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Equilibrium thickness of carbon target interacting with nitrogen and neon ion beams

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ABSTRACT

The method for calculation of the target thickness which is required for the formation of equilibrium charge distribution of ions is proposed. The description of nonequilibrium processes is based on empirical estimations of charge-exchange cross sections, taking the density effect for solids into account. The variation of the average charge and the width of the nonequilibrium charge distribution as a function of the target thickness is analyzed. The results of calculations for nitrogen and neon ions in carbon are compared with experimental data.

1. Introduction

The interest in the description of processes of ion penetration through thin films has recently been increased in connection with the development of nanotechnologies.

It is known that the passing of the ion beam with intermediate energy through matter is accompanied by processes of electron capture and loss which lead to a change in the ion charge. If a target thickness t is large, then the equilibrium charge distribution is formed in the ion beam. The value of target thickness, required to form the equilibrium charge distribution, is called the equilibrium target thickness T. For $t \geqslant T$ parameters of charge distribution are independent on the initial ion charge q_0 and the target thickness t. For $t < T$ the average ion charge and, consequently, the energy loss depend on q_0 and t [1–3].

The equilibrium target thickness T can be calculated if charge exchange (electron capture and loss) cross sections are known in a given matter. However, there are only few published studies of the charge exchange cross sections and nonequilibrium charge fractions in solids. The experimental data are available for light ions passing through thin carbon [4–9], beryllium [5] and aluminum [10] films. The energy of ions under consideration usually exceeds several MeV/amu. At the same time, the formation of charge equilibrium is interesting for investigation in a wide energy region. The absence of computer programs for calculation of the nonequlibrium charge distributions of any ions in an arbitrary matter can also be related to the lack of information about cross sections. Therefore, the development of methods for estimating the equilibrium thickness of solid targets is important.

The equilibrium target thickness T was evaluated previously in our works [11–13] using the experimental data for ions in celluloid, carbon and gaseous targets. Experimental studies of attainment of the charge equilibrium for intermediate energies of ions in beams passing through solids and gases show that the equilibrium thickness of solid films differs from the analogous value in gases [11]. The difference between equilibrium thickness in solid and gas increases for $q_0 > \overline{q}$, where $\overline{q}$ is equilibrium ion charge, and also with increasing of the nuclear charge of incident ions. It was shown that T depends on the velocity and initial charge of ions [11], and the dependence of T on q_0 has a minimum as the initial charge approaches the charge equilibrium value [12,14].

We proposed the method for calculating the charge exchange cross sections based on the empirical estimations of experimental cross sections for electron loss and capture by ions with the nuclear charges $Z\,(5 \leqslant Z \leqslant 10)$ in gases with the corrections, taking density effect for solids into account [15,16]. The obtained cross sections for structureless (amorphous or polycrystalline) targets allow evaluating parameters of nonequilibrium distributions of ions and the equilibrium target thickness. In this paper we present a method for calculating the dependence of the equilibrium target thickness on the projectile energy E and the initial charge q_0. For nitrogen and neon ions passing through carbon, we compare the calculated values with the experimental data.

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2. Method for calculating equilibrium target thickness

The charge distribution of ions passing through the matter can be described using charge fractions. These dimensionless parameters present a relative number of ions with the charge q in the ion beam. If the target thickness is small and the equilibrium charge distribution has no time to establish, then the charge fractions of ions $\Phi_q(t)$ depend on both the target thickness t and the initial ion charge q_0. The charge fractions in the ion beam are described by the system of differential equations:

$$\frac{d\Phi_q(t)}{dt} = \sum_k \Phi_k(t)\sigma_{kq} - \Phi_q(t)\sum_k \sigma_{qk}, \qquad \sum_q \Phi_q(t) = 1, \tag{1}$$

where $\Phi_q(t)$ are the nonequilibrium charge fractions, σ_{qk} are electron loss ($q < k$) and electron capture ($q > k$) cross sections.

The average charge $\overline{Q}(t)$ and the width of the charge distribution $D(t)$ are defined as

$$\bar{Q}(t) = \sum_q q\Phi_q(t); \quad [D(t)]^2 = \sum_q [q - \overline{Q}(t)]^2 \Phi_q(t), \tag{2}$$

and reach their equilibrium values $\bar{q}$ and d, respectively, for $t \geqslant T$ [12]. The charge fractions $\Phi_q(t)$ become independent on t and q_0 for $t \to \infty$ and $\Phi_q(t) \to F_q$, where F_q are equilibrium charge fractions.

In this work, we use two conditions for the formation of the charge equilibrium.

1. In the first case, the equilibrium is assumed to be reached if $\bar{Q}(t) \to \bar{q}$ and the average charge deviates from $\bar{q}$ less than $\varepsilon \cdot \bar{q}$, where ε is some small value [13]:

$$|\overline{Q}(t) - \bar{q}|/\bar{q} = \varepsilon \quad \text{for } t = T_q. \tag{3}$$

In the presence of two charge fractions in the ion beam, the analytical solution of the system (1) is known [17] and analytical expression can be written for average charge:

$$\overline{Q}(t) = \bar{q} + (q_0 - \bar{q}) \cdot \exp[-\beta t], \tag{4}$$

where the value β depends on the charge exchange cross sections. The average charge $\overline{Q}(t)$ decreases monotonically in the case of $q_0 > \bar{q}$ when the ion captures electrons during the formation of the charge equilibrium and $\overline{Q}(t)$ increases monotonically in the case of $q_0 < \bar{q}$ when the ion losses electrons. If $|q_0 - \bar{q}| > \varepsilon \cdot \bar{q}$ the equilibrium target thickness T_q can be expressed from Eqs. (3) and (4) as

$$T_q = \frac{1}{\beta}\ln\frac{|q_0 - \bar{q}|}{\varepsilon\bar{q}}. \tag{5}$$

If $|q_0 - \bar{q}| \leqslant \varepsilon \cdot \bar{q}$, then it is assumed that $T_q \to 0$. It was shown previously [18,19] that Eqs. (4) and (5) can be used to estimate T_q in the presence of three and four charge components in the ion beam. Then, β depends not only on the charge exchange cross sections but also on q_0.

