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Translated by H. Kasha
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SOVIET PHYSICS JETP VOLUME 34(7), NUMBER 3 SEPTEMBER, 1958

RANGE AND SPECIFIC IONIZATION OF MULTIPLY-CHARGED ION IN A GAS

Ia. A. TEPLOVA, V. S. NIKOLAEV, I. S. DMITRIEV, and L. N. FATEEVA

Moscow State University

Submitted to JETP editor September 20, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 559-568 (March, 1958)

The range and specific ionization in air, argon, and hydrogen have been measured for the ions from Be to Ne at velocities between 1.5×10^8 and 12×10^8 cm/sec. For $v \leq 5 \times 10^8$ cm/sec, the specific ionization and the range of an ion is approximately proportional to the particle velocity v. At higher velocities, the range is proportional to v^2 and the specific-ionization curves have a flat maximum, as in the Bragg curve for α particles. The stopping power of a substance, B, is not the same for all ions and decreases with increasing Z of the ion.

1. INTRODUCTION

IN connection with the study of nuclear reactions induced by multiply-charged ions and by hypernuclei, interest has increased recently in the passage of charged ions of light elements, with atomic numbers $Z > 2$, through matter. Particularly interesting are the ranges and specific ionizations of these ions. A theoretical prediction of these characteristics is a rather complicated matter, owing to the difficulties of accounting for the charge exchange, which comes prominently into play at an ion velocity v close to the velocity of its orbital electrons. Recent publications describe the stopping of ions in photo emulsion[1-3] and in air,[3-5] using certain simplifying assumptions concerning the effective ion charge and the stopping power B of the substance. These reports need an experimental verification.

The only information available up to recently was on the ranges (referred to air) of recoil nuclei in a condensation chamber, at velocities from 2×10^8 to 7×10^8 cm/sec.[6-11] A short time ago reports were published on the ranges of many accelerated ions in gases, at velocities below 1×10^8 cm/sec,[12] and of lithium,[13] beryllium, and nitrogen[14] ions at higher velocities. The ranges of certain multiply-charged ions in photoemulsion[15-18] and of nitrogen ions in nickel[19] were also measured. As to specific ionization, there exist, in addition to a report[19] concerning its constancy at velocities from 10×10^8 to 20×10^8 cm/sec, also data (in gases) for neon and nitrogen ions in the velocity region below 3×10^8 cm/sec (Ref. 20), and also for lithium ions.[13,21]

In this investigation, we studied the ranges and the specific ionizations of ions from Be to Ne, at velocities from 1.5×10^8 to 12×10^8 cm/sec in argon, air, and hydrogen.

2. DESCRIPTION OF THE EXPERIMENT

In this work, as in the work reported in Ref. 13, we employed a focused ion beam extracted from a 72-cm cyclotron. After passing through a system of 1×10 mm slits, the beam entered the registering apparatus (Fig. 1).

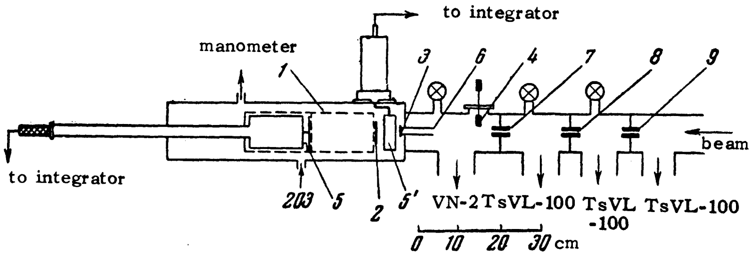

FIG. 1. Diagram of measuring apparatus.

