## Title
THE RANGE-ENERGY RELATION IN EMULSION. PAST I: RANGE MEASUREMENTS



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## PART I: RANGE MEASUREMENTS

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## ABSTRACT

Simultaneous exposures have been made of Ilford G.5 emulsion to magnetically analyzed mesons as well as to hydrogen and helium nuclei of various velocities. Measurements of the particle ranges have been made for equivalent proton energies of 1.295 Mev to 700 Mev. Individual particle momenta were known to better than one part in a thousand. Especial care was taken to maintain the emulsion density at an accurately measured value. Curves and formulae used for converting particle ranges to their proton equivalents at other emulsion densities are given. Detailed procedures for correcting ranges of particles that traverse gaps between pellicles are described. Various effects that influence range measurements are discussed. Comparisons with existing data are made. Good agreement is found to exist only when the emulsion densities are known, and a correct procedure is employed to adjust the measured ranges to standard conditions. An empirical correction of the Vigneron range table is made.

# THE RANGE-ENERGY RELATION IN EMULSION
## PART I: RANGE MEASUREMENTS*

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## Introduction

For some time it has been realized that a complete experimental restudy of the range-energy relation in emulsion would be desirable. The technique of stacked emulsion pellicles has been developed so that emulsion now is a most important instrument for high-energy physics, but empirical range-energy data have not been available for very high particle velocities. Even at low energies the range curve has not been known well, because the density of the emulsion from which most of the information came[1] was not known, or was known to differ from that of the stacked emulsion. Recently, the need for reliable data at very high as well as at low velocities for measuring the decay energies of hyperons and of K mesons became acute, making this work imperative.

Some possible pitfalls in a range-energy experiment are reliance on secondary standards or unproven methods for the estimate of particle energies, and failure to measure true rectified particle ranges. Measurement of the momenta of particles by deflecting them through 180° in an accurately measured magnetic field greatly reduces the first uncertainty. Also, by measurement of the visible length of particle tracks in emulsion, one may avoid a scattering correction in measuring the rectified range. The advantages of incorporating these features in a range-energy experiment were obvious, therefore when we undertook new measurements we introduced these techniques as well as precise knowledge of the emulsion density. In another respect the experiment described below deviates from convention. It is usual to collimate beams strongly to obtain a group of monoenergetic particles by bending in a magnetic field. This, however, leads to slit scattering. We prefer to use a small source

*This work was done under the auspices of the U. S. Atomic Energy Commission.

and an open geometry. We calculate momenta from the known source position and the observed point and direction of intersection of each particle trajectory with the emulsion. This enables us to calculate individual momenta to a part in one thousand, or better, and every track provides useful range data. The investigation was designed primarily to yield information regarding the mean ranges; their statistical distribution has been the subject of another study.[2]

## Measurement of Emulsion Density and Shrinkage Factor

The Ilford G.5 emulsion used in this experiment was from a single manufacturing batch (Z9299). Prior to use it was stored 50 feet underground for several weeks in the manufacturer's tight packaging. Equilibrium with respect to the water content of the emulsion therefore was approached.[3] Seventeen samples were taken, just after exposure, from throughout the emulsion volume, and exterior edges were trimmed from them. The density of each piece (of about 1 g) was determined by weighing in air, in carbon tetrachloride, and again in air to check the original weight, by the method developed in this laboratory.[3] The individual densities in $g/cm^3$ were: 3.824, 3.834, 3.838, 3.832, 3.814, 3.836, 3.810, 3.810, 3.821, 3.819, 3.808, 3.827, 3.830, 3.825, 3.828, 3.813, 3.815 (Av. 3.8225). The fluctuations are real, and their existence has previously been mentioned in connection with the measurement of range straggling.[2] They have important implications. In this study the samples taken were each about 4 $cm^2$ of 600-micron emulsion. In smaller volume elements even greater variations must take place. For short ranges, density fluctuation of the order of 1% therefore may be expected, and data from any one emulsion plate cannot be relied upon to be better than this no matter how many ranges are measured. (It is suggested that this effect may be one reason why a number of observers have found an apparent difference between ranges in samples of G.5 and of C.2 emulsion, which at the same density should not be detectably different in stopping power.) Long ranges, which sample a large part of the emulsion volume, are less affected by local density fluctuations, but a contribution to the range straggling from the emulsion heterogeneity may nevertheless be expected.

The area and weight of each piece of emulsion, along with the density, gave the average thickness. This agreed to within 1/2% with the average thickness of the sheets determined from the over-all dimensions of the stacks into which the emulsion was assembled.

