. DISCUSSION OF RESULTS

The several range measurements in water and ice are compared with the theoretical ranges in Table I. The latter were evaluated from the general relationship for the stopping power of polyatomic media derived by Webb:⁴

$$\frac{\Delta R_0}{\Delta R} = \frac{dA_0}{d_0} \left[\frac{p_1 s_1}{A_1} + \frac{p_2 s_2}{A_2} + \dots + \frac{p_i s_i}{A_i} \right], \quad (1)$$

in which R and d refer to the range and density of the test substance, A_0 represents the atomic weight of the average air atom 14.56, and $d_0 = 0.001226$ g/cc is the density of dry air at 15°C and 76 cm of Hg pressure. It is assumed in the derivation of Eq. (1) that the stopping power of the molecule or mixture of atoms is an additive property of the atomic stopping powers s_i of component atoms of atomic weight A_i and fractional abundance p_i . As applied to water, using the chemical symbols as subscripts to designate the individual atomic components:

$$\frac{\Delta R_0}{\Delta R} = \frac{dA_0}{d_0} \left[\frac{2s_H + s_O}{2A_H + A_O} \right]. \quad (2)$$

Since $2A_H + A_O = M$, the molecular weight of water, and

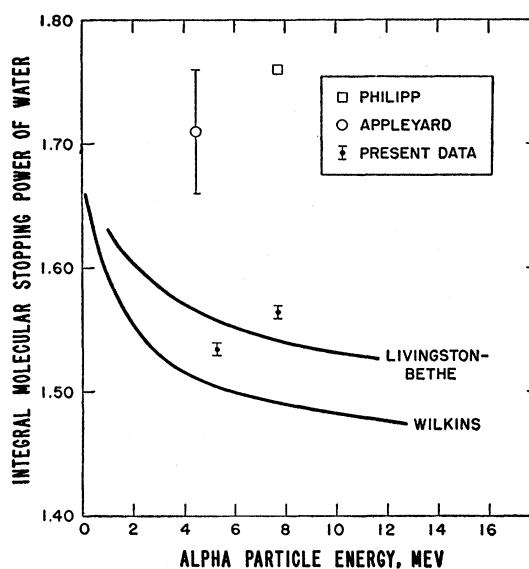


FIG. 6. Comparison of experimental and theoretical values of the stopping power of water.

designating $2s_H + s_O$ by $s(\text{H}_2\text{O})$, this simplifies to

$$\Delta R_0/\Delta R = (dA_0/d_0M)s(\text{H}_2\text{O}). \quad (3)$$

Integral values of $s(\text{H}_2\text{O})$ were evaluated by a graphical integration of the Livingston-Bethe² values for the differential atomic stopping powers of hydrogen and that estimated by Webb⁴ for oxygen as a function of alpha-particle energy, and the range in water was computed from

$$R = R_0 d_0 M / dA_0 s(\text{H}_2\text{O}). \quad (4)$$

On this basis the integral molecular stopping power of water for Po and RaC' alpha-particles is estimated at 1.56 ± 0.02 and 1.54 ± 0.02 , respectively, and the corresponding ranges in liquid water are 37.4 ± 0.5 and 68.0 ± 0.9 microns, respectively. The indicated limits originate from uncertainties in the extrapolation of $s(\text{H}_2\text{O})$ at small alpha-particle velocities. Uncertainties in the absolute values of s_i are of a larger magnitude and introduce an additional variation of about 6 percent in the evaluation of $s(\text{H}_2\text{O})$, as indicated by the curves in Fig. 6.

The range measurements with polonium alpha-particles are about 1 to 2 percent larger than theory, and the RaC' values are about 2 percent low. In the evaluation of different factors which might introduce errors in the measurements as a result of photographic processing only the Ross effect appears to be significant. In the development of a large circular area equidistant between two small circles, the images of the latter tend to contract towards the area of major blackening. The degree of the contraction depends on the nature of the developer and the tanning of the gelatin during processing. Mees¹⁴ states that for most developers close doubles separated by 100 microns or less suffer a contraction of about 1.6 microns when the gelatin dries. The radiocolloid image is a close approximation to the Ross test object. Owing to the greater chemical action on the gelatin in the development of the core, the position of the end point tracks might conceivably be drawn towards the center of the image. Qualitatively, this helps to explain the generally low range measurements obtained with radium sulfate radiocolloids. The cores of these images are of greater density than that produced by polonium radiocolloids; owing to the concomitant registration of alpha-particles from Ra, Rn, RaA, and RaC' a greater tanning action on the gelatin can be anticipated. Because of the very weak development employed in these experiments the maximum contraction was probably less than 1 percent of the measured range.

¹⁴ C. E. K. Mees, *The Theory of the Photographic Process* (MacMillan Company, New York, 1946).