The measurement method consisted of moving a charged-particle recorder, attached on a movable rod, along the trajectory of the beam inside the stopping chamber, to measure the relative ionization along the path. The particle speed was determined from the intensity of the field of the focusing magnet, calibrated for α particles and deuterons of known energy. The value of the field, in turn, was determined from the ranges of α particles in air and of deuterons in air and hydrogen, using tabulated data on the energy dependence of the range.[22] The accuracy of the speed determination did not exceed 2% and that of the corresponding energy determination did not exceed 4%. To obtain ions of different velocities, we varied the magnetic field intensity and the frequency of the electric field between the dees of the cyclotron. The gases BF_3, air, and Ne were introduced into the ordinary arc source of the cyclotron. Beryllium ions were obtained from a source with a beryllium plug.

The ions were stopped in chamber 1 (Fig. 1), filled with gas at pressure suitable for operation of the proportional counter and at the same time sufficient to keep the total range of the ions within the chamber. The average pressure was approximately 40 mm mercury for air, 35 for argon, and 130 for hydrogen. At low velocities ($v < 4 \times 10^8$ cm/sec), pressures up to 2 mm mercury were used, and the ions were registered in this case with an ionization chamber. An inclined mercury manometer, accurate to ± 0.3 mm Hg, was used to measure pressure from 1 to 50 mm Hg. Higher pressures were measured with an ordinary U-shaped manometer.

The vacuum portion of the cyclotron was separated from the stopping chamber with a celluloid film 3, $\sim 120\ \mu g/cm^2$ thick. An identical film 4 was placed in the vacuum a certain distance away from film 3. Film 4 could be placed in the path of the beam to determine the air equivalent of the first film.

The specific ionizations and the ranges of ions with velocity from 4×10^8 to 12×10^8 cm/sec were measured with a proportional counter and a linear amplifier 2. The counter comprised a rectangular brass box with a 3×10 mm slit for the admission of the particles. The collecting electrode was a tungsten wire 60 microns in diameter, stretched parallel to the slit and placed 7 mm off the center of the slit. The counter was 6 mm deep and was not separated from the stopping chamber. The pulses at the output of the linear amplifier were measured both visually with a cathode ray oscillograph, and on the film of a loop oscillograph 60 mm wide. As a check, each series of measurement was repeated many times.

The ranges of nitrogen ions at velocities from 1.5×10^8 to 4×10^8 cm/sec were measured with a flat ionization chamber 5, recording the total current at a given portion of the ion path. A chamber approximately 3 mm deep was attached to the moving rod together with the counter. The high voltage electrode, measuring 8×2 cm, was in the form of a tungsten wire mesh 60 microns thick, the distance between wires being 1 mm. The particles entered the chamber through the mesh and moved in the chamber in the direction of the electric field. The current in the ionization chamber was measured with an integrator. The readings of the measuring chamber were related to the readings of a monitor chamber 5′, located at the input to the stopping chamber, and providing passage for the entire beam. To avoid energy losses in the film, a differential vacuum system was employed with a pressure drop from 10 to 2×10^{-5} mm Hg, obtained by four stages 6 — 9, separated by 1×10 mm channels 4 to 10 cm long. To provide comparison with the results obtained with the counter, control measurements were made at 5 and 8×10^8 cm/sec, using the film instead of the differential vacuum.

3. PROCESSING OF THE RESULTS AND EXPERIMENTAL ERRORS

The measurements yielded the dependence of the pulse amplitudes (or of the ionization current) on the distance between the recorder and the point of entry of the beam into the stopping chamber. The end of the range was determined from the x-intercept of the experimental curve for the specific ionization. At a pressure of 760 mm mercury, the range was calculated from the formula

$$R = l(p/760) + \Delta R,$$

where l is the length of the ion path in the stopping chamber, p is the pressure in the chamber in mm Hg, and ΔR the equivalent of the celluloid film when operating with the counter, averaged over all measurements for the given ion and gas. This equivalent amounted to ~1 mm for air and argon and ~4 mm for hydrogen.

