Modern Physics Letters B
Vol. 34, No. 14 (2020) 2050150 (13 pages)

DOI: 10.1142/S021798492050150X

Influence of energy losses on charge distribution of fast ions passing through solid matter

Yu. A. Belkova, N. V. Novikov* and Ya. A. Teplova

Lomonosov Moscow State University,
Skobeltsyn Institute of Nuclear Physics,
Moscow 119991, Russia
**nvnovikov65@mail.ru*

Received 30 September 2019
Revised 19 November 2019
Accepted 28 November 2019
Published 9 March 2020

The charge distribution of fast multicharged ions passing through a matter is studied taking ion energy losses into account. Within the framework of the proposed method, we show that the changes in the charge exchange cross-sections, caused by the decreasing of ion energy, affect the process of the formation of the equilibrium ion charge distribution. The target thickness, required for obtaining the equilibrium ion charge distribution, reaches the maximum value for ions without electrons and hydrogen-like ions. The equilibrium target thickness increases with increasing in ion nuclear charge and energy and for fast heavy ions becomes comparable with their range.

Keywords: Charge fractions; mean charge; width of the ion charge distribution; inelastic energy losses of ions.

1. Introduction

The study of charge and energy distributions of ions passing through gaseous and solid targets is one of the perspective directions of the development of the physics of atomic collisions.[1] The process of charged particle propagation through a matter and the related changes in their energy and charge belong to problems that are studied actively in various scientific areas. Interest of the fundamental science in this complicated process is caused by the development of methods for describing particle–matter interaction including the description of several competing inelastic processes, such as electron capture and loss by ion, target atom ionization, ion energy loss. The regularities of changes in the charge of an ion when its energy changes are important for applying ion beams in accelerating installations, the radiative study of materials, and mass spectrometry.

*Corresponding author.

The problem is to describe the process of the penetration of ions with the nuclear charge Z, the initial charge q_0, and the energy E_0 through a target. If the energy E of the ion passing through a thin layer does not change significantly ($E \approx E_0$), the following system of charge exchange equations is used to describe the charge distribution of ions[2]:

$$\frac{d\Phi_q}{dx} = \sum_{q' \neq q} \Phi_{q'}(E_0, x)\sigma_{q',q}(E_0, Z) - \Phi_q(E_0, x) \sum_{q' \neq q} \sigma_{q,q'}(E_0, Z)\,, \tag{1}$$

where q is the charge of ions after their passage through a layer with the thickness x, $\sigma_{q,q'}(E, Z)$ is the cross-sections for loss ($q < q'$) and capture ($q > q'$) of electrons by the ion, and $\Phi_q(E, x)$ are the charge fractions that are equal to the relative number of ions with the charge q. If the cross-sections $\sigma_{q,q'}(E, Z)$ are known online application BREIT[3] may be used for solution of a set of the balance equations (1). As the layer thickness x increases, the equilibrium charge distribution establishes; the charge fractions $\Phi_q(E_0, x)$ become independent of x: $\Phi_q(E_0, x) \to F_q(E_0)$. Nevertheless, according to the experimental data,[4] the charge distribution varies as a target thickness function after the charge equilibrium is attained because the energy of ions decreases during their stopping. A typical example of such variation is shown for incident 65 MeV Cu^{9+} ions in carbon foil.[4]

Several experimental studies are known, where the dependence of charge fractions or of the ion charge distribution parameters on the target thickness was considered,[4–15] but they dealt with solid targets, mainly carbon. Published data on nonequilibrium charge distributions in gases[16,17] are less than those on distributions in solids. On the other hand, the ion charge exchange cross-sections required for simulation of nonequilibrium charge distributions are represented much more completely for gases than for solids. The development of methods for calculating the charge exchange cross-sections for ions in solid targets in a wide ion energy interval is important since the simulation strongly depends on the quality of cross-sections. There are several computer codes,[18–20] which allow to evaluate the charge distribution of ions in gases and solid media. Codes differ in ion energy range and cross-section estimation methods.

In our previous papers,[21–23] we developed methods for estimating the cross-sections $\sigma_{q,q\pm1}(E, Z)$ and $\sigma_{q,q\pm2}(E, Z)$ in a wide interval of ion energies E for gaseous and solids targets. The estimate is based on experimental cross-sections,[24,25] as well as empirical values of the charge mean[26] and width[27] in the equilibrium charge distribution of ions. Using the data on charge exchange cross-sections, we studied conditions for the formation of the equilibrium ion charge distributions that were based on the changes in the mean charge and the charge distribution width as functions of x. For a small target thickness, when ions lose a small part of their energy and the change in the charge exchange cross-sections caused by the slowing down of the ions is small, Eq. (1) can be used. The calculated results for the target thickness at which the equilibrium charge distribution is established are in qualitative agreement with experimental data for ions with $Z \leq 10$.[8,11]

The situation becomes more complex for heavier ions ($Z > 10$). If the initial ion charge q_0 is close to equilibrium charge, the thin layer approximation (1) is valid. However, when we simulated the formation of equilibrium charge distribution for bare nuclei or multicharged ions using approximation (1), we found that the calculated equilibrium target thickness became larger than the range of ions with energy E_0. Our motivation is based on the assumption that this discrepancy between the calculated and experimental data leads to the necessity of improving the traditional method for calculating the charge distribution of ions (1) so that the energy loss must be taken into account in simulations.

