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Energy loss calculations for fast light ions in celluloid including charge-exchange processes

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Abstract

A method is proposed to calculate the charge-exchange energy loss $(-\mathrm{d}E/\mathrm{d}x)_{ex}$ and electronic energy loss $(-\mathrm{d}E/\mathrm{d}x)_{el}$ on the basis of the electron capture and loss cross-sections, extracted from the experimental data. The experimental and calculated results are presented for energy loss of projectile ions Be, B, N and O with 0.35 MeV/nucleon, passing through celluloid films. The dependence of energy loss on the initial charge of projectile ions and target thickness in nonequilibrium conditions is examined.

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Keywords: Energy loss; Charge exchange

1. Introduction

Energy loss of ions passing through matter has been the subject of intensive studies starting from the classical works of Bohr, Bethe and Bloch and still remains interesting now. The energy loss is the result of various processes, their relative significance depends primarily on the energy and atomic number of the projectile ion. The analysis becomes more complicated for ion stopping in solids.

For fast ions the electronic energy loss, $(-\mathrm{d}E/\mathrm{d}x)_{el}$, dominates, caused by excitation and ionization of target atoms. Earlier this process was described with Bloch's formula [1], which ignored charge-exchange processes. Later various correction terms were introduced, reviewed by Sigmund [2]. For fast ions, possessing few electrons, the ionic charge changes with penetration depth and the energy loss $(-\mathrm{d}E/\mathrm{d}x)_{el}$ varies correspondingly. Usually an effective charge i_{eff} is used to describe the energy loss in matter. The detailed analysis of electron capture and loss by projectile ion allows to examine the dependence of i_{eff} and $(-\mathrm{d}E/\mathrm{d}x)_{el}$ on the target thickness and the initial

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ionic charge i_0. Here it would be noted that the dependence of $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}}$ on i_0 was studied recently by some authors [3–5]. Besides the performed analysis makes it possible to evaluate the energy loss, caused directly by charge exchange, $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{ex}}$.

In the present work we report a method to examine charge-exchange processes and to calculate the energy loss $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}}$ and $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{ex}}$ dependences on the initial charge of projectile ion and target thickness.

2. Results and discussion

In the calculations we used our experimental results for charge-state distributions F_i of fast light ions with ionic charge i, passing through solid targets [6]. The electron capture $\sigma_{i,i-1}$ and electron loss $\sigma_{i,i+1}$ cross-sections were obtained from experimental charge-state distributions for the Be, B, N and O ions in celluloid according to the method, presented in [7]. Then the energy loss, caused by charge-exchange processes, can be evaluated on the basis of the expression, established earlier [6]:

$$(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{ex}} = N_{\mathrm{t}} \sum F_i \sigma_{i,i\pm1}(J + E_k), \quad (1)$$

where N_{t} is the target density, $E_k = mv^2/2$ is the kinetic energy of the electron, acting in charge exchange, where m is the electron mass and v is the projectile velocity. J is the electron binding energy in target atom for electron capture process or electron binding energy in projectile ion for electron loss process. The J values for atoms and ions are taken from [8].

The energy loss, caused by interaction of projectile ion with target electrons, was calculated according to Bloch's formula [1],

$$(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}} = \left(4\pi e^4/mv^2\right) i_{\mathrm{eff}}^2 Z_{\mathrm{t}} N_{\mathrm{t}} \left[\ln\left(2mv^2/I\right) - Q\right], \quad (2)$$

where e and m are the electron charge and mass, Z_{t} and N_{t} are the target charge and density, v is the projectile velocity, I denotes the mean ionization potential of target, $Q = \mathrm{Re}\psi[1 + \mathrm{i}(i_{\mathrm{eff}}e^2/\hbar v)] - \psi(1)$, ψ is the digamma function, $\mathrm{i} = \sqrt{-1}$. It is necessary to outline that in (2) the atomic number of projectile ion is replaced by the averaged effective charge i_{eff}, taking into account the various charge states of ions, passing through the matter. i_{eff} is calculated as $i_{\mathrm{eff}}^2 = \sum i^2 \cdot F_i$.

The energy loss calculations are complicated in such targets as celluloid, because the target parameters Z_{t} and I cannot be defined exactly. As it was mentioned earlier [9] the chemical properties of medium do not influence on the energy loss, and for complex targets the Bragg addition rule is valid. It means that the atoms of various chemical elements in celluloid contribute independently to the energy loss. But if we summarize directly the energy losses on all elements in celluloid, as it was proposed in [10], the value will differ strongly from the experimental energy loss.

In our calculations we used some averaged values of the target charge and ionization potential, defined as [9]

$$NZ_{\mathrm{t}} = \sum N_i Z_i, \quad N \ln I = \sum N_i \ln I_i, \quad (3)$$

where Z_i and I_i are the atomic number and ionization potential of elements in celluloid and N_i is the amount of various atoms in celluloid molecule. The obtained values of I and Z_{t} provide an agreement between calculated and experimental energy losses in the charge equilibrium region. In the present work the values $Z_{\mathrm{t}} = 5.6$ and $I = 40$ eV were used, obtained from (3) for celluloid; the mean ionization potentials for target elements were taken from tables [10].

