theory if the reduced width was not more than a factor of two greater than the Wigner-Teichman limit.) Elkind[15] reports a new level of B^{11} at 10.32±0.02-Mev excitation with width 54±17 kev from the reaction $B^{10}(d,p)B^{11}$. This level is too narrow to be identified with our level at 10.23 Mev. From the limits of observation given by Elkind one can infer that if the intensities of groups corresponding to our broad levels at 9.86 and 10.23 Mev were less than half of the intensity of the 10.32-Mev group (at 90°), they would have escaped detection in Elkind's experiment. From our measurements we conclude that the cross section for excitation of the 10.32-Mev level is less than 0.006 barn for the $Li^7+\alpha$ reaction.

The authors wish to thank Professor W. A. Fowler, Professor R. F. Christy, Professor T. Lauritsen, and Professor C. C. Lauritsen for their suggestions and criticism, and Mr. R. W. Kavanagh for aid with many aspects of the experiment.

[15] M. M. Elkind, Phys. Rev. 92, 127 (1953).

PHYSICAL REVIEW VOLUME 96, NUMBER 2 OCTOBER 15, 1954

Range of Nitrogen Ions in Emulsion

H. L. REYNOLDS AND A. ZUCKER
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received June 17, 1954)

The range of nitrogen ions in Ilford C-2 emulsion was measured for energies from 4 to 28 Mev. The rate of energy loss over this entire energy region is approximately 1.5 Mev per micron.

INTRODUCTION

THE range-energy characteristics of particles heavier than helium are difficult to predict from theory because such particles pick up electrons as they near the end of their range. In general, charge pickup and loss is observed when the ion velocity is comparable to the velocities of orbital electrons. Experimentally determined ranges of lithium and boron in emulsion[1] have illustrated the process of charge pickup, although the range over which charge pickup occurs for these particles is rather short. Miller[2] has measured the range of carbon ions in emulsion but his results apply mainly to energies higher than 30 Mev, which is above the region of charge pickup.

The range-energy relation for nitrogen ions in nickel below 30 Mev has been discussed previously.[3] It was shown that as nitrogen ions slow down in nickel they pick up electrons in such a manner that dE/dx remains nearly constant. Such behavior in emulsion would be in contrast to a calculation by Freier *et al.*,[4] which indicates that the observable thinning of the tracks of heavy nuclei as they slow down in emulsion is due to a decrease in dE/dx as the charge of the particle decreases. The range in emulsion of nitrogen ions from 4 to 28 Mev was measured with the nitrogen beam of the ORNL 63-inch cyclotron by methods described below.

[1] W. H. Barkas, Phys. Rev. 89, 1019 (1953).
[2] J. F. Miller, University of California Radiation Laboratory Report UCRL-1902, 1952 (unpublished).
[3] Reynolds, Scott, and Zucker, Phys. Rev. 95, 671 (1954).
[4] Freier, Lofgren, Ney, and Oppenheimer, Phys. Rev. 74, 1818 (1948).

EXPERIMENTAL METHOD

Since the range of nitrogen ions in nickel is known for energies from 8 to 28 Mev, this portion of the range-energy curve was obtained by exposing 50-micron Ilford C-2 emulsions in the deflected cyclotron beam. To vary the energy, thin nickel foils were placed directly in front of the emulsions. The initial beam energy was determined as before[3] by observing the energy of recoil protons from a gas target. The emulsions were exposed in an evacuated chamber which was mounted on the exit port of the cyclotron. A $\frac{1}{4}$-in. brass plate with a $\frac{1}{32}$-in. slit was used as a shutter. The shutter was mounted on a Lucite rod which extended through a seal in the vacuum chamber. The shutter, thus insulated from ground, was used as a beam monitor. When a satisfactory current struck the plate the slit was rotated rapidly by means of the Lucite rod, thus exposing the emulsion to a short burst of ions. Results obtained in this manner are indicated by crosses in Fig. 1.

