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ABSTRACT

The extension of positive particle ranges caused by pickup of electrons at low velocities has been studied in Ilford C2 emulsion. Ranges of Li^8 and B^8 nuclei were measured in emulsion and compared with tracks of helium and hydrogen isotopes of the same velocity. The empirical range-energy relation adduced for light nuclei is:

$$\frac{Z^2R}{M} \doteq F\left(\frac{T}{M}\right) + \underset{.12\,Z^3}{\cancel{0.46Z^2 + 0.0063\,Z^4}}$$

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Introduction

It has recently[1] been found possible to collect and physically analyze the products formed when the high energy beam of the 184-inch cyclotron is employed to disintegrate atomic nuclei. A reliable analysis of the products of atomic number greater than two was, however, difficult because the range-energy relations in nuclear track emulsion for multiply charged fragments were uncertain. In the preliminary work in which protons bombarded carbon, no "hammer" tracks indicative of the presence of Li^8 and B^8 were found. With further searching on these plates, a few such tracks have now been found, and hammer tracks are also seen in fair abundance on plates exposed to the disintegration products of various light elements bombarded with alpha particles or deuterons. In the present experiment about one splinter in two hundred was Li^8, and about one in 5000 was B^8.

The unmistakable appearance of the tracks which they produce make Li^8 and B^8 extremely useful isotopes to employ in studying the range-energy relations for multiply charged ions. At low velocities a positive particle tends to be neutralized by electrons, thus reducing its rate of energy loss. It is the purpose of this experiment to utilize the tracks of Li^8 and B^8 to evaluate the range correction arising from this effect.

Identification and Measurement of Tracks

Tracks of a particular nuclear species are identified by plotting the range, R, versus the radius of curvature, ρ, for each track. The tracks of a particular nuclear species will then fall on a characteristic locus. For the present measurements a beryllium ribbon was bombarded by the internal alpha particle beam of the cyclotron. The disintegration products were observed in three intervals of radius of curvature simultaneously by placing Ilford C2 200 micron plates in accurately known positions. Particles leaving the target reached the plates after being bent 180° in the magnetic field. The particles entered the emulsion making a small angle of dip with the surface. The position of the track and its entrance angles were sufficient data from which to calculate the momentum. The radial distribution of the magnetic field in the cyclotron is accurately known. Definite identification of hammer tracks as B^8 as well as Li^8 was made by a study of the ρ vs R curves. Loci assignable to B^8 bent in the magnetic field while carrying 5, 4, and 3 units of charge were found as well as loci of Li^8 carrying 3, 2, and 1 units of charge. Additional short unresolved hammer tracks were seen which were attributed to B^8 carrying one or two units of charge. I designate by Z' the actual number of charges carried by an ion of atomic number Z while it is deflected in the magnetic field. Its momentum then is $Z'(e/c)H\rho$.

The range is taken to be the length of the path along the trajectory in the emulsion between the extremities of the first and last grain. Badly scattered tracks were not measured. The grain density was so high, particularly for tracks of He, Li, and B that no appreciable error could have been introduced by failure to see all of the track. No correction for such effects were made.

In the plates the tracks of many nuclear species coming from the target are found, including isotopes of hydrogen and helium. These tracks are important to the experiment as their ranges provide an overall calibration of the geometry, magnetic field intensity, and emulsion stopping power.

The Range Extension

As a basis for the analysis of range data, I have assumed that a particle of charge Ze loses energy at the rate[2]:

$$\frac{dT}{dR} = Z^2 f(\beta) \tag{1}$$

where T is the kinetic energy in Mev of the ion, R is its residual range in microns, and βc its velocity. Since T/M is a function solely of the velocity, M being the ionic atomic weight, Eq. 1 can be written:

$$g(\beta)\, d\beta = Z^2/M\, dR, \tag{2}$$

with $g(\beta)$ a function of the velocity alone. When the nucleus is moving with a sufficiently high velocity, one assumes that it is completely stripped so that the charge is not a function of the velocity. In a range interval where this condition holds, one may integrate (2) and obtain:

$$\int_{\beta_0}^{\beta} g(\beta)\, d\beta = G(\beta) - G(\beta_0) = \frac{Z^2R}{M} - \frac{Z^2R_0}{M} \tag{3}$$

