Electron-beam method of multiple ionization of atoms

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The theoretical principles are presented and a review is given of the present experimental development of the electron-beam method of obtaining ions of high charge states, including nuclei completely stripped of their electron shells. The basic features of the method and the present level of its development already make it possible to obtain beams of ions such as helium-like xenon (Xe^{52+}) and to investigate physical ionization processes with the participation of particles inaccessible for other methods. The electron-beam method of ionization has made it possible to develop ion sources of a new type for accelerators of high-energy heavy ions, the so-called cryogenic electron-beam ionizers. The most topical problems in the further development of the method and its applications in different fields of physics are considered.

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INTRODUCTION

It is well known that the concept of the atom along ago lost its literal meaning—it would be difficult to find a significant number of reasonably stable isotopes whose nuclei have not been split by man. Nevertheless, in the period since it was established that the main constituents of an atom are a nucleus and an electron shell surrounding it, the separation of the nucleus by stripping its electron shell has not yet been achieved for an absolute majority of the elements despite the fact that the energy requirements for such preparation of an atom are much less than for any nuclear transformation.

Interest in this problem, formulated more or less clearly, has existed since the first observation in 1886 by Goldstein[1] of ion beams and the creation in 1910 by J.J. Thomson[2] of an ion source. Since the fifties of our century, the problem of obtaining and investigating the properties of multiply ionized atoms has acquired great practical importance in connection with the idea of accelerating heavy ions and the development of heavy-ion nuclear physics. The investigation of electron-oscillation gas discharges (of the type of a Penning discharge[3]) made it possible to develop devices for obtaining intense beams of multiply charged ions such as C^{4+}, N^{5+}, O^{5+}, Xe^{11+}, etc., which was a significant success.[4-6] However, because of some fundamental limitations it has not yet proved possible to obtain ions with significantly higher charges using ionization by this method. Moreover, it is obvious that the part of the problem which cannot be solved by this method is much more difficult, since the ultimate task is to obtain and investigate the properties of ions of high charge states, including nuclei of all the elements up to uranium completely stripped of electrons. The magnitude of the problem is brought home by the fact that compared with the Xe^{10+} ion the binding energy of the last electron in the U^{91+} ion is approximately 10^3 times greater, and the effective cross section for ionization by electron impact is approximately 10^6 times less even for optimal energy of the ionizing electrons.

The practical need for fundamental and applied investigations in this direction has become especially clear during the last decade with, in particular, the development of the methodological base of relativistic nuclear physics, on the one hand, and the obtaining of plasmas of even higher temperature in research installations and prototypes of controlled thermonuclear-fusion reactors, on the other.

Because of the inadequacy of the theoretical methods, the fundamental investigations include experimental measurements of the energy dependences of the effective cross sections for ionization of positive ions, especially hydrogenlike ions in the 1S state, by electron impact; experimental study of the complete spectrum of phenomena associated with charge-exchange processes involving ions, including nuclei completely stripped of electrons, on various targets, in particular atomic hydrogen at relatively low energies and molecular nitrogen at high energies; and also deionization processes in collisions of highly charged ions and nuclei with surfaces of solids, etc. Great interest attaches to experimental investigation into the dependence of nuclear properties and, in particular, the characteristics of radioactive decay on the degree of ionization of the electron shell; this is a problem that for a number of decades has been discussed only theoretically.

The applied investigations have as their first aim the development of facilities for obtaining beams of ions with higher and higher charge states to be used in various fields of science and technology, especially in accelerators of charged particles as ion sources. For example, for the acceleration of heavy ions to relativistic energies, the use of beams of nuclei completely stripped or electrons is regarded as optimal. If such beams are obtained directly in the ion source, the relativistic accelerating complex can be simplified to the greatest extent possible. Clearly, the key to the solution of all these problems, and others too, is the development of a new and more effective method of ionization.

In recent years, essentially three different directions of investigation have developed here: the refinement of the method of obtaining multiply charged ions in a gas discharge with microwave heating of plasma electrons at the cyclotron resonance frequency (ECR method),[7] the use of the high-temperature plasma produced

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irradiating the surface of a working body by a high-intensity pulse of laser radiation,[8] and the development of the pulsed electron-beam method of ionization. This method was proposed[9] in the Joint Institute for Nuclear Research in 1967 and is currently being successfully developed at several research centers in the Soviet Union and a number of other countries.

The pulsed electron-beam method of ionization involves: 1) the obtaining of a sufficiently extended electron beam of given energy and given density; 2) the creation of a trap configuration of the electric field along the ion beam; 3) the injection of a definite number of ions of the working substance into the trap during a definite period of time; 4) containment of the ions in the electrostatic trap within the electron beam during a period of time sufficient for the ions to reach the required charge state; 5) extraction of the ions from the trap along the electron beam and preparation for the next cycle.

This method is now the most effective and makes it possible to obtain positive ions of all charge states up to ions of the type Xe^{52+}, including Kr^{34+} ions, and nuclei of elements up to argon (Ar^{18+}) completely stripped of electrons; in the future, it is very probable that it will be possible to obtain all positive ions and nuclei of all elements up to uranium (U^{92+}).

1. THEORETICAL PRINCIPLES OF THE ELECTRON-BEAM METHOD OF IONIZATION

As a rule, a multiply charged ion cannot be obtained by electron impact as a result of a single collision of a fast electron with an atom. Several collisions are required, each involving removal of one electron to the continuum with a corresponding increase in the charge state of the ion. In such a case,[10]

$$P_{q\to q+1} = \sigma_{q\to q+1}\,(j\tau_i).$$

where $P_{q\to q+1}$ is the probability of transition of the charge state q of the ion to $q+1$, $\sigma_{q\to q+1}$ is the effective cross section for ionization of the positive ion of charge q by electron impact, and $j\tau_i$ is the ionization factor (the product of the flux density j of the bombarding electrons and the time of bombardment τ_i of the stationary ion target).

To obtain ions of mean charge $\bar{q}$ from singly charged ions, the ionization factor

$$j\tau_i = \sum_{q=1}^{\bar{q}-1} \sigma^{-1}_{q\to q+1}$$

is required.

In each case, $\sigma_{q\to q+1}$ can be estimated using, for example, Lotz's empirical formula.[11] In this approximation, calculations were made of the $j\tau_i$ values needed to obtain Ne, Ar, Kr, Xe, and U ions of all charges from singly charged ions under the condition that the ionization takes place at electron energy $E_e = 2I_{q-1}$, where I_{q-1} is the binding energy of the last electron in the shell of the ion of charge $q-1$.[12] The results of the calculation are given in Fig. 1.

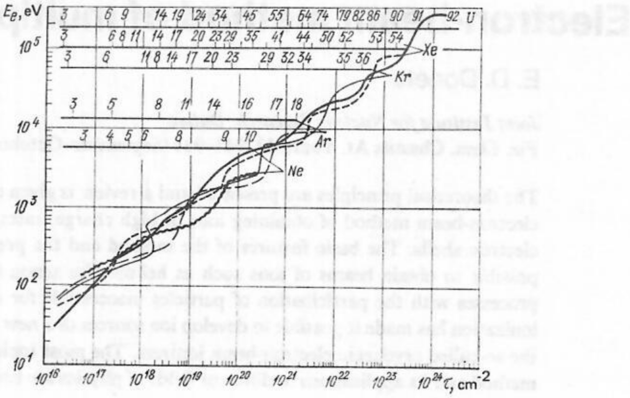

FIG. 1. Calculated values of $j\tau_i$ needed to obtain Ne, Ar, Kr, Xe, and U ions of the given charge states for the corresponding energies of the bombarding electrons.

If the obtaining of U^{92+} nuclei is regarded as the most difficult ionization task, it can be seen from Fig. 1 that its solution requires a factor $j\tau_i \approx 2\times10^{24}$ cm^{-2}. This means that if an electron beam of flux density 6.3×10^{22} cm$^{-2}\cdot$sec^{-1} (10^4 A/cm^2), for example, is used, the time of bombardment of the stationary ion target must be about 30 sec, and the possible recombination processes must be suppressed, i.e., the ions must be contained in the beam for a long time.

Methods of obtaining dense extended electron beams are fairly well known, and we shall not describe them here. We merely point out that to focus the beam, i.e., to ensure that it has a constant shape and area of its section over an appreciable length, a longitudinal magnetic field is usually employed. Thus, the ions in the beam are in a fairly strong magnetic field.

For radial containment of the ions in the electron-beam method of ionization, the natural dip ΔU in the potential produced by the space charge of the electron beam is used.[9] It is well known that in the axisymmetric case

$$\Delta U = S^-(2\ln R/r_0 + 1),$$

where S^- is the linear charge density of the fast electrons of the beam, r_0 is the beam radius, and R is the radius of the drift tube in which the beam moves.

To vary the potential along the axis of the system, there are several possibilities, the simplest of which is to make the drift tube in sections and apply different potentials U_{dt} to the different sections.[10] To close the electrostatic trap within the beam in the axial direction, it is sufficient to apply $U_t \geqslant |S^-(2\ln(R/r_0)+1)|$ at the end sections.

The radial containment forces disappear completely if there is complete compensation of the electron space charge by the ion space charge. Under this assumption,

$$C^+ = 3.36\cdot10^{11}\, I_e L E^{-1/2},$$

where C^+ is the capacitance of the electrostatic trap (the number of elementary charges), I_e is the beam current in amperes, L is the length of the trap in meters, and E_e is the electron energy in kilo-electron-volts.

Because the electron beam always exists in a container with some residual gas pressure, a closed trap configuration of the potential cannot exist infinitely long. If all the ions that arise from the residual gas a accumulate in the trap, remaining singly charged, then after a time interval τ_c the radial containment force disappears.

If Lotz's formula is used to find the ionization cross section, the compensation time τ_c can be estimated by means of the expression

$$\tau_c = 7.5 \cdot 10^4 \frac{E_e^{1/2} I}{n \ln E_e/I},$$

where τ_c is the compensation time in seconds, n is the number of atoms of the residual gas per cubic centimeter, I is the ionization potential in electron volts, and E_e is the electron energy in electron volts. Thus, if a trap is used to contain the ions of the working substance with a view to multiple ionization, the necessary value of the factor $j\tau_i$ can be attained only when $\tau_i \ll \tau_c$.[10]

In contrast to other ways of using electron beams for ionization, the electron-beam method is pulsed and requires successive implementation of the main operations listed above. The dynamics of the ions in the electron beam during the process of injection, containment, ionization, and extraction can be described qualitatively in the framework of the model of single ions, a self-consistent field, and the collective model.[13]

The criterion for validity of the model of single ions is $S^+ \ll |S^-|$, or rather $S^+ \approx 10^{-2}|S^-|$, which means that the space charge of the ions, whose linear density is S^+, does not influence the motion of the ions in the field of the space charge of the electrons. When $S^+ \approx |S^-|$, one can use the self-consistent field approach, in which the field of the ions has a strong influence on their own motion but does not influence the motion of the electrons. The collective model takes into account interaction between the electron and ion fields and the occurrence of collective effects.

Injection of Ions into the Trap. The most natural method of filling the electrostatic trap with ions is to generate them directly in the trap from the atoms of a cloud of the working gas under the influence of the electron beam. In the axisysmmetric case, mostly singly charged ions with kinetic energies near the thermal energy are produced with equal probability at any point r_i of the beam section. These ions then execute oscillatory motions with respect to the point of minimum potential.