The low-energy portion of the curve was determined as follows: Plates exposed to the direct full-energy beam were scanned for nitrogen-proton elastic collisions. From conservation of momentum and energy it can be shown that

$$E_N=\frac{E_P[1-(M_P/M_N)]^2}{4(M_P/M_N)\cos^2\alpha},$$

where E_N and E_P are the nitrogen and proton energies after the collision, M_N and M_P are the nitrogen and proton masses, and α is the angle between the recoil proton and continuing nitrogen ion. E_P was determined from the measured proton range and the range-energy curves for protons published by Rotblatt.[5] Particle ranges were measured with a filar eyepiece which was calibrated with a Bausch and Lomb stage micrometer. The projected angle was measured with a rotating microscope stage. By measuring the dip of both tracks and the emulsion shrinkage coefficient, the "dip" angle was determined. The projected angle and the dip angle were combined to determine α, the true angle between the nitrogen and proton tracks. All measurements were repeated by a second observer.

The errors in this second type of experiment are quite large. The percentage error in E_N due to inaccuracies in measuring α is proportional to $\tan\alpha\Delta\alpha$. For an angle α of 50 degrees and an error $\Delta\alpha$ of ± 2 degrees, the percentage error in E_N is nearly 9 percent. Because of the rapid increase of the error with increasing angle, an upper limit was set for the angles of events used. All events with a dip angle greater than 20 degrees and a projected angle greater than 50 degrees were discarded. These criteria, together with the imperfect events found, resulted in the discarding of approximately 80 percent of the proton recoil events located in the survey. The useful events remaining were grouped in $\frac{1}{2}$-micron intervals; a statistically weighted mean was used for each interval. Approximately 90 events were used to obtain the results shown as circles in Fig. 1. Ilford C-2, 50-micron plates at a relative humidity of approximately 25 percent were used for both types of measurements.

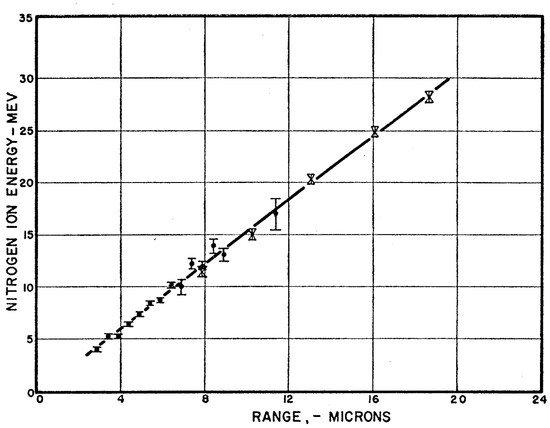

Fig. 1. Range-energy curve for nitrogen ions in Ilford C-2 emulsions. The crosses were obtained by bombardment of the plates with nitrogen ions of known energy; the dots are the results of proton-scatter events observed in the emulsion. Probable errors are shown on all points.

[5] J. Rotblatt, Nature **165**, 387 (1950).

DISCUSSION

The curve in Fig. 1 represents the experimental range-energy curve of nitrogen ions in emulsion. Probable errors are shown on all points. A calculation by Lonchamp[6] predicts a range approximately 10 percent smaller from 10 to 30 Mev with a somewhat larger dE/dx than our data indicate below 10 Mev. The difference is probably due to inaccurate charge-velocity relations used by Lonchamp.

Lonchamp[7] has concluded from considerations of the photographic process that the thinning down of the tracks of heavy ions as they approach the end of their range can be explained by the fact that the thickness of the developed track is due mainly to δ rays which at low ion velocities no longer have sufficient range to broaden the track. This conclusion is supported by our evidence that the rate of energy loss is nearly constant over the region of thin-down for ions with masses near that of nitrogen.

We wish to thank Mrs. W. Bowelle for her assistance in scanning and Professor L. D. Wyly for many helpful discussions.

[6] J. P. Lonchamp, J. phys. radium **14**, 89 (1953).
[7] J. P. Lonchamp, J. phys. radium **14**, 433 (1953).