Nuclear Instruments and Methods in Physics Research B5 (1984) 10–13
North-Holland, Amsterdam

ATTAINMENT OF EQUILIBRIUM CHARGE DISTRIBUTIONS IN FAST ION BEAMS PASSING THROUGH SOLID FILMS

V.P. ZAIKOV, E.A. KRAL'KINA, N.F. VOROBJEV, I.S. DMITRIEV, V.S. NIKOLAEV and Ya.A. TEPLOVA

Institute of Nuclear Physics, Moscow State University, 117234 Moscow, USSR

Received 14 December 1983 and in revised form 24 April 1984

The thicknesses T_s of carbon targets needed for equilibration of the charge distribution in H, He and N ions beams have been calculated in the energy range $E = (0.03–100)$ MeV/amu. The calculations have shown that for N ions at $E = 0.1$ MeV/amu the value of T_s is 20 times T_g in a gas target and that the difference decreases with increasing energy.

1. Introduction

In the thirties it was found that the mean output charge of ions passing through solids was higher than for gases. This finding was the starting point for two alternative physical models for the passage of ions through solids constructed by Bohr and Lindhard [1] and by Betz and Grodzins [2]. The two models can be improved and verified on the basis of new experimental facts obtainable by studying the characteristics of ion beams passing through solids and gases [3–17]. Quite a number of features of the output parameters of an ion beam ejected from a solid stripper have been revealed up to now. These features include the delay of the attainment of equilibrium charge distributions for ions in solids compared with gases (see ref. [13]). An investigation of the equilibrium parameters of ion beams passing through gases is given in ref. [17]. The target thickness which has to be used to attain charge equilibrium and the width of the charge distribution have been found to vary inversely with the electron loss and capture cross sections for ions whose charge is close to the mean equilibrium charge. Thus, an increase in the equilibrium thickness of a solid suggests a decreased rate of charge-exchange processes in solids, calculated per target atom, compared with gases. This observation contradicts the Bohr–Lindhard model based on the assumptions of an unchanged capture cross sections and an increased electron loss cross section for solids [1].

The Betz–Grodzins model suggests that the processes of multiple excitation of ions play an important role in the passage of ions through solid films, in contrast to gases [2]. The authors of this model believe that the ion excitation process is important for the occurrence of equilibrium in solids. Multiple excitation should lead to the delay of the attainment of equilibrium charge distribution. This conclusion is not well founded and requires model calculations because the cross sections for ion excitation by target atoms are as a rule close to the charge-exchange cross sections. All the processes mentioned above should be considered to describe correctly the attainment of equilibrium in solids.

The present paper proposes a model for the passage of ions through solid targets which contains an increase in the electron loss cross section and a decrease in the electron capture cross sections. The equilibrium thicknesses of carbon targets are calculated as a function of energy for H, He and N ions. The results are compared with the equilibrium thicknesses of a nitrogen target.

2. Model for the passage of ions through solids

2.1. Equilibrium thickness calculations

The number of ions of a given charge varies continuously as the ions pass through solids or gases, and reach an equilibrium value after traversing a target thickness T. Each of the charge state components attains equilibrium, generally speaking, at its own value of target thickness T. In the present work, the equilibrium target thickness T is meant to be the thickness needed for the equilibration of the mean charge $\bar{i}$ and the width of charge distribution to be obtained within 1%. The values of the equilibrium thicknesses for gaseous T_g and solid T_s targets are not obtainable from direct measurements, and can only be obtained from the experimental dependences of the charge components of an ion beam on the target thickness.

Fig. 1 presents a set of equilibrium thicknesses of nitrogen, carbon and celluloid targets obtained from experimental non-equilibrium charge distributions