The measurements of the film equivalent did not show it to depend on the ion velocity, but an approximately linear dependence on the ion charge was observed. In hydrogen, the reduction in the value of the equivalent from the proton to the neon ion amounted to 30% in neon, 15% in argon, and 5% in air. Since the accuracy in the measurement of the equivalent did not exceed 15 — 30%, the observed law can be considered only approximate. In measurements with the ionization chamber, ΔR represented the effective length of channel 6, equal to $(63 \pm 3)(p/760)$ mm, which was calculated with the Knudsen formula for viscous flow.

The absolute values of the specific energy losses in Mev/cm was obtained from the pulse amplitude vs. distance curve by two methods: (A) normalization with respect to energy, as described in Ref. 16, and (B) comparison of the pulse from a given ion with the pulse from a proton of known energy, for identical counter positions. Both methods yielded equal values, within the limits of experimental error. Table I gives the results of the comparison for argon. To check the procedure, specific ionization vs. velocity curves were obtained for α particles and deuterons, and these curves agreed quite satisfactorily with the available data.[22,23]

The major error, both in the determination of the range and in the determination of the specific ionization, was due to the considerable spread of the pulses within a single series and between various series of measurement. Calculations have shown that in the region with $v > 3 \times 10^8$ cm/sec the spread within any one series can be accounted for almost entirely by statistical fluctuations of the coefficient of gas amplification. Differences between series was probably due to counter-voltage fluctuations. The summary error, which includes in addition to the above error also the errors in the measurements of the pressure and of the film equivalent, is shown in Figs. 2 — 4 to fluctuate between 2 and 7% for the range and between 7 and 15% for the specific ionization, depending on the ion and on the velocity (at $v > 3 \times 10^8$ cm/sec).

TABLE I

Ion	dE/dx, Mev/cm	
	A	B
$^{9}Be^{+2}$	5.0±0.4	5.2±0.5
$^{11}B^{+2}$	6.2±0.6	5.8±0.6
$^{14}N^{+3}$	9.1±0.4	8.5±0.8
$^{16}O^{+3}$	9.6±0.5	9.5±1.0

Figure 2 shows, by way of an example, the experimental points obtained by measuring the dependence of the specific ionization on the range for the ions ^{11}B and ^{14}N in air and in hydrogen. The solid line represents the average of the experimental points.

4. RESULTS

The results of the range measurement are shown in Fig. 3 in the form of the dependence of Z^2R/A on E/A, i.e., in units that are independent of the isotopic mass of the ion A. The solid lines on the graph were obtained by integrating the curves of the specific ionization and are continued dotted to the range measured at maximum energy E. The dots represent the results of direct measurement of the ion ranges at various velocities. The points fit the curves within experimental accuracy. This shows that, within the experimental error, the average energy required to produce a single pair of ions is independent of the velocity and of the type of ion, i.e., that the forms of the curves of specific ionization and of average energy loss dE/dx coincide, as was indeed assumed in the normalization of the specific-ionization curve.

Comparison of the ranges of the ions in various gases shows that, for equal velocity, the range is greater by 6% in argon and by a factor of 3.7 times in hydrogen, compared with air, and that this ratio diminishes somewhat with increasing Z of the ion (by ~10 — 20% as Z increases from 5 to 10). At a velocity $v < 5 \times 10^8$ cm/sec, the range of the ion is proportional to the velocity, and at higher velocities the dependence of R on v changes, the range becoming approximately proportional to v^2 at velocities ~6 — 8 × 10^8 cm/sec.

The specific ionization, as can be seen from Fig. 5, is proportional to the velocity at $v < 5 \times 10^8$ cm/sec, and at $v \sim 6 - 8 \times 10^8$ cm/sec it has a maximum similar to the Bragg curve for α particles. At the maximum, $dE/dx \approx 1.5\,Z$ Mev/cm.