The aim of this paper is to study the interrelation between ion charge exchange and decreasing of ion energy and to calculate the equilibrium target thickness for fast multicharged heavy ions passing through a matter.

2. Charge Exchange Cross-Sections

In our work, we have developed the method for estimating charge exchange cross-sections[21–23] for ions, using three approximations:

(1) The description of cross-sections of loss $\sigma_{q,q+1}(E, Z, Z_t)$ and capture $\sigma_{q,q-1}(E, Z, Z_t)$ of one electron by ions in gases is based on the experimental data for $Z = 1$, 2, 7, 10, 18, 36, and 54 (Refs. 28–33) and on theoretical dependence of cross-sections on ion energy. The dependence of the electron loss cross-section $\sigma_{q,q+1}(E, Z, Z_t)$ on ion energy has a maximum when the collision velocity and the velocity of valence electrons in the ion are close. The cross-section $\sigma_{q,q+1}(E, Z, Z_t)$ decreases as $1/E$ for fast collisions.[34] The dependence of the electron capture cross-section $\sigma_{q,q-1}(E, Z, Z_t)$ on energy is described in the Oppenheimer–Brinkman–Kramers approximation.[35]

(2) It is known[29] that the probability of electron capture in solid targets is less than in gases, but the probability of electron loss is vice versa. In our calculations, the charge exchange cross-sections in solid targets differ from those in gases by a scale factor $C_{g-s}(E, Z, Z_t) \geq 1$ that does not depend on q[22]:

$$\sigma^{\text{sol}}_{q,q+1}(E, Z, Z_t) = \sigma^{\text{gas}}_{q,q+1}(E, Z, Z_t) \times C_{g-s}(E, Z, Z_t)\,, \tag{2}$$

$$\sigma^{\text{sol}}_{q,q-1}(E, Z, Z_t) = \sigma^{\text{gas}}_{q,q-1}(E, Z, Z_t)/C_{g-s}(E, Z, Z_t)\,. \tag{3}$$

The equilibrium charge fractions $F_q(E)$ and the equilibrium mean charge of ions in a solid target

$$\overline{q}(E) = \sum_q qF_q(E) \tag{4}$$

are calculated using cross-sections $\sigma^{\text{sol}}_{q,q\pm1}(E, Z, Z_t)$. From the relation $C_{g-s}(E, Z, Z_t) \geq 1$ it follows that the equilibrium mean charge of ions in a solid target is larger than in gases. The scale factor $C_{g-s}(E, Z, Z_t)$ is calculated from the normalization $\overline{q}(E)$ to empirical mean ion charge in a solid target $\overline{q}^{\text{sol}}(E, Z, Z_t)$.[26]

(3) The ratio of charge exchange cross-sections in the processes with one and two electrons is the same for capture and loss and does not depend on the charge of ions q:

$$W^{\rm sol}(E,Z,Z_t) = \sigma^{\rm sol}_{q,q+2}(E,Z,Z_t)/\sigma^{\rm sol}_{q,q+1}(E,Z,Z_t)$$
$$= \sigma^{\rm sol}_{q,q-2}(E,Z,Z_t)/\sigma^{\rm sol}_{q,q-1}(E,Z,Z_t) < 1\,. \quad (5)$$

The equilibrium charge fractions $F_q(E)$ and the charge distribution width

$$[d(E)]^2 = \sum_q [q - \overline{q}(E)]^2 F_q(E) \quad (6)$$

are recalculated using cross-sections $\sigma^{\rm sol}_{q,q\pm1}(E,Z,Z_t)$ and $\sigma^{\rm sol}_{q,q\pm2}(E,Z,Z_t)$. The scale factor $W^{\rm sol}(E,Z,Z_t)$ is obtained from the normalization of $d(E)$ to the empirical value $d^{\rm sol}(E,Z,Z_t)$.[27]

The ratio between the loss and capture cross-sections is important for formation of the equilibrium charge distribution of ions. The dependences of the electron capture and electron loss cross-sections on the ion energy are different. As a consequence, the values of charge exchange cross-sections become equal for some energy $E : \sigma_{q,q+1}(E,Z,Z_t) \approx \sigma_{q,q-1}(E,Z,Z_t)$.[36] So, an ion with a charge q can equally lose or capture one electron and, consequently, $\overline{q}(E) \approx q$. For example, we obtain $\overline{q}(E') \approx 12$ at $E' = 1.78$ MeV/amu for sulfur ion in carbon (Fig. 1), where $\sigma_{12,13}(E') \approx \sigma_{12,11}(E')$; $\overline{q}(E'') \approx 13$ at E'' =2.60 MeV/amu, where $\sigma_{13,14}(E'') \approx \sigma_{12,13}(E'')$, etc. These mean charges are close to the corresponding empirical values.[26] Figure 1 shows that the value of the equilibrium charge decreases with decreasing in ion energy.