In the model of single ions, the potential energies E_i of the ions will lie between 0 and $-qS^-$ with a constant number of ions per unit energy range. In their motion, the ions do not leave the beam, which is very important for example, in the investigation of the ionization process.

Since the real injection time in the self-consistent field model is always appreciably greater than the ion oscillation period, the characteristics of the motion of an ion with frequency ω_i change adiabatically with respect to the slow variation of the field. Since ω_i is determined by the rigidity of the system, and growth of the ion space charge can be expressed as a decrease in rigidity, ω_i decreases during the injection process. For constancy of the adaibatic invariant, the energy of the oscillations must also decrease.

It can be shown by a simple argument that the amplitude of the oscillations of a given ion during the injection process increases, leading ultimately to accumulation of the most energetic ions at the wall of the drift tube. New ions are produced under conditions of decreasing self-consistent field. When $S^+ = |S^-|$, equilibrium is established between the current of the ions moving to the wall and the ion charge generated per unit time. At the same time, the mean ion energy is near the thermal energy. If the injection is now stopped, then subsequently, in the ionization process, the growth in q will be accompanied by a growth in S^+, which results in the ions moving out of the beam. This introduces significant uncertainty into the analysis of the ionization process.

There is a possibility of obtaining a column of ions in the axial region of the tube in order to avoid subsequent loss of ions during the ionization process. For this, ions are injected into a beam of relatively low density S^-_{in} until the condition $S^+ = |S^-_{in}|$ is satisfied, and then S^- increases to the normal value S_t.[9] In this case, the motion of the ions is the opposite of the motion considered earlier: ω_i and E_i increases while r_i decreases, leading to a concentration of the ions in the axial region. Another possibility is to inject the ions with axial confining potential barriers $U_t < |S^-(2\ln(R/r_0) + 1)|$. In this, the most preferable case, the column of ions in the axial region is formed by ions of thermal energies.

To ensure a pulsed injection of the ions into the electron beam, one can use a pulse-generated cloud of atoms of the working gas, which can be obtained by means of a laser beam in the case of solid working substances. However, at the present time the electron pulse-injection method is used. In this method, the working gas enters the injection region continuously and the electron beam always intercepts the cloud of working gas produced in this section, but appropriate axial distributions of the potential are used to ensure that the actual position of interception is contained within the electrostatic trap for only a controlled interval of time.[14]

The arrangement of the drift tube with cloud of working gas in region A and the corresponding distributions of the potential are shown in Fig. 2.[13] The distribution in Fig. 2a precedes the beginning of injection of the ions into the trap B. The directions of motion of the positive ions of the working gas and of the ions of the background gas in region B generated by the presence of the electron beam in region A are shown by the arrows.

When the injection commences, the distribution of the

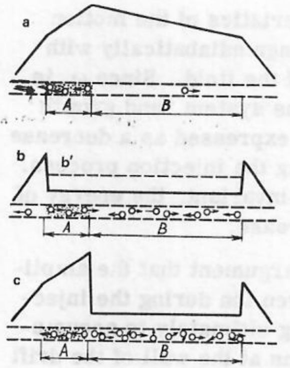

FIG. 2. Injection of ions from region A into the trap B. The distributions of the potentials during the preparation are shown in Fig. 2a, during injection in Figs. 2b and 2b′, and at the start of ionization in Fig. 2c.

potentials (see Fig. 2b) combines regions A and B into a single trap, so that the ions generated in region A are freely distributed in the region A + B.

Once the necessary number of ions has been introduced into the electron beam, the distribution of the potentials shown in Fig. 2c is established; in it, the ions that are then generated in region A move away in the direction shown by the arrow, while the ions intended for subsequent ionization are contained in the trap in region B.

In this method, there are four different parameters that can be used to regulate the number of ions introduced into trap B:

1) the electron current during the injection time;

2) the injection time (τ), during which regions A and B are united to form a common trap;

3) the level of the axial trapping barrier during the injection time,

$$U_t \leqslant |S^-(2\ln R/r_0+1)|;$$

4) the concentration of atoms of the gas in region A.

A necessary condition for realization of pulsed electron injection is of course elimination of a possibility of gas passing directly from region A to region B.

Containment of the Ions. Ionization. If the ions injected into the trap with initial charge q_{in} are to reach the final charge state q_f, they must be contained in the electron beam for a time

$$\tau_i \approx \frac{1}{j}\sum_{q_{in}}^{q_f-1}\sigma^{-1}_{q-q+1}.$$

The basic characteristics of the radial motion of the ions with allowance for the dynamics of the charge state in the model of single ions is as follows. If q increases at the point of production of the ion, i.e., at $r_{i,max}$, then in the absence of a magnetic field the trajectory does not change but the energy E_i of the ion increases in proportion to q, $\omega_i \sim \sqrt{q}$, and $r_{i,max}$ is conserved, since the rigidity changes nonadiabatically. Similar changes take place in the presence of a magnetic field.

But if q increases at $r_i < r_{i,max}$, the ion cannot subsequently reach $r_i = r_{i,max}$, although E_i and ω_i increase.

Thus, by the end of the ionization process the energy spread of the ensemble of ions increases ($0 \leqslant E_i \leqslant -q_f S^-$) with a smaller increase in the most probable energy, ω_i increases as $\sqrt{q}$ with a smaller increase in the most probable frequency, and the most probable value of $\overline{r}_i$ decreases, i.e., there is a more or less significant concentration of ions in the direction of the beam axis.

We now consider the self-consistent field model. If there is adiabatic increase in S^- after the end of injection, then, on the one hand, ω_i and E_i decrease, while $r_{i,max}$ increases because of the increasing compensation; conversely, ω_i and E_i increase and $r_{i,max}$ decreases because of growth in q. If $|S^-_{in}| < |S^-_f|\, q_{in}/q_f$ in this case, it is possible to keep all the ions in the trap until the end of the ionization process.

If a core of ions with near-thermal energies is formed as a result of injection in the axial region of the beam, so that in this region the charge of the beam is fully compensated, while the main part of the beam is free of ions, the region with ions will be overcompensated during the process of ionization by the ion charge. If at the beginning of the ionization process the confining voltage is increased, $U_t \geqslant |S^-|(2\ln(R/r_0)+1)$ (see the transition from Fig. 2b′ to Fig. 2c), then the ions cannot leave the trap in the axial direction, and their charge compensation the region of the beam free of ions. In this case, it is possible to obtain the maximal number of ions if the final charge value, since at the end $S^+ \approx |S^-|$.

Ion Extraction. The ions are extracted from the trap B in the region of the electron beam in the axial direction by the creation of an appropriate axial distribution of the potentials along the beam (Fig. 3).[13] The ion extraction can be passive, when the right-hand barrier for the ions is removed (see Fig. 3a) and the ions leave the trap by virtue of their kinetic energy (in the model of single ions) or by virtue of the axial gradient of the self-consistent electric field of the ion space charge. As the ions are extracted, they can be made monochromatic by a more or less gradual transformation of the

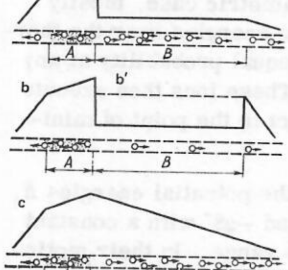

FIG. 3. Extraction of ions from the trap B. The distributions of the potentials during passive extraction are shown in Fig. 3(a), during the monochromatization in Fig. 2b→2b′, and during active and fast extraction in Fig. 2b→2c.

potential distribution b into the distribution b′ (see Fig. 3). Fast active extraction occurs when the distribution b is transformed into the distrubution c with greater or lesser gradient of the external electric field along the system.

If certain relationships are satisfied between the parameters of the electron beam, the density of the ion charge, and the characteristics of the ions and the external fields, an instability can arise in the ion–electron system. The development and stabilization of one form of instability was considered by Bonch-Osmolovskiĭ[15]; in particular, he showed that in the case of 10% compensation and a longitudinal magnetic field of order 5 T it is possible to use an electron beam with $j \approx 6.3 \times 10^{23}$ cm$^{-1}\cdot$sec^{-1}, i.e., the ionization factor needed to obtain the uranium nuclei U^{92+} can be achieved during $\tau_1 \approx 1.5$ sec.

In constructing the above model of the electron-beam method of ionization we used essentially only simple electrostatic considerations and we analyzed an idealized system consisting of slow ions and a beam of fast electrons. The actual situation which obtains in an attempt at experimental realization of the method is anavoidably more complicated as regards the number of species of participating particles and fields as well as with regard to the processes that take place.

Therefore, the effectiveness of the method and the limits of its applicability could be established only experimentally.

2. EXPERIMENTAL DEVELOPMENT OF THE ELECTRON-BEAM METHOD OF IONIZATION

To test a number of basic propositions, two experimental facilities were developed at the Joint Institute—the electron-beam ionizers IÉL-1 and IÉL-2 with normal conduction solenoids 0.16-m and 1-m long, respectively. The IÉL-1 ionizer[10,16-18] was used, in particular, to investigate the accumulation in an electrostatic trap of ions of the residual gas, i.e., during continuous supply of the working substance (actually, a regime of prolonged injection). It was shown that the accumulated ion charge generated within the electron beam is determined by the current I_e, the energy E_e, the pressure of the residual gas, and the accumulation time. The curve of the accumulated ion charge as a function of the accumulation time reaches saturation at a state near complete compensation. The effectiveness of the ion containment was investigated by measuring the dynamics of the accumulated charge and analyzing the charge values of the ions during the time of flight. In particular, it was established that the spectra of charge states are shifted to larger values of $\overline{q}$ with increasing time of containment of the ions in the trap, i.e., the multiply charged ions are formed not in a single collision but as a result of successive transition of the lower charge states to the higher. It proved possible to obtain a residual gas pressure of order 2×10^{-8} Torr within the trap. Growth of ion charge states to C^{5+}, N^{6+}, and O^{7+} was observed as the containment time was increased to 20 msec and $j\tau_1$ was accordingly increased to 2×10^{17} cm^{-2} [for $j_e \approx 10^{18}$ cm$^{-2}\cdot$sec^{-1}].

Experiments with the IÉL-2 facility[18] showed that for number of ions per pulse can be increased by increasing I_e and the volume of the trap, especially its length. The establishment of a potential gradient along the axis of the drift structure led to complete extraction of the ions from a trap about 1-m long, i.e., a regime of active, fast extraction was realized. It was also established experimentally that the passage of the electron beam through the structure of the drift tube, accuracy of which is harder to achieve, the longer the length of the system, has a decisive influence on the operation of the ionizer. If the beam is nonaxial by an amount comparable with its diameter and the distance to the tube wall and there is even minimal bombardment of the wall, it is almost impossible to make the facility function.