Comparison of the curves of the specific ionization in various gases shows that it is possible to employ for all ions a factor 0.92 ± 0.05 in converting from argon to air, and 0.29 ± 0.01 in converting from hydrogen to air. These coefficients, accurate to ~10%, can be considered equal to the

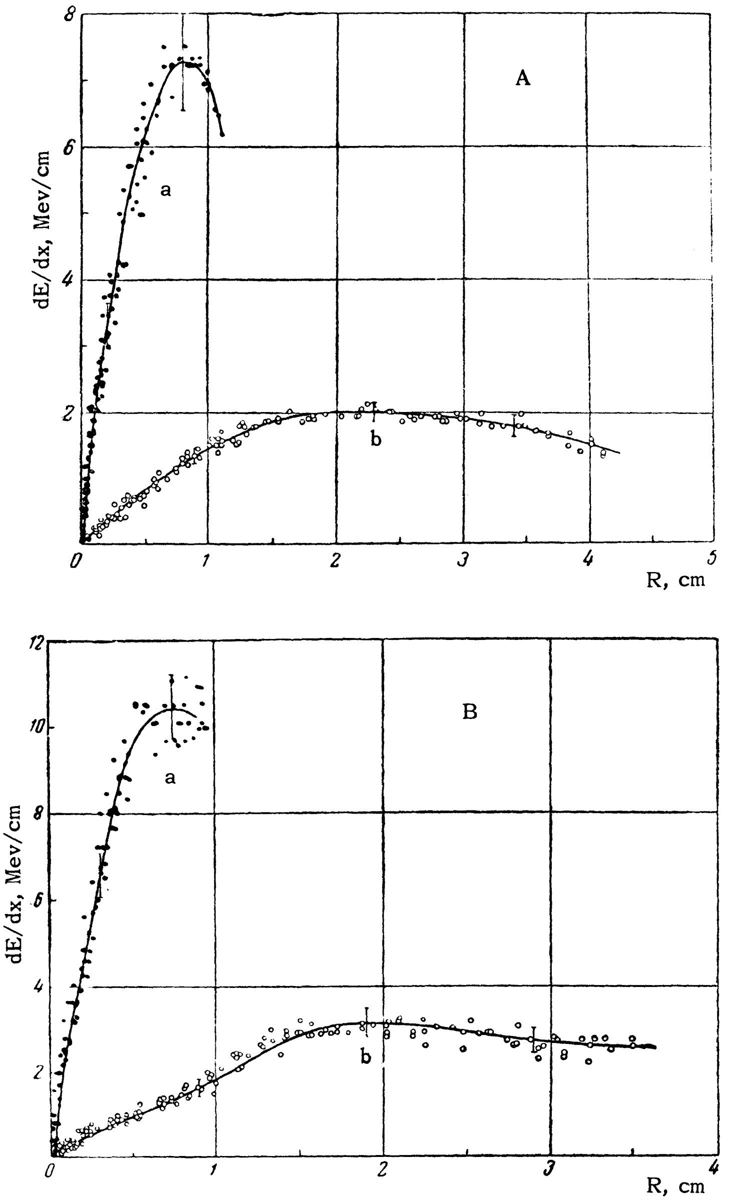

FIG. 2. Specific ionization: A – ^{11}B, B – ^{14}N; a – in air, b – in hydrogen, depending on the residual range at 760 mm Hg.

