DIFFERENTIAL AND INTEGRAL CROSS SECTIONS FOR THE LOSS AND CAPTURE OF ELECTRONS BY FAST N^+, Ne^+, *AND* Ar^+ *IONS*

L. I. PIVOVAR, M. T. NOVIKOV, and A. S. DOLGOV

Physico-technical Institute, Academy of Sciences, Ukrainian S.S.R.

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The charge distributions were measured in beams of nitrogen, neon, and argon ions, as a function of the energy and the scattering angle for single collisions with atoms of neon, argon, krypton, and xenon. For argon ions, it was found that, at high energies, the L-shell electrons took part in the interaction. A comparison is made between the total differential cross sections for the scattering of nitrogen, neon, and argon ions and the calculated differential cross sections for the scattering in the case of a Coulomb potential with an exponential screening. The results are given of measurements of the total cross sections for the capture of one electron and the loss of several electrons by N^+, Ne^+, and Ar^+ ions in single collisions with neon, argon, krypton, and xenon atoms, and the total cross sections obtained are compared with the data of other authors.

1. INTRODUCTION

THE present study is a continuation of earlier investigations of the scattering of ions and of the processes of electron capture and loss by Ar^+ and Kr^+ ions in single collisions with atoms of some inert gases.[1,2] Measurements were made of the angular and energy distributions of the charge in beams of nitrogen, neon, and argon ions when N^+, Ne^+, and Ar^+ ions suffered single collisions with Ne, Ar, Kr, and Xe atoms. We measured also the total differential cross sections for the scattering of ions, i.e., the cross sections in which all the scattered particles were allowed for, irrespective of their charge.

From these measurements, we determined the partial integral cross sections for the loss of several electrons by an ion, corresponding to the angular intervals 1–2° and 1–3°. The partial electron loss and capture cross sections, corresponding to the angular interval 0–1°, were found by direct measurements. From all these data, we were able to determine, in some cases, the values of the integral cross sections for the loss of several electrons by N^+, Ne^+, and Ar^+ ions. For N^+ and Ne^+ ions, the measurements were carried out in the energy range 250–1400 keV. For Ar^+ ions, the energy range was from 250 to 1800 keV for collisions with Ne and Xe atoms, and from 1000 to 1800 keV for collisions with Ar and Kr atoms.

2. RESULTS OF MEASUREMENTS AND DISCUSSION

The measurements were carried out using the apparatus described in detail in earlier communications[1,2] and therefore we shall not describe the apparatus again. We used beams of $^{14}N^+$, $^{20}Ne^+$, and $^{40}Ar^+$ ions and targets were Ne, Ar, Kr, and Xe gases containing impurities in amounts not exceeding 0.1%. It should be mentioned that in the present study we extended upward the range of the argon-ion energies and, at the same time, increased the intensity of the primary ion beam compared with an earlier investigation.[1]

a) The charge state, the average charge, and the average ionization energy losses. Figures 1–3 give curves representing the charge distributions of nitrogen, neon, and argon ions in the case of single collisions in various gases, as a function of the ion energy. The curves in these figures are given for the scattering angles, in the laboratory system, $\theta = 1–3°$.

The distribution of the charged fractions of nitrogen ions is not given in Fig. 1 for the scattering angle of 2° because of the large experimental error, which was due to the insufficient sensitivity of the measurement method. It is evident from the figures that the curves representing the same number of lost electrons, for the same scattering angles θ, shift toward higher energies on going from

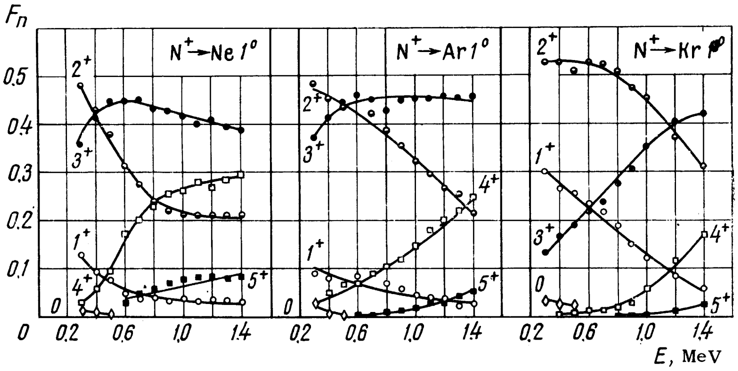

FIG. 1. Dependence of the distribution of charge fractions on the energy of nitrogen ions in neon, argon, and krypton.