Experience of operation with the IÉL-1 and IÉL-2 models showed that an electron-beam ionizer can in principle be realized but that new technical solutions must be found in order to develop an efficient facility. In 1971, the proposal was made at the Joint Institute to construct an ionizer based on cryogenic technology and superconductivity, and the cryogenic ionizers KRION-1 and KRION-2 were later constructed.[19-21] The main arguments for this course were the following: Cryogenic technology ensures the best vacuum, and cooling of the drift tubes to 4.2 °K also makes it possible to realize pulsed injection of the working substance for the majority of gases; superconductivity ensures a magnetic field intensity that is effectively unrestricted for the required purposes, and moreover, because of the large number of thin windings, it is easier to obtain the necessary axial homogeneity of the field of the focusing solenoid; further, the realization of superconductivity can be organically combined with the cryogenic vacuum technology; finally, the energy needed to sustain the magnetic field is negligible, which is a very important consideration. The ionizer KRION-1 was developed as a source of nuclei of light elements for the synchrophasotron, while KRION-2 was developed especially for research purposes.

The two ionizers have a similar construction, which is based on a cryogenic-magnetic system. The superconducting magnetic systems[22,23] with 1.2-T and 2.25-T solenoids, respectively, 1.2-m long operate in the frozen-current regime. The cryogenic-magnetic system has three temperature terminals: room temperature, 78 °K, and 4.2 °K with bases, respectively, on the vacuum casing, and on the bodies of the liquid-nitrogen and liquid-helium cryostats. The electron- and ion-optical system has three groups of elements connected to these temperature terminals. The technical realization of the constructions is very felicitous and has ensured reliable use of the ionizers for several years.

The electron- and ion-optical system of the ionizer KRION-2, the distribution of the magnetic field induction, and the distribution of the electric potentials for controlling the axial motion of the ions along the axis of the ionizers are shown schematically in Fig. 4. The working gas enters the third section of the drift tube through a channel at temperature 78 °K; the sections

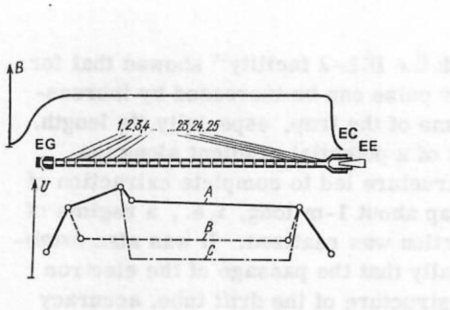

FIG. 4. Arrangement of the electron- and ion-optical systems of the KRION ionizer: EG is the electron gun, 1–25 are the sections of the drift tube, EC is the electron collector, and EE is the extracting electrode. The distribution of the magnetic induction B along the ionizer axis is shown, as well as the distributions of the electric potentials U along the drift structure of the ionizer.

of the drift tube from 7 to 22 have $T = 4.2\,°K$, which ensures that the pressure of the residual and working gases in this region in the presence of the electron beam are $\leq 1\times10^{-10}$ Torr for KRION-1 and $\leq 1\times10^{-12}$ Torr for KRION-2.

When KRION-1 was used, the complete sequence of operations of the electron-beam method of ionization was realized for the first time, this including pulsed electron injection, which was realized for the gases C_2H_4, N_2, Ar, and Xe. A total of 10^{10}–10^{11} ions was injected into the beam during 50–100 μsec, which is difficult to achieve by any other injection method. The ionization factor achieved was 6×10^{18} cm^{-2} for $E_e = 4$ keV, and beams of C^{6+} and N^{7+} nuclei were obtained, which made it possible to begin work on adapting this ionizer for the accelerator conditions; the ions Ar^{13+} and Xe^{29+} were also obtained.[19]

The problems of injection, containment, and ionization of the ions by electron impact were basically investigated using the ionizer KRION-2.[14] Here, six-fold magnetic compression of the area of the electron beam was acheived, and the limiting parameters were as follows: $E_e = 22$ keV, $J_e = 4.2\times10^{21}$ cm$^{-2}\cdot$sec^{-1} (650 A/cm^2), $\tau_1 = 5.5$ sec, and $j\tau_1 \approx 8.1\times10^{21}$ cm^{-2}.

Investigation of the Capacitance of the Ion Trap.[24] The capacitance C^+ of the electrostatic ion trap is the limiting value of the ion charge Q^+ accumulated in the electron beam over the given length L (sections 2 + 22) with increase of any one of three variables (q_g, the gas flux in the region of the third section; τ_{inj}, the injection time; and U_t, the height of the barrier at section

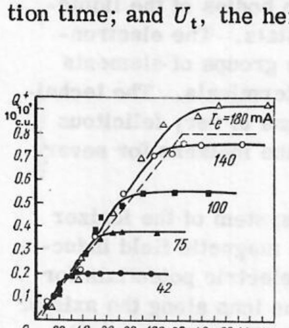

FIG. 5. Dependence of the total ion charge Q^+ in the trap on the trapping potential U_t.

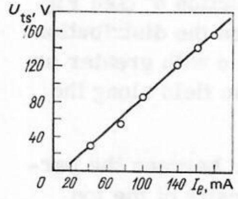

FIG. 6. Dependence of the trapping potential at saturation on I_e.

23) when the other two are already fairly large. Figure 5 shows the family of curves $Q^+ = f(U_t)$ for different values of I_e at $E_e = 8$ keV. All the curves are similar—there is an approximately linear increase and a transition at U_{ts} in accordance with the theory based on the self-consistent field model (the broken line for $R/r_0 = 10$, $I_e = 140$ mA). The dependence of U_{ts} on I_e, which is a straight line in accordance with the fact that the natural dip in the potential on the beam axis is proportional to the current for unchanged energy of the electrons, is shown in Fig. 6.

If a charge Q^+ less than C^+ is introduced into the electron beam (for example, by decreasing q_g), then saturation occurs in the function $Q^+ = f(U_t)$ at a U_{ts} which is smaller than for $Q^+ = C^+$. The dependence of U_{ts} on Q^+ for $I_e = 150$ mA, $E_e = 8$ keV is shown in Fig. 7. An anomaly occurs at $Q^+ \approx 3\times10^{-2}C^+$, when U_{ts} ceases to decrease with further decrease in Q^+. The value of U_{ts} at this point is equal to the potential difference between the boundary of the beam and its axis. This picture corresponds to the model of single ions and indicates that the ions do not pass outside the electron beam.

In the self-consistent field model, C^+ is equal in modulus to the number of fast electrons over the length of the trap and, hence, is proportional to I_e for E_e = const. The family of curves $C^+ = f(I_e)$ for several values of E_e is shown in Fig. 8a. It can be seen that linear growth of C^+ is observed only up to a definite value of I_e, at which a deviation from linear growth of C^+ begins, this being followed by a decrease in C^+ with increasing I_e. We shall call this the critical (I_e^{cr}) value of the beam current. The dependences $Q^+ = f(I_e)$ for $Q^+ < C^+$ are shown in Fig. 8b. It is found that in this interval the value of I_e^{cr} does not de-

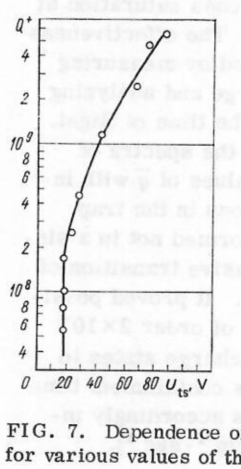

FIG. 7. Dependence of the trapping potential at saturation for various values of the ion charge in the trap.

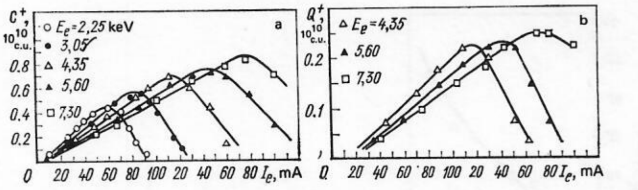

FIG. 8. Dependence of the trap capacitance (a) and the total charge in the trap (b) on the beam current for different values of the electron energy.

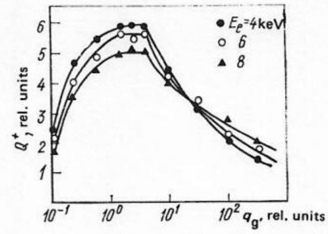

FIG. 10. Dependence of the ion charge in the trap on the flow of gas into the injection region.

pend on the number of ions in the trap. In the study of the dependence of I_e^{cr} on the various regime parameters of the ionizer (the gas flux q_g, the heating of the cathode, i.e., the perveance of the beam in the electron gun, the distribution of the voltage on the structure behind the anode, and the voltage on the cathode) it was established that I_e^{cr} depends only on E_e, increasing linearly with the beam energy (Fig. 9). This, in particular, indicates that the process leading to ejection of ions from the trap begins at a definite value of S^-/v (v is the electron velocity), this value being constant for all energies and currents of the electron gun. It follows from the family of curves in Fig. 8a that in accordance with the self-consistent field model $C^+ \sim E_e^{-1/2}$ for $I_e = \text{const}$ and for $I_e < I_e^{cr}$.

The dependences of Q^+ on the gas flux q_g in Fig. 10 were obtained for $U_t > U_{ts}$ with $\tau_{inj} = 1.5$ msec = const, and $I_e < I_e^{cr}$. It can be seen that Q^+ initially increases, reaching the value C^+, and then when $q_g > q_g^{cr}$ it decreases, indicating a process leading to ejection of ions from the trap or deformation of the trap. It follows from Fig. 11 that the ion ejection mechanisms for $I_e \geq I_e^{cr}$ and for $q_g \geq q_g^{cr}$ are independent.

A characteristic feature of the experimental dependence $Q^+ = f(\tau_{inj})$ for $q_g < q_g^{cr}$ and $U_t \geq U_{ts}$—this dependence is rather difficult to describe theoretically—is the transition to saturation, when $Q^+ = C^+$, which corresponds to the self-consistent field model. Study of the dependence of C^+ on the length of the trap in the interval from 0.15 to 0.95 m revealed a linear growth.

Investigation of Containment of the Ions in the Beam.[24] The containment within the beam of the ions introduced into it during the complete time τ_i is the most important condition of realization of the electron-beam method of ionization. The containment efficiency was studied as follows. At the initial time, n_0 nitrogen ions were injected into the beam, this number being measured by $Q^+/\bar{q}$, where Q^+ is the ion charge measured directly after the completion of injection, and $\bar{q}$ is the mean charge of the ions measured by means of a time-of-flight spectrometer, The value of n was measured as a function of the containment time for different values of E_e and I_e and for $U_t \geq U_{ts}$. The dependences $Q^+ = f(\tau_i)$ and $n = f(\tau_i)$ for three values of n_0 for the same I_e ($< I_e^{cr}$) and E_e are given in Fig. 12. We see that for small n_0 all the ions are contained in the trap until the end of the ionization cycle ($\tau_i = 100$ msec). But once a certain value n_0 is reached, ions begin to be lost after a certain time τ_i, although Q^+ still continues to grow because of the increase in $\bar{q}$. If $\eta = S^+/|S^-|$ (the compensation level) is already near unity when $\tau_i = 0$, the loss of ions begins when $\tau_i = 0$, and $\partial Q^+/\partial \tau_i$ is maximal at $\tau_i = 0$.

The dependence $Q^+ = f(\tau_i)$ for $\eta_0 = 1$ was investigated for different values of I_e and E_e. These data, transformed into the dependence $\eta = f(\tau_i)$, are given in Fig. 13. It is interesting that for all $I_e < I_e^{cr}$ the curves almost coincide. A difference appears when $I_e = I_e^{cr}$, and the larger I_e, the steeper the drop in the curve $\eta = f(\tau_i)$. The dependence of the rate of loss of the relative ion charge $(1/\eta)\partial\eta/\partial\tau_i = f(\eta)$ for $I_e < I_e^{cr}$ is shown in Fig. 14. It can be seen that the rate of loss approaches 0 at $\eta \approx 0.15$, which means that the ionization process can be realized during a prolonged period with effectively no loss of ions from the trap.