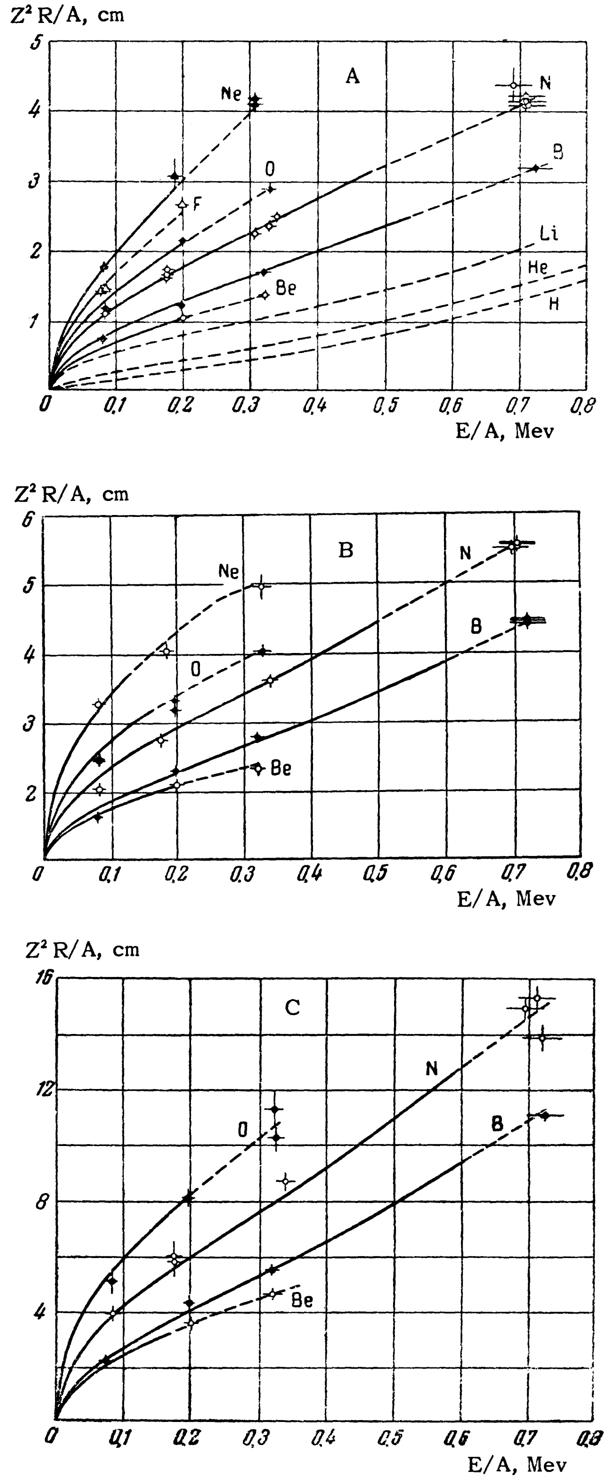

FIG. 3. Dependence of the ion ranges on the energy at a pressure of 760 mm Hg. A – in air, B – in argon, C – in hydrogen. Values of the ranges in air for the protons and the α particles were taken from Ref. 22, those for the Li ions – from Ref. 13.

ratio of $N_0 Z_S^{2/3}$ for the given substances, where N_0 is the number of atoms per cm^3 of matter, and Z_S is the atomic number of the medium, On the whole, the dependence of the specific ionization on Z and on Z_S can be written

$$-\frac{dE}{dx} \approx N_0 Z_s^{2/3} Z f(v),$$

where f(v) is independent of the medium and of the ion within ±10 – 15%.

5. INTERPRETATION OF THE RESULTS

The ranges of ions in air, measured by means of an ionization chamber (see Fig. 4), are approximately 1 mm shorter than the ranges obtained with the aid of the counter. A similar difference is observed also in argon (~1 mm) and in hydrogen (~2 mm). Qualitatively this can be attributed to nuclear collisions. It is known that at the end of the range there is an increase in the number of elastic collisions between the ions and the atoms

