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ABSTRACT

Three new range points in the low-energy region have been determined for Ilford G.5 emulsion of known density. The particle energies were accurately known, and special precautions were taken to avoid certain types of errors known to have been associated with earlier measurements. The equivalent proton ranges in emulsion of density 3.815 g/cm^3 are: 1.295 Mev, 20.8 ± 0.2 microns; 2.420 Mev, 54.04 ± 0.55 microns; and 13.959 Mev, 988.2 ± 4.5 microns.

These measurements confirm and supplement the results of our more elaborate program of range measurements by a different method.

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I. INTRODUCTION

In an experiment[1] to determine the range-momentum relation for charged particles in Ilford G.5 emulsion of known density, several points at low velocity were measured. All the measured ranges were high compared with the tabulated[2] values. Although in the past the emulsion density and its variation with depth have not been sufficiently recognized as variables in range measurements, it is known that the existing range-energy curves correspond to emulsion that is dryer--and consequently denser--than stacked emulsion.

To check the information obtained in the first experiment, some new measurements have been made. Part of this work is designed to eliminate the uncertainties associated with the entry of a particle through a free surface of the emulsion. The errors envisioned are of two sorts: (a) those arising from difficulty in determining the true point of entry and (b) those associated with a variation with depth of the density of the emulsion, such as might be caused by drying of the emulsion surface.

Two new points were derived from the ranges of recoil protons in G.5 emulsion that had been exposed to neutrons from the $d(d,n)He^3$ and the $t(d,n)He^4$ reactions. A third point was obtained from the observed range of Pu^{239} alpha particles in emulsion of known density.

The Q value assumed for the $d(d,n)He^3$ reaction was 3.268 ± 0.004 Mev,[3] and that for the $t(d,n)He^4$ reaction was 17.577 ± 0.018 Mev.[4] A mean energy of 5.142 Mev[5] was assumed for the alpha particles whose energies were too close together to be resolved by range.

II. RANGE MEASUREMENTS OF RECOIL PROTONS

Stacks of emulsion of density 3.837 g/cm^3 were exposed to two groups of neutrons: (a) those emitted at 90° from a 37-kev deuteron beam incident on a target of titanium deuteride, and (b) those emitted at 90° to a 500-kev deuteron beam incident similarly on a target of titanium tritide. The mean neutron energy was calculated as 2.456 ± 0.003 Mev from the d-d reaction and 14.097 ± 0.018 Mev from the d-t reaction.

In a small volume of each stack the ranges of protons recoiling within an angle of 10° to the line connecting the target and the axis of the stacks were measured. At low proton velocities the probability of a proton collision with another proton of the emulsion is large. This is evident from the frequent appearance of minute "forks" or mere "blobs" at the ends of proton tracks. Of course division of the proton kinetic energy with another proton causes the range measurement to be too low, and tracks showing such terminal collisions have not been used for these measurements. The recoil energy T_p of the proton is given by $T_n \cos^2\phi$, where T_n is the neutron energy and ϕ is the angle between the neutron and the recoiling proton. The angle of each track was measured and a mean energy calculated from the angle and from the known energy distribution in the beam. The average proton recoil energy from the d-d neutrons was calculated to be 2.420 ± 0.003 Mev, while from the d-t neutrons the mean proton energy was 13.959 ± 0.018 Mev. The mean ranges found were 53.81 ± 0.51 microns from the d-d neutrons and 984.0 ± 4.4 microns from the d-t neutrons. The range measurements are very insensitive to the shrinkage factor, which was measured as 2.1 ± 0.1.

III. ALPHA-PARTICLE RANGE MEASUREMENT

A G.5 emulsion plate of 600 microns thickness was stored in a closed vessel near 25°C at a relative humidity of 50% until its weight stabilized (7 days).

A stainless steel disk onto which had been evaporated a very thin layer of Pu^{239} was placed in contact with the emulsion surface for a time calculated to give a suitable density of tracks. The plate was then developed and scanned under oil immersion. The microscope eyepiece reticle and the Z coordinate (the fine-focus adjustment) were carefully calibrated. Since the shrinkage factor in the surface layer of emulsion was not necessarily the same as the average shrinkage factor for all the emulsion, a method of determining both the shrinkage factor and the range was utilized. Only tracks that showed no appreciable scattering were selected. In addition, only those making a clean entry into the emulsion and with no ambiguity at the terminus were measured. The measurements consisted of observing the horizontal projection x of the track length from the extremities of the first and last track grains, and the vertical distance z from the point where the alpha particle stopped to the emulsion surface. Then if the shrinkage factor is S, the range R is given by

$$R = (x^2 + S^2 z^2)^{1/2}.$$

When the value of x^2 on the abscissa was plotted against z^2 on the ordinate, the points representing many alpha particles were found to be distributed about a straight line.[6] The intercept of this line on the abscissa was taken to be the square of the true range, and the ordinate intercept was taken to be R^2/S^2. The range was found to be 21.4 ± 0.2 microns, and the shrinkage factor obtained for the 20-micron-thick surface layer varied from 2.04 to 2.14 in different sets of data. The mean shrinkage factor for the emulsion batch was 2.08. The average emulsion density was 3.835 g/cm^3. It is assumed that this figure represents the density in the surface layer, and because of this assumption there is an element of uncertainty about the validity of this range point.

IV. PROTON RANGES UNDER STANDARD CONDITIONS

The above alpha-particle range must be converted to an equivalent proton range. The quantity[7]

$$\lambda = \frac{z^2 R}{M} - 1.2 \times 10^{-5} z^3$$

is a measure of the range that is a function only of the particle velocity, and is applicable to all heavy particles. In this expression λ is in centimeters, z is the particle charge in electronic units, R is the particle range in centimeters, and M is the particle mass in units of the proton mass. The second term is a correction for the range extension caused by the neutralization of slow positive particles when they pick up electrons. It is usually negligible for singly charged particles. This formula enables us to convert any particle range into the range of a proton of the same velocity. The equivalent proton kinetic energy is $\tau = T/M$, where T is the kinetic energy of the particle having range R.

It is also necessary to convert the measured ranges to the range in G.5 emulsion of standard density (3.815 g/cm^3). This cannot be done exactly, because the density of emulsion is not precisely a single-valued function of its water concentration, but if the volume of added water is assumed to be additive with the volume of standard emulsion, then one may derive the approximate relationship

$$\frac{\lambda}{\lambda_d} = \frac{d - 1}{2.815} + \frac{3.815 - d}{6.63} \lambda^{0.025},$$

valid over the range λ = 0.001 cm. to 100 cm. Here λ_d is the value of λ in emulsion of density d (in g/cm^3). The three new points we have measured then become, under standard conditions:

τ (Mev)	1.295	2.420	13.959
$\lambda \times 10^4$ (cm)	20.7 ± 0.4	53.92 ± 0.55	988.1 ± 4.5

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