In this expression $\beta_0 c$ is some lower velocity still sufficiently high that the nucleus remains stripped, and R_0 is the corresponding range. Thus for $\beta > \beta_0$ one can write:

$$\frac{Z^2R}{M} = G(\beta) + B_Z \quad . \tag{4}$$

Insofar as the above assumptions are valid, the range of an arbitrary particle is derivable from the universal function $G(\beta)$ and the constant B_Z, which is characteristic of the element, and is a measure of the range extension caused by electron pickup. If Z^2R/M is plotted against β, a separate locus may be anticipated for each element, but at high velocities the curves will be expected merely to be displaced by a constant amount from each other, corresponding to the differences in the values of the B_Z. In particular, if the range of an alpha particle or other helium isotope is measured at the same velocity as that of an ion of atomic number Z, then:

$$\frac{Z^2R}{M} - 4\left(\frac{R}{M}\right)_{He} = B_Z - B_2 \qquad (5)$$

is obtained by subtraction, and the effect relative to helium can be obtained.

Normalization of Ranges

The range increments being evaluated are generally small and are obtained from the differences of two large numbers. Errors are easily introduced under these conditions and a method of analysis should be used which minimizes insofar as possible the systematic errors. In this article a calibration procedure for each plate was employed which eliminates many of the potential sources of difficulty. A careful study of the range-energy relations for Ilford C2 emulsion was made by Wilkins[3], who based his results primarily on alpha particle points. In the present experiment, the plates were subjected to normal (~ 50 percent) humidity before being placed in the cyclotron vacuum where they remained about fifteen minutes before bombardment. It is well known that a period of many hours is required for the water content of emulsions to stabilize so that it is hardly to be expected that the stopping power of the plates employed in this experiment was identical to that used by Wilkins in his calculations. Such a difference, if it exists, would cause all ranges to deviate systematically by roughly the same percentage from those of Wilkins. Since the range is approximately proportional to a power of the momentum, a small percentage error in the momentum also can be corrected by a percentage adjustment in the range. I have, therefore, normalized Wilkins' data to the existing conditions by adjusting his ranges to match the measured ranges of helium tracks in the plates. To good approximation, this procedure eliminates from the data small errors in geometry, magnetic field intensity, and stopping power. I rely on Wilkins' results chiefly in assuming that the shape of his curve is correct over a limited interval.

In Table I, measured values of Z^2 R/M are tabulated for groups of helium tracks from each of the plates used in this study. The values predicted by Wilkins are listed in a parallel column. The measured range has been divided by Wilkins' range, and the ratio listed in the last column. Wilkins' ranges have been multiplied by the ratio appropriate to the plate being studied in obtaining the normalized quantity $\left(\frac{4R}{M}\right)_N$ of Table II.

The normalization factors for plates I and II check and are sufficiently near unity that they are fully explainable in view of the possible difference in stopping powers mentioned above, or possibly as an effect traceable to the uncertainty in the absolute value of the magnetic field intensity. On the other hand, there appears to be a significant change in the ratio for the third plate. Since the relative momenta are known with high accuracy, this effect can most simply be interpreted as a one percent inconsistency in Wilkins' ranges for alpha particles of $\approx$ 20 Mev when compared with those in the region of 5-10 Mev.

Results

In Table II are listed the ranges of groups of particles which were identified and measured in this study. The helium isotopes were employed in finding the normalization factors shown in Table I and are not listed again in Table II. The energies calculated from the momenta are entered in Table II as well. The hydrogen isotopes listed were measured in order to make the data complete, but to evaluate $B_1 - B_2$ accurately, lower energy particles should be used. Actually the individual determinations of $B_1 - B_2$ appear more consistent than one might have expected. The standard deviations given are statistical and do not include systematic errors arising from possible incorrect normalization factors. For long ranges the determination of $B_1 - B_2$ depends very sensitively on the normalization. The present measurement of $B_1 - B_2$ is somewhat lower in absolute value than the figure of - 1.38 microns adopted by Wilkins[3]. The quantities B_Z are much larger for lithium and boron than for hydrogen, and, therefore, are not so sensitive to normalization errors. In the case of Li the two points bracketted were not used in determining $B_3 - B_2$ since for these points $\beta < Z/137$. At $\beta \approx Z/137$ the pickup process is expected to become important. Whereas for the other isotopes points were determined using 25 to 100 individual tracks, the B^8 tracks were so rare and the pickup effect so large that each point was determined using five tracks, all of which, however, lay within two percent of the average momentum for the group.

For small Z one may suppose that $B_Z = aZ^2 + bZ^4 + \ldots$

Taking $a = 0.46$ and $b = 0.0063$, one obtains a good fit to the lithium and boron data. The calculated value of $B_1 - B_2$ using these coefficients is - 1.47 microns. Although this is more than half a micron greater than the present experimental estimate, it is in good accord with Wilkins' adopted value.

