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CALCULATIONS OF EQUILIBRIUM THICKNESSES OF CHARGE-EXCHANGE TARGETS IN ACCELERATOR DEVICES

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Abstract.- The equilibrium thicknesses of targets T have been calculated for some heavy ions using the cross sections of electron loss and capture in the energy range $E/A \leq 5 \times 10^3$ MeV/nucleon. The calculated thicknesses are compared with the experimental values of T obtained by analyzing the results of the studies of ion charge distributions in targets of various thicknesses.

As a fast-ion beam traverses matter, the number of ions of given charge changes and approaches the equilibrium value determined by the energy and charge of the ions and by the parameters of medium. Determination of the minimum thickness of matter layer T , which is necessary for the equilibrium charge state to be established, is of considerable practical interest, in particular, when calculating the charge-exchange targets used in many-stage accelerators of heavy ions [1]. The values of T may be calculated using the cross sections of electron loss and capture by heavy ions. Such calculations were made earlier for fast negative hydrogen ions H^- in hydrogen, helium, and nitrogen at $E/A = (1-6)\times10^2$ MeV/nucleon[2] and for uranium ions at $E/A = (2-8)\times10^2$ MeV/nucleon in heavy media with the charge of atomic nuclei of medium $Z_m = 22 - 28$ [3]. The analysis of the experimental equilibrium thicknesses for fast ions in solid media has made it possible to establish the empirical dependence of T on E/A at E/A = 0.1-10 MeV/nucleon [4].

The cross sections of electron loss and capture by fast ions in gaseous media are used here to calculate the values of T for some ions at $E/A = (0.1-5) \times10^3$ MeV/nucleon and to compare the calculated thicknesses T with the experimental values of T inferred from the non-equilibrium charge distributions of fast ions.

The change of the charge composition of the ion beam traversing a target of rarefied gas is described by the set of N differential equations

$$\frac{d\Phi_k(t)}{dt} = \sum \Phi_i(t)\sigma_{ik} \qquad (1)$$

where $\Phi_i(t)$ is the relative fraction of ions with charge i in the ion beam; t is the thickness of the gaseous layer; σ_{ik} at $i \neq k$ is the cross section of the inelastic collision in which an ion with charge i turns out to be an ion with charge k $(\sigma_{kk} = -\sum \sigma_{ik})$. The equilibrium distribution of charges in the ion beam is given by the values of $\Phi_i(\infty)$ at $t \to \infty$. In accordance with the practical limitations of the accuracy in the values of $\Phi_i(t)$, we shall assume that the charge fractions $\Phi_i(t)$ reach their equilibrium values $\Phi_i(\infty)$ at the target thickness $t \geq T_i$ satisfying the condition

$$|\Phi_i(t) - \Phi_i(\infty)| = \varepsilon\,\Phi_i(\infty) \qquad (2)$$

where ε is a certain given small value. At various charges i , the values of T_i are different and depend on the charge distribution in the beam at t = 0 . In connection with this, it will be expedient to examine, together with thickness T_i, the thicknesses T_a for the values of a characterizing the entire set of the charge fractions Φ_i. Chosen as such values were the parameters associated with the first statistical moments, namely the mean ion charge

$\bar{i}(t) = \sum i \varphi_i(t)$ and the distribution half-width $d(t) = \{\sum (i-\bar{i})^2 \varphi_i(t)\}^{1/2}$

Therefore, we examined the equilibrium thickness T_a determined by the condition

$$|a(T_a) - a(\infty)| = \varepsilon a(\infty) \qquad (3)$$

where a is $\bar{i}$ or d.

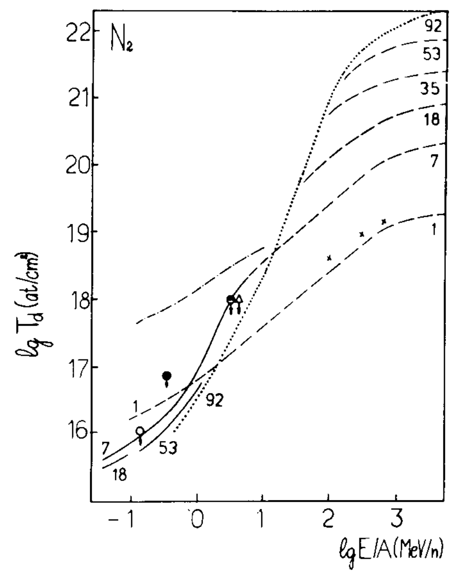
In the high energy range where the approximation of two-component system is valid (N=2) the expressions for T_a at $\varepsilon << 1$ may be obtained in the analytical form