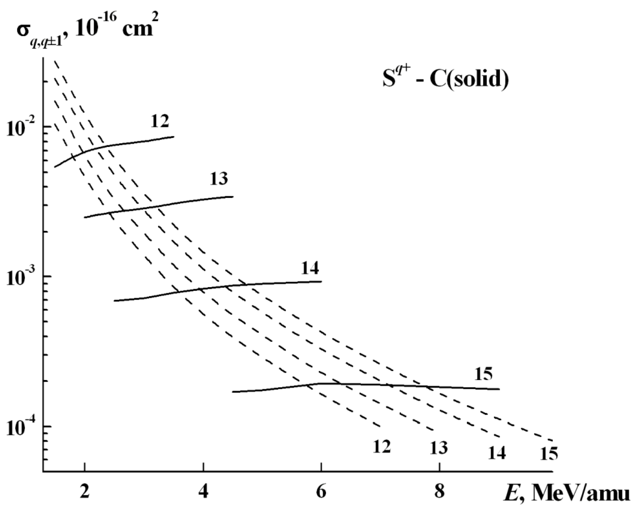

Fig. 1. Dependence of the electron loss (solid lines) and electron capture (dashed lines) cross-sections on energy sulfur ions in carbon targets. The numbers near the lines indicate the charge of the ions q.

3. Method of Calculations

To calculate the charge and energy distributions of ions passing through the target, we propose to use the system of differential equations including the charge exchange equations, in which the charge fractions and the electron loss and capture cross-sections depend on the ion energy that varies during ion passage through the matter, and the equation for the energy losses:

$$\frac{d\Phi_q}{dx} = \sum_{q' \neq q} \Phi_{q'}(E,x)\sigma_{q',q}(E,Z) - \Phi_q(E,x) \sum_{q' \neq q} \sigma_{q,q'}(E,Z)\,, \tag{7}$$

$$-\frac{dE}{dx} = S_n(E,Z) + S_e(E,Z,\overline{Q}(E,x))\,, \tag{8}$$

where $S_n(E,Z)$ are the energy losses in elastic ion–atom collisions and $S_e(E,Z,\overline{Q}(E,x))$ are the inelastic energy losses, which depend on the mean charge of ions:

$$\bar{Q}(E,x) = \sum_q q\Phi_q(E,x)\,. \tag{9}$$

The preequilibrium charge distribution of ions is characterized by mean charge (9) and the charge distribution width:

$$[D(E,x)]^2 = \sum_q [q - \overline{Q}(E,x)]^2 \Phi_q(E,x)\,. \tag{10}$$

The system of Eqs. (7) and (8) is solved with the initial condition:

$$\Phi_{q0}(E_0, 0) = 1\,, \tag{11}$$

and the normalization one:

$$\sum_q \Phi_q(E,x) = 1\,. \tag{12}$$

When solving the system of Eqs. (7) and (8), it is necessary to take two peculiarities into account. On the one hand, a decrease in the ion energy E results in a change in the cross-sections $\sigma_{q,q'}(E,Z)$, the charge fractions $\Phi_q(E,x)$, and the mean charge of ions $\bar{Q}(E,x)$. On the other hand, the inelastic energy losses S_e depend on $\bar{Q}(E,x)$. Consequently, the system of Eqs. (7) and (8) reflects the correlations between the ion distributions over the charge q and the energy E. This is its distinction from the traditional system of Eq. (1), where the thin-layer approximation is used ($E \approx E_0$). When describing the charge and energy distributions of ions in forms (7) and (8), it is assumed that the properties of target remain unchanged during the interaction with the ion beam.

For a rigorous solution of the system of Eqs. (7) and (8), complete data are required on the energy loss dependence on the preequilibrium ion mean charge

$S_e(E, Z, \overline{Q}(E, x))$ or on energy losses $S_e(E, Z, q)$ for ions of all charges q. These values are interconnected:

$$S_e(E, Z, \overline{Q}(E, x)) \approx \sum_q \Phi_q(E, x) S_e(E, Z, q)\,. \tag{13}$$

There are no such complete data at present, and it is unlikely that they will be obtained in the near future. Modern programs[37,38] provide an estimate of the inelastic energy losses only for ions with an equilibrium charge distribution. As a first approximation to solve the problem we consider $q_0 \approx \overline{q}(E_0)$ and use the equilibrium inelastic energy losses from the SRIM code[37]:

$$S_e(E, Z, \overline{Q}(E, x)) \approx S_e^{\mathrm{SRIM}}(E, Z)\,. \tag{14}$$

In this approximation, the inelastic energy losses are independent on the ion charge q, and so the ions of all charges passed through the layer thickness x, have the same energy E.