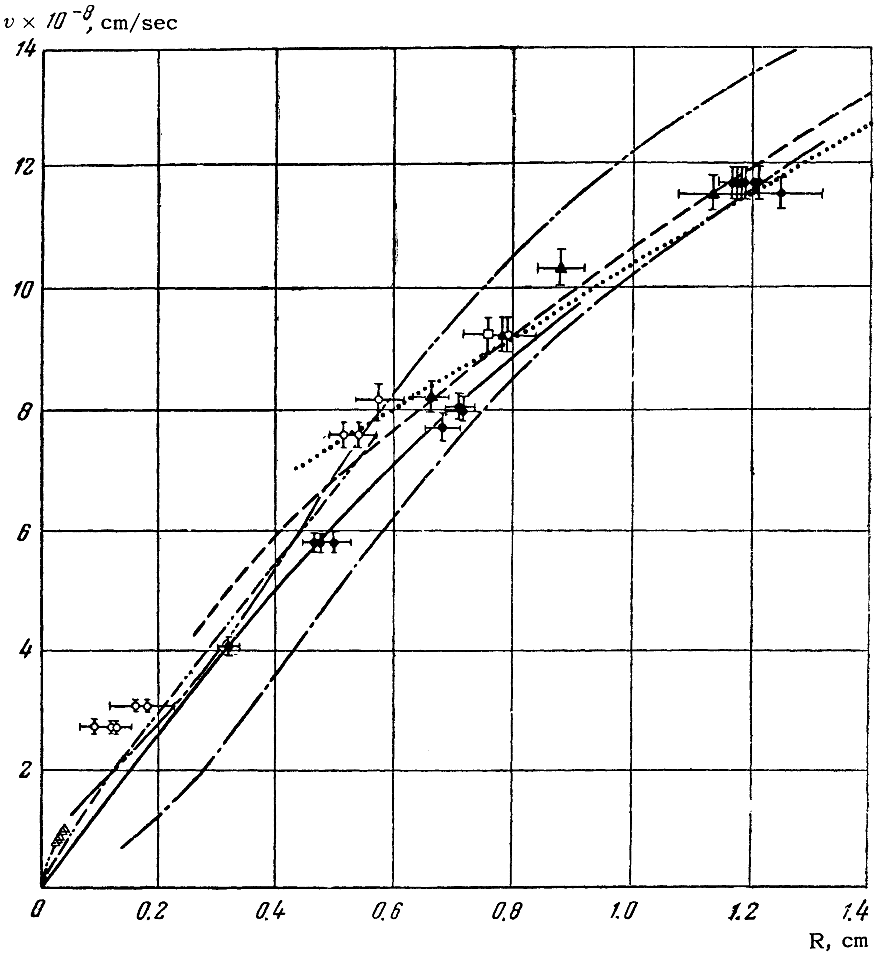

FIG. 4. Dependence of the ranges of ^{14}N ions on the velocity in air at 760 mm Hg: — our experimental results, obtained with a proportional counter, and o — with an ionization chamber; ▲— measurements in a condensation chamber,[14] Δ— values obtained in Ref. 12, ••——••— measurements of recoil nuclei,[6,8] ...— measurements in photoemulsion, recalculated for air.[15] Calculated curves: ————— from Ref. 3, —••—••— from Ref. 4, and —•—•— from Ref. 5.