After the processing in the usual way with 5% glycerine in the alcohol drying baths, the emulsion thicknesses were measured again. The various estimates of the shrinkage factor all are included in the interval 1.97 to 2.02. (This includes one measurement derived statistically from the ranges of $\mu$ mesons originating in $\pi$-$\mu$ decays with varying dip angles, which gave $2.02 \pm 0.03$.)

## Apparatus and Exposure

The experiment was carried out in the vacuum chamber of the 184-inch cyclotron. Pions, protons, tritons, deuterons, $He^3$, and alpha particles of various velocities originating simultaneously in a small target were deflected through 180° and intercepted by emulsion. The slightly nonuniform magnetic field was mapped at the time of the experiment by use of the proton-moment magnetometer of Varian Associates. The distances from the target to the various emulsion stacks and pellicles were known to within 0.1% or better.

To insure that the density of the emulsion remained unchanged when it was introduced into the vacuum, the following steps were taken.

(a) For detecting long-range particles the emulsion was made up into tightly clamped stacks. An edge of each was milled flat. The stacks were exposed to particles incident normal to the milled surfaces. From the theory of water diffusion in emulsion we know that the thickness of emulsion that is dried out when such a stack is left in vacuum for the half hour required to carry out the experiment is negligible compared with the particle ranges.

(b) For tracks of less than a centimeter a more difficult problem was presented. To solve it two devices known as "mousetraps" were constructed, which clamped emulsion surfaces together tightly until a few seconds before the exposure to the beam (which lasted only 3 seconds). Just before exposure an electric signal caused the "trap" to snap open and expose a fresh surface of emulsion to the beam, which entered the emulsion with a small angle of dip.

Particles emitted forward from the polystyrene target were deflected through 180° and detected below the plane of the circulating proton beam. The apparatus for doing this was developed on the basis of experience gained in earlier work in which the problems were similar.[4,5] Figure 1 shows the apparatus used.

## Calculation of Momenta

The calculation of the momenta followed closely the method developed in connection with the measurement of meson masses.[5] The target dimensions were kept sufficiently small that when the secondary-particle momenta were calculated on the assumption that the particles came from the center of the target, the mean values would never be in error by as much as 0.1%. In addition, the dimensions were chosen so that the calculated momentum spread caused by the finite target size would increase the apparent range straggling only inappreciably. The actual dimensions were: height (parallel to the magnetic field), 1/2 in.; length (parallel to the proton beam), 3/8 in.; thickness (the radial dimension), 1/16 in. The thickness is the most critical, since this dimension directly affects the diameter of the secondary-particle orbits. So that the length could be kept reasonably large, and in order that the precession of the orbits might have a negligible effect, only those particle tracks were included in the analysis for which the angle $\theta'$ was in the interval $\pm 5^{\circ}$. (The angle $\theta'$ is the horizontal projection of the angle between the particle orbit and the perpendicular to the edge of the emulsion stack (coincident with the radial line) at the point where the particle enters the emulsion. See Fig. 2, Ref. 5.) This also reduced the momentum uncertainty caused by errors of about $\pm 1^{\circ}$ in the measurement of $\theta'$, since the momentum formula is insensitive to $\theta'$ when it is near zero.

## Measurement of Ranges

The range is defined[2] by $R_0 = \int (dx_0^2 + dy_0^2 + dz_0^2)^{1/2}$. The integration is considered to be taken along the locus of the latent image of the particle track in the unprocessed emulsion. After processing, the range is found in good approximation from

$$R_1 = \int (dx^2 + dy^2 + S^2\, dz^2)^{1/2} ,$$

when the distortion, aside from shrinkage, is small, and the z dimension (normal to the emulsion surface) shrinks in processing by a factor S.

Each long track was measured independently by two or more observers. The measurement of the range is carried out by breaking up the trajectory into a number of segments. Each segment approximates a straight line. The number of separate segments measured is determined by a general consideration of the amount of measurement error that can be tolerated. This was set at about 0.1% in this experiment. The x, y, and z projections of the length

of each segment are measured either by an eyepiece reticle calibrated to 0.1% or by a mechanical stage with a screw motion of similar accuracy. Calling the projections of the ith segment $\Delta x_i$, $\Delta y_i$, and $\Delta z_i$, one computes an estimate of the range from

$$R_s = \sum_i (\Delta x_i^2 + \Delta y_i^2 + S^2 \Delta z_i^2)^{1/2} .$$

The track is taken to extend between the extremities of the first and last grains in the track. Tracks that show evidence of inelastic scattering are discarded. It is required that the distribution of ranges be consistent with the expected range straggling.[6]