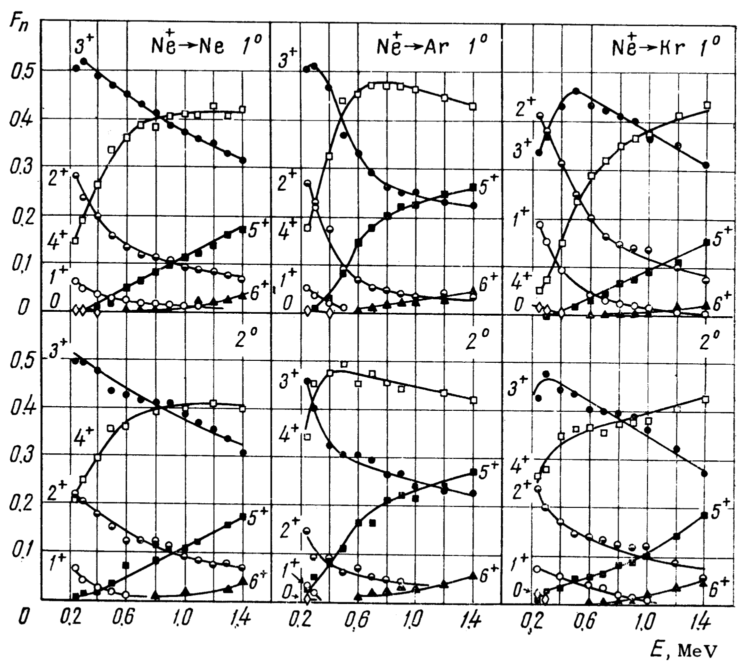

FIG. 2. Dependence of the distribution of charge fractions on the energy of neon ions in neon, argon, and krypton.

Ne to Kr targets in the case of nitrogen ions, while in the case of neon and argon ions there is a shift toward higher energies in Ne, Kr, and Xe compared with Ar. It is evident from Fig. 3 that the argon ion beams contained relatively large amounts of ions whose degree (multiplicity) of ionization was 9–10. This indicated the participation of the inner L-shell electrons of the argon atom in the interaction of colliding particles. These data, together with those obtained earlier for krypton ions,[2] show clearly the considerable role played by the inner-shell electrons in close-range atomic collisions.

Figure 4 shows the dependence of the average charge $\bar{n}$ in single collisions on the velocity of nitrogen, neon, and argon ions. The same figure includes the data on the average charge for lower velocities of Ne and Ar ions, taken from the paper of Jones et al.[3] The average charge of neon and argon ions increases approximately linearly when the ion velocity is increased in the range of low velocities. At ion velocities higher than (1–2) × 10^8 cm/sec, there are deviations from the linear dependence in the direction of a slowing down of the rise in the average charge. It is evident from Fig. 4 that the $\bar{n} = f(v)$ curves for the ions being investigated are very similar. The differences are confined to the value of the average charge, which increases rapidly as the atomic number of the ion is increased.

The calculations of the average energy losses due to the ionization of fast neon and argon ions in their interaction with Ne, Ar, Kr, and Xe atoms show that these energy losses depend both on the distance of the closest approach between nuclei r_0, and on the incident-ion energy E. For the same value of r_0, the average ionization energy losses increase when the energy E is increased. At sufficiently high Ne ion velocities, the average ionization loss depends mainly on the energy E; this follows from the fact that at a fixed ion energy, the average ionization energy losses of a fast