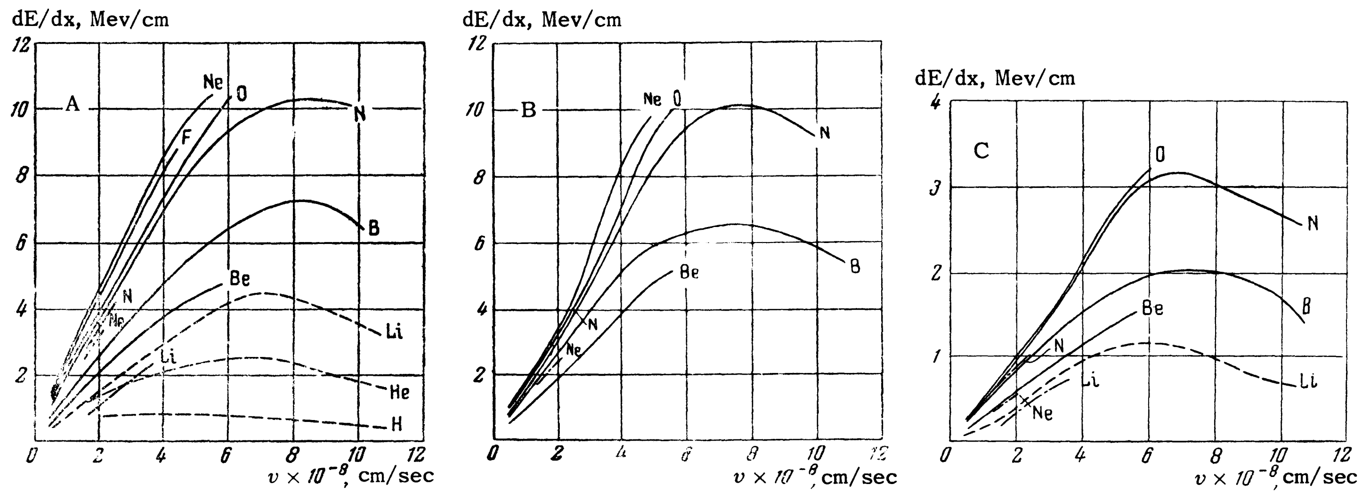

FIG. 5. Specific ionization of multiply-charged ions as function of the velocity: A – in air, B – in argon, C – in hydrogen. Solid line – results of this investigation, dotted line – from Refs. 22, 23, and 13; dash-dot line – from Refs. 21 and 20.

of the substance, leading to greater energy losses per collision and to greater deflection angles. Since the dimensions of the input slit of a proportional counter are small, the counter recorded essentially the ions that did not experience elastic collisions and whose range was greater than the range of most ions that entered into the ionization chamber. A theoretical estimate of this effect, based on the classical approximation,[24,25] leads to a range difference that is close to that observed experimentally.

Figure 4 gives all the published data on the ranges of the ^{14}N ions in air. According to Ref. 14, the ranges of accelerated nitrogen ions, measured in a condensation chamber, are approximately 5% less than our values, but this can also be attributed to the influence of nuclear collisions. The curve obtained from data on the ranges of the recoil nuclei,[6,8] a curve characterized by low statistics and large spread of individual points, differs on the average from our results by 10%. An analogous correspondence is observed also for oxygen, fluorine, and neon ions.[6-9] Only in the case of the boron ions are the ranges of the recoil nuclei (see Ref. 11) approximately 1.5 mm smaller than ours; this apparently can be attributed only partially to nuclear collisions.

Figure 4 gives also the curve for the ranges of nitrogen ions in photoemulsion,[15] recalculated for air using a value of 1800 for the stopping power. The fact that the curves agree within 15% shows that the stopping power of the photoemulsion with respect to air is the same for these ions as the stopping power for α particles.

For comparison with experiment, Fig. 4 shows three calculated curves.[3-5] The curve from Ref. 4 is close to the experimental curve for a velocity $v = 6 \times 10^8$ cm/sec, but at greater velocities it gives undervalued ranges. To the contrary, the curves from Refs. 3 and 5 do not agree with experiment at low velocities, but at $v > 7 \times 10^8$ cm/sec they agree with the experimental curve within 10%.

The measured specific-energy losses for the ^{14}N ions agree, within the limits of experimental error, with the previously obtained data[20] (Fig. 5). However, the specific-energy losses for the ^{20}Ne ions, cited in the same reference, are 30% lower than those obtained in our work. Such a discrepancy can be hardly attributed to various influences of nuclear collisions. The curve of Ref. 11 for the specific-energy losses for ^{11}B ions, calculated from the ranges, differs from our curve by not more than 10%. The value of the specific ionization calculated in Ref. 5 for nitrogen and beryllium ions is too high, and at the maximum it exceeds the experimental value by approximately 30%.