Information about the ion dynamics during the ionization process can be obtained by studying the distribution of the ions with respect to the potential energy, which can be readily found by measuring $Q^+ = f(U_t)$ at small η, i.e., in the model of single ions. The function $Q^+ = f(U_t)$ can be transformed to the number-density distribution ρ_i of the ions at rest in a section of the beam as a function of the radial position r of the

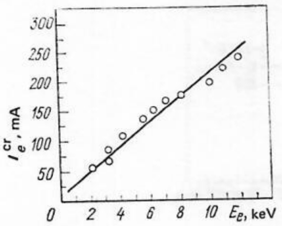

FIG. 9. Dependence of the critical beam current on the electron energy.

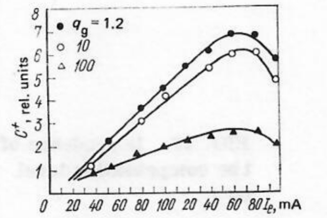

FIG. 11. Dependence of the trap capacitance on the beam current at $E_e = 7.43$ keV for different values of the gas flow rate.

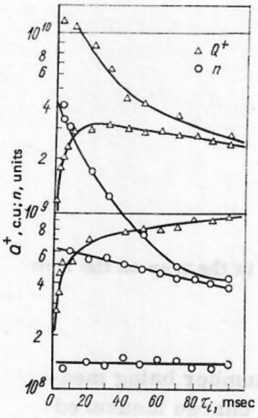

FIG. 12. Dependence of the ion charge Q^+ and the number of ions n in the trap on τ_i.

element of the section, for which one uses the law of the radial distribution of the potential of the electron beam free of ions. Figure 15 shows the results of such measurements, from which it follows that at $\tau_i = 1$ msec all the ions are uniformly distributed in the beam, while at $\tau_i = 100$ msec the majority of them remain in the beam, though there is a small fraction of the ions that are heated and periodically leave the beam in the radial direction.

The investigations showed that there are definite ranges of the parameters of the ion–electron system ($I_e < I_e^{cr}$) within which the processes of injection and containment of the ions can be satisfactorily described in the model of single ions and the self-consistent field model. Bearing in mind that I_e^{cr} is independent of η in a certain interval, it can be assumed that the system consisting of the electron beam, the drift tube, and the end electrodes is a dynamical system in which the processes become nonlinear when $I_e \geq I_e^{cr}$, which leads to intensification of the collective motions of the electrons, whose energy is transferred to the ions. The linear part of the processes also leads to certain losses of the ions when $I_e < I_e^{rc}$. The identification and suppression of this process are very important for the further improvement of the electron-beam method of ionization.

Production of Multiply Charged Ions and Nuclei. Experiments to obtain multiply charged ions and nuclei in the ionizer KRION-2 were made for $I_e < I_e^{cr}$. In Fig. 16, such experiments are illustrated by means of the evolution of the charge-value spectra of the ions for

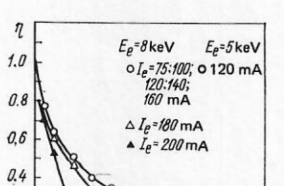

FIG. 13. Dependence of the compensation level on τ_i.

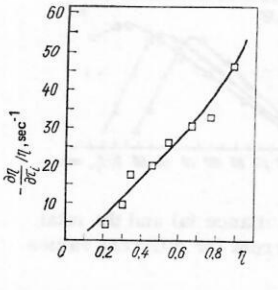

FIG. 14. Dependence of the rate of loss of the relative ion charge on the compensation level.

C, O, Ne, Ar, Kr, and Xe, respectively.[24] This figure demonstrates with great clarity one of the important differences between an electron-beam ionizer and all other sources of multiply charged ions. This is that during the ionization process the ions of the low charge states are completely depleted, going over into ions with higher charge states. As a result, there is a more or less narrow spectrum of charge values at the ionizer exit, and in the limit there are only nuclei completely stripped of their electron shells. The main features of all evolutions are as follows: a) the increase in the charge value of the ions continues until $\tau_i = 5.5$ sec and later, i.e., the recombination processes, if there are any, proceed with effective cross sections less than 10^{-22} cm^2; b) for relatively large η, the spectra evolve more slowly than at small η, indicating radial loss of ions from the beam during containment; the spectra may differ somewhat depending on the point of time in the ion pulse at which the probe is taken for analysis, indicating that the extraction with monochromatization for the experiments is made too rapidly.

In the experiments now being done with the ionizer KRION-2, the ionization factor $j\tau_i = 8.1 \times 10^{21}$ cm^{-2} for $E_e = 20$ keV has been achieved. Beams of all multiply charged ions and nuclei of C, O, Ne, and Ar, and also ions of Kr (up to Kr^{34+}) and Xe (up to Xe^{52+}) have been obtained. To obtain ions with higher charges, the fac-

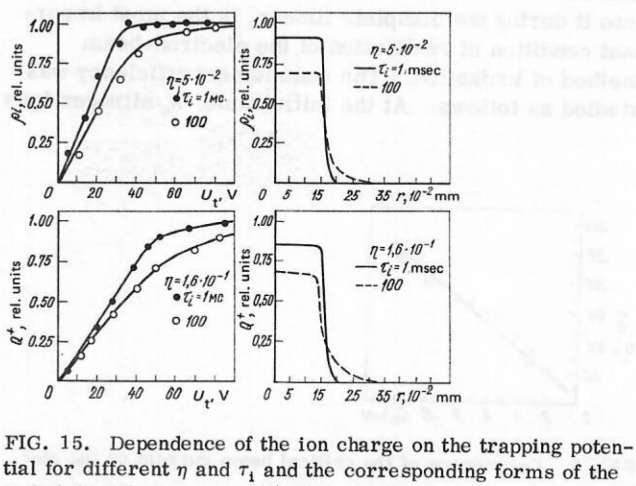

FIG. 15. Dependence of the ion charge on the trapping potential for different η and τ_i and the corresponding forms of the radial distributions $\rho_i = f(r)$ of the ions.

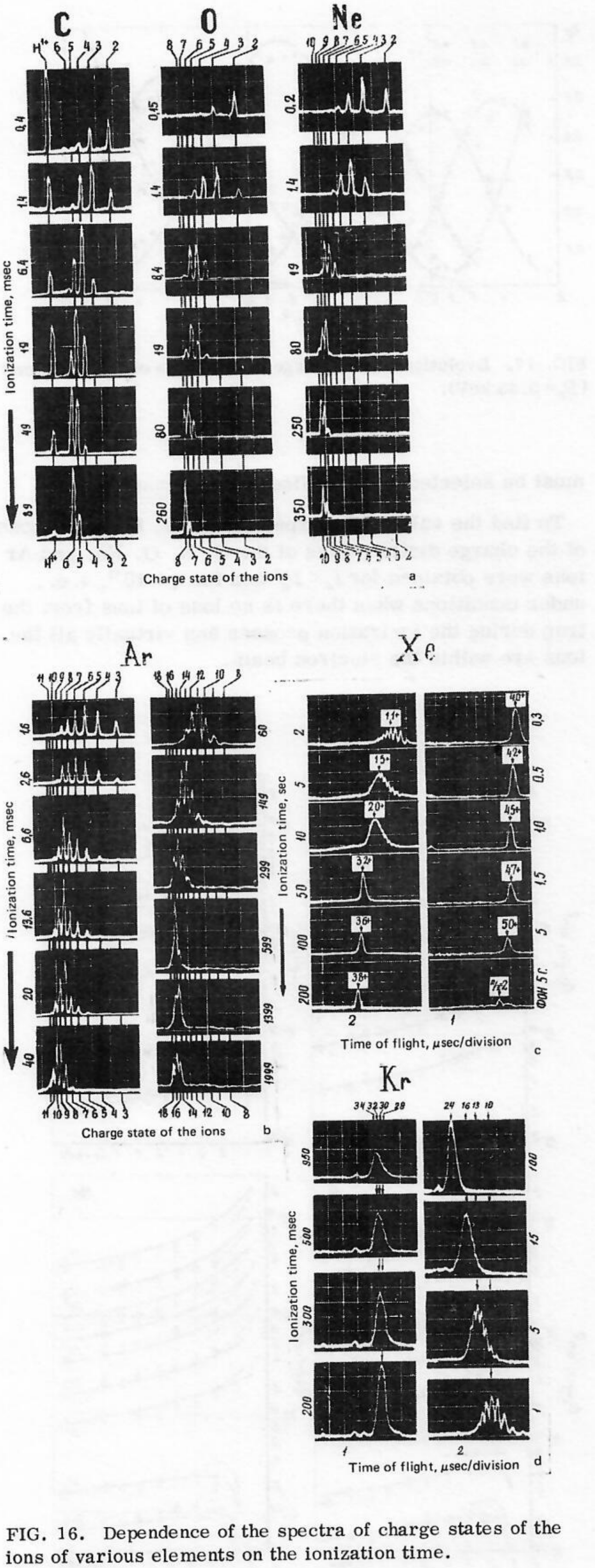

FIG. 16. Dependence of the spectra of charge states of the ions of various elements on the ionization time.

tor $j\tau_1$ can be increased by increasing j (with an increase in E_e) and τ_1. If the linear growth of I_e^{cr} persists until $E_e \approx 250$ keV, it will be possible to realize a factor $j\tau_1 \approx 10^{24}$ cm^{-2} and obtain U^{92+} uranium nuclei even without suppression of the process of ion ejection from the beam.

The viability of the electron-beam method of ionization was also recognized later by other Soviet[25] and foreign[26-29] specialists.

The main attention of the experimentalists during recent years has been concentrated on obtaining higher electron flux densities j_e in the electron-beam ionizers, since it is clear that theoretically the "output" of the ionizer (the number of ions per 1 sec) increases in proportion to j_e^2 if the diameter of the electron beam is unchanged and in proportion to j_e if the beam current I_e is constant.

In this connection, a significant event was the, unfortunately, episodic observation by Arianer *et al.*[29] of supercompression of the electron beam in the ionizer CRYEBIS, when ions of the types Ar^{18+}, Kr^{34+}, and Xe^{44+} were obtained during anomalously short ionization times τ_1.

All the above experiments were made in the dc regime, when the electrons emitted by the cathode pass once through the drift space. A number of experimental studies have also been made which show that the development of an ionizer with accumulation of electrons in the drift space by making them execute axial oscillations could be promising.[13]

3. CURRENT APPLICATIONS OF THE ELECTRON-BEAM METHOD OF IONIZATION

Investigation of Ionization of Positive Ions by Electron Impact. Until recently, the main method used to measure effective ionization cross sections $\sigma_{q\to q+1}$ was the method of intersecting ion–electron beams. The main advantage of this method is the high resolution with respect to the electron energy; the main disadvantage, the low sensitivity. Therefore, processes were investigated in which ions with not more than two or three charge units participated. It was only in 1979 that Crandall *et al.*[30] published their report of investigations of ions with somewhat higher charges.