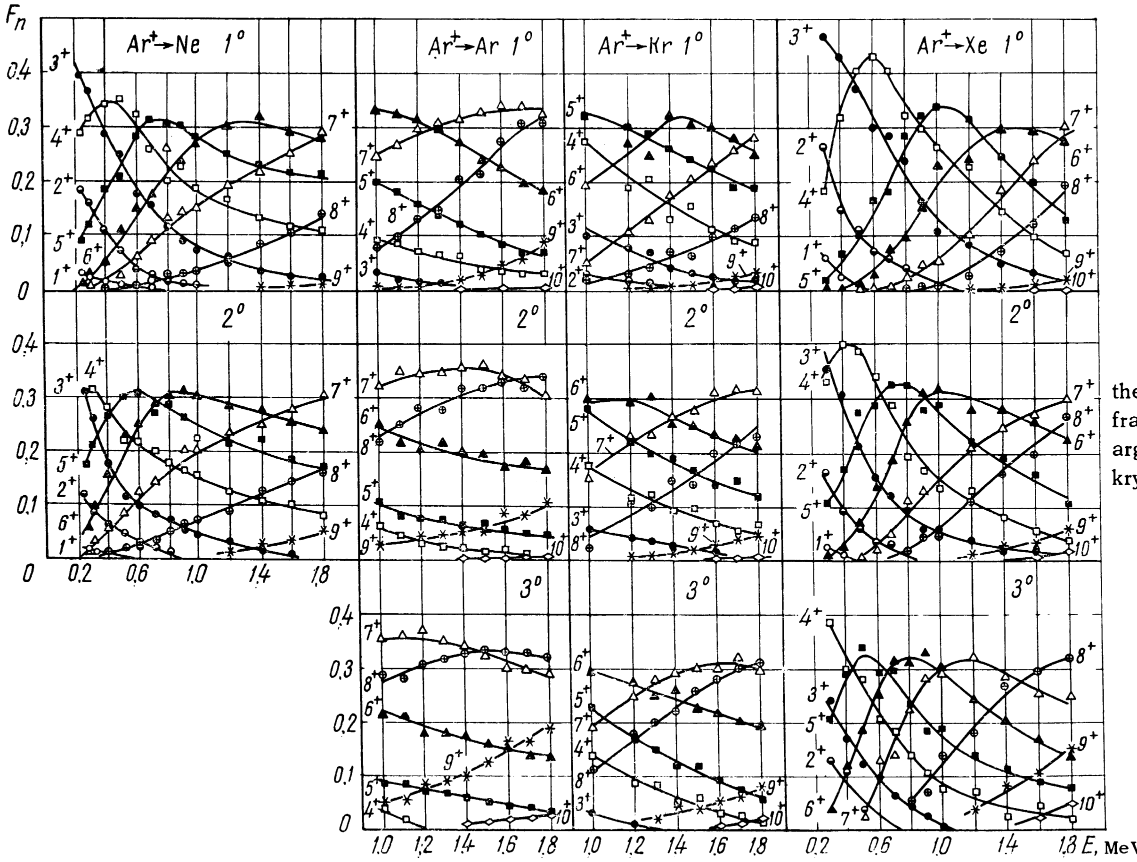

FIG. 3. Dependence of the distribution of charge fractions on the energy of argon ions in neon, argon, krypton, and xenon.

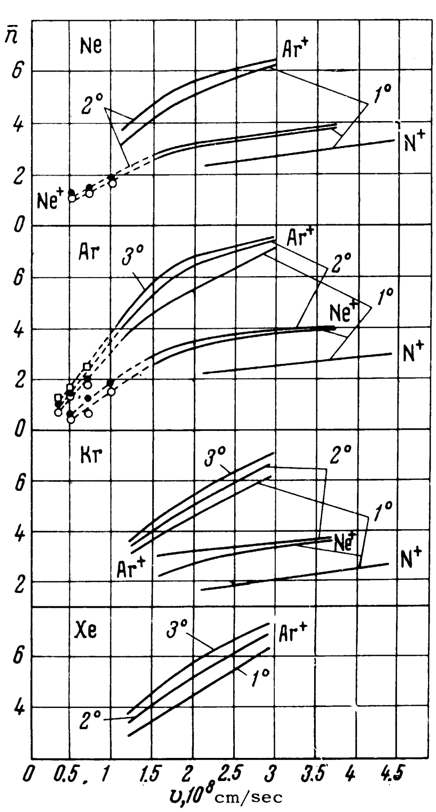

FIG. 4. Dependence of the average charge on the velocity of nitrogen, neon, and argon ions; ○, ●, □ – the average charge for $\theta = 1$, 2, and 3°, respectively, taken from[3].

particle are practically unaffected by the variation of the scattering angle θ or, which is equivalent, the variation of r_0.