0168-583X/84/$03.00

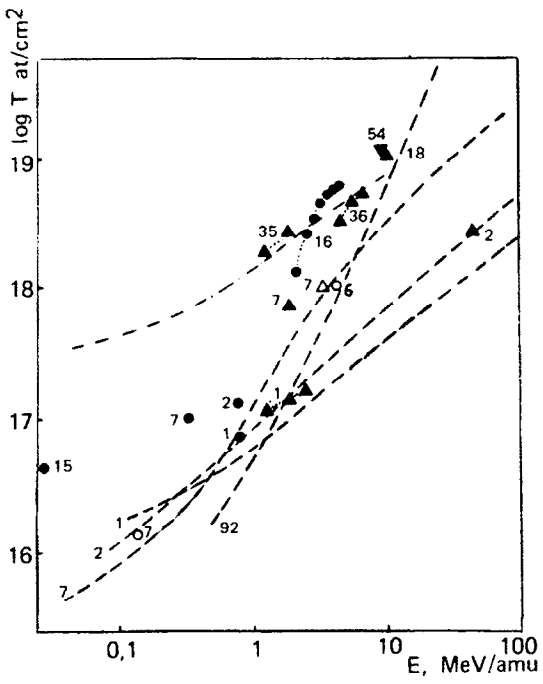

Fig. 1. The dependence of T_s and T_g on E for various ions with initial charges $i_0 = i$. The symbols indicate the experimental values of T_s and T_g in the following way: in nitrogen for C: ○ - [9], for N: ○ - [8], △ - [9], in organic films for N: ● - [6], ▲ - [7], Ar: ▲ - [12], in carbon films for H: ● - [3], ▲ - [4], He: ● - [3], ▲ - [5]; P ● - [10], S: ● - [11], Br: ▲ - [13], Kr: ▲ - [14], Xe: ▼ - [15]. -.- the empirical curve for T_s from [16]; - - - the calculated values T_g from [17]. The numbers on the curves and the signs indicate the nuclear charge Z of the incident ions.

[3–16]. The errors in the values of T_g and T_s obtained are due to the error in the measured charge components and thicknesses of the targets and vary, as a rule, within 30–50%. Unless otherwise specified, the values of T_g and T_s are obtained for the initial ion charge i_0 close to i, $|i_0 - i| \leqslant 0.5$. Fig. 1 demonstrates vividly that the values of T_s are in excess of T_g over the entire energy range. The result obtained confirms the conclusion of ref. [13] made on the basis of the values of T_g and T_s that have to be used to put a Br ion beam in equilibrium.

To account for the observed behaviour of T_g and T_s we have numerically calculated the nitrogen and carbon targets thicknesses needed for equilibrium of H, He and N ion beams in the energy range 0.03–100 MeV/amu. The values of T_g were calculated using the well-known set of linear differential equations

$$\frac{d\phi_i}{dx} = \Sigma\sigma_{ki}\phi_k - \phi_i\Sigma\sigma_{ik}, \qquad (1)$$

where the ϕ_i, the relative number of ions of charge i, are unknowns; σ_{ki} is the cross section in case of the transition from the k to i charge state. We recall that the lifetime of an ion in a fixed charge state τ_i in gases is large compared with the radiation lifetime of the excited states of ions τ_{rad} and, therefore, the set of equations (1) contains the total cross sections for electron capture and the cross sections for electron loss from the ground state of the ions. The present calculations are based on the data from ref. [18].

The situation with solids is quite different. Owing to a high atomic density, the rate of charge-exchange processes is in this case much higher, so the excited states fail to decay via the radiative channel before the next event of electron capture or loss occurs, i.e. $\tau_i \ll \tau_{rad}$. Hence, the passage of ions through solids is expressed mathematically through a set of linear differential equations

$$\frac{d\phi_{inl}}{dx} = \Sigma\sigma_{kn'l',inl}\phi_{kn'l'} - \phi_{inl}\Sigma\sigma_{inl,kn'l'}, \qquad (2)$$

where the charge-excited components ϕ_{inl}, i.e. the relative numbers of ions of charge i in the excited state nl, are unknowns; $\sigma_{kn'l',inl}$ is the cross section in case of the transition from the $kn'l'$ to the inl state. The above statement is true for ions of low and medium nuclear charge Z.

The passage of ions in excited states through solids leads to increased electron loss cross sections compared with gases. However, this is not the only feature of the passage of ions through solids. Another consequence of the high atomic density in solids is the smallness of the interatomic distance d. In carbon d is ≈ 2.44 Å. As a result, charge-excited states whose size is in excess of d, cannot exist in a solid. Therefore, states with principal quantum number $n = 1$ are allowed for hydrogen and helium ions, with $n \leqslant 3$ in $N^{+5,\ldots 6}$, and with $n \leqslant 2$ for N ions of lower charges i and for N atoms. The existence of ions in solids in low-excited states only leads to decreased electron capture cross sections compared with gases. Indeed, at velocities $v < [6I_{max}/\mu]^{1/2}$ (I_{max} is the binding energy of the highest possible excited state in a solid, μ is the electron mass) electrons in gases are most probably captured into the highly-excited states which are not realized in solids. At a fixed ion velocity, the decrease in the electron capture cross section in solids is a minimum for hydrogen and a maximum for nitrogen ions. As the energy of ions increases, the role of excited states in electron capture becomes less important, so that the electron capture cross sections in solids and gases become comparable. The decrease in the electron capture cross sections has been confirmed by experimental results [6].