As the layer thickness x increases, the charge fractions $\Phi_q(E, x)$ tend to the equilibrium ones $F_q(E)$, which can be calculated as a result of solving the system of homogeneous equations

$$\sum_{q' \neq q} F_{q'}(E)\sigma_{q',q}(E, Z) - F_q(E) \sum_{q' \neq q} \sigma_{q,q'}(E, Z) = 0\,. \tag{15}$$

The equilibrium charge fractions $F_q(E)$ and the parameters of the equilibrium charge distribution of ions (4) and (6) are independent of initial conditions (11). If the ion energy losses in the matter are taken into account, the ion energy $E(x)$ decreases with increasing layer thickness x (8). This results in a change in cross-sections $\sigma_{q,q'}(E, Z)$ in (15), and, as a consequence, the dependence of parameters (4) and (6) on the thickness x appears in Eqs. (7) and (8).

The criterion for the determination of the target thickness required for establishing the equilibrium charge distribution of ions is the difference between the parameters corresponding to the solutions of the systems of Eqs. (7), (8) and (15). The dependence of the mean charge $\overline{Q}(E, x)$ on the target thickness makes it possible to calculate the target thickness T_q at which the mean charge differs from the equilibrium one $\overline{q}(E)$ by at most several percent:

$$|\overline{Q}(E, T_q) - \overline{q}(E)|/\overline{q}(E) = \delta\,. \tag{16}$$

It should be noted that $T_q \approx 0$ if the initial ion charge q_0 is close to the equilibrium value. Then it is important to consider the formation of the width of the equilibrium charge distribution. It is possible to determine the target thickness T_d at which the width of the ion charge distribution $D(E, x)$ differs slightly from that of the equilibrium charge distribution $d(E)$:

$$|D(E, T_d) - d(E)|/d(E) = \delta\,. \tag{17}$$

The relation between T_q and T_d depends on the difference between q_0 and $\overline{q}(E_0)$.[23] The target thickness at which the equilibrium ion charge distribution is established is calculated in the form

$$T_{qd}(E_0, Z, q_0) = \max\{T_q, T_d\}\,. \tag{18}$$

The target thickness required for establishing the equilibrium charge distribution of ions with any charge q_0 is determined by maximum among all values in an interval $0 \le q_0 \le Z$:

$$\tilde{T}_{qd}(E_0, Z) = \max\{T_{qd}(E_0, Z, q_0 = 0), \ldots, T_{qd}(E_0, Z, q_0 = Z)\}\,. \tag{19}$$

This quantity characterizes the upper boundary of the target thickness, where the processes related to the nonequilibrium ion charge distributions must be taken into account.

Let the path length of ions until their full stopping be equal to an ion range $R(E_0, Z)$. The evolution of the charge distribution of ions passing through the matter can be divided into two parts. At the initial stage, for a small target thickness ($x < \tilde{T}_{qd}$), the parameters of the ion charge distribution depend on initial conditions (11), and $\overline{Q}(E, x)$ and $D(E, x)$ change with increasing x. As the target thickness increases ($x > \tilde{T}_{qd}$), the equilibrium ion charge distribution is characterized by the parameters $\overline{q}(E)$ and $d(E)$, which are independent of q_0. It is necessary to underline that as the ion energy E decreases with increasing of x, and the equilibrium quantities $\overline{q}(E)$ and $d(E)$ also depend on x.

4. Results of Calculations

When calculating the equilibrium target thickness required for ions with the nuclear charges $Z > 10$, the results of calculating $\sigma_{q,q\pm1}(E, Z)$ (2), (3), and $\sigma_{q,q\pm2}(E, Z)$ (5), the data on the ion energy losses $S_n^{\mathrm{SRIM}}(E, Z)$ and $S_e^{\mathrm{SRIM}}(E, Z)$,[37] and the value $\delta = 0.05$ are used. Figure 2 shows the results of calculating of the mean charge $\overline{Q}(E, x)$ of sulfur ions for different initial charges q_0 and the equilibrium mean charge $\overline{q}(E)$, for which the energy losses of ions passing through the matter are taken into account. As the target thickness increases, the character of the change in the mean charge depends on the ratio of the initial charge q_0 and the equilibrium one $\overline{q}(E_0)$. Ions with $q_0 < \overline{q}(E_0)$ lose electrons, and the mean charge $\overline{Q}(E, x)$ increases. For ions with $q_0 > \overline{q}(E_0)$, capture of electrons results in a decrease in $\overline{Q}(E, x)$. Such dependence corresponds to the experimental data. At the target thickness $T_q \approx 80$ μg/cm^2, the mean charge $\overline{Q}(E, x)$ of sulfur ions reaches the equilibrium value $\overline{q}(E)$. Sulfur ions with energy $E_0 = 2$ MeV/amu and with average charge $\overline{q}(E_0) \approx 12.7$ passing through 100 μg/cm^2 thick carbon target are slowing down to $E = 1.94$ MeV/amu.[37] The decrease in the ion energy by 2 MeV results in a change in the cross-section ratios, for example, $\sigma_{12,13}/\sigma_{12,11}$decreases from 1.52 to 1.34 (Fig. 1). The inclusion of the energy losses of ions (8) into calculations of charge distribution leads to a decrease in $\overline{q}(E)$ with increasing layer thickness. As a result, ions whose mean charge $\overline{Q}(E, x)$ increases ($q_0 < \overline{q}(E_0)$), reach $\overline{q}(E)$ at a smaller target thickness than ions whose mean charge $\overline{Q}(E, x)$ decreases ($q_0 > \overline{q}(E_0)$).