In the present investigation we used a range of energies wide enough to ensure a sufficiently generous overlapping region of Ne^+ and Ar^+ ion velocities. Therefore, it seemed interesting to compare the values of the average ionization energy losses ΔE_i for neon ions in argon and for argon ions in neon for the same closest approach distances and equal relative velocities. The relevant data are presented in the table. It follows from the table that, under the same conditions, the values of the ionization energy losses are higher for argon ions than for neon ions and that this difference increases systematically when the ion velocity is increased. This fact, together with a similar result obtained in the collisions of argon and krypton ions,[2] allows us to conclude that when unlike particles collide, the ionization energy losses are greater for atoms of higher atomic number.

In conclusion, we shall compare the charge distribution we obtained with the curves of Russek.[4, 5] This comparison shows that, in the case of neon ions colliding with Ar and Kr atoms, the amplitudes of the maxima and the intersections of the corresponding charge fraction curves have

Average ionization energy losses of fast Ne^+ and Ar^+ ions in collisions with Ar and Ne atoms

10^{-8} v, cm/sec	10^9 r_0, cm	$Ne^+ \to Ar$ ΔE_i, eV	$Ar^+ \to Ne$ ΔE_i, eV	10^{-8} v, cm/sec	10^9 r_0, cm	$Ne^+ \to Ar$ ΔE_i, eV	$Ar^+ \to Ne$ ΔE_i, eV
1.55	1.74	152	153	2.4	1.0	219	276
1.69	1.6	168	179	2.6	0.86	220	300
1.96	1.36	180	220	2.76	0.76	221	321
2.19	1.17	191	254	2.94	0.70	226	345

values close to those reported in [5]. In the case of argon ions, there is a more or less close agreement with the data reported in [4].

b) The differential scattering cross sections and the integral cross sections for the capture and loss of electrons. Figure 5 shows the total differential scattering cross sections, σ^*, for nitrogen, neon, and argon ions when they interact with Ne, Ar, Kr, and Xe atoms. The continuous curves in Fig. 5 represent the differential cross sections for the elastic scattering of these ions, calculated on the assumption that the interaction may be represented by a Coulomb potential with an exponential screening.[6]

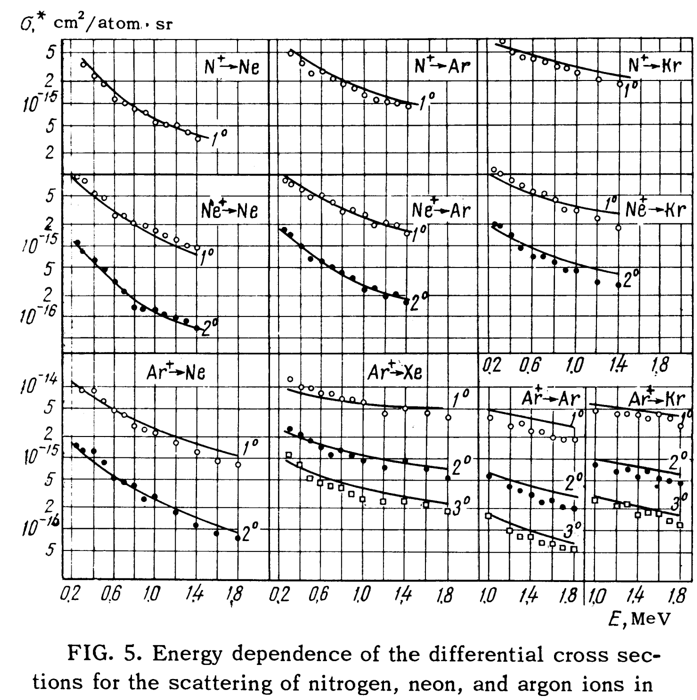

FIG. 5. Energy dependence of the differential cross sections for the scattering of nitrogen, neon, and argon ions in neon, argon, krypton, and xenon. The continuous curves were calculated using the formulas given in[6].

It is evident from Fig. 5 that, in the majority of cases, the experimental and calculated cross sections agree within the limits of the experimental error. However, at high energies of argon ions the experimental values of the differential scattering cross sections are lower than the calculated ones. This is probably due to some unsuitability of the potential selected to describe the elastic interaction between atoms in these cases.