To facilitate comparison of our measurements with that of other investigators, the data have been placed on a common basis by computing the molecular stopping power of the water molecule. The present work indicates an essentially constant stopping power which is independent of the state of the molecule¹⁵ or its isotopic composition, in accord with modern concepts on the stopping of ionizing particles by interaction with the electrons in the medium.¹⁶ As shown in Fig. 6 the present measurements are in fair agreement with the stopping power evaluated by Wilkins from range measurements in thorium-loaded emulsions containing high concentrations of water, and agree closely with the Bethe stopping power theory.

The several independent estimates of the stopping power of water appear to fall into two groups of high (1.76–1.71) and low (1.53–1.51) values. The experiments yielding the smaller value were made under conditions such that the entire range is measured in a thick layer of water in the absence of a liquid-air interface. In the experiments yielding high stopping powers the alpha-particles dissipate the greater part of their energy in a thin film of water immediately below the air interface. The discrepancy between the methods of measurement may originate in the following factors:

1. Inadequate corrections for the stopping power of the air gap and counting windows between the surface of the water and the detector.
2. The existence of an anomalous electronic density at the air-water interface.

These factors do not affect the measurements with submerged photographic detectors as employed by Wilkins and in the present investigation, but may be significant with external detectors. If the interface factor per se is of appreciable magnitude, it should be possible to demonstrate anomalous surface densities in liquids of high cohesive pressure by precise differential range measurements using submerged and external detectors in conjunction with monoenergetic alpha-particle sources of low energy.

¹⁵ In the course of these experiments a measurement of the range of polonium alpha-particles in water vapor at 25.3°C was made by exposing an emulsion at glancing incidence to a point source of polonium enclosed in an evacuated tube containing water vapor at equilibrium with the liquid. From the position of the tracks of minimum discernibility (1 micron) a range in water vapor of 3.76 mg per cm² was estimated, which is equivalent to a molecular stopping power of 1.55 ± 0.04 . This estimate, based on a single determination, is in good agreement with the value of 1.57 reported by Philipp using a scintillation screen to measure the range of RaC' alpha-particles in water vapor.

¹⁶ It is noteworthy that the Bragg-Kleeman stopping power rule (see reference 1) valid over a wide range of media composition, fails in the case of heavy water, owing to its assumed dependence of range on the square root of the mass of the atoms rather than their charge.

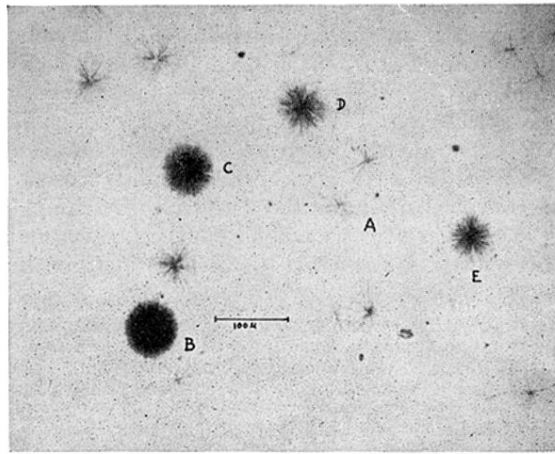


FIG. 2. Low power field of polonium radiocolloid images recorded on emulsion exposed below water.

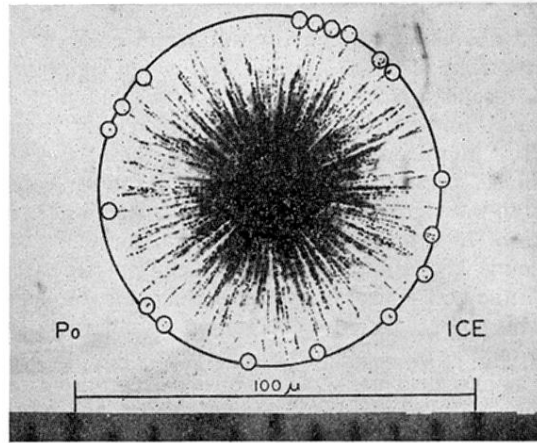


FIG. 3. Photomicrograph of a polonium radiocolloid recorded in an emulsion exposed in water frozen at -5°C . Typical end point tracks are enriched.

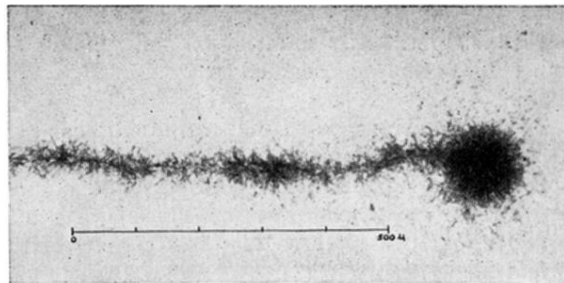


FIG. 5. Path of a radium sulfate radiocolloid recorded on surface of emulsion. The colloidal particle moved a distance of 3 mm before becoming permanently fixed to the gelatin. The test plate contained several similar tracks, and it is possible that the linear movement originated from vibrations initiated by the starting and stopping of the refrigeration mechanism. The lateral small angle scatter may represent the Brownian movement of the colloidal particle.