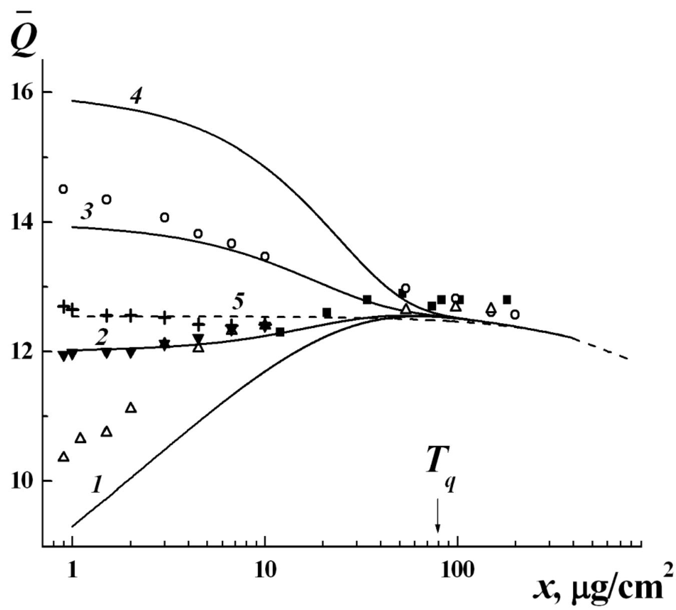

Fig. 2. Dependence of mean charge on the carbon target thickness for sulfur ions at E_0 = 2 MeV/amu. Solid lines indicate the results of calculation of $\overline{Q}(E,x)$: (1), $q_0 = 7$; (2), $q_0 = 12$; (3), $q_0 = 14$; and (4), $q_0 = 16$. The dashed line denotes the results of calculation of the equilibrium mean charge $q(E)$. The arrow indicates the equilibrium target thickness T_q. Symbols are for experimental data: (Δ)$q_0 = 7$, ($\blacktriangledown$) $q_0 = 12$, (+) $q_0 = 14$, (o) $q_0 = 16$ and $E_0 = 2$ MeV/amu,[14] and ($\blacksquare$) $q_0 = 6$ and $E_0 = 2.17$ MeV/amu.[6]

The incident beam contains ions in a single charge state, and $D(E, x = 0) = 0$. As the thickness increases, ions with $q \neq q_0$ appear in the charge distribution and the charge ion distribution width increases (Fig. 3). When the layer thickness is $T_d \approx 90$ μg/cm^2, the difference between the parameter $D(E,x)$ and the equilibrium value $d(E)$ does not exceed δ. We note that the interval of x where $D(E,x) > d(E)$ exists for ions with $q_0 > \overline{q}(E_0)$, and the ion charge distribution width $D(E,x)$ increases for ions with $q_0 < \overline{q}(E_0)$ (Fig. 3). The maximum of function $D(E,x)$ for ions with $q_0 > \overline{q}(E_0)$ can be explained by the increase in the number of charge fractions $\Phi_q(E,x)$. There are ions with charges from $q = 12$ to $q = 16$ in the charge distribution of S^{16+} ions at $x' \approx 20$ μg/cm^2 ($\overline{Q}(E,x') \approx 14$, see Fig. 2), and the parameter $D(E,x)$ reaches maximum value. This differs from experimental data,[14] but is consistent with the calculations of the same work. On the other hand, the equilibrium value $d(E)$ corresponds to the experimental data. The main contributions to $d(E)$ are made by components with initial charges close to the average equilibrium charge (curves 2 and 3 in Fig. 3), and the effect of the fractions with $q_0 = 7$ and $q_0 = 16$, for which there is a discrepancy from experiment, decreases rapidly. Therefore, the calculated values can be used to determine $T_{qd}(E_0, Z, q_0)$ (18) and $\tilde{T}_{qd}(E_0, Z)$ (19). For further improvement of calculation methods new experimental data in the preequilibrium region are necessary.

