Loss of electrons by a multicharged ion during channeling

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(Submitted 22 March 1979)

Pis'ma Zh. Eksp. Teor. Fiz. **29**, No. 9, 574–577 (5 May 1979)

We show that in the course of propagation of a multicharged ion in a crystal in the channeling mode the probability of electron loss by an ion at certain "resonant" ion velocities increases considerably. The effect of suppression of the vacancy formation probability in the more external shell as compared to internal is also predicted.

PACS numbers: 61.80.Mk, 61.80.Jh

1. Let an ion with charge eZ_1, having not less than one electron in its orbit, move along a channeled trajectory in the direction of given crystallographic axes. We shall assume that these axes consist of identical atoms placed at a distance d from each other. For the process in question, short distances ρ between the ion and one of the chains are important and, therefore, for the sake of simplicity, we shall assume that the ion moves in the field of one chain. Let one of the characteristic collision frequencies $\omega_k = 2\pi kv/d$ (v is ion velocity, k is harmonic number) be similar to the energy difference ω_0 of the ground and excited electron states in an ion. As we shall demonstrate below, the most important practical case occurs when the lifetime of an excited electron—associated with the detachment of the electron from ion—is either shorter or of the order of the ion transit time through the crystal. In this case, perturbation theory is not applicable. The solution of the Shroedinger equation for the electron wave function in an ion requires the use of the two-level approximation. We shall not present the general formulas for the probability $W(\rho)$ of electron loss by an ion after transit through a crystal with thickness L. We shall only show the results of calculations for a critical case where the difference of uncertainties $\Delta\Gamma$ in the energy levels of the ground and excited states is considerably smaller than either the extent of their splitting V_{12} by

the chain field, or the resonance defect $\delta = \omega_k - \omega_0$:

$$W(\rho) = 1 - \exp\left[-\frac{(\Gamma_1 + \Gamma_2)L}{2v}\right]\left[\mathrm{ch}\,\frac{\Delta\Gamma L/v}{2(1+\xi^2)^{1/2}} - (1+\xi^2)^{-1/2}\,\mathrm{sh}\,\frac{\Delta\Gamma L/v}{(1+\xi^2)^{1/2}}\right]. \tag{1}$$

Above, Γ_1 and Γ_2 are widths of the ground and excited states, respectively, determined by the process of electron detachment; $\Delta\Gamma = \Gamma_1 - \Gamma_2$; $\xi = 2|V_{12}|/\delta$

$$V_{12} = \exp\left(-\frac{4\pi^2 k^2 u^2}{d^2}\right)\frac{|x_{12}|^2}{d^2}\left[\left|\frac{\omega_0}{v}V\left(\frac{\omega_0}{v},\rho\right)\right|^2 + \left|\frac{\partial}{\partial\rho}V\left(\frac{\omega_0}{v},\rho\right)\right|\right]^2, \tag{2}$$

$|X_{12}|$ is the matrix element of the electron dipole moment in an ion; u^2 is the mean square of the amplitude of thermal oscillations of the crystal atoms; $V(\omega_0/v,\rho)$ is the Fourier term of the electrostatic atomic potential $v(z)$, $[r = (\rho^2 + z^2)^{1/2}]$:

$$V\left(\frac{\omega}{v},\rho\right) = \int_{-\infty}^{\infty} \exp(i\omega z/v)\, U\left(\sqrt{\rho^2 + z^2}\right) dz \tag{3}$$

Under conditions of strong resonant interaction we get

$$W(\rho) = 1 - \exp\left[-\frac{(\Gamma_1 + \Gamma_2)L}{2v}\right]. \tag{4}$$

In this case, the decay of the initial state is exponential; however, the index of the exponential contains (in addition to Γ_1) the rate of decay of the excited level Γ_2. As a rule, the probability of electron detachment from an ion from an excited state $|2\rangle$ is considerably higher than from the ground state ($\Gamma_1 \ll \Gamma_2$). Thus, it follows from Eqs. (1) and (4) that the probability of electron loss by an ion under the conditions of resonance ($\xi \gg 1$) is considerably higher than the corresponding probability in the absence of resonance ($\xi \ll 1$). Recently, this effect was observed by Datz and coworkers.[11] The process under consideration may be used to obtain fast multi-charged ions. It is also significant that the electron loss by ions in the course of channeling is free from an increase in the angular divergence of the ion beam as is the case in an amorphous medium.

2. In contrast to an amorphous target, the inequality $\Gamma_1 \ll \Gamma_2$ is satisfied in a crystal for certain ion velocities only.

The following expression may be written for the width Γ_i of an arbitrary state $|i\rangle$ of electron in an ion

$$\Gamma_i = \frac{c}{(2\pi)^2 \hbar v d}\sum_{k=1}^{\infty}\frac{\sigma_i^{(P)}(2\pi k v/d)}{k}\left[\left|\frac{2\pi k}{d}V\left(\frac{2\pi k}{d},\rho\right)\right|^2 + \left|\frac{\partial}{\partial\rho}V\left(\frac{2\pi k}{d},\rho\right)\right|\right]^2 \times$$

$$\exp\left(-\frac{4\pi^2k^2u^2}{d^2}\right)+\frac{c}{(2\pi)^2\hbar vd}\int_0^\infty\left[1-\exp\left(-\frac{\omega^2u^2}{v^2}\right)\right]\frac{\sigma_i(P)(\omega)}{\omega}\left[\left|\frac{\omega}{v}\;V\left(\frac{\omega}{v},\rho\right)\right|^2\right.$$

$$\left.+\left|\frac{\partial}{\partial\rho}\;V\left(\frac{\omega}{v},\rho\right)\right|^2\right],$$

where the first term describes the coherent portion of the probability of electron detachment from an ion per unit time under the effect of the atomic chain, and the second—incoherent part, depends on the thermal oscillation of the atomic lattice; $\sigma_i^{(P)}(\omega)$ is the photoeffect cross section at the i-th ion subshell.

Let the magnitude of $\omega_{\min}=2\pi v/d$—frequency of ion collisions with the chain atoms—be of the order of the ionization threshold Y_K of a certain internal (for instance, K-) shell while $\omega_{\min}$ is much greater than the ionization threshold Y_L of the next (for instance, L-) shell. Inasmuch as $\sigma_K^{(P)}(\omega)$ near its threshold is considerably greater than $\sigma_L^{(P)}(\omega)$ (and there are no frequencies in the perturbation spectrum of the regular chain at a sufficiently small amplitude of thermal oscillations ($Y_L u \ll v$)), according to Eq. (5) we get $\Gamma_K \gg \Gamma_L$. The frequencies under consideration are remote from the resonance condition and, therefore, it follows from Eq. (1) for $\xi\to\infty$ that the probability of formation of vacancies in the K-shell is considerably higher than the probability of formation of the L-vacancies. If, moreover, the Messi criterion ($Y_\rho \lesssim v$) is satisfied for both shells, the ion beam will be enriched by the K-vacancies as a result of collisions with a relatively thin crystal. This effect may be used as an effective means of selective ionization of many-electron atoms.

[1)]In Ref. 1. the effect of coherent excitation of a channeled ion was investigated (see also Refs. 2–4).

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