$$T_{\bar{i}} = \frac{\ln\left\{\dfrac{|\varphi_i(0) - \varphi_i(\infty)|}{\varepsilon\,\bar{i}(\infty)}\right\}}{\sigma_{z-1,z} + \sigma_{z,z-1}} \qquad (4)$$

$$T_d = \frac{\ln\left\{\dfrac{\sigma^2_{z-1,z} - \sigma^2_{z,z-1}}{\sigma_{z-1,z}\,\sigma_{z,z-1}} \cdot \dfrac{|\varphi_z(0) - \varphi_z(\infty)|}{2\varepsilon}\right\}}{\sigma_{z-1,z} + \sigma_{z,z-1}} \qquad (5)$$

The experimental cross sections σ_{ik} for ions with nuclear charges $Z \leqslant 53$, which are necessary in the calculations, were taken from the reviews [5,6]. Besides that, the cross sections σ_{ik} obtained by the semi-empirical methods [7,8] were used for the uranium ions. In the extremely high energy range where but two components are practically conserved in the ion beams the cross sections $\sigma_{z-1,z}$ of electron loss by hydrogen-like particles were calculated to the Born approximation [9], while the cross sections $\sigma_{z,z-1}$ of electron capture by nuclei were estimated using the results of [10,11].

It was assumed when calculating the thicknesses T that $\varepsilon = 0.01$ and $|\Delta i| = |i_c - \bar{i}(\infty)| \leqslant 1/2$. The equilibrium thicknesses T_d determined from the experimental dependences $\varphi_i(t)$ [12-19] reduced to $|\Delta i| \leqslant 1/2$ differ from the thicknesses T calculated on the basis of the cross sections σ_{ik} by, on the average, not above 30% (see Fig. 1).



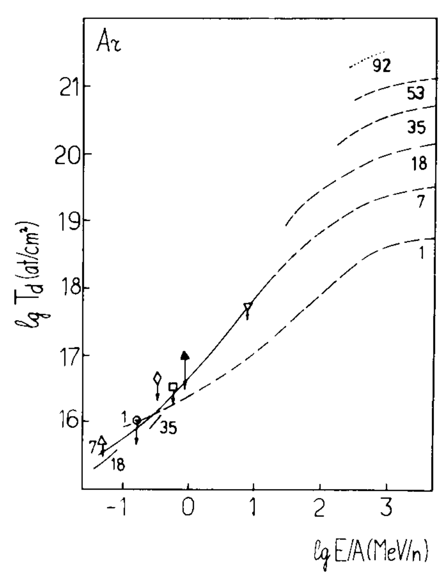


Fig. 1. Equilibrium thicknesses T_d as function of E/A. The values of Z of ions are shown near the curves. ——— and — — — are the results of the calculation on the basis of σ_{ik} for N $\geqslant$ 3 and for N = 2 consequently.

a) The nitrogen target. The experimental data for nitrogen ions (○) are from [19], (●) from [13], (◓) from [16], and for carbon ions (△) from [16]. The arrows indicate the values of T at $|\Delta i| \leqslant 1/2$. (×) the calculated thicknesses T for H^- ions from [2]. (—·—·—) – the values T for ions in solid target obtained in [4].

b) The argon target. The experimental data for carbon ions (▽) from [18], for oxigen ions (□) from [12], for neon ions (◊) from [12], for bromium ions (○) from [15], and for iodium ions (△) from [14], and (▲) from [17]. The arrows indicate the values of T at $|\Delta i| \leqslant$ /2. (- - - - - - - -) the calculated thicknesses T for uranium ions in heavy media with Z_m = 22 – 28 from [3].

The general trend of the dependence of T_d on E/A is the same for all ions, namely, as E/A increases, the values of T_d increase monotonically. In this case, the dependence of T_d on E/A enhances as energy increases in the region E/A $\lesssim$ 3 MeV nucleon and gets weaker at E/A > 100 MeV/nucleon. The dependence of T_d on the ion nuclear charge Z in various energy ranges is different, namely T_d decreases with increasing Z at E/A $\lesssim$ 0.1 MeV/nucleon and increases rapidly with rising Z at E/A > 100 MeV/nucleon. At all energies of particles, the values of T_d decrease monotonically with increasing the nuclear charge of atoms of medium Z_m.

It can be seen from Fig. 1a that the thicknesses T in solid target at E/A =(0.1– 10)MeV/nucleon obtained in [4] are 2–20 times the respective thicknesses in nitrogen target. The application of the method for calculating the equilibrium thicknesses T in rarefied gases to solid targets necessitates the knowledge of the effective cross sections of charge exchange in these media.

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