Consider a coordinate frame in which the beginning of the track is at the origin and the terminus of the track lies near the x axis. The coordinates of the terminus are designated X, Y, and Z. As a check of the range measurements, the independently measured sum $\Sigma \Delta x_i \equiv R_x$ may be compared with X. For tracks that lie in a single sheet of emulsion, the measured difference $X - R_x$ is a random variable of expectation value zero. The situation is more complicated when a track traverses several pellicles. The finite grain spacing, the possibility of surface erosion, surface graininess, imperfect matching of the coordinate frames in the two pellicles, loss of sensitivity at the surface, and the possibility of air gaps between surfaces, all may introduce systematic contributions to the expectation value of $X - R_x$. (In some important published researches, tissue paper has been packed between pellicles, but we avoided such a further complication.) We find that a systematic effect generally exists, and the expectation value of $X - R_x$ is normally positive. Whereas $R_s$ is a lower limit for the true range, $R_t \equiv R_s + (X - R_x)$ is an approximate upper limit; $R_s$ will be less than the true range if some of the path in emulsion is not seen and measured, and $R_t$ will exceed the true range if gaps exist between pellicles. The meaning of $R_t$ is made clearer if it is written $X + (R_s - R_x)$. The quantity X is then the main contribution to the measurement, but, because of scattering, a contribution to the range (given to sufficient accuracy by $R_s - R_x$) comes from the y and z components of the particle motion. To investigate the existence of air gaps, a statistical approach may be taken. If air gaps exist, the magnitude of $R_t$ should be positively correlated with the magnitude of $X - R_x$. To make particles of slightly different momenta comparable, one utilizes as a standard an existing range-momentum curve from

which the measured ranges deviate only by small amounts. Suppose R is the standard range for a particle of momentum p, and $R_s$, X, $R_x$, and $R_t$ are the corresponding quantities introduced above. Then we define

$$\mu \equiv \frac{R_t - R}{R}, \text{ and } a \equiv \frac{X - R_x}{R}.$$

If gaps occur between the pellicles, a functional relationship exists between $\langle\mu\rangle$ and a, where $\langle\mu\rangle$ (in a small velocity interval) is the average value of $\mu$ as a function of a.

The intercept $\langle\mu\rangle_0$ is the value of $\mu$ that would be obtained were there no gaps. Although it cannot be shown rigorously that the relation between $\mu$ and a is always linear, our data do not justify a more refined analysis. In Fig. 2 is shown the least-squares straight line calculated from measured values of $\mu$ and a for pions in a small stack. The true range is taken to be

$$R\,[1 + \langle\mu\rangle_0] .$$

When only a limited number of tracks are measured, as for the long-range groups, the data may be insufficient to define well the slope of the line, and another procedure is preferred. The value of a tells one how accurately the measurement of the depth of penetration, X, agrees with the measured $\Sigma\Delta x_i$. Large values of a correspond to large possible errors. Tracks giving large a's may be discarded without biasing the range measurement. If this is done, the mean value $\langle a\rangle$ calculated for the remaining tracks is an indication of the possible systematic error introduced by the air spaces in the stack. In these cases we have discarded the tracks with values of a exceeding 0.007 and corrected the over-all mean value, $\langle\langle\mu\rangle\rangle$, of $\mu$ to $\langle\langle\mu\rangle\rangle - \frac{\langle a\rangle}{2}$. Then we have compounded the quantity $\frac{\langle a\rangle}{3}$ with the range straggling in calculating the standard deviation of the point.

For the long-range groups of tracks a correction was necessary because the probability of scattering out of the stack became important. Since near the end of the range the two highest-energy groups had characteristic survival lengths of only 3.5 and 2 cm, a correction of 0.2% was found necessary for each of these ranges.

Measurement of the range in emulsion stacks is complicated by a number of additional effects. Because the particles enter the edge of the stack, the range measurement must be carried out to the original position of the edge. The edges of the stack were milled flat, and before processing a 1-millimeter grid was contact-printed on each pellicle. The grid position was the same with

respect to the tracks to within a few microns on each sheet. After the pellicles are mounted and processed, the edge is of course distorted and blackened, but we have found, by using the grid as a reference system, that the line of contact of the emulsion edge with the glass (when viewed by a long-focus objective through the glass) is a reliable indication of the original edge position. Of course if the emulsion has pulled away from the glass, or if the pellicle has been mounted so wet and warm that it is distorted, this will not be true. By milling two opposite edges of the stacks, we discovered an effect for which corrections were required. Clamping the stack causes an outward distortion or flow of the emulsion which is at least partially reversible on releasing the pressure. Therefore the X and Y components of particle ranges shrink when the compressive force is relieved. This effect was found to amount to 0.2% in the largest stacks to 0.5% in the smallest stack employed in this experiment. This correction was made, but no other distortion effects were found that could significantly affect the ranges.