On the basis of the pulsed electron-beam method of ionization, a new method of measurement was developed and the first measurements were made of the cross sections for all positive ions of C, N, O, Ne, and Ar, including the hydrogenlike ions, and qualitative results were also obtained for Kr (up to Kr^{33+}) and Xe (up to Xe^{47+}).[21,31-35]

The ionization cross sections of the ions were measured as follows.[35] A portion of ions of the investigated element were relatively low charge values ($1 \leq q \leq 4$) was introduced into an electron beam. Immediately after injection, the charge spectrum of this portion of ions was measured. Since the signal produced by the current of the ion bunch usually had a half-width of about 50 μsec, and a narrow (about 100 nsec) packet is separated for the time-of-flight analysis, five or six cycles were needed to obtain reliable information, so that different time sections of the ion signal were tested each time. The analyzer was operated in the current regime, so that the amplitude of the line was proportional to the total electric charge of the ions of given charge state in the packet. The spectrum of charge states was then transformed into the distribution, normalized to unity, of the number of ions with respect to the charge states (the charge distribution) as follows:

$$n_q = \frac{1}{q}\sum_{k=1}^{a} A_q^{(k)} \Big/ \sum_{q_{\min}}^{q_{\max}} \frac{1}{q} \sum_{k=1}^{a} A_q^{(k)}, \quad \sum_{q_{\min}}^{q_{\max}} = 1,$$

where n_q is the number of ions of charge state q, normalized to unity; $A_q^{(k)}$ is the amplitude of the line of the packet of ions of the charge state q in experiment k; a is the number of experiments; and $q_{\min}$ and $q_{\max}$ are the minimal and maximal charge states of the ions in the bunch.

At any time τ_i measured from the end of injection the new charge distribution was measured in other cycles. The form of this distribution, for other fixed parameters, is determined solely by the value of τ_i and the effective ionization cross sections, which are not known and they can be extracted from the results of the measurements.

The kinetic equation for the number n_q is

$$\frac{dn_q}{d(j\tau_i)} = -\sum_{f=1}^{f_{\max}} n_q\sigma_{q\to q+f} + \sum_{r=1}^{r_{\max}} n_{q-r}\sigma_{q-r\to q}, \quad (1)$$

where f and $f_{\max}$ are the number and the maximal possible number of electrons that can be simultaneously stripped from an ion of charge state q; $\sigma_{q\to q+f}$ is the cross section of this process; r and $r_{\max}$ are the number and the maximal possible number of electrons that can be simultaneously stripped from the ion of charge state $q-r$; and $\sigma_{q-r\to q}$ is the cross section of this process.

In the special case of successive ionization,

$$dn_q/d(j\tau_i) = -n_q\sigma_{q\to q+1} + n_{q-1}\sigma_{q-1\to q}. \quad (2)$$

To find all the unknown σ, it is convenient to measure the dependences $n_q = f(j\tau_i)$ for all q in Eq. (1), i.e., to obtain the evolution of the charge distribution of the ions (Fig. 17).[35] Several tens of vertical sections are taken in the evolution, the coefficients n_q and $dn_q/d(j\tau_i)$ are extracted, and a set of canonical systems of equations (1) are derived, the solution of each system giving a corresponding set of values of the unknown σ. If all the system are on an equal footing, the result is a set of values of the unknowns σ, these determining the average over the complete experiment (for all $j\tau_i$) σ and the probable deviation $\Delta\sigma$.

Using regularized iterative processes of the Gauss–Newton type and a computer program written by Aleksandrov,[37] Bochev *et al.*[36] developed a program for solving the inverse ionization problem. In it, one finds a set of σ that, being substituted into the condition of the direct problem, give the smallest deviation of the evolution of the charge distribution then obtained from the experimental evolution. It was found that the two methods give values of σ that agree to within the errors. The model used to solve the inverse problem must be selected and justified in each case.

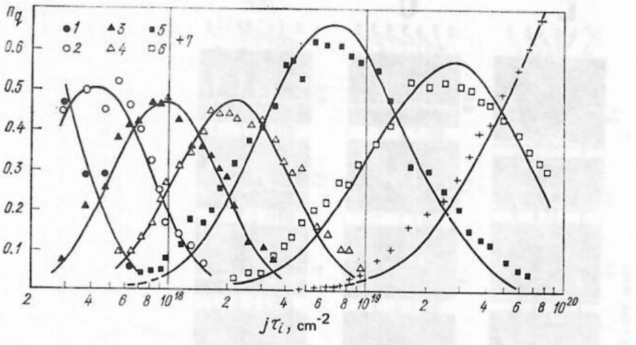

FIG. 17. Evolution of the charge distribution of nitrogen ions ($E_e = 5.45$ keV).

To find the values of σ experimentally, the evolutions of the charge distributions of the C, N, O, Ne, and Ar ions were obtained for $I_e < I_e^{cr}$ and for $\eta = 10^{-2}$, i.e., under conditions when there is no loss of ions from the trap during the ionization process and virtually all the ions are within the electron beam.

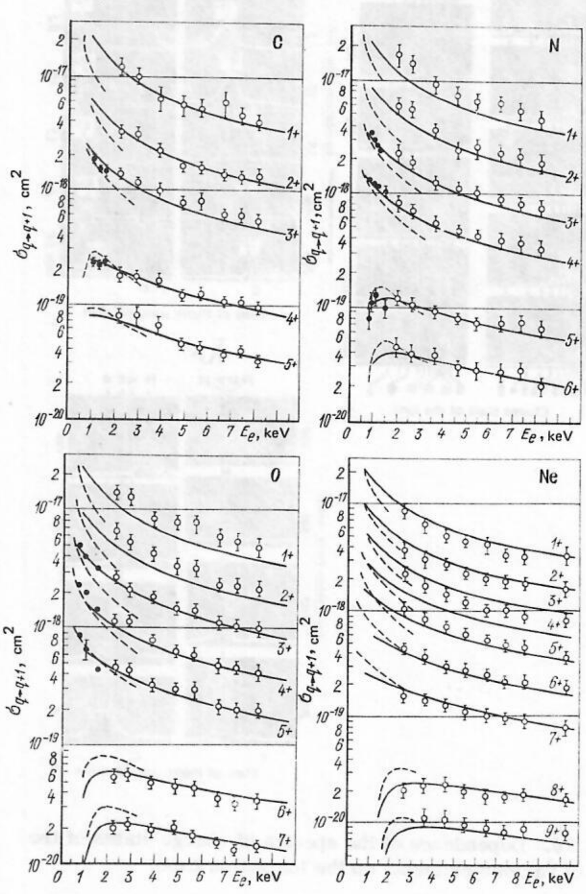

FIG. 18. Energy dependences of $\sigma_{q\to q+1}$ for C, N, O, and Ne ions. The open circles are the data of Ref. 35, the black circles the data of Ref. 30, the continuous curves are in accordance with Lotz's formula,[11] and the broken curves in accordance with Salop's.[38]

All the evolutions for the ions C, N, O, and Ne were processed using the model of successive ionization (2). The satisfactory agreement between the experimental and calculated evolutions for appropriate choice of $\sigma_{q\to q+1}$ indicates that this model correctly reproduces the process of transition from the lower to the higher charge states (see, for example, Fig. 17). The experimental dependences of $\sigma_{q\to q+1}$ on the energy of the bombarding electrons obtained by the method described above for C, N, O, and Ne are shown in Fig. 18.[35] We have also plotted the available results of the recent experiments of Crandall *et al.*[30] in an energy interval close to the one for these data. It can be seen that these data and Crandall's agree after extrapolation over a relatively small energy interval. This agreement can be regarded as independent confirmation that the method developed on the basis of the electron-beam method of ionization gives quantitatively correct results.

Detailed examination of Fig. 17 reveals some systematic deviations of the calculated evolutions from the experimental evolutions, and these are also characteristic of the evolutions for nitrogen and other elements. As a rule, the experimental point lie somewhat higher than the corresponding curves $n_q = f(j\tau_i)_{cal}$ in the regions of $j\tau_i$ values in which ions with charge q first appear in the spectrum, and also when they disappear. This could be an indication of a process of two-electron ionization of the ions of these elements, but the accuracy of the measurement of the evolutions must be improved if the value of $\sigma_{q\to q+2}$ is to be extracted reliably.

The argon atom is a rather complicated system, in which the number of possible ionization paths increases. Therefore, the evolutions for the Ar ions were obtained and analyzed in three ranges of variation of q and, accordingly, $j\tau_i$: $2 \leqslant q \leqslant 12$, $8 \leqslant q \leqslant 15$, $15 \leqslant q \leqslant 18$ at $E_e = 11$ keV and, in part, at $E_e = 7.8$ and 2.2 keV. Because the evolution at 11 keV indicated an appreciable contribution from two-electron ionization (for $2 \leqslant q \leqslant 12$) which was also noted at 2.2 keV,[31] this evolution was analyzed under the assumption that besides the main transitions the transitions $Ar^{4+} \to Ar^{6+}$, $Ar^{5+} \to Ar^{7+}$, $Ar^{6+} \to Ar^{8+}$, $Ar^{7+} \to Ar^{9+}$ are also possible. For the remaining intervals, the model of successive ionization was used. The experimental results for $E_e = 11$ keV (Ref. 35) and 2.2 keV (Ref. 31) are shown in Fig. 19.

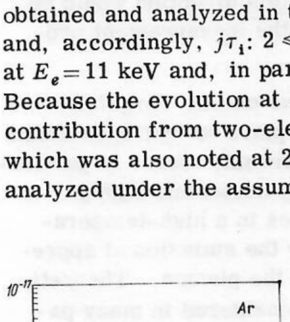

FIG. 19. Experimental data[31,35] and calculated values (continuous and broken curves; Lotz[11] and Salop[30]) of cross sections of one- and two- electron ionization for argon ions of the charge values q.

At $E_e = 7.8$ keV, the following values of the cross sections were obtained: $\sigma_{15\to16} = (1.40 \pm 0.21) \times 10^{-20}$ cm^2, $\sigma_{16\to17} = (1.75 \pm 0.25) \times 10^{-21}$ cm^2, $\sigma_{17\to18} = (7.4 \pm 0.9) \times 10^{-22}$ cm^2.[35]

Natural mixtures of the isotopes were used when Kr and Xe were ionized. A characteristic feature of the charge-state spectra was the insufficiently good resolution of the lines for $q \geqslant 10$–15. Therefore, we extracted from the evolutions of the charge distributions the dependence of the mean charge value $\bar{q}$ on $j\tau_i$. Then, regarding the relation $\sigma_{\bar{q}\to\bar{q}+1}(j\tau_i) = 1$ as the condition of an increase in $\bar{q}$ by unity, we found from such dependences the values of $\sigma_{\bar{q}\to\bar{q}+1}$ for different $\bar{q}$ (Fig. 20).[35] Naturally, in such an approach the irregularities associated with the presence of shells are lost to a considerable extent, and the incompleteness of the ionization model can also have a significant influence. Nevertheless, the $\sigma_{\bar{q}\to\bar{q}+1}$ values for such a large number of highly charged Kr and Xe ions were obtained for the first time experimentally and can be of value, primarily for further development of ionization studies.