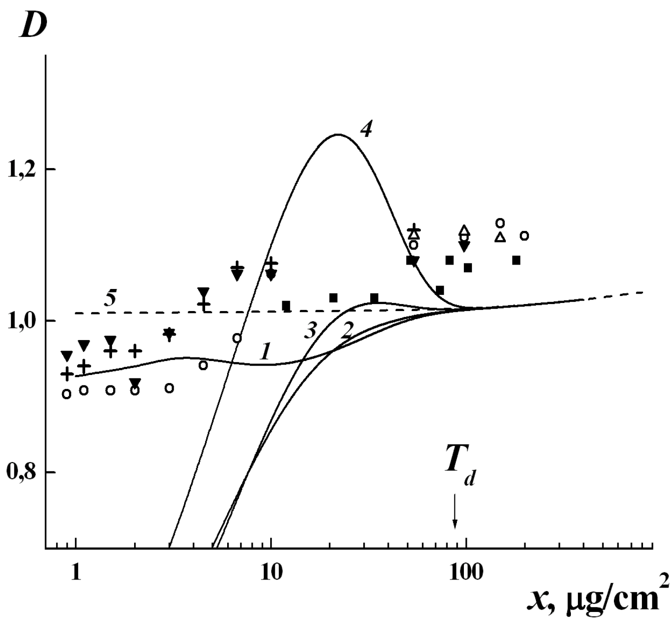

Fig. 3. Evolution of the charge distribution width with the carbon target thickness for sulfur ions at $E_0 = 2$ MeV/amu. The solid lines denote the calculation results for $D(E, x)$: (1), $q_0 = 7$; (2), $q_0 = 12$; (3), $q_0 = 14$; and (4), $q_0 = 16$. The dashed line denotes the results for $d(E)$. The arrow indicates the equilibrium target thickness T_q. The experimental data[6,14] are denoted as in Fig. 2.

In calculations, we take into account the processes of loss and capture of two electrons ($\sigma_{q,q\pm2}(E, Z) > 0$). As a result, the width of the equilibrium charge distribution d increases at $E_0 = 2$ MeV/amu from $d(E) = 0.84$ to $d(E) \approx 1.0$. The value of the calculated parameter $d(E)$, which is less than the experimental values in Fig. 3 by 10%, can be explained by the necessity of taking into account the processes of the loss and capture of three electrons or more in one collision in the calculations.

The calculations of $T_{qd}(E_0, Z, q_0)$ dependence on E_0 were carried out for S^{14+}, S^{15+}, and S^{16+} ions. The target thickness that is required for forming the equilibrium charge distribution $T_{qd}(E_0, Z, q_0)$ (18) usually increases with increasing q_0 and becomes maximum at $q_0 \approx Z$ (Fig. 4). The experimental data[14] are available only for S^{16+} ions. The charge fraction measurements for S^{14+} and S^{15+} ions were carried out only for thin targets ($x \leq 10$ μg/cm^2). This feature of $T_{qd}(E_0, Z, q_0)$ is related to the decrease in the cross-sections in the energy interval where $\sigma_{q,q-1}(E, Z) \approx \sigma_{q,q+1}(E, Z)$ (Fig. 1) and to the increase in the mean free path between inelastic collisions with the change in the ion charge.[23] The exception is the case where $q_0 \approx \overline{q}(E_0)$. Then, the mean charge $\overline{Q}(E, x)$ reaches its equilibrium state rapidly ($T_q \to 0$), and a minimum appears in the dependence $T_{qd}(E_0, Z, q_0)$ on the energy E_0. Such minima for sulfur ions with $q_0 = Z - 1$ and $q_0 = Z$ (cases 1 and 3 in Fig. 4) exist at $E_0 \approx 3$ and ≈ 6 MeV/amu. In

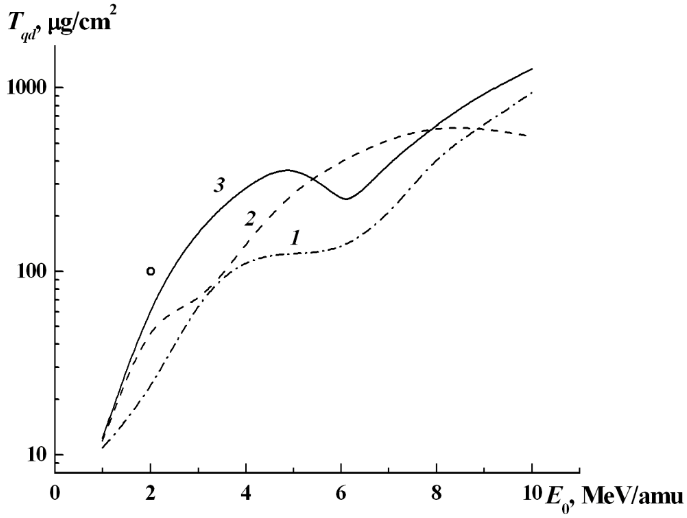

Fig. 4. Dependence of the target thickness T_{qd} for the formation of equilibrium charge distribution in the case for sulfur ions in carbon targets with the energy E_0: (1), $q_0 = 14$; (2), $q_0 = 15$; and (3), $q_0 = 16$. Symbol (o) indicates experimental data for $q_0 = 16$.[14]

this energy interval, $T_{qd}(E_0, Z, q_0)$ for $q_0 = Z - 1$ exceeds the corresponding value for $q_0 = Z$.

