# Enhancement of the role of low multipole transitions in the Coulomb excitation of nuclei in crystals

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(Submitted 4 February 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 6, 287–290 (25 March 1991)

A different degree of suppression of the Coulomb excitation cross sections of various levels of nuclei in crystals compared to an amorphous target is predicted. The effect is related to the multipole order of the transition and a redistribution of the impact parameters of the collisions.

In the Coulomb excitation (CE) of nuclei and atomic levels of ions passing through crystals it is possible for coherence effects[1,2] to arise. These effects tend to increase the CE cross section when the momentum transferred in the process coincides with one of the reciprocal lattice vectors. If the condition for the appearance of coherence effects in CE (Ref. 2) is not satisfied, another interesting effect can occur in a crystal: exchange of the relative CE probabilities for transitions of various multipole orders compared to the same probabilities in an amorphous target. The physical reasons for this are the following: 1) The channeling of nuclei in a crystal, which leads to a specific distribution of impact parameters of the collisions between nuclei and crystal nuclei, and 2) different dependence of the CE functions on the collision impact param-

 0021-3640/91/060298-04$01.00  

eter for different types (multipole orders) of nuclear processes. Let us describe this effect for the example of the CE of $^{19}$F nuclei, which have two low-lying levels at 110 keV (transition of the $E1$ type) and 197 keV (transition of the $E2$ type). The probability for CE of multipole order $\pi\lambda$ in a collision with a target nucleus $Z_1$ with impact parameter $b$ is given by the expression[3]

$$P_{if}^{\pi\lambda}(b) = \left(\frac{Z_1 e^2}{\hbar c}\right)^2 \sum_{|\mu|\leq\lambda} \left(\frac{\omega}{c}\right)^{2(\lambda-1)} \frac{B(\pi\lambda, I_i \to I_f)}{e^2} |G_{\pi\lambda\mu}\left(\frac{c}{v}\right)|^2 K_\mu^2(\xi), \tag{1}$$

where

$$B(\pi\lambda, I_i \to I_f) = \sum_{M_f,\mu} |< I_f M_f|M(\pi\lambda\mu)|I_i M_i >|^2$$

is the standard reduced probability for an electromagnetic transition of multipole order $\pi\lambda$, $\hbar\omega$ is the transition energy, $K_\mu(\xi)$ is a modified Bessel function of the second kind, $\xi = \omega b/\gamma v$, and $\gamma = 1\sqrt{1 - v^2/c^2}$ is the Lorentz factor of the nucleus. The functions $G_{\pi\lambda\mu}$ are independent of $\hbar\omega$ and for the $E1$ and $E2$ transitions in question have the form ($\beta = v/c$) (Ref. 3):

$$G_{E11}\left(\frac{c}{v}\right) = -G_{E1-1}\left(\frac{c}{v}\right) = \frac{1}{3}\sqrt{8\pi}\frac{1}{\beta}; \quad G_{E10}\left(\frac{c}{v}\right) = -i\frac{4}{3}\sqrt{\pi}\frac{1}{\gamma\beta};$$

$$G_{E22}\left(\frac{c}{v}\right) = G_{E2-2}\left(\frac{c}{v}\right) = -\frac{2}{5}\sqrt{\pi/6}\frac{1}{\gamma\beta^2};$$

$$G_{E21}\left(\frac{c}{v}\right) = -G_{E2-1}\left(\frac{c}{v}\right) = i\frac{2}{5}\sqrt{\pi/6}\left(\frac{2}{\beta^2} - 1\right);$$

$$G_{E20}\left(\frac{c}{v}\right) = \frac{2}{5}\sqrt{\pi}\frac{1}{\gamma\beta^2}. \tag{2}$$

In order to obtain the CE cross section in an amorphous target, it is necessary to integrate (1) over all impact parameters larger than the sum of the radii of the colliding nuclei $R = 1.2(A_1^{1/3} + A_2^{1/3})$F:

$$\sigma_{if}^{\pi\lambda}(am) = \left(\frac{Z_1 e^2}{\hbar c}\right)^2 \sum_{|\mu|\leq\lambda} \left(\frac{\omega}{c}\right)^{2(\lambda-1)} \frac{B(\pi\lambda, I_i \to I_f)}{e^2} |G_{\pi\lambda\mu}\left(\frac{c}{v}\right)|^2 g_\mu(\xi),$$

$$g_{-}\mu(\xi) = g_{-\mu}(\xi) = \pi\xi^2[K_{\mu+1}^2(\xi) - K_\mu^2(\xi) - K_{\mu+1}(\xi)K_\mu(\xi)2\frac{\mu}{\xi}], \tag{3}$$

where we have introduced the adiabaticity parameter $\xi = \omega R/\gamma v$.

In order to obtain the cross section for the CE of nuclei channeled in a crystal, we must take into account the actual impact parameter distribution $\varphi(b)$ in the crystal:

$$\sigma_{if}^{\pi\lambda}(cryst) = (\frac{Z_1 e^2}{\hbar c})^2 \sum_{|\mu|\le\lambda} (\frac{\omega}{c})^{2(\lambda-1)} \frac{B(\pi\lambda, I_i \to I_f)}{e^2} |G_{\pi\lambda\mu}(\frac{c}{v})|^2 f_\mu,$$

$$f_\mu = \int d^2\vec{b}\varphi(b) K_\mu^2(\omega b/\gamma v). \tag{4}$$

Here for simplicity we disregard thermal vibrations of the crystal nuclei.