It is known that the average energy loss can be calculated from the formula

$$-dE/dx = (4\pi e^4/mv^2) i^{*2} \cdot N_0 \cdot B(v),$$

where i^* is the effective ion charge, and B is the stopping power of the substance. In the abovementioned calculations of the ranges and specific-energy losses,[1-5] the value of B was assumed the same for all ions and was determined from the values of dE/dx and i^* for protons or α particles. The values of B calculated in our work from the values of dE/dx, and the values of the rms charge from the equilibrium distribution of the charges in the ion beam,[26] have shown that in the velocity range $v < 3-5 \times 10^8$ cm/sec B diminishes with increasing Z and is approximately 20% lower for ^{20}Ne than for the ^{11}B ions. A similar character of the dependence of B on Z follows from the known Bloch formula for the specific-energy losses,[22] according to which

$$B = Z_s[\ln(2mv^2/I) - Q],$$
$$Q = R\psi[1 + j(i^*e^2/\hbar v)] - \psi(1),$$

where ψ is the logarithmic derivative of the Γ function and $R\psi$ is the real part of ψ. As Z increases, the mean charge, and consequently also the the quantity Q (which depends on the ratio of the mean charge to the ion velocity) increases and the stopping power B diminishes.

The Bloch formula is applicable only when the ion velocity v is considerably greater than the velocity u of the orbital electrons of the atoms of the substance. At $v \sim 3-5 \times 10^8$ cm/sec, this condition is not satisfied for a considerable number of electrons. One can assume, however, that at least for those electrons with $u < v$, the dependence of the stopping power on the ion charge fits the Bloch formula, and that the contribution to the stopping produced by electrons with $u > v$ is independent of Z. As a result, we can assume that $B = B_0 - Z_S^* Q$, where B_0 is independent of Z, and Z_S^* is the effective number of electrons of the atoms of the substance, for which the Bloch formula is valid.

As the velocity increases, Z_S^* should also increase, and should approach Z_S in the limit. The dependence of Q on v in the region $v \sim 3-6 \times 10^8$ cm/sec is weak, since the value of the mean charge is approximately proportional to v (Ref. 26). At greater velocities, when the mean charge increases more slowly, Q diminishes. At the same time, as the velocity increases, the value B_0 increases rapidly, i.e., B becomes on the whole less dependent on Z.

TABLE II

Ion	Air			Argon		
	B	Q	$B+3Q$	B	Q	$B+6Q$
He	10.8±0.3	0.29	11.7±0.3	20.4±0.6	0.29	22.1±0.6
B	10.0±0.8	0.58	11.7±0.8	20.0±1.5	0.60	23.6±1.5
N	9.8±0.7	0.74	12.0±0.7	17.8±1.3	0.75	22.3±1.3
O	8.6±0.6	0.82	11.1±0.6	15.6±1.0	0.84	20.6±1.0
Ne	8.2±0.5	0.92	11.0±0.5	16.4±1.0	0.92	21.9±1.0

We determined the value of Z_S^* from the values of B and Q, corresponding to the experimental values of the mean ion charge in gases.[26] In the velocity region $v \sim 4-5 \times 10^8$ cm/sec, it turned out to be close to 3 for air, ~6 for argon, and ~1 for hydrogen, i.e., $Z_S^* \approx Z_S^{2/3}$. The values of B, Q, and $B_0 = B + Z_S^* Q$ for $v = 4 \times 10^8$ cm/sec are given in Table II (the data from the survey of Ref. 24 are used for the α particles). The values of B_0, as can be seen from the table, are the same for all ions within ±7%.

It must be noted, that the close agreement between the theoretical calculations, based on the assumption that B is independent of Z, with experiment is to certain extent fortuitous and may be due to the fact that the dependence of the mean charge on Z is assumed in these investigations to be somewhat weaker than actual.

In conclusion, I express my gratitude to S. S. Vasil' ev for interest in this work and for a discussion of its results, to the cyclotron crew headed by G. V. Kosheliaev, and also to B. M. Makuna for help in this work.

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