In order that the rate of energy loss as calculated theoretically may be compared with the slope of the empirical energy-range curve, we require that the technique of measurement yield the true integral of the path in standard unprocessed emulsion. It is possible, of course, to adopt other conventions on what is meant by the range in emulsion, and "ranges" differing from ours could be obtained by measurements on the same tracks. Some observers, for example, disregard scattering in the vertical plane in rectifying ranges. Another approximation that is sometimes made in adjusting ranges to standard conditions is to assume that the product of the density obtained from the overall weight and volume of the stack and the total distance traversed by the particle in coming to rest in the stack is a constant. This is correct, however, only if the voids in the stack are homogeneously distributed and if the actual emulsion density is standard.

## Adjustment of Data to Equivalent Proton Ranges under Standard Conditions of Density

All our measured ranges have been converted to equivalent proton ranges. The conversion is made through the quantity $\lambda \equiv \frac{z^2 R}{M} - B_z$. This quantity is a function solely of the particle velocity, $\beta c$. (It is the actual range in centimeters of an antiproton of this velocity.) R is the range in centimeters of any heavy positive particle of velocity $\beta c$, charge $Ze$, and mass M in units

of the proton mass. The term $B_z$ is added to correct for the range extension caused by the neutralization of positively charged particles by electron attachment at low velocities. At velocities sufficiently high that the ion remains stripped, $B_z$ is a constant. An estimate of it has been made by Barkas:[6]

$$B_z \approx 1.2 \times 10^{-5} z^3 \text{ cm} .$$

The particle kinetic energy we symbolize by T. The quantity $\tau = T/M$ is the kinetic energy of a proton of velocity $\beta c$. This experiment is designed to determine the relationship between $\tau$ and $\lambda$. It yields, therefore, range-energy relations for all heavy charged particles. In the conversion of ranges to an equivalent range at a standard emulsion density, changes in density are not correctly allowed for by taking the range to vary inversely with the density. The variations of density of emulsion arise chiefly from changes in its water content, and the stopping behavior of water is appreciably different from that of standard emulsion. Water is relatively more effective in stopping at low particle velocities. We do not quote emulsion ranges in $g/cm^2$ because such ranges would not be independent of the water content of the emulsion.

We have made some studies of the variation of the emulsion volume with changes of the water content, and have found that emulsion behaves somewhat as if it were a porous structure containing voids that may absorb water. Normally the volume change of an emulsion sample is not as great as the volume of water added or removed, but if sufficient time elapses for adjustments in the emulsion structure to take place, additivity of the volumes is approached. By waiting two weeks between changes of the ambient humidity we found, for 600-micron G.5 emulsion, that the volume increments in $cm^3$ averaged 94% of the weight increments in grams. Ilford Ltd. have estimated this to be 3%. Let us select a density $d_0$ $g/cm^3$ as the density of "standard" emulsion. To obtain a simple and accurate formula for the range in emulsion of some other density, d $g/cm^3$, we make the rather good approximations: $d\lambda_d/d\lambda \approx \lambda_d/\lambda$ and $d\lambda_w/d\lambda \approx \lambda_w/\lambda$. Here $\lambda_d$ is the range in emulsion of density d and $\lambda_w$ is the range in water. Then we have

$$\frac{\lambda}{\lambda_d} = \frac{rd - 1}{rd_0 - 1} + \frac{r(d_0 - d)}{rd_0 - 1} \frac{\lambda}{\lambda_w} ,$$

where r ($= \frac{\Delta V}{\Delta W}$) is the ratio of the volume increment in cubic centimeters to the weight increment in grams brought about by the addition of moisture to emulsion. The range curve for water has been calculated as described in Part 2 of this report. With this one may determine the correction required to adjust ranges measured in Ilford G.5 emulsion of arbitrary density to the corresponding ranges in standard emulsion. The correction factors are graphed in Fig. 3 for the three cases (a) r = 1 $cm^3/g$ (additivity of volumes), (b) r = 0.94 $cm^3/g$ (from our measurements), (c) r = 0.84 $cm^3/g$ (from Ilford measurements). The correction factor is seen to depend rather strongly on $\beta$ and to a less extent on r. We have made our range corrections using r = 0.94 $cm^3/g$.

## Results

In a previous publication some meson ranges measured in this program were reported.[8] In this article we include several new velocity points derived from the ranges of hydrogen and helium isotopes as well as more extended meson data. A re-examination of the possible sources of error has also been made. The inclusion of several small corrections described in Section V has had the general effect of increasing the ranges. The particle-mass ratios[5] are known well enough so that no appreciable error is introduced by them in the conversion to equivalent proton ranges. Since many of the ranges deviate considerably from those reported in the literature for emulsion plates, an independent investigation[9] was carried out to check our results by different methods.[9] Table I, which is the most recent and most complete list of our measured ranges, contains these results in addition to the data obtained in the experiment described here. Some of the measurements were made in Strasbourg.