From the measured charge fractions and the total differential scattering cross sections, we determined the differential cross sections for the electron loss by N^+, Ne^+, and Ar^+ ions using the formula $\sigma^*_{1n} = \sigma^* F_n$. Numerical integration of the function $\sigma^*_{1n}(\theta)$ for the investigated angular intervals makes it possible to calculate some integral cross sections for the electron loss. The partial integral cross sections representing the processes of electron capture σ_{10} and loss σ_{1n} by N^+, Ne^+, and Ar^+ ions in the angular range 0–1° were measured directly. The total effective cross sections for the electron loss were determined by adding the partial cross sections corresponding to the angular intervals from 0 to 180°. Because $\sigma^*_{1n}(\theta)$ decreased rapidly when the angle θ was increased, in many cases it was possible, without committing a large error, to neglect the quantity σ_{1n} in the interval from 2–3 to 180° and to assume that $\sigma_{1n} \approx \sigma_{1n}(0-1°) + \sigma_{1n}(1-3°)$ was the total ef-

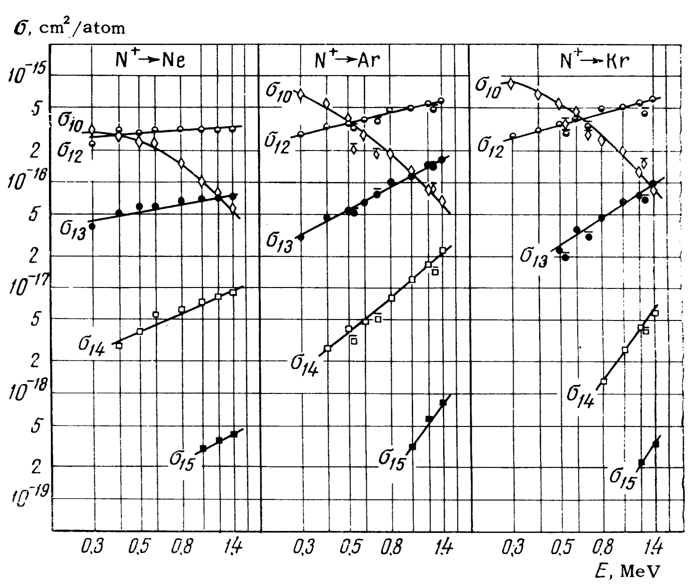

FIG. 6. Energy dependence of the total effective cross sections for the capture σ_{10} and loss σ_{1n} of electrons by nitrogen ions in neon, argon, and krypton. The points marked with a bar above them were taken from[7-9].

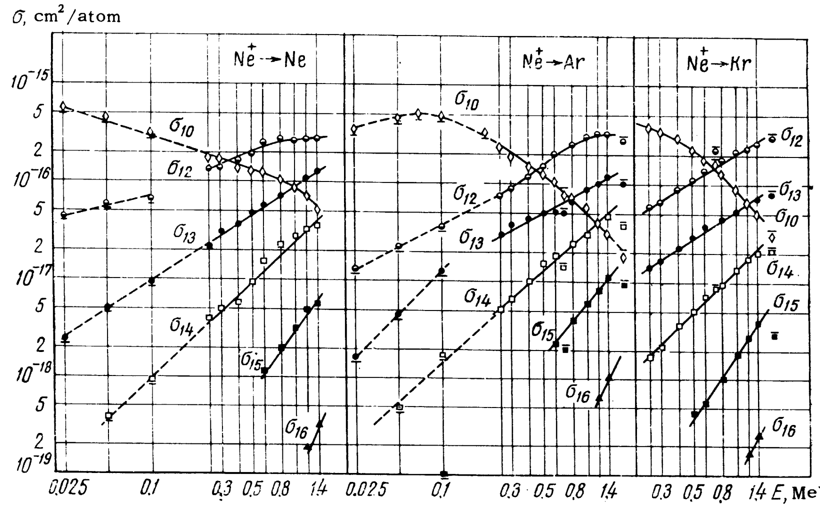

FIG. 7. Energy dependence of the total effective cross sections for the capture σ_{10} and loss σ_{1n} of electrons by neon ions in neon, argon, and krypton. The points marked with a bar above them were taken from[3] and those with a bar below were taken from[7-9].

fective cross section for the loss of (n − 1) electrons by N^+, Ne^+, and Ar^+ ions.