In summing up the above discussion, we should again emphasize that the excited components passing through solids have increased electron loss and decreased electron capture cross sections compared with dilute gases.

In the numerical calculations we obtained the partial cross sections for single-electron capture using the formula

$$\sigma_{in'l'(i-1)nl} = \sigma^{OBK}_{in'l'(i-1)nl} \frac{\sigma^{exp}_{i,i-1}}{\sigma^{OBK}_{i,i-1}}, \quad (3)$$

where $\sigma^{OBK}_{in'l'(i-1)nl}$ and $\sigma^{OBK}_{i,i-1} = \sum_{n=1}^{12} \sum_{l=0}^{n-1} \sigma^{OBK}_{1s(i-1)nl}$ are the partial and total electron capture cross sections in C calculated in the OBK approximation [19], $\sigma^{exp}_{i,i-1}$ is the experimental electron capture cross section in nitrogen. In calculating the single-electron loss cross section in C we used the dependence of $\sigma_{i,n'l'(i+1)nl}$ on the binding energy for a nitrogen target from ref. [20]. The cross sections of the capture and loss of more than one electron were assumed to be zero. Auger processes and ion excitation by target atoms were neglected.

3. Results and discussion

The results for T_g and T_s obtained at an initial charge i_0 close to $\bar{i}$ are shown in fig. 2. It is seen from the figure that the values of T_s are in excess of T_g. As the energy of

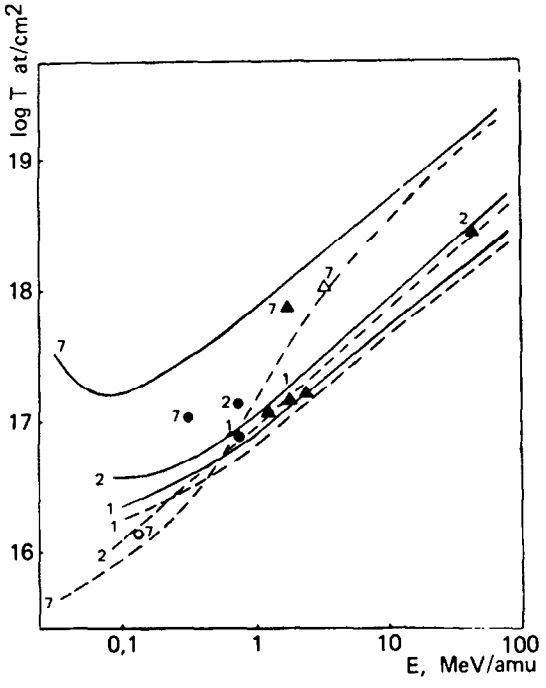

Fig. 2. The calculated E dependence of the equilibrium thicknesses of T_g (N_2) – – – and T_s (C)—for incident H, He and N ions with initial charge $i_0 = \bar{i}$. The symbols indicate the experimental values of T_s and T_g in nitrogen for N in the following way: ○ – [8], △ – [9], in organic films for N: ● – [6], ▲ – [7] and in carbon films for H: ● – [3], ▲ – [4]; He: ● – [3], ▲ – [5]. The numbers on the curves and the signs indicate the nuclear charge Z of the incident ions.

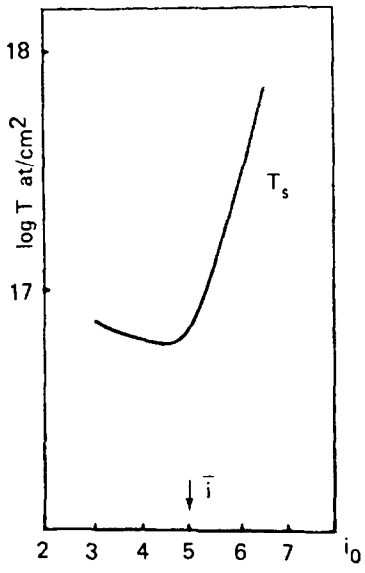

Fig. 3. The dependence of T_s on the initial ion charge i_0 for nitrogen ions in carbon films. $E = 0.335$ MeV/amu.

ions decreases and the nuclear charge of ions Z increases, the difference between T_g and T_s increases. For example, at $E \geq 1.5$ MeV/amu T_s does not exceed T_g by more than 20% for H and He ions and at $E = 0.1$ MeV/amu T_s is 1.2, 3 and 20 times T_g for H, He and N ions, respectively. From figs. 1a and 1b it follows that the calculation results are in qualitative agreement with experiment. Comparison between the absolute values of the calculated and experimental T_s has little meaning because we have disregarded the surface effects and the autoionization decay of the excited states of ions transmitted through a film.

