

Electrodisintegration of relativistic channeled nuclei in crystals

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The "pure" processes of electrodisintegration and Coulomb excitation of channeled nuclei can be observed as a result of motion of relativistic nuclei in crystals in the channeling mode. The disintegration cross section of 50- and 100-GeV deuterons in a tungsten crystal is calculated. The experimental conditions for observing the processes are discussed.

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There is a process that makes it possible to suppress nuclear interactions in crystals even at high energies of incident particles and in this way to isolate the electromagnetic channeling effect of particle channeling in crystals¹ (see high-energy experiments in Ref. 2). In the case of channeling the energy of a particle corresponding to the motion along the planes or axes of the crystal $E_{\parallel} \approx E$ is arbitrary, and the transverse energy $E_{\perp} = E\psi^2 < V$ (V is the continuous potential of the atomic series or of the plane and ψ is the angle of entry into the crystal); i.e., in the three-dimensional problem of Coulomb excitation the usual condition for small penetrability of the Coulomb barrier of the nucleus is replaced here by the corresponding two-dimensional or one-dimensional condition $E_{\perp} < V$. Therefore, purely electromagnetic interaction of hadrons and nuclei with nuclei in the relativistic energy region can be observed in the case of channeling.

Such processes can be analyzed both in the lattice nuclei and in the channeled nuclei. Since the disintegration products in the latter case have relativistic energies and a narrow cone of the angle of divergence, below we shall examine just this type of processes.

The simplest case is that of axial channeling of nuclei in the crystal. Suppose that the momentum of the nucleus is parallel to one of the crystal axes ($p \parallel z$); in this case the potential of the Coulomb interaction with the lattice is

$$V(\mathbf{r}) = \sum_{\mathbf{k}} \bar{V}_{\mathbf{k}} e^{i\mathbf{k}\mathbf{r}} = \sum_{k_{\parallel}, k_{\perp}} \bar{V}_{\mathbf{k}_{\perp}} e^{ik_{\perp}\rho} + \sum_{k_{\parallel} \neq 0} e^{ik_{\parallel}z} \sum_{\mathbf{k}_{\perp}} \bar{V}_{\mathbf{k}} e^{ik_{\perp}\rho}, \quad (1)$$

where $k^2 = k_{\parallel}^2 + k_{\perp}^2$. Further, at high energies we can assume that the interaction of nuclei with each chain of atoms comprising the crystal occurs independently³; therefore, going over to a single-chain approximation we have for the chain potential

$$V(\mathbf{r}) = V(\rho) + \sum_{k_{\parallel}} e^{ik_{\parallel}z} V_{k_{\parallel}}(\rho); \quad (2)$$

$$V(\rho) = \left(\frac{a}{2\pi} \right)^2 \int d^2\mathbf{k}_{\perp} e^{i\mathbf{k}_{\perp}\rho} \bar{V}_{\mathbf{k}_{\perp}}; \quad V_{k_{\parallel}}(\rho) = \left(\frac{a}{2\pi} \right)^2 \int d^2\mathbf{k}_{\perp} V_{\mathbf{k}} e^{i\mathbf{k}_{\perp}\rho}. \quad (3)$$

Here \bar{V}_k are the Fourier components of the lattice potential that depend on the temperature of the crystal,⁴ ρ is the radius vector of the transverse chain of the plane, $k_{\parallel} = (2\pi s/a)$, a is the lattice constant, and $s = \pm 1, \pm 2, \dots$.

In channeling problems the influence of the second term in Eq. (2)^{1,4} on the motion of fast particles is usually ignored. However, the longitudinal periodicity of the potential (2) with respect to z can influence the internal degrees of freedom of the channeled particles (nuclei, ions). In atomic phenomena, for example, this takes the form of resonant excitation of the levels of the channeled ions.⁵ The excitation of nuclear levels, which is a more complex problem because of their small widths, should be examined separately. Therefore, the processes involving channeled nuclei with a transition to the continuous spectrum may turn out to be simpler processes for experimental observation—electrodisintegration with the emission of neutrons, protons, etc. Let us examine, for example, the disintegration of a simple nuclear system—a deuteron by a periodic Coulomb field of the crystal. To calculate the cross section of a high-energy process, we shall use the equivalent-photon method⁶ after replacing the second term in Eq. (2) in the system with $p_z = 0$ by the equivalent photon (EP) flux of the period of a chain in the z direction $n(\omega_s, \rho)$. In contrast to the ordinary spectrum, the EP spectrum here is a discrete spectrum with the frequencies $\omega_s = (2\pi c/a)\gamma\beta s$, $s = 1, 2, \dots$, while γ and β is the Lorentz factor and the velocity of the longitudinal motion of deuteron, respectively ($\beta \sim 1$). The spectral density of the EP flux from one period in the z direction, which depends on the impact parameter ρ and on the thermal vibrations of nuclei σ^2 , can be determined by using Eqs. (2) and (3) and the atomic potential $Ze \exp(-\kappa r)/r$:

$$n(\omega_s, \rho) = \frac{Z^2 e^2}{\hbar c} \frac{\omega_1}{\omega_s} \exp \left[- \left(\frac{2\pi\sigma s}{a} \right)^2 \right] \left| \frac{1}{2\pi^2} \frac{\partial}{\partial \rho} \int \frac{d^2 k_{\perp} \exp \left(- \frac{\sigma^2 k_{\perp}^2}{2} + i k_{\perp} \rho \right)}{k_{\perp}^2 + \kappa^2 + \left(\frac{2\pi s}{a} \right)^2} \right|^2, \quad (4)$$