Figures 6–8 show the dependences, on the ion energy, of the integral effective cross sections for the electron loss σ_{1n} and capture σ_{10} by N^+, Ne^+, and Ar^+ ions in collisions with Ne, Ar, Kr, and Xe atoms. The same figures include the experimental values of the effective cross sections of the corresponding processes, reported in the papers of Dmitriev, Nikolaev, et al.[7-9] The integral effective cross sections for the loss of (n − 1) electrons by singly charged nitrogen, neon, and argon ions increased in the whole investigated range of energies. Only the cross section σ_{12} for neon and argon ions had maxima for some of the targets. In the majority of cases, the increase in the cross sections σ_{1n} when the energy increased was described, over wide ranges of the energy E, by power functions, which followed from the approximately linear dependence $\sigma_{1n} = f(E)$ plotted on logarithmic scale. The tangents of the slopes of these straight lines increased when the degree of ionization increased. The cross sections for the electron capture σ_{10} decreased systematically when the ion energy increased in the investigated range of energies.

The experimental errors in the determination of the integral cross sections did not exceed 15–20%. The experimental values of the effective cross sections for the electron capture and loss by Ne^+ ions in Ne and Ar, in the energy range 25–100 keV, taken from [3] and the data of the present study in the energy range 200–1400 keV fitted, in most cases, smooth curves representing the corresponding processes.

Nikolaev, Dmitriev, et al.[7-9] did not measure the scattering of the incident ions in the investigation of the cross sections of the electron loss and capture by N^+ and Ne^+ ions in Ar and Kr. However, a comparison of the values of the cross sections σ_{10}, σ_{12}, σ_{13}, and σ_{14} for nitrogen ions, obtained in the present study, and of the corresponding cross sections reported in [7-9] showed that at energies above 500 keV the differences did not ex-

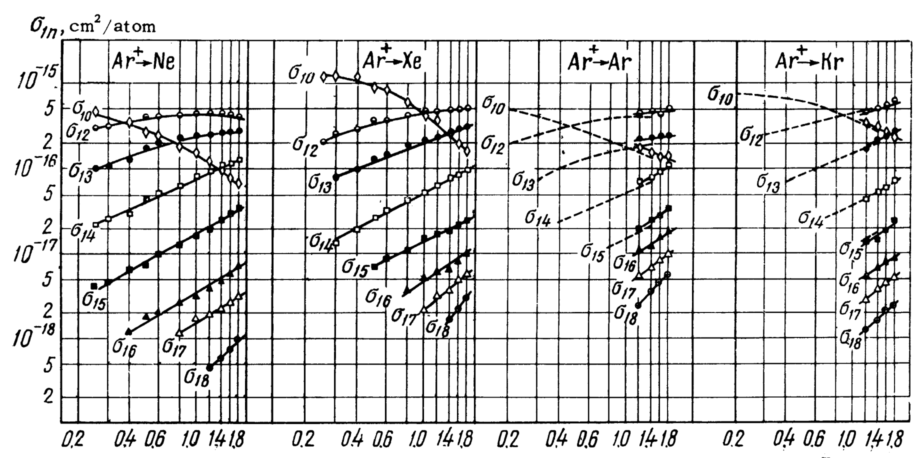

FIG. 8. Energy dependence of the total effective cross section for the capture σ_{10} and loss σ_{1n} of electrons by argon ions in neon, argon, krypton, and xenon. The dashed curves were taken from[1].

ceed, in most instances, the limits of the experimental error. At energies of the order of 700 keV and higher, the differences between the values of the cross sections σ_{10}, σ_{12}, σ_{13} for Ne^+ ions also lay within the limits of the permissible experimental error. The differences between the values of the cross sections σ_{14} and σ_{15}, obtained in the present study, and those reported in [9] were greater, which may be explained by the fact that the influence of the ion scattering was ignored in the measurements of the cross sections for higher degrees of ionization reported in [9].

In the range of energies we investigated, there were practically no data on the integral cross sections for the electron capture and loss by Ar^+ ions with which we might compare the results of our investigations. A comparison of isolated results for the interaction of Ar^+ ions with argon and krypton atoms has been given in [1].

In conclusion, we regard it as our pleasant duty to express our gratitude to A. K. Val'ter, Academician of the Ukrainian Academy of Sciences, for his interest in this study, and to the operators of the accelerator, Kh. M. Khurgin and V. G. Rubashko, for their help in carrying out the experiments.

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