In the numerical calculation of T_s we have revealed an interesting dependence of T_s on the initial charge i_0. As seen from fig. 3 when i_0 becomes greater than $\bar{i}$, the equilibrium thickness increases sharply due to the low values of the electron capture cross sections in solids. A substantial increase in T_s at $i_0 = 6$ and 7 was observed in an experiment [6] in which the passage of N ions, at $E = 0.335$ MeV/amu, through a celluloid film was studied. A rapid increase in T_s is observed at i_0 exceeding the mean output charge $\bar{i}$ measured in the same experiment. This suggests an excess of mean charge of the ions inside the film over the mean output charge. It will be noted that the set of equations (2) gives values of $\bar{i}$ that exceed by 20–30% the experimental values of the mean output charge for gases and solids.

4. Conclusion

The results of calculating the equilibrium thicknesses of solid targets have demonstrated that the absence of

highly-excited states and the disregard of the ion excited-state decay in solids do not preclude correct understanding of the main qualitative factors in the experimentally observed relationship between T_s and T_g.

References

[1] N. Bohr and J. Lindhard, Kgl. Danske Vidensk. Selsk. Mat. Fys. Medd. 28 (1954) no. 7.

[2] H.D. Betz and L. Grodzins. Phys. Rev. Lett. 25 (1970) 211.

[3] N. Cue, N.V. de Castro-Faria, M.J. Gaillard, J.C. Poizat and J. Remillieux. Nucl. Instr. and Meth. 170 (1980) 67.

[4] M.J. Gaillard, J.C. Poizat, A. Ratkowski, J. Remillieux and M. Auzas, Phys. Rev. A16 (1977) 2323.

[5] I. Katayama, G.P.A. Berg, W. Hüzlimann, S.A. Martin, J. Meissburger, W. Oelert, M. Rogge, J.G.M. Römer, J. Tain, B. Styczen and G. Gaul, Phys. Lett. 92A (1982) 385.

[6] I.S. Dmitriev, V.S. Nikolaev and Ya.A. Teplova, Atomic particles interaction in matter (FAN, Tashkent, 1972) p. 114.

[7] H.L. Reynolds, L.D. Wyly and A. Zucker, Phys. Rev. 98 (1955) 1825.

[8] M. Asari, Y. Kido and F. Fukusawa, J. Phys. Soc. Japan 42 (1977) 982.

[9] T. Tonuma, Y. Miyazawa, S. Karasawa and I. Kohno, J. Appl. Phys. 9 (1970) 1306.

[10] W.N. Lennard, J.E. Jackman and D. Phillips, Phys. Lett. 79A (1980) 309.

[11] U. Scharger, C. Henrichs, J.D. Fox, von Brentano, L. Degener, J.C. Sens and A. Pape, Nucl. Instr. and Meth. 146 (1977) 573.

[12] H.H. Heckman, E.L. Hubbard and W.G. Simon, Phys. Rev. 129 (1963) 1240.

[13] C.D. Moak, H.O. Lutz, L.D. Bridwell, L.C. Northcliffe and S. Datz, Phys. Rev. Lett. 18 (1967) 41.

[14] E. Baron and B. Delaunay, Phys. Rev. A12 (1975) 40.

[15] K. Blashe, B. Franzke and R. Steiner, CSI-JI-77 (1977) p. 120.

[16] E. Baron, IEEE Trans. Nucl. Sci., NS-26 (1979) 2411.

[17] I.S. Dmitriev, V.P. Zaikov, E.A. Kralkina, V.S. Nikolaev and Ya.A. Teplova, Proc. 9th Conf. on Cyclotrons and their Applications, Caen (1982) p. 299.

[18] V.S. Nikolaev, I.S. Dmitriev, L.N. Fateeva and Ya.A. Teplova, Zh. Exp. Teor. Fiz. 40 (1961) 989.

[19] M.R.C. McDowell and J.P. Coleman, Introduction to the theory of ion–atom collisions (North-Holland, Amsterdam, 1970).

[20] I.S. Dmitriev, V.P. Zaikov and Yu.A. Tashaev, Nucl. Instr. and Meth. 164 (1979) 329.