It is interesting to compare the first experimentally measured effective ionization cross sections of the hydrogenlike ions C^{5+}, N^{6+}, O^{7+}, Ne^{9+}, and Ar^{17+} (Ref. 35) with the theoretical cross sections obtained by the Coulomb–Born–Oppenheimer method[39] in the framework of the dependence $Z^4\sigma_{1S\to K} = f(E_e/I)$, where I is the potential for ionization from the state 1S, and Z is the charge of the nucleus. The results are given in Fig. 21. It can be seen that there is reasonable quantitative agreement between the experiment and theory, but that there is a certain mean deviation of the complete set of experimental points in the direction of larger $Z^4\sigma_{1S\to K}$ values by about one measurement error unit.

At the present time, the accuracy of the experimental

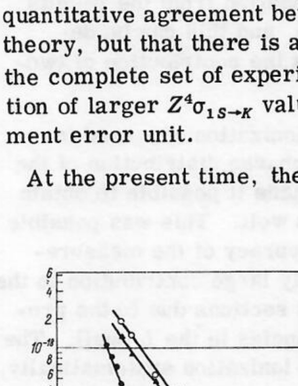

FIG. 20. Experimental effective values of $\sigma_{\bar{q}\to\bar{q}+1}$ for ions of Kr (black circles for $E_e = 8.5$ keV) and Xe (open circles for $E_e = 8.5$ keV, and black triangles for $E_e = 18$ keV).[35]

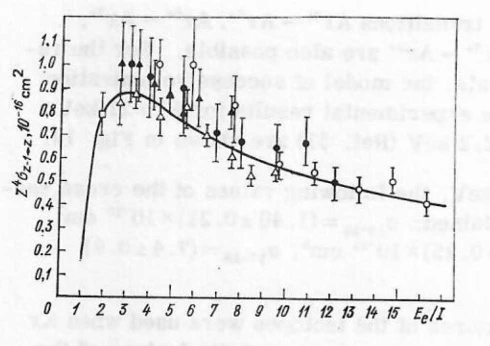

FIG. 21. Dependence of the reduced cross section for ionization of hydrogenlike ions on the electron energy. The open circles are for C^{5+}, the black circles for N^{6+}, the open triangles for O^{7+}, the black triangles for Ne^{9+}, and the open squares for Ar^{17+} (experiment of Ref. 35); the continuous curve is the Coulomb–Born–Oppenheimer calculation for $Z=128$.[38]

data does not permit the dependence of the reduced cross section on the charge of the nucleus to be extracted. However the problem of experimental investigation of this dependence can be posed and solved. For this, it is in the first place necessary to increase the accuracy in the measurement of the initial sections of the curves $n_q=f(j\tau_i)$ in order to take into account two-electron ionization of the heliumlike ions and thus increase the accuracy in the measurement of $\sigma_{1S\to K}$.

For the heliumlike ions and others up to boronlike ions good agreement is observed between the experimental points and those calculated using Lotz's formula, while there is an appreciable deviation from Salop's calculations by the method of two-body collisions.[38] But for ions with more than five electrons, one observes a systematic deviation from the results obtained using Lotz's formula, and this can be decreased by taking into account the contribution of two-electron ionization.

The model of two-electron ionization was used to analyze the evolutions of the charge distribution of the Ar ions near $q=8$, and this made it possible to obtain the values of $\sigma_{4\to 6}, \sigma_{5\to 7}, \sigma_{6\to 8}$ as well. This was possible at the present-day level of accuracy of the measurements because of the relatively large contribution to the Ar^{4+} and Ar^{6+} ionization cross sections due to the probability of occurrence of vacancies in the L shell. The order to study many-electron ionization systematically, it is necessary to increase the accuracy in the determination of the experimental evolutions of the charge distribution and automate the measurement process. However, it can already be noted that near large shells a situation is realized in which $\sigma_{q\to q+1}$ may be smaller than $\sigma_{q+1\to q+2}$ and even smaller than $\sigma_{q\to q+2}$. This phenomenon can be explained if Salop's model[40] is valid, which indicates that removal of an electron from the L shell to the continuum leads with high probability to the ejection of one more electron if there are two or more electrons in the M shell. Figure 19 shows the values of $\sigma_{q\to q+1}$ (continuous curve) and $\sigma_{q\to q+1}$ (broken curve) calculated in accordance with Lotz's formula and corrected under the assumption that Salop's model is valid. It should be noted that there is fairly good agreement between the experiment and the calculation. The calculation did not take into account the autoionization process when L electrons are excited.

Brief examination of investigations in which the electron-beam method of ionization has been used to investigate the ionization of positive ions by electron impact shows that this method already makes it possible to measure the constants of the interaction of electrons with ions of much higher charge states than in other methods and therefore provides a more secure basis for finding the rates of generation of highly charged ions and nuclei in the hot plasmas in the prototypes of thermonuclear reactors, designing heavy-ion sources for accelerators, etc.

The extension of investigations in this field is very topical. First, it is desirable to extend the experiments to the regions near the energy thresholds of the corresponding ionization processes. Further, to investigate many-electron ionization it is necessary to improve the method in order to increase the accuracy with which the experimental curves $n_q=f(j\tau_i)$ are measured, and it is also necessary to improve the method of computer analysis of the data.

Extension of systematic investigations to elements heavier than Ar requires improvements in the system for analyzing the charge states of the ions and also experiments with elements such as Fe, W, etc; it is also necessary to develop a method for introducing atoms of heavy working substances into the electron beam of the ionizer. It should also be noted that the ionization processes that could and should be investigated are very many, and successful work in this direction would be difficult without automation of the measurement process.

Investigation of Charge of Ions on Gas Targets. Such experiments, in the first place on hydrogen atoms and molecules, are of great interest, since, in particular, the capture of electrons by nuclei and highly charged ions of heavy impurities in a high-temperature plasma is accompanied by the emission of appreciable energy, which may cool the plasma. Theoretically, this question has been considered in many papers, but experimental investigations were begun only at the end of 1979 in joint experiments by the Joint Institute for Nuclear Research and the A. F. Ioffe Physicotechnical Institute using beams of the KRION-2 ionizer.[41-43]

The most important aspects of this program of investigations are the obtaining of the absolute values of the effective cross sections $\sigma_{Z\to Z-1}$ for capture of an electron by nuclei of various elements from hydrogen atoms and the obtaining of the experimental picture of the population of the states of the excited nucleus—electron system, which ultimately determines the spectrum of the radiation accompanying capture. The experiments used electromagnetic separation of the primary beam from the ionizer KRION-2 and electrostatic separation of the charge-exchange component of

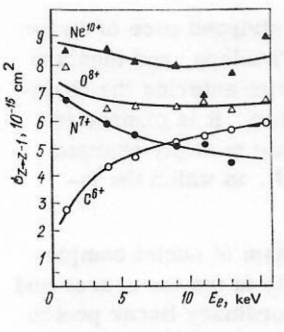

FIG. 22. Energy dependences of the cross sections of electron capture by C, N, O, and Ne nuclei from hydrogen molecules.[42]

the ion beam and the primary beam.

The results of these first measurements of the energy dependences of the effective cross sections for electron capture by C, N, O, and Ne nuclei from hydrogen molecules at low energies are given in Fig. 22.[42]

These results not only give the numerical values of $\sigma_{Z\to Z-1}$ for different energies of the nuclei in the low-energy range, but also show that the individual characteristics of the energy levels of the system (consisting of a nucleus completely stripped of electrons and a hydrogen molecule) at low temperatures determine not only the absolute values of $\sigma_{Z\to Z-1}$ but also the nature of the energy dependence, which may be different even for nuclei of neighboring elements.

First measurements were also made of the energy dependences for x-ray emission cross sections at low-energies (0.6–8 keV/nucleon) for the cases C^{6+}, O^{8+}–H_2.[43] The radiation accompanying electron capture was selected by means of absorbing filters and detected by a secondary-emission detector. It was shown that electron capture takes place to states with large values of the principal quantum number and an approximately uniform population of states with different orbital angular momenta.

Thus, the use of the electron-beam method of ionization makes it possible, once the rate of generation of ions and nuclei of the impurities in a hot plasma has been found, to determine another important characteristic needed to describe the equilibrium plasma state, namely, the deionization rate of these impurities and the forms of radiation in this process; this is very important for plasma diagnostics.

The problem involved in investigations in this field are very many. In the first place, we must mention the use of atomic hydrogen targets, and also the transition to investigations of more highly charged ions and nuclei Using the electron-beam method of ionization, it is possible to create a method for measuring the effective charge-exchange cross sections of multiply charged ions on such ions as targets, i.e., mutual charge exchange.[13] Consideration of this problem appears somewhat exotic, since even experiments to measure the effective cross sections of mutual charge exchange of ions with one or two charge units are a great rarity. The main difficulty in such an experiment is to achieve an ion target of sufficient density or a sufficient duration of the ion–ion interaction. Either of these may be achieved if multiply charged ions of two different species are generated in the same electron beam in adjacent regions separated by an additional potential barrier and are then mixed in the same beam by raising the potential of one of the regions.

The results of such investigations can be very helpful for constructing a steady picture of the charge distribution of ions in the plasma types of multiply charged ion sources, for analyzing the evolutions of the charge distributions of the ions in the electron-beam method of ionization, and also for estimating the ion-beam loss due to internal friction in strictly focusing synchrotrons with slow accumulation of energy during acceleration of heavy ions, etc. These investigations could give unexpected results, since this region has hardly been touched by experiments.

Interaction of Ions of High Charge States with Surfaces of Solids. The investigation of the interactions of atomic particles with surfaces of solids is an independent and very extensive branch of experimental physics. It would be very complicated to consider the changes for the entire group of phenomena observed when ions collide with a surface in the case when their charge becomes appreciably greater than one unit.

One of the features of highly charged ions is that their potential energy can reach several tens or hundreds of kilo-electron-volts, this energy being released on deionization. Thus, the energy of complete deionization is 35 keV for Xe^{39+}, 51 keV for Xe^{44+}, 100 keV for Xe^{52+}, 200 keV for Xe^{54+}, and 500 keV for U^{92+}. Now one of the important features of the electron-beam method of obtaining such ions is their relatively low kinetic energy, which can reach only a few tens or hundeds of electron volts.[44]

This combination creates unique conditions for investigating potential electron emission from the surface of metals and also ion emission from the surface of semiconductors and insulators.

A theory of Auger neutralization of multiply charged ions on metal surfaces has been developed. The main conclusion is that it is a step process with step of about 20 eV, the total coefficient of secondary emission being proportional to the total deionization energy of the ion. Experimentally, the theory is confirmed only for relatively lowly charged ions such as Kr^{6+} and Xe^{7+} with total deionization energy 200–300 eV and coefficient of secondary electron emission $\gamma \approx 5$–7. Does γ increase to several thousands in investigations with ions such as Xe^{54+}? Should not one expect a much smaller value of γ and for the Auger electrons a much harder spectrum, which could be used for diagnostic purposes?

Parilis[46,47] considered sputtering of the surfaces of nonmetals under the influence of slow multiply charged ions. The mechanism, called "Coulomb explosion," takes the form that the Auger neutralization of a multiply charged ion on such a surface is accompanied by the accumulation of a large positive charge in a small domain of the matter. The repulsion energy of the ions of the solid exceeds the sublimation energy, and there is an "explosion" of the section of the surface.