Consequently, to calculate $\tilde{T}_{qd}(E_0, Z)$ in relation (19), only two values of q_0 can be retained:

$$\tilde{T}_{qd}(E_0, Z) = \max\{T_{qd}(E_0, Z, q_0 = Z - 1), T_{qd}(E_0, Z, q_0 = Z)\}\,. \tag{20}$$

For $q_0 \leq Z - 2$, $T_{qd}(E_0, Z, q_0)$ is less than $\tilde{T}_{qd}(E_0, Z)$ in the entire energy interval under consideration.

The calculations of target thickness (20) as a function of the energy E_0 and the ion nuclear charge Z made it possible to determine the upper boundary of the interval for the carbon target thickness where the nonequilibrium ion charge distribution must be taken into account. To estimate the relation between the parts of target thickness of ions where their charge distribution is equilibrium or nonequilibrium, the calculations of the ratio $\tilde{T}_{qd}(E_0, Z)/R(E_0, Z)$ are carried out (Fig. 5), where $R(E_0, Z)$ is the ion range. For ions that are lighter than neon, the equilibrium charge distribution of ions is established in surface target layers, and $\tilde{T}_{qd}(E_0, Z)/R(E_0, Z) \to 0$ in the energy interval under study. As Z and E_0 increase, the thickness $\tilde{T}_{qd}(E_0, Z)$ becomes comparable with the ion range. So, $\tilde{T}_{qd}(E_0, Z)/R(E_0, Z) \geq 0.5$ for ions with $Z \geq 36$ at $E_0 = 3$ MeV/amu and with $Z \geq 24$ at $E_0 = 6$ MeV/amu. In this case, for a larger part of the ion range, their charge distribution depends on q_0 and remains nonequilibrium.

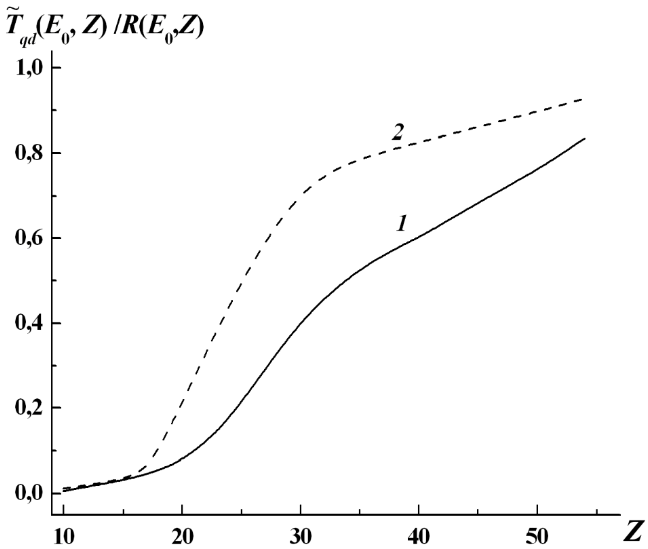

Fig. 5. Dependence of the ratio of equilibrium target thickness $\tilde{T}_{qd}(E_0, Z)$ to the ion range $R(E_0, Z)$ on the ion nuclear charge Z and the energy E_0: (1), $E_0 = 3$ MeV/amu and (2), $E_0 = 6$ MeV/amu.

5. Conclusions

In this paper, we have proposed a method involving an interrelated consideration of the two processes accompanying the propagation of ions through matter: the formation of ion charge distribution and ion stopping. The inclusion of the energy losses of ions into calculations of charge distribution leads to a change in $\overline{q}(E)$ and $d(E)$ with increasing layer thickness.

The ion range in the matter can be divided into two parts. For small target thickness, when $x < T_{qd}(E_0, Z, q_0)$, the charge distribution of ions is nonequilibrium, the mean charge and the charge distribution width depend not only on the nuclear charge Z and the ion energy E_0, but also on the initial ion charge q_0. When ion charge distribution reaches equilibrium, $x \geq T_{qd}(E_0, Z, q_0)$, and the parameters of the ion charge distribution depend only on the ion energy, decreasing due to ion stopping. The results of our calculations show that the target thickness $T_{qd}(E_0, Z, q_0)$ required for establishing the equilibrium charge distribution, reaches its maximum value for ions without electrons and for hydrogen-like ions and increases with increasing in the energy E_0 and the ion nuclear charge Z.

For fast multiply charged ions, the maximum equilibrium thickness $\tilde{T}_{qd}(E_0, Z)$ becomes comparable with the ion range and therefore, the ion charge distribution is nonequilibrium at the larger part of the range.

The proposed theoretical method can be useful for ion beam applications. The proper definition of equilibrium target thickness $\tilde{T}_{qd}(E_0, Z)$ makes it possible to obtain the ion beams with certain charge distributions.