Let us consider axial channeling. The accurate calculation of the impact parameter distribution of channeled nuclei for this case is an independent, complicated problem. For a qualitative analysis we can use[4] simplified (zero emission angle relative to the axis) distributions: the equilibrium distribution $\varphi_{un}(b)$ with cutoff at small impact parameters and the statistical distribution $\varphi_{eq}(b)$ (a thick crystal and many oscillations):

$$\varphi_{un}(b) = \theta(b - b_{min})\theta(b_{max} - b);$$
$$\varphi_{eq}(b) = -Ln(1 - b^2/b_{max}^2)\theta(b_{max} - b), \tag{5}$$

where $\theta(x)$ is the step function. In the first case, multiplying $P_{if}^{\pi\lambda}(b)$ from (1) by $\varphi_{un}(b)$ and integrating over impact parameters, we obtain the result in analytic form, with the cross section for the CE of channeled nuclei in the crystal described by an expression of the type (4) with the replacement $g_\mu(\xi) \to g_\mu(\chi_{min}) - g_\mu(\chi_{max})$, and $\chi_{min,max} = \omega b_{min,max}/\gamma v$. In the second case the integration of $P_{if}^{\pi\lambda}$, $\varphi_{eq}(b)$ over impact parameters was done numerically. We assumed $b_{min} = \sqrt{\bar{u}^2}$ ($\bar{u}^2$ is the rms amplitude of the thermal vibrations), which holds for channeled nuclei, $\pi b_{max}^2 = 1/n$, and $n$ is the density of axes.

The results of calculations of the cross sections of the CE of the 110- and 197-keV levels of the $^{19}F$ nucleus in an amorphous target and for channeling are shown in Fig. 1. Because of the different dependence of the probabilities on the impact parameter, the cross sections for the CE of various multipole orders in an amorphous target and in a crystal are completely different. For example, in an amorphous target (solid lines in Fig. 1), $\sigma_{E2}(197 \text{ keV}) \gg \sigma_{E1}(110 \text{ keV})$. The suppression of small impact parameters in a crystal in the case of channeling, described by the functions $\varphi(b)$, now leads to $\sigma_{E2}(197 \text{ keV}) \ll \sigma_{E1}(110 \text{ keV})$, shown by the pairs of long- and short-dash lines in Fig. 1. Therefore, for CE in a crystal the picture is changed completely compared to an amorphous target; in fact, only the $E1$-type transition due to distant collisions survives up to $\gamma \approx 10^2$. As the nuclear energy increases, the difference between the CE cross sections of a given multipole order in a crystal and an amorphous target decreases. This behavior stems from the relativistic growth of the transverse dimensions of the field of the target nucleus in the c.m. frame of the incident nucleus, i.e., the increase in the contribution of distant collisions. Meanwhile, the difference between the CE cross sections for different multipole orders $\pi\lambda$ grows. This growth is related to the logarithmic growth of the dipole cross sections common to many processes and the saturation of the cross sections with $\lambda > 1$ with increasing nuclear energy.[3]

The effects we have described should also be observed for other sets of nuclear levels of different multipole order, beginning at the nuclear energies and emission

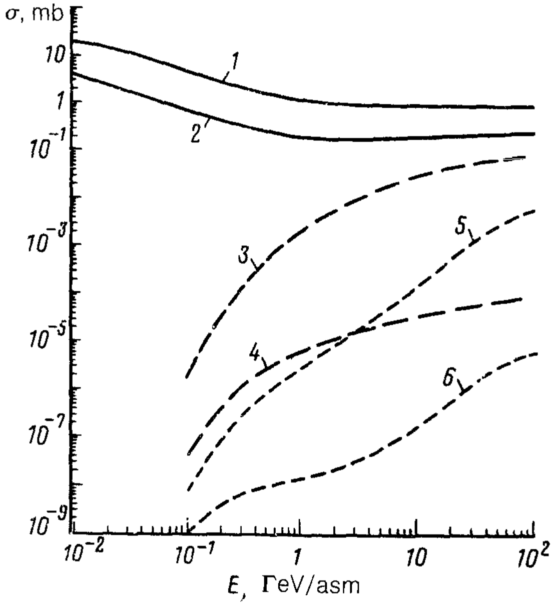


FIG. 1. Energy dependence of the CE cross sections of levels of the nucleus $^{19}$F: 110 keV ($E1$ transition)—curves 2, 3, 5, and 197 keV ($E2$ transition)—curves 1, 2, 6. The solid lines are the CE cross sections in an amorphous Au target, and the long-dash and short-dash lines are the CE cross sections for ⟨110⟩ axial channeling in Au with the distributions $\varphi_{un}(b)$ and $\varphi_{eq}(b)$, respectively; $b_{min} = \sqrt{\overline{u}^2}(T = 78\ \text{K})$. Curves 3–6 are not valid near the resonance energies (Ref. 2) for the coherence effect: $\gamma v = \omega a_{\parallel}/2\pi k,\ k = 1,2,..$ .

angles in a crystal at which channeling and the related redistribution of impact parameters become possible. The magnitude of the effect also depends on the temperature and type of crystal, the type of channeling (axial or planar), and the emission angle relative to the axis or plane. The effect should also be observed for target nuclei, for example, in the LiF crystal, for the CE of fluorine nuclei by channeled protons or ions. It is interesting to study the influence of the above-described effect and coherent CE on each other.[2]

This possibility of the relative suppression of higher multipole transitions in the CE of nuclei in channeling in crystals can prove interesting (together with coherent CE) for the selective excitation of nuclear levels.

The authors are grateful to S. A. Vorob'ev for his support of the study and useful discussions.

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Translated by Patricia Millard