Writing $G(\beta) = F(T/M)$, we obtain as a range-energy relation for light elements:

$$\frac{Z^2 R}{M} = F\left(\frac{T}{M}\right) + 0.46\, Z^2 + 0.0063\, Z^4 \qquad \beta > Z/137 \tag{6}$$

It is not unreasonable to suppose that Eq. 6 will give ranges correct to about a micron for all combinations of charge and mass through the isotopes of boron or slightly beyond. F(T/M), of course, is to be determined for the particular sample of emulsion from the range-energy curve of any light nucleus in that stopping material.

Acknowledgments

Miss Esther Jacobson made many of the range measurements and carried out the numerical reduction of a large part of the data for this study. Dr. Helge Tyren also measured many of the ranges and participated actively in the exposure of the plates.

References

1. Walter H. Barkas and J. Kent Bowker, Phys. Rev., 87, 207 (1952).
2. M. S. Livingston and H. A. Bethe, Rev. Mod. Phys., 9, 245 (1937).
3. J. J. Wilkins, "Range-Energy Relations for Ilford Nuclear Emulsion", A.E.R.E. G/R 664, Harwell, 1951.

TABLE I

Calculation of Normalization Factors

T is the kinetic energy in Mev calculated from the momentum of the particle. M is the atomic weight of the ion, R is the measured range in microns, and $\left(\frac{4R}{M}\right)_W$ is taken from Wilkins' tables for the value of T/M listed.

	Isotope	T/M	$\left(\frac{4R}{M}\right)$	$\left(\frac{4R}{M}\right)_W$	Ratio
Plate I	He^4	1.264	21.8 ± 0.3	21.27	1.025
	He^4	1.334	23.6 ± 0.3	22.94	1.031
	He^3	2.221	49.6 ± 0.3	48.30	1.027
		adopted factor	1.027 ± 0.002		
Plate II	He^4	2.236	50.0 ± 0.3	48.80	1.025
	He^3	3.936	121.9 ± 0.6	118.50	1.029
		adopted factor	1.027 ± 0.002		
Plate III	He^4	4.700	160.5 ± 0.6	158.00	1.016
	He^3	8.187	401.7 ± 1.2	396.00	1.015
		adopted factor	1.0155 ± 0.0005		

TABLE II

Observed Ranges and Derived Range Corrections

Ion	T_{Mev}	R_{micron}	$\frac{Z^2R}{M}$	$\left(\frac{4R}{M}\right)_N$	$\frac{Z^2R}{M} - \left(\frac{4R}{M}\right)_N$
H^3	2.890	42.6 ± 0.4	14.1 ± 0.13	15.01	− 0.91 ± 0.13
H^2	2.508	41.1 ± 0.2	20.4 ± 0.1	21.39	− 0.99 ± 0.10
H^3	6.217	129.7 ± 0.4	42.99 ± 0.13	43.81	− 0.82 ± 0.13
H^2	9.265	312.6 ± 1.5	154.1 ± 0.75	154.90	− 0.8 ± 0.75
H^1	5.006	177.8 ± 0.7	176.4 ± 0.7	177.60	− 1.20 ± 0.7
		adopted $(B_1 - B_2)$	. . . .		− 0.9
Li^8	1.139	3.82 ± 0.1	4.28 ± 0.13	2.25	(2.03 ± 0.13)
Li^8	2.672	5.96 ± 0.1	6.69 ± 0.13	4.57	(2.12 ± 0.13)
Li^8	4.325	9.1 ± 0.12	10.21 ± 0.15	7.50	2.71 ± 0.15
Li^8	5.793	11.6 ± 0.1	13.01 ± 0.13	10.50	2.51 ± 0.13
Li^8	9.138	19.46 ± 0.2	21.64 ± 0.25	18.72	2.92 ± 0.25
Li^8	10.69	22.97 ± 0.2	25.76 ± 0.25	23.51	2.25 ± 0.25
Li^8	22.41	64.9 ± 0.22	72.80 ± 0.26	69.72	3.08 ± 0.26
		adopted $(B_3 - B_2)$	. . . .		2.7
B^8	18.47	20.99 ± 0.4	65.4 ± 1.3	52.40	13.0 ± 1.3
B^8	26.83	34.78 ± 0.4	108.4 ± 1.3	93.80	14.6 ± 1.3
B^8	60.09	115.6 ± 1.0	360.2 ± 3.0	350.00	10.2 ± 3.0
		adopted $(B_5 - B_2)$	. . . .		13.5