## Discussion and Comparison With Other Measurements

Many emulsion-range data for low velocities have been published, and the emulsion densities corresponding to some of these range measurements probably are known fairly well. Some experiments that we have performed indicate that, if the emulsion came to equilibrium in vacuum, the density was probably 4.00 to 4.03 $g/cm^3$. Ilford Ltd. give 4.033 $g/cm^3$ for the mean density of many samples of G.5 emulsion dried over $H_2SO_4$.[7] For thin layers (50 microns or less) of C.2, E.1, and G.5 emulsion in vacuum for 2 or 3 hours, this condition probably was approached. In any case the surface layer, containing

Table I

Range points derived from the measurements. The errors indicated are standard deviations. Because many different kinds of particles were measured, normalized quantities are tabulated: $\tau = T/M$ and $\lambda = z^2 R/M - 1.2 \times 10^{-5} z^3$. The particle kinetic energy is symbolized by T. The quantity M is the mass of the particle in units of the proton, R is the range in centimeters, and z is the number of units of positive electric charge carried by the particle.

| Particle | $\tau$ (Mev) | $\lambda$ (cm) |
|---|---|---|
| $\alpha$ | 1.295 | $20.7 \pm 0.2 \times 10^{-4}$ [a] |
| p | 2.421 | $53.9 \pm 0.6 \times 10^{-4}$ [a] |
| t | 2.450 | $55.67 \pm 0.34 \times 10^{-4}$ |
| d, t, $He^3$, $\alpha$ | 5.00 | $175.1 \pm 2.0 \times 10^{-4}$ [b] |
| d | 5.477 | $204.6 \pm 0.64 \times 10^{-4}$ |
| $\alpha$ | 5.477 | $205.5 \pm 1.1 \times 10^{-4}$ |
| $He^3$ | 10.00 | $562.7 \pm 2.6 \times 10^{-4}$ |
| p | 13.96 | $988.3 \pm 7.4 \times 10^{-4}$ [a] |
| p | 21.21 | $2056 \pm 5 \times 10^{-4}$ |
| $\mu^+$ | 36.55 | $5345 \pm 22 \times 10^{-4}$ |
| $\pi^+$ | 200 | $10.31 \pm 0.07$ |
| $\pi^+$ | 340 | $24.74 \pm 0.10$ |
| $\pi^+$ | 540 | $51.15 \pm 0.45$ |
| $\pi^+$ | 700 | $74.97 \pm 0.36$ |

[a] From Reference 9.

[b] Ranges measured in Strasbourg.

the tracks of the slowest grazing-incident particles, will have dried out. For longer ranges, where greater depths of penetration into emulsion are experienced, it is no longer certain that the emulsion has dried out completely. In Reference 3 the theory of the drying is given, and it is shown that very long times in vacuum are required for emulsion to reach its maximum density. In connection with the range measurements now being reported we performed drying experiments with pellicles of 600-micron emulsion suspended in vacuum with both surfaces free. (This makes the unmounted pellicle equivalent in drying behavior to a 300-micron plate.) Table II shows how the mean density of one pellicle varied with time. Evidently the density of the deepest layers in this pellicle was little affected for perhaps the whole first day of evacuation.

Accurate range data were obtained by Cüer and Jung for proton energies up to 5.2 Mev.[10] As they used thin emulsion layers in vacuum for long periods, we may assume that the emulsion attained a density of $\approx 4.01$ g/cm$^3$.

Rotblat[11] and Gibson, Prowse, and Rotblat[12] have also made many range measurements in the low-velocity region. They have published a smoothed table derived from their measurements on emulsion that had been kept in vacuum for certain times depending on the thickness. Although it was thought that the time in vacuum was sufficiently long in each case for an equilibrium to be attained, the times cited were, we think, insufficient for the greater thicknesses. They estimated the density of their emulsion as 3.94 g/cm$^3$. This figure does not correspond to dryness, and the deep layers of emulsion probably had a lower density, while the surface layer was certainly rather dry. The differences between our measurements and those by Gibson et al. for protons above 5 Mev can be entirely attributed to incorrect assumptions regarding what emulsion densities to associate with their various measured points. In an early study Bradner et al. demonstrated the effect on the range of varying the emulsion dryness,[13] but--although an attempt was made to maintain normal laboratory humidity conditions--no measurements of the emulsion densities were obtainable, and their data cannot be cited because of this important deficiency. This remark applies equally to many other measurements that we do not quote for the same reason.