Fig. 1 presents the experimental data and calculated energy loss values of projectile ions Be, B, N and O with 0.35 MeV/nucleon in celluloid films for charge equilibrium. The calculations show that for B, N and O ions the electronic energy loss $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}}$ dominates and the charge exchange energy loss $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{ex}}$ is no higher than 5% of $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}}$ in accordance with the well-known results in this energy region. But for Be ions $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{ex}}$ is sufficiently larger, than for other ions, and reaches 40% of $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{el}}$. This fact can be explained by the analysis of energy loss cross-sections. Really for Be ions the loss cross-section of K-electron with large binding energy has the maximal value, so the energy loss, caused by electron loss, $(-\mathrm{d}E/\mathrm{d}x)_{\mathrm{loss}}$, increases. For other ions under consideration the electron loss occurs mainly

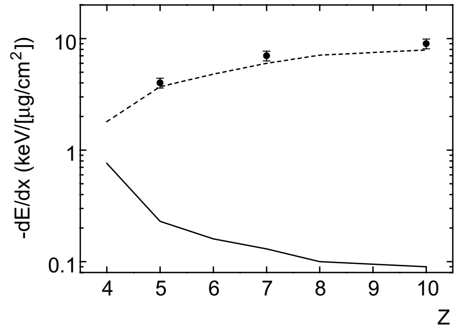

Fig. 1. Energy loss of light ions with energy 0.35 MeV/nucleon in celluloid versus atomic number of projectile ions: (●) experimental data [6], (solid line) calculations of charge-exchange energy loss $(-dE/dx)_{ex}$, (dashed line) calculations of electronic energy loss $(-dE/dx)_{el}$.

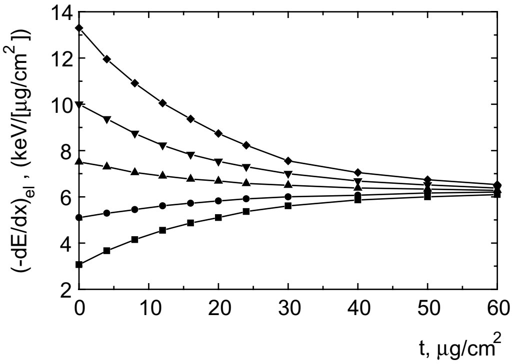

Fig. 2. Energy loss $(-dE/dx)_{el}$ of O ions with energy 0.35 MeV/nucleon in celluloid depending on initial charge of projectile ion i_0 and target thickness: (■) $i_0 = 3$, (●) $i_0 = 4$, (▲) $i_0 = 5$, (▼) $i_0 = 6$, (◆) $i_0 = 7$.

from the L-shell, and the corresponding energy loss is rather small. The electron capture energy loss, $(-dE/dx)_{cap}$, is only 10% of $(-dE/dx)_{loss}$ for Be ions. For other ions $(-dE/dx)_{cap}$ increase and for O ions reaches 80% of $(-dE/dx)_{loss}$, but the summed charge-exchange energy loss (1) decreases with increasing of atomic number Z.

From the formula (2) it can be seen that the energy loss depends on the ionic effective charge i_{eff}. If we know the electron capture and loss cross-sections, we can calculate the charge fractions F_i and i^2_{eff} for various values of target thickness and initial ionic charge i_0. The earlier calculations for projectile N ions, passing through celluloid [11], showed that for small target thickness, where charge equilibrium is not yet obtained, the effective charge depends strongly on i_0, and the energy loss also varies for different i_0. Fig. 2 presents the electronic energy loss, calculated according to (2) for O ions with 0.35 MeV/nucleon in celluloid films. It can be seen that energy losses for ions with greater i_0 are more than those for ions with smaller i_0 in the whole pre-equilibrium area. This result coincides with the works of other authors, both experimental [3,4] and theoretical [5].

The charge-exchange energy loss (1) also depends on the initial ionic charge i_0 both for electron loss and electron capture processes, and $(-dE/dx)_{ex}$ becomes constant only when charge equilibrium is reached [11].

3. Conclusion

The proposed method allows the calculation of the charge-exchange energy loss $(-dE/dx)_{ex}$ on the basis of the electron capture and loss cross-sections, extracted from the experimental data for fast light ions, passing through celluloid films. For Be ions the value of $(-dE/dx)_{ex}$ is found to be significantly higher than for other ions. Also it is possible to examine the dependence of electronic energy loss $(-dE/dx)_{el}$ on target thickness and initial charge of projectile ion in the pre-equilibrium area. The presented results coincide with experimental data and qualitatively agree with results of other authors, obtained for other targets and higher projectile energies.

Further detailed analysis seems us to be interesting in order to evaluate the contribution of the described effect in the total energy loss and ranges of ions in solids.

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