There are virtually no experimental data on this matter. The discovery and experimental investigation of the "Coulomb explosion" mechanism in semiconductors and insulators under the influence of highly charged ions would have not only purely scientific but also important applied significance, since this mechanism represents a powerful sputtering factor to be taken into account for materials facing a high-temperature plasma.

Recently, experiments were begun using the ionizer KRION-2 to observe the hard characteristic x-ray radiation accompanying deionization of the ions Ar^{17+} and Ar^{18+} on a metal surface. Even the preliminary results of these experiments indicate that on this basis it is possible to create a convenient method for diagnozing ion beams of such type.

Accelerator Technology. The very rapid development in recent years of new methods for obtaining highly charged ions is due to the first place to the need to improve the methodological basis of nuclear physics, and, in particular, relativistic nuclear physics.[48,49] The development of the electron-beam method of ionization is no exception. The entire program to develop and investigate the electron-beam ionizers KRION-1 and KRION-2 had as its main aim the obtaining of relativistic heavy-ion beams in the synchrophasotron at Dubna. The cryogenic electron-beam ionizer CRYEBIS was developed as a source of nuclei of light elements for the synchrotron SATURN-2.[27]

A feature of the multiply charged ions to relativistic energies is that in the existing synchrotrons one can actually accelerate only nuclei completely stripped of orbital electrons. This is true at least for the elements at the beginning of the periodic table. Because of the large size of the equilibrium orbit and the relatively slow accumulation of energy, the thickness of matter that the accelerated ion must traverse is so great that no electron structure can survive. Conversely, a nucleus completely stripped of electrons is in this respect the most stable system, since the probability that a nucleus captures an electron from atoms of the residual gas at the usual injection energies is small and decreases rapidly with increasing energy. However, it is an extremely difficult task to obtain a beam of nuclei completely stripped of electrons (ions with $A/q \approx 2$) for a high-energy accelerator (a machine with a short capture time).

At the present time, this problem is solved in two different ways. The first is by cascade acceleration of ions with relatively low charge. This method is possible only if there is an injector or specialized accelerator of multiply charged ions in the accelerator complex. In the BEVALAC accelerator complex, this is the role played by the Super HILAC.[50] In this case, ions are obtained by means of a source with Penning-type discharge, which ensures high intensities of ions with relatively low charge. After preliminary acceleration, the ions are stripped once or twice during acceleration to 8.5 MeV/nucleon, and then are stripped to the nuclear state before entering the chamber of the BEVATRON accelerator. It is planned to use the same method to accelerate multiply charged ions to high energies at Damstadt, in which the intended injector is the UNILAC.

The other way is to obtain a beam of nuclei completely stripped of electrons directly in the ion source and to accelerate these nuclei in an ordinary linear proton accelerator. This method was used at Dubna to accelerate C, N, O, and Ne nuclei to high energies with the synchrophasotron.[51] The ion source was the electron-beam ionizer KRION-1.

At the present time, there are also plans to develop and use electron-beam ionizers with accelerators of low and intermediate energies.[52,53] However, the fact that a new ion source such as the electron-beam ionizer was used for the first time to accelerate heavy ions in a synchrotron is not, of course, fortuitous. There is a significant correspondence between the quality of the ion beam and the regime in which it is obtained in such an ionizer and the requirements on the beam imposed by the synchrotron method of acceleration. This correspondence dictates: 1) the maximally high charge state of the ions in the ionizer; 2) the pulsed nature of its operation, with the time required for the ionization process being appreciably greater than the time of injection of the neutrals into the beam and extraction of the ions from the ionization region; 3) the extraction time, which may amount to only a few microseconds. Various other technical characteristics of a cryogenic ionizer also correspond very satisfactorily to its use at the high-voltage terminal of a synchrotron injector.

It follows from the fundamental relations that describe synchrotron acceleration that it is preferable to achieve the maximal possible charge-to-mass ratio for the ion in order to achieve maximal energy during minimal time for minimal radius of the equilibrium orbit and minimal final induction of the confining field.

Somewhat more complicated is the question of the choice of the charge state of the ion that ensures a minimal loss of the accelerated heavy ions due to charge exchange on the residual gas in the synchrotron chamber. It should be noted that the reduction to a minimum of these losses is due of the main technical problems in the acceleration of heavy ions to relativistic energies.

The effective charge-exchange cross section of an ion of charge q in a collision with atoms of the residual gas is basically determined by the cross section for capture and loss of one electron ($\sigma_{q\to q-1}$ and $\sigma_{q\to q+1}$, respectively). It is obvious that for a given element $\sigma_{q\to q+1}$ decreases with increasing q, i.e., with decreasing number of electrons remaining in the ion shells, since the number of electrons participating in the process is smaller, and they are bound more strongly to the nucleus. In contrast, $\sigma_{q\to q-1}$ increases rapidly with increasing q. Thus, it is natural to expect that for every sufficiently heavy element there is a value of the charge q^* (the optimal value) for which the losses of ions during the acceleration process are minimal. It is well known that $\sigma_{q\to q-1}$ depends strongly on the ion velocity v (as v^k, where $k \approx 7$) and its charge value (as q^5), whereas the value of $\sigma_{q\to q+1}$ passes through a maximum, which depends on the binding energy of the electrons of the outer subshell, and then varies as v^{-2}.[54]

Under such conditions, q^* is to a large degree determined by the initial and final energies of the ions that undergo synchrotron acceleration. The absence of systematic experimental data means that exact values of q^* cannot be given in each case. Estimates show[13] that if the initial and final energies of the ions are 10 MeV/nucleon and 10 GeV/nucleon, respectively, then it is expedient to accelerate nuclei completely stripped of electrons only up to elements with $Z \approx 30$. For heavier elements, it is preferable to keep a certain electron structure. Moreover, whereas for xenon ($Z = 54$) it is preferable to keep the K shell, for heavier elements a minimum of the losses is achieved by accelerating an ion carrying the K shell and part of the L shell, while for uranium loss one can keep the K and the L shell.

Electron-beam ionizers are capable of providing ion beams with charge values q^* and even higher. In particular, in the ionizer KRION-2 are ionization factor $j\tau_i \approx 8\times 10^{21}$ cm^{-2} has been realized and ions of the type Xe^{52+} have been obtained. It is clear that the ionization capacity of the method is not yet exhausted.

Thus, the charge value of the ions obtained from electron-beam ionizers corresponds fully to the requirements that must be met for effective and optimal acceleration in synchrotrons, which cannot be said at present about any other type of ion source. Since March 1977, the ionizer KRION-1 has been regularly used to obtain relativistic beams of C, N, O, and Ne nuclei in the synchrotron of the High Energy Laboratory at the Joint Institute for Nuclear Research.[55] A program of physics experiments in relativistic nuclear physics is being carried out these beams, mainly using track detectors. and there are also electronic experiments and biological investigations.

Important, but as yet unfortunately unique, experience has now been gained in the practical use of the electron-beam ionizer as an accelerator source of C, N, O, and Ne nuclei. We list below the aspects of this experience which we regard as the most important.

1. The plasma ion sources of all types currently used in accelerators of charged particles are characterized by the fact that the quality of the ion beam is usually maintained at the optimal level by the active intervention of an operator or a computer in the operating regime of the source. The reason for this is the instability inherent in plasma discharges.

The experience of working with the pioneering electron-beam ionizers has shown that the stability of their regimes corresponds to the characteristics of electron-beam devices and can be maintained over several days without intervention of an operator. Accordingly, the following method of exploitation is used on the accelerator. After mounting of the ionizer in the high-voltage position of the injector, cooling, and excitation of the magnetic field of the solenoid, the operator obtains the standard operating regime, after which the ionizer is transferred to the autonomous operating regime, in which there is no intervention by either the operator or a computer. There is merely synchronization of the time of extraction of ions from the electron beam and injection of ions into the synchrotron ring.

The ionizer KRION-1 has been used in such a regime on the synchrophasotron during six experimental periods. The total time of operation with beam is now more than 3000 h, and at the present time such a method of exploitation appears optimal.

2. The connection between the vacuum regions of the ionizer, in which the pressure of the residual gas in the region of the trap is 10^{-10}–10^{-12} Torr, and the injector, which has a pressure of about 10^{-6} Torr maintained by oil–vapor pumps, presents a problem. As a rule, the result of direct connection is a more or less rapid condensation of hydrogen on the walls of the drift tube surrounding the ionization region, and this has the consequence that the ionizer no longer functions. The problem is solved by making a connection only during the time the ion beam passes from the ionizer to the injector.

3. In the stable operating regime a nuclear beam of intensity $1\times 10^{10}/Z$ nuclei/pulse can be achieved without a special difficulty at the exit of the ionizer for light elements. An electron beam with a current of about 0.1 A is used in the ionizer. The main problem that must be solved in this field is the transition to the use of electron beams with currents of a few amperes, which would make it possible to raise the pulse intensity of the nuclear beam to $(5–10)\times 10^{11}/Z$, thus making the method of direct acceleration of nuclei competitive with the cascade method as regards intensity as well.

Finally, we note that electron-beam ionizers, mainly for various accelerators, are being developed intensively at a number of physics centers; specialized international seminars are regularly held on this problem; and various aspects of the problem are discussed at other symposia and conferences. All this gives grounds for very optimistic estimates of the prospects of the electron-beam method of ionization in the future. As confirmation of this, we give, in a somewhat modified form, the illustration of Kutner and Becker,[56,57] which shows the relationship between the possibilities of the various methods for obtaining highly charged xenon ions (Fig. 23) and also the parameters of beam produced by an electron-beam ionizer that could in the opinion of the present writer be constructed[13] (Fig. 24).

Nuclear Physics. As a rule, all experimental investigations of the properties of comple nuclei are made in the presence of the electron shell. In the majority of cases, the influence of the Coulomb field of the orbital electrons on the nuclear properties is negligibly small,

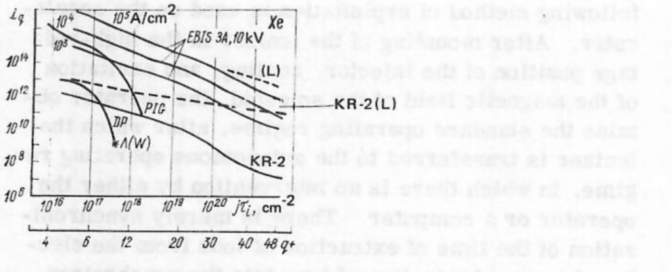

FIG. 23. Mean and pulse (broken curves) intensities i_q of xenon ion beams of different charge values for different types of ion source: DP, duoplasmatorn; PIG, source of Penning type; L, laser ion source for tungsten ions; Kr-2 (KRION-2); EBIS 3A, 10 kV, Becker's estimates for an electron-beam ionizer with electron beam current 3 A at energy 10 keV with the indicated density (the data of Ref. 29 correspond to density 10^5 A/cm^2). The necessary values of $j\tau_i$ are also indicated.

and in other cases (for example, in an estimate of α-decay energy from the experimentally measured α-particle energy) corrections that are more or less theoretical are made.

Storodubtsev[58] has considered systematically the influence of the electron shells of atoms on the radioactive properties of their nuclei. In the best understood case of radioactive transformation with capture of an orbital electron, one must expect a strong dependence of the probability of this form of decay for the nuclei of ions, with no decay at all for nuclei completely stripped of electrons. Such an experiment has not yet been made under laboratory conditions.