Assuming that the trajectory of a deuteron is formed by the first term $V(\rho)$ of the potential (2), we have a distribution in the impact parameters $f(\rho)$ near each chain of atoms, if we take into account the conditions of entry into the crystal. Integrating Eq. (4) with respect to ρ with allowance for the weights of the trajectories $f(\rho)$ in the simple case when the region $R_{\min} = R_{\min}(\psi)$ near each chain is eliminated, we obtain the spectral density of the EP flux, which is averaged over the trajectories:

$$\bar{n}(\omega_s) \approx \frac{Z^2 e^2}{\hbar c} \frac{\omega_1}{\omega_s} \exp \left[- \left(\frac{2\pi\sigma s}{a} \right)^2 \right] \left[\kappa_s R_{\min} \right]^2 \times \frac{1}{\pi} \left\{ K_0^2(\kappa_s R_{\min}) + \frac{2K_0(\kappa_s R_{\min})K_1(\kappa_s R_{\min})}{\kappa_s R_{\min}} - K_1^2(\kappa_s R_{\min}) \right\};$$

$$\kappa_s^2 = \kappa^2 + \left(\frac{2\pi s}{a} \right)^2. \quad (5)$$

Using Eq. (5) and the deuteron photodisintegration cross section $\sigma_p(\omega)$, we can determine the total disintegration cross section in one period of the chain of relativistic deuterons that are channeled in the crystal (ϵ is the binding energy):

$$\sigma_d = \sum_{s_{min}}^{\infty} \bar{n}(\omega_s) \sigma_p(\omega_s), \quad s_{min} = \epsilon/\hbar\omega_{\perp}. \quad (6)$$

It follows immediately from Eq. (5) that the dependence of the cross section on the temperature of the crystal and on the energy of the deuterons is strong. In fact, at $s = s_{min}$ the exponent in Eq. (5) is equal to $(\epsilon\sigma/\hbar c\gamma)$, i.e., the cross section is noticeable when

$$\gamma > \gamma_c = \frac{\epsilon\sigma}{\hbar c}. \quad (7)$$

The numerical estimate of (6) can be obtained by weighting according to the spectrum (5) the experimental cross section $\sigma_p(\omega)$ from Ref. 7 and summing over the frequencies (Fig. 1). The calculations were performed for $a = 2.74$ Å, $R_{min} = \sigma$, $\kappa^{-1} = 0.126$ Å, $Z = 74$, and $\sigma = 0.022$ Å (the $\langle 111 \rangle$ axis is for tungsten). For 50 GeV $\sigma_d = 0.50$ mb ($\gamma \approx \gamma_c$); for 100 GeV $\sigma_d = 7.01$ mb ($\gamma > \gamma_c$). As a possible source of high-energy neutrons, such process would produce an angular divergence of $\sim 10^{-4}$ rad and an energy straggling of $\Delta E/E \approx 10^{-4}$.

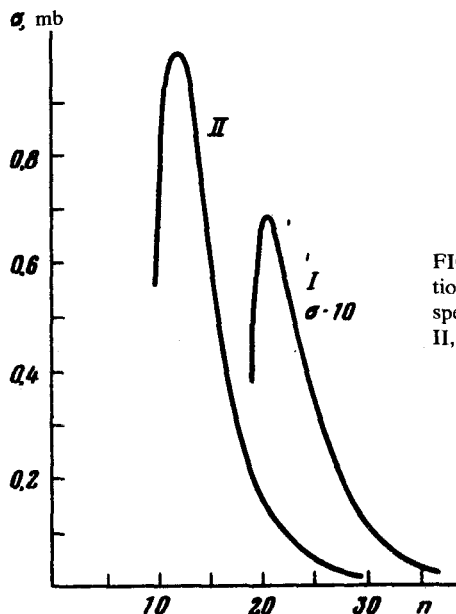


FIG. 1. Dependence of the electrodisintegration cross section of a deuteron on the number of the harmonic in the spectrum of equivalent photons of the chain: I, for 50 GeV; II, for 100 GeV.

Using such method, we can examine photonuclear-type processes with channeled nuclei under the action of EP in the Coulomb field of the crystal. For experimental investigation of such processes the optimum thickness of the crystal apparently should be $l_0 \sim a/\psi_L$ (ψ_L is the Lindhardt angle¹), which, in addition to establishing the condition for good channeling by suppressing nuclear interactions, makes it possible to avoid a burst of nuclear reactions during channeling due to a mismatch of phases of the nondiagonal elements of the density matrix⁴ (for 100 GeV $l_0 \sim 10^4 \text{ \AA}$). However, the products of nuclear reactions generated by the unchanneled part of the beam evidently have much wider angular distributions.

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