The range of the $\mu$ meson from the decay of the pion is an important point of comparison. Here we are in virtually perfect agreement with the measurements made in the G Stack[14] when allowance for the emulsion density is made. The adjusted range from the G stack is $602.2 \pm 2.1$ microns and our measurement is $602.7 \pm 2.2$ microns. The $\mu$-meson range in standard

Table II

Vacuum desiccation of emulsion. Mean density of a sample of unmounted 600-micron G.5 emulsion as a function of time in vacuum. (For mounted emulsion multiply all time intervals by four.)

| Time in vacuum (hours) | Mean density |
|---|---|
| 0 | 3.812 |
| 2.75 | 3.853 |
| 4.5 | 3.871 |
| 21.0 | 3.927 |
| 27.5 | 3.946 |
| 45.5 | 3.962 |
| 69.5 | 3.986 |
| 172 | 4.010 |
| 334 | 4.021 |
| 502 | 4.022 |

emulsion then is known to be 602.2 ± 1.5 microns. Although the range straggling is large for μ mesons, if a few hundred flat tracks are measured in a sample of emulsion, its density can be obtained reasonably well by comparing the measured range with 602.2 microns and calculating the density ratio, using Fig. 3.

By an ingenious use of the momentum balance in the decay of the τ meson, G. L. Bacchella et al. have found a way to develop an emulsion range curve beyond the τ-μ decay point without making momentum measurements.[15] An objection in principle to their method is that they assume a form for the range-energy relation that cannot have the same shape as the theoretical curve and, in fact, crosses it at two points. At 200 Mev our measured range is 1.5 ± 0.7% higher than their curve, and at 340 Mev it is 0.4 ± 0.4% lower, when allowance for the emulsion density difference is made by means of the μ-meson ranges.

There are no emulsion range measurements in the literature at higher velocities for which the particle energy has been measured in a direct way. A number of measurements in which the range in emulsion has been compared with the range in copper are available, but since by the method of measurement the actual rectified particle ranges are not seen, and the stopping power of copper is not well known in any case, we shall not undertake detailed comparisons with these measurements.

## The Empirical Range-Energy Relation

Too few points were measured in this work alone to define a continuous empirical range-energy relation, but the new points are sufficient to correct to standard conditions an existing smooth table such as that of Vigneron[1] (and its extension by Barkas and Young[16] using Vigneron's mean ionization potential without shell corrections. This mean ionization potential was first proposed by Cüer and Jung[10]). Table III lists the corrections as a function of particle energy. In Part 2 of this report it is found that the measured ranges determine a mean ionization potential for emulsion of 331 ± 6 ev when the K- and L-shell corrections for the various elements are included in the Bethe-Bloch stopping formula. It is well to remember that small differences in the technique of measurement can easily affect the measured ranges by 1% or so. For the greatest accuracy, therefore, this range-energy relation must be used in conjunction with the range-measurement procedure and the corrections described above.

Table III

Percentage by which the measured ranges exceed Vigneron's. The values of $\tau$ are the equivalent proton energies at which our measurements are made.

| $\tau$ (Mev) | Percentage |
|---|---|
| 1.295 | 2.0 ± 1.0 |
| 2.421 | 2.2 ± 1.1 |
| 2.45 | 3.7 ± 0.6 |
| 5.00 | 2.6 ± 1.2 |
| 5.477 | 3.0 ± 0.3 |
| 5.477 | 3.4 ± 0.6 |
| 10.00 | 2.2 ± 0.5 |
| 13.96 | 0.9 ± 0.8 |
| 21.21 | 1.3 ± 0.2 |
| 36.55 | 1.2 ± 0.4 |
| 200 | 0.7 ± 0.7 |
| 340 | 1.0 ± 0.4 |
| 540 | 1.4 ± 0.9 |
| 700 | 1.3 ± 0.5 |

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## References


1. See the compilation by L. Vigneron, J. phys. radium 14, 145 (1953).
2. Barkas, Smith, and Birnbaum, Phys. Rev. 98, 605 (1955).
3. A. Oliver, Rev. Sci. Instr. 25, 326 (1954).
4. W. H. Barkas and H. Tyren, Phys. Rev. 89, 1 (1952).
5. Barkas, Birnbaum, and Smith, Phys. Rev. 101, 778 (1956).
6. W. H. Barkas, Phys. Rev. 89, 1019 (1953). In this experiment $Li^8$ and $B^8$ ranges were measured as well as ranges, in the same emulsion plates, of hydrogen and helium isotopes that had been magnetically analyzed along with the heavy ions. This enables one to make precise comparisons of ranges of various particles at the same velocity. Although it was stated in this paper that neither the emulsion density nor the absolute value of the magnetic field was accurately known, the ranges measured in this experiment are sometimes cited as if they were absolute measurements.
7. Letter of 24 January 1956 from C. Waller to E. Gross.
8. Barkas, Barrett, Cüer, Heckman, Smith, and Ticho, Phys. Rev. 102, 583 (1956).
9. Barkas, Smith, and Heckman, Range-Energy Measurements in Emulsion, UCRL-3513, Aug. 1956.
10. P. Cüer and J. J. Jung, Sci. et Ind. Phot. 22, 401 (1951).
11. J. Rotblat, Nature 167, 550 (1951).
12. Gibson, Prowse, and Rotblat, Nature 173, 1180 (1954).
13. Bradner, Smith, Barkas, and Bishop, Phys. Rev. 77, 462 (1950).
14. Davies et al., Nuovo Cimento 2, 1063 (1955).
15. G. L. Baccella et al., Nuovo Cimento 4, 1529 (1956).
16. W. H. Barkas and D. M. Young, Emulsion Tables. I. Heavy-Particle Functions, UCRL-2579(rev.), Sept. 1954.