References

1. P. Sigmund, *Particle Penetration and Radiation Effects: Penetration of Atomic and Molecular Ions*, Vol. 2 (Springer, New York, 2014), 602 pp.
2. S. K. Allison, *Rev. Mod. Phys.* **30** (1958) 1137.
3. N. Winckler, A. Rybalchenko, V. P. Shevelko, M. Al-Turany, T. Kollegger and Th. Stohlker, *Nucl. Instrum. Meth. Phys. Res. B* **392** (2017) 67.
4. K. Shima, T. Ishihara, T. Miyoshi and T. Mikumo, *Phys. Rev. A* **28** (1983) 2162.
5. E. Baron and B. Delaunay, *Phys. Rev. A* **12** (1975) 40.
6. U. Scharfer *et al.*, *Nucl. Instrum. Meth.* **146** (1977) 573.
7. C. J. Woods *et al.*, *J. Phys. B* **17** (1984) 867.
8. V. P. Zaikov *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **17** (1986) 97.
9. L. B. Bridwell, H. J. Hay and L. F. Pender, *Aust. J. Phys.* **31** (1988) 681.
10. A. Blazevic, H. G. Bohlen and W. Oertzen, *Phys. Rev. A* **61** (2000) 032901.
11. Y. Sato *et al.*, *Nucl. Instr. Meth. Phys. Res. B* **225** (2004) 439.
12. T. Miyoshi *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **251** (2006) 79.
13. T. Miyoshi *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **258** (2007) 329.
14. M. Imai *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **267** (2009) 2675.
15. M. Imai *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **354** (2015) 172.
16. V. S. Nikolaev, I. S. Dmitriev and Ya. A. Teplova, *Izv. Acad. Nauk SSSR, Ser. Fiz.* **27** (1963) 1078 (in Russian).
17. T. Tonuma *et al.*, *J. Phys. Soc. Jpn.* **34** (1973) 148.
18. C. Scheidenberger, Th. Stohlker, W. E. Meyerhof, H. Geissel, P. H. Mokler and B. Blank, *Nucl. Instrum. Meth. Phys. Res. B* **142** (1998) 441.
19. J. P. Rozet, C. Stéphan and D. Vernhet, *Nucl. Instrum. Meth. Phys. Res. B* **107** (1996) 67.
20. E. Lamour, P. D. Fainstein, M. Galassi, C. Prigent, C. A. Ramirez, R. D. Rivarola, J. Rozet, M. Trassinelliand and D. Vernhet, *Phys. Rev. A* **92** (2015) 42703.
21. N. V. Novikov and Ya. A. Teplova, *Phys. Lett. A* **378** (2014) 1286.
22. Yu. A. Belkova, N. V. Novikov and Ya. A. Teplova, *Nucl. Instrum. Meth. Phys. Res. B* **343** (2015) 110.
23. Yu. A. Belkova, N. V. Novikov and Ya. A. Teplova, *Nucl. Instrum. Meth. Phys. Res. B* **373** (2016) 35.
24. N. V. Novikov and Ya. A. Teplova, *J. Phys.: Conf. Ser.* **194** (2009) 082032.
25. N. V. Novikov and Ya. A. Teplova, Database on charge-changing cross-sections in ion-atom collisions, http://cdfe.sinp.msu.ru/services/cccs.
26. G. Schiwietz *et al.*, *Nucl. Instrum. Meth. Phys. Res. B* **225** (2004) 4.
27. N. V. Novikov and Ya. A. Teplova, *Phys. Lett. A* **377** (2013) 463.
28. H. H. Lo and W. L. Fite, *At. Data Nucl. Data Tables* **1** (1970) 305.
29. H. D. Betz, *Rev. Mod. Phys.* **44** (1972) 465.
30. H. Tawara, T. Kato and Y. Nakai, *At. Data Nucl. Data Tables* **32** (1985) 235.
31. W. K. Wu, B. A. Huber and K. Wiesemann, *At. Data Nucl. Data Tables* **40** (1988) 57.
32. W. K. Wu, B. A. Huber and K. Wiesemann, *At. Data Nucl. Data Tables* **42** (1989) 157.
33. I. S. Dmitriev, Ya. A. Teplova, Yu. A. Belkova, N. V. Novikov and Yu. A. Fainberg, *At. Data Nucl. Data Tables* **96** (2010) 85.
34. M. R. C. McDowell and J. P. Coleman, *Introduction to the Theory of Ion-Atom Collisions* (North-Holland Publishing Company, London, 1970), 442 pp.
35. V. S. Nikolaev, *Sov. Phys. Usp.* **8** (1965) 269.

36. Yu. A. Belkova, N. V. Novikov and Ya. A. Teplova, *J. Surf. Invest. X-ray, Synchr. Neutron Techn.* **3** (2009) 188.
37. J. F. Ziegler, *SRIM: The Stopping and Range of Ions in Matter*, http://www.srim.org.
38. P. Sigmund and A. Schinner, *Nucl. Instrum. Meth. Phys. Res. B* **195** (2002) 64.