2. In the other case, the equilibrium thickness of the charge distribution is assumed to be reached if $D(t) \to d$. The expression for $D(t)$ can be written [14]:

$$D^2(t) = \left[d^2 + (q_0 - \bar{q})^2 \exp(-\beta t)\right] \times [1 - \exp(-\beta t)]. \tag{6}$$

It should be noted that $D(t) \to 0$ when only one charge fraction is in the ion beam. It can be realized for $t \to 0$ or when the ion energy increases significantly, so $\Phi_Z(t) \to 1$, the charge exchange cross sections decrease, and $\beta \to 0$. In the presence of two and more charge fractions, the charge equilibrium is reached when the relative deviation of parameter $D(t)$ from its equilibrium value d is less than ε. By analogy with (3), we can write:

$$|D(t) - d|/d = \varepsilon \quad \text{for } t = T_d \tag{7}$$

At a small difference between q_0 and $\bar{q}$, the width of the nonequilibrium charge distribution $D(t)$ is a monotonically increasing function. For a significant difference between q_0 and $\bar{q}$, the function $D(t)$ can be nonmonotonic. For $q_0 = 0$ in energy region, when $\bar{q} \to Z$ or for $q_0 = Z$ in energy region, when $\bar{q} \to 0$ the function $D(t)$ at first increases and reaches its maximum and then decreases and reaches equilibrium value d. In this case, the additional condition for the determination of T_d (7) is used that the derivative $dD(t)/dt$ is small.

The equilibrium target thicknesses T_q and T_d calculated using the criteria (3) and (7) respectively can differ [13]. It will be correct to assume that the charge equilibrium is reached when both criteria are fulfilled. So we introduce

$$T_{qd} = \max(T_q, T_d). \tag{8}$$

The equilibrium charge distribution for ion with initial charge q_0 is established when $t > T_{qd}$ but T_{qd} differs for ions with various q_0. Then we define T_{max} as the maximum of the all T_{qd} (8) for $0 \leqslant q_0 \leqslant Z$. For $t > T_{max}$ the equilibrium charge distribution is formed for any q_0 value.

3. Results of calculations

The charge exchange cross sections for solid targets were estimated using the theoretical method [16] based on experimental cross sections in gases and the gas–solid correction. With the help of computer code [20] we have obtained the electron loss and electron capture cross sections for the interaction of nitrogen and neon ions with carbon target in the interval of ion energy between 1 keV/amu and 10 MeV/amu. We neglected in (1) the processes of loss and capture of two or more electrons because the ratio $\sigma_{q,q+2}/\sigma_{q,q+1}$ is small ($\sigma_{q,q+2}/\sigma_{q,q+1} < 0.2$ [4]). We used the value $\varepsilon = 0{,}03$ for equilibrium target thickness calculations.

The results of $\overline{Q}(t)$ calculations for neon ions in carbon and the experimental data obtained from [7] are presented in Fig. 1. The comparison shows that the proposed method makes it possible

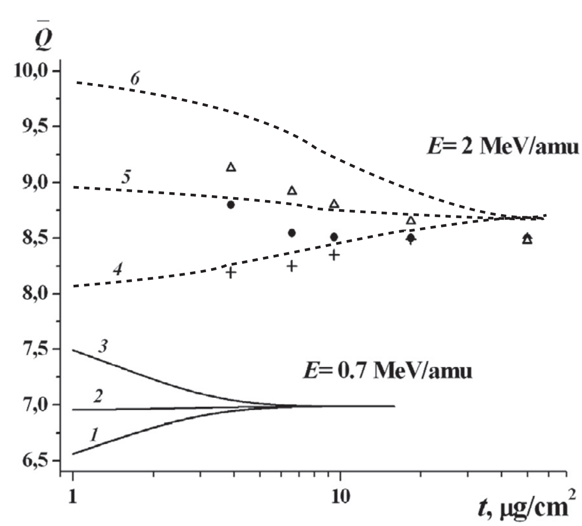

Fig. 1. Nonequilibrium average charge $\overline{Q}(t)$ of neon ions with energies of 0.7 and 2 MeV/amu as a function of the carbon thickness. The solid and dashed lines correspond to the results of the calculations in approximation (4) with the charge exchange cross sections determined by the method [16]. The results of the calculations: 1 – E = 0.7 MeV/amu, $q_0 = 6$; 2 – E = 0.7 MeV/amu, $q_0 = 7$; 3 – E = 0.7 MeV/amu, $q_0 = 8$; 4 – E = 2 MeV/amu, $q_0 = 8$; 5 – E = 2 MeV/amu, $q_0 = 9$; 6 – E = 2 MeV/amu, $q_0 = 10$. The symbols denote the experimental data [7] for E = 2 MeV/amu: (+) – $q_0 = 8$, (●) – $q_0 = 9$, and (Δ) – $q_0 = 10$.