## Legends

Fig. 1. Photograph of the apparatus. It is mounted on a cart which enters the cyclotron vacuum chamber through an air lock. The target is the small polystyrene parallelopiped suspended on the right. The emulsion stacks are clamped between bakelite boards. The control box shown operates the armature, which rotates in the cyclotron field and provides the power for tripping the "mousetraps," one of which is shown to the right in the line of the four stacks. The proton beam of the cyclotron circulates above the cart and only the target is in the median plane to intercept the beam. The target support is not bombarded because the cyclotron beam is radially clipped by other probes.

Fig. 2. Illustration of method for eliminating effect of air spaces in stack. The percent range excess (100 $\mu$) plotted against the percent range missing (100 a) for each track measured in an emulsion stack.

Fig. 3. Curves for adjusting measured ranges to equivalent ranges in standard emulsion. The correction depends on the particle velocity, $\beta c$.

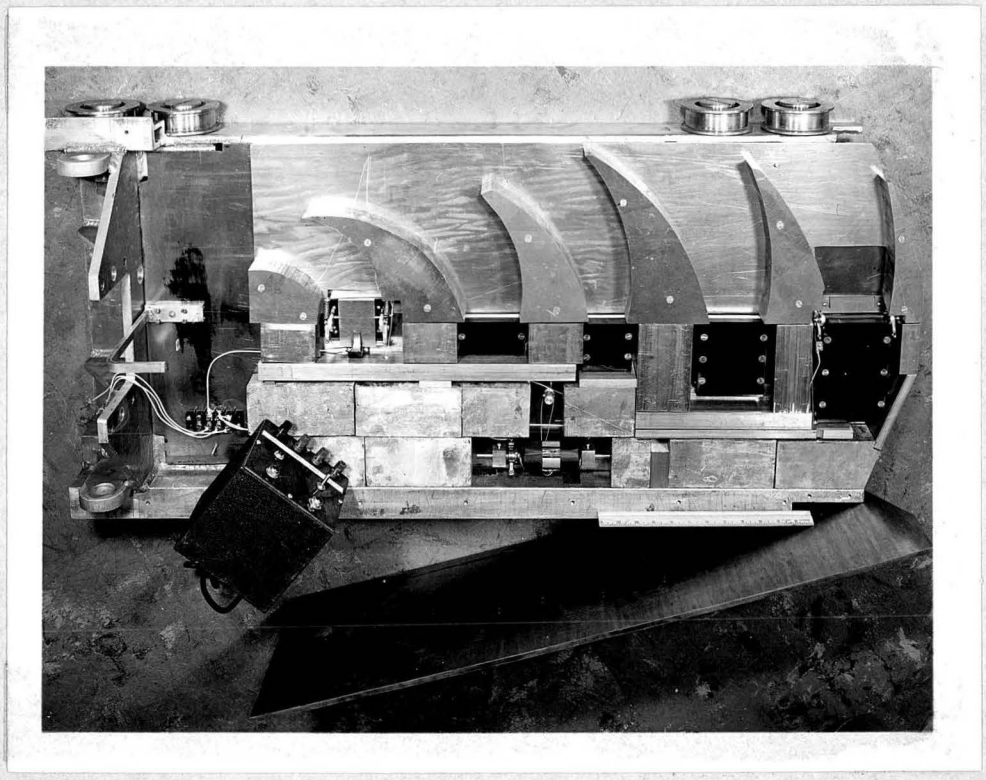

Fig. 1

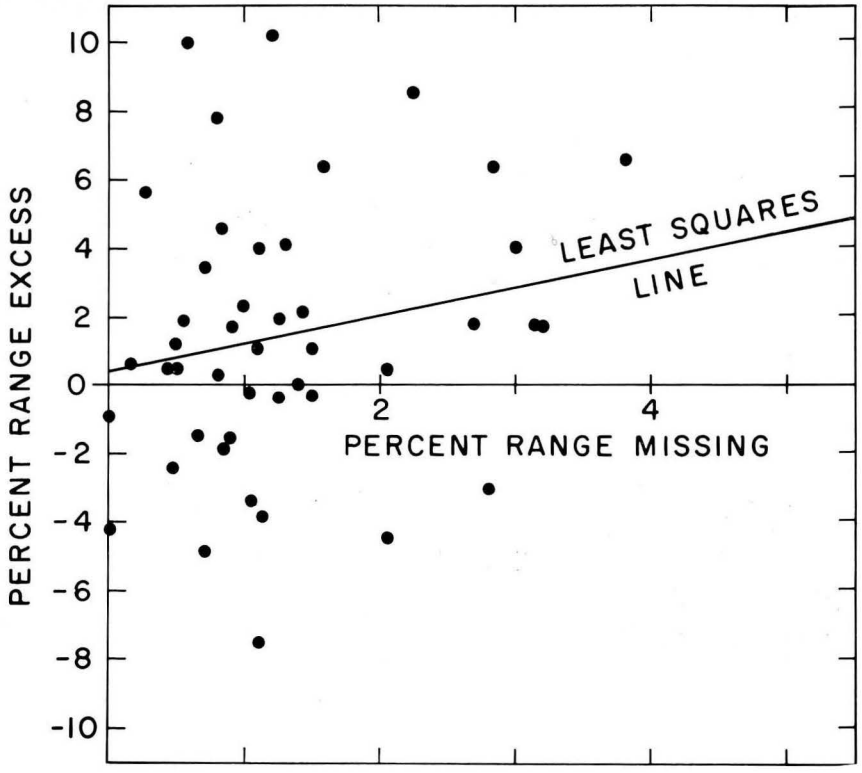
PERCENT RANGE EXCESS
10
8
6
4
2
0
-2
-4
-6
-8
-10
2
4
PERCENT RANGE MISSING
LEAST SQUARES
LINE

Fig. 2

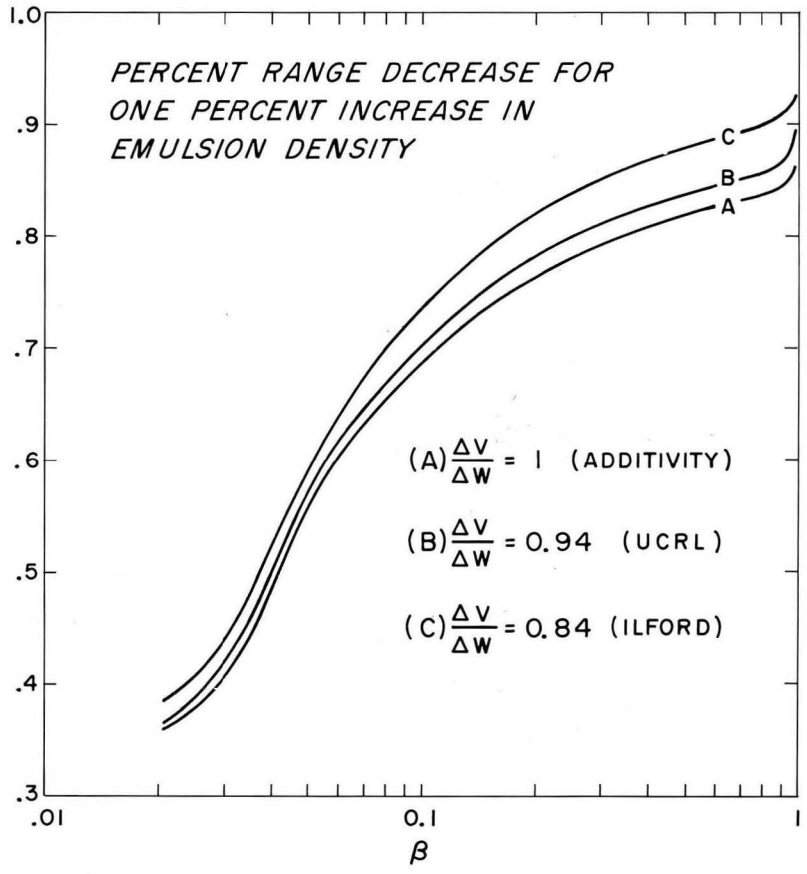
PERCENT RANGE DECREASE FOR
ONE PERCENT INCREASE IN
EMULSION DENSITY
1.0
.9
.8
.7
.6
.5
.4
.3
.01
0.1
1
β
C
B
A
(A) ΔV/ΔW = 1 (ADDITIVITY)
(B) ΔV/ΔW = 0.94 (UCRL)
(C) ΔV/ΔW = 0.84 (ILFORD)

Fig. 3