Another form of radioactive transformation in which orbital electrons participate directly, and in which there is therefore a strong dependence on the state of the electron shell, is internal conversion of γ rays.

For β decay, one must expect several interesting effects from an investigation of the radioactivity of nuclei completely stripped of electrons, namely:

1) capture of a β^- particle in an excited bound state or in the ground state of a hydrogenlike ion of the daughter nucleus with emission of monochromatic antineutrinos of one or several energies;

2) the suppression to zero of the probability of β^- decay in individual cases;

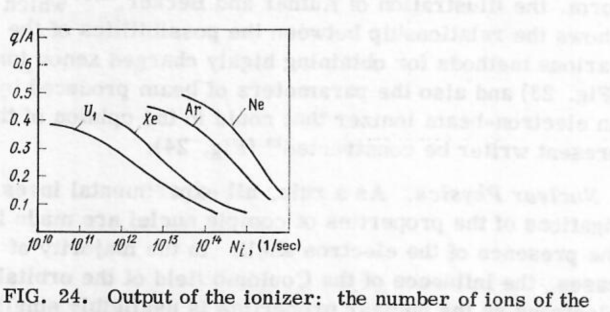

FIG. 24. Output of the ionizer: the number of ions of the indicated elements per second for different values of q/A.

3) deformation of the β spectra involving a certain depletion in the low-energy part of the β^- spectrum and an appreciable enrichment of this part of the spectrum for β^+ decay and some other decays.

The expected change in the β-decay properties of nuclei completely stripped of electrons is explained by the absence of the partial screening of the coulomb field of the nucleus by the field of the orbital electrons that one has in the case of an atom.

We note that screening also has an appreciably influence on the binding of the electrons nearest the nucleus. For example, for $Z=92$ the binding energy of a 1S electron is 130 keV for an ion containing only the K shell, whereas in the atom the 1S electrons are bound with an energy of 116 keV. This means that the density of the probability of finding 1S electrons on the surface of the nucleus increases with increasing degree of ionization of the atom, which, in its turn, must lead toa certain increase in the probability of K capture, this probability decreasing sharply following single ionization of the K shell and then becoming zero for a nucleus without electrons.

Since the electrons penetrate into the region of the nucleus and change its Coulomb field with their charge, one must also expect the electron shell to have an influence on "purely" nuclear processes such as α decay and spontaneous fission. Prior to the development of the electron-beam method of ionization, there were only attempts at a theoretical consideration of the influence of the degree of ionization of the atom on the radioactive properties of the nucleus. The present level of development of the method makes it possible to consider experimental investigation of the radioactive properties of nuclei of strongly ionized atoms, going as far as the case when these properties are completely free of influence of the electron shell.

The first proposal on this subject[59] was made in 1969 and establishes a connection between two problems: the development of the electron-beam method of obtaining and confining for a prolonged period ions of high charge states and the investigation of the radioactive properties of emitters in the ionic or nuclear state. The first problem has now been largely solved. This makes it possible to plan definite experiments dealing with the second problem.[13] In Ref. 13, the present author considered an experimental in which the influences of the electron shell on the properties of α decay could be studied.

The influence of the electron shell of an atom on the probability of α decay was considered quantitatively for the first time in a theoretical investigation by Erma.[60] To describe the potential near the nucleus of the neutral atom, Erma added to the usually employed nuclear potential the potential of the field of the electron shell, using the statistical Thomas–Fermi model to find this correction. Considering the motion of an α particle in the total modified field, Erma found that qualitatively the effect of screening is manifested in an increase in the probability of α decay and that the nuclei of the atoms ^{222}Rn, ^{212}Po, and ^{147}Sm decay 1.55, 1.22, and 2.60 times more rapidly than the corresponding nuclei completely stripped of electrons.

Of course, the use of the Thomas–Fermi potential is solve this problem is not justified, since the α-particle turning point is at distances much less than those at which the quasiclassical approximation used to obtain the Thomas–Fermi equation is valid. Erma's study should therefore be regarded as exploratory.

The later theoretical studies of Refs. 61 and 62, in which the S-electron wave functions are used to find the potential of the electrons in the region of the nucleus, do not, unfortunately, contain quantitative data on the charge in the probability of decay of nuclei of highly ionized atoms.

The screening of the field of the nucleus by the field of the orbital electrons also influences the energy of α particles, which for nuclei completely stripped of electrons must be 30–40 keV higher than for the corresponding nuclei of the atoms.[63,64]

The main characteristics of the electron-beam method of ionization that make it possible to plan experimental investigation of the dependence of the shift in the probability of α decay ($\Delta\lambda$) and the α-particle energy (ΔE_α) on the charge state of the emitting ions[13] are the following:

1) the possibility of obtaining ions in all charge states, including nuclei;

2) the confinement of the ions in the ionization region for a very long period (several seconds at the present time and 10–100 times longer in the future);

3) the comparatively small size of the ionization region, which makes it possible to surround it by α-particle detectors with high detection efficiency.

An alpha emitter suitable as working substance for the ionizer must at the present time satisfy a number of rather stringent requirements, namely, a sufficiently high specific activity, since about 10^8 ions can be present simultaneously in the ionization region; a gaseous state and, moreover, sufficient volatility at temperatures near 78 °K, since the evaporation of a solid radioactive substance near the electron beam of the ionizer is at present so complicated that the experiment appear unrealizable; the existence of an effectively continuous source of supply of the given radioactive gas—a single experiment does not suffice, and complete experiments require time, a year or more. The possibilities for obtaining highly charged ions with the ionizer KRION-2 are now such that nuclei of α-active elements at the end of the periodic table can be obtained after a time of about 100 sec. This means that for experiments it is convenient to have an alpha emitter with about the same half-life ($T_{1/2}$), provided the other two requirements are satisfied.

The above conditions restrict the possible emitters so strongly that a suitable isotope might not exist. Fortunately, however, there is the isotope $^{220}Rn_{86}$, which belongs to the natural radioactive family of thorium. The scheme of radioactive transforma-

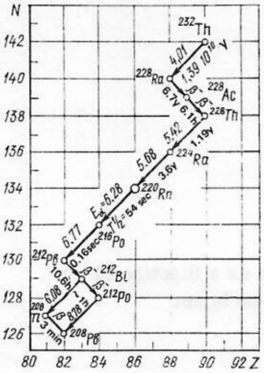

FIG. 25. Scheme of radioactive transformations of the thorium series.

tions of the thorium series is shown in Fig. 25. It is interesting to note that after the decay of $^{220}Rn_{86}$ the isotope with the longest half-life, $^{212}Pb_{82}$, has $T_{1/2} = 10.6$ h, which creates exceptionally favorable conditions for experiments. It is readily seen that $^{220}Rn_{86}$ satisfies all the requirements listed above and is suitable for experiments in this direction.

The ionizer KRION-2 can provide a basis for the experiment. To achieve the final aim of obtaining radon nuclei it is necessary to increase the energy of the electron beam to about 200 keV, the density (linearly with the energy) to 1500 A/cm², and the containment time of the ions to 100 sec. Experiments with ions up to Rn^{76+} can already be begun.

As a continuous source of ^{220}Rn atoms, it is convenient to use a container with a fine powder of the oxide of natural thorium, and as α-particle detectors to use surface-barrier detectors of cylindrical shape with sensitive layer on the inside facing the electron beam of the ionizer.

In considering the method to be used in the measurements, it must be borne in mind that during the ionization process ions may be lost from the beam in the axial and radial directions with subsequent sorption (in the latter case) on the walls of the drift tube or detector; this results in background α radiation when both ΔE_α and $\Delta\lambda$ are being determined. For the determination of ΔE_α, the operation of subtracting the background is fairly simple, but the measurements associated with the determination of $\Delta\lambda$ appear at present to present much greater problems.

We propose the following procedure in the measurements.[13] At a certain time τ, which is measured from the time of introduction of the low-charge Rn ions into the electron beam, the counting rate n_τ of the α particles is measured for all radon ions and stoms in the electron beam and on the wall of the drift tube. The electron beam is then switched off directly after the measurement, but the axial containment of the ions in the trap is maintained. The disappearance of the space charge of the electrons has the result that the radon ions move to the walls of the drift tube, where they are neutralized. Directly after the beam has been

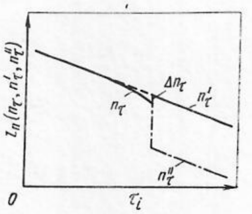

FIG. 26. The α-particle counting rates as a function of the time τ that the Rn ions are in the electron beam.

switched off, a new measurement is made of the α-particle counting rate n'_τ for all atoms on the wall of the drift tube. The difference $n_\tau - n'_\tau = \Delta n_\tau$ arises because of the difference $\Delta\lambda = \lambda_0 - \lambda_q$, where λ_0 is the decay probability for nuclei of the atoms ^{220}Rn, and λ_q is the decay probability for the nuclei of the ions $^{220}Rn^{q+}$.

To establish the number of ions that must be associated with the observed Δn_τ, the Rn ions in the beam at the time τ in the following cycle of measurements are extracted from the ionizer in the axial direction directly after the measurements of n_τ. The α-particle counting rate for the radon atoms on the walls of the drift tube, n''_τ is measured directly after the extraction. The difference $\delta n_\tau = n'_\tau - n''_\tau$ gives the number of ions of charge q that must be associated with the observed change Δn_τ in the counting rate.

The dependence of the α-particle counting rate on τ are plotted in Fig. 26. We note that in this method of measurement the main observed effect is the jump Δn_τ, which must be measured with the greatest possible accuracy in one cycle. The number of atoms corresponding to the effect is measured in two neighboring cycles. The accuracy is then lower, but the requirements on the result are appreciably lower. Making measurements for different values of τ, it is possible to find the dependence $\Delta\lambda = f(q)$.

Calculations show that at the present time such a method could result in the experimental determination of a change of order

$$\Delta\lambda/\lambda \geqslant 10^{-3}.$$

Similar experiments to study K capture and $\beta^\pm$ decay can be considered, especially since the theoretically predicted effects in these cases are much larger.

CONCLUSIONS

At the present time there is an interest in ions with high charge states in their own right, on the one hand, and, on the other, as a means for physics investigations, and we shall therefore briefly evaluate the electron-beam method of ionization from the two points of view.

The progress in improving the ionization factor during ten years from 10^{17} to 10^{22} cm^{-2}, with a correspond ing growth in the energy of the ionizing electrons, and analysis of studies in this field suggest that in the near future as ionization factor of approximately 10^{24} cm^{-2} with an electron energy of about 250 keV will be achieved, i.e., at the present time the majority of ions can be obtained, while in the near future all ions of all sufficiently stable elements will become accessible for investigation of their properties. For this, there are no fundamental problems in the electron-beam method of ionization, and the experimental skill of the investigators can solve the problems.

The extension of the use of ions in high charge states as a means of investigation will be governed by the successes achieved in the electron-beam method of ionization in increasing the intensity of the ion beams. Here, the main problems are the identification and suppression of the observed instability of the linear ion-electron system,[24] understanding of the process of ion supercompression of an electronbeam,[29,65,66] and investigation of the reflection regime of operation of an electron-beam ionizer.[13]

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