Use of the anomalous passage effect to obtain stimulated emission of γ quanta in a crystal

Yu. Kagan

I. V. Kurchatov Atomic Energy Institute
(Submitted May 21, 1974)
ZhETF Pis. Red. **20**, 27–30 (July 5, 1974)

The possibility of increasing the coherent active region in the generation of the paired Bragg state of γ quanta in a crystal by nuclei is demonstrated. To this end it is necessary that the Borrman effect be realized for one of the polarizations, that the suppression effect be simultaneously absent, and that the state with this polarization be an eigenstate of the crystal.

1. The possibility of observing stimulated emission of γ quanta of nuclei decaying in a crystal under conditions of the Mössbauer effect encounters great difficulties because the problem is critically sensitive to the values of the corresponding physical parameters (see, e.g., [1]). This is connected to a noticeable degree by the limited mean free path of the γ quanta in the medium, owing to absorption (and inelastic scattering) by the electrons. It seems at first glance that this limitation is of principal character and cannot be overcome.

Under conditions of Bragg diffraction in a perfect crystal, however, a coherent superposition of two waves (that differ by the reciprocal-lattice vector **K**) can be realized, and the absorption is greatly reduced for this superposition. This is the so-called Borrman effect (BE), [2] which occurs for waves with σ polarization (the electric field vectors are perpendicular to the scattering plane) and is connected with the fact that the total electric field has nodes at the lattice sites.

However, the vanishing of the electric field at the nucleus makes stimulated decay impossible if an electric dipole transition takes place. It was precisely this circumstance which led to the statement that the BE cannot be used to obtain stimulated γ radiation.[3]

2. Actually the resonant interaction of nuclei with an electromagnetic field in a crystal depends on the multipolarity of the transition and on the character of the hyperfine structure, and is determined in the general case by other components or derivatives of the field at the location of the nucleus. The vanishing of the electric field does not play a decisive role by itself.

At the same time, however, in resonant interaction of Bragg-scattered γ quanta with nuclei, an effect of suppression of the nuclear reaction (SE) takes place[4,5] (see also[6]). This effect is connected with the vanishing of the amplitude for the production of an excited nucleus in the resultant superposition state. In accordance with the reciprocity theorem, nuclei on which the SE is realized do not generate when this state decays.[7] This leads to the first condition for the possibility of using anomalously weak absorption by electrons, viz., it is necessary that there be no suppression effect for the superposition state with σ polarization for which the BE is realized.

The second requirement is that the state with σ polarization be an eigenstate of the electromagnetic field in the crystal, i.e., that no coherent transfer from the σ polarization to the π polarization take place and restore the absorption by the electrons when the γ quanta are propagated.

An analysis, which is easily carried out within the framework of the results obtained on the general theory of scattering of resonant γ quanta in crystals[4–6] shows that there exists a broad spectrum of cases for which both conditions are satisfied simultaneously. Thus, the second condition is automatically satisfied if the scattering is determined by the electrons, and if nuclei take part it is satisfied if the nuclear levels are not split (the transitions of type $M1$, $E1$, and $E2$ are of interest). For the $M1$ transition, the SE takes place for π polarization (the total magnetic-field vector at the nucleus vanishes), but does not take place in fact for the σ polarization. In the case of $E2$ transitions and an arbitrary choice of the Bragg reflection, the suppression effect does not exist in general for either polarization. Only in the case of the $E1$ transition is the suppression effect realized for the σ polarization and the first condition is violated.

In the case of hyperfine splitting of nuclear levels, simultaneous satisfaction of both conditions calls already for a special choice of the orientation of the scattering plane relative to the configuration of the field that produces the hyperfine splitting (see[6]).

3. In simple cases {one atom per unit cell; two identical atoms per unit cell under the condition $\exp[i\mathbf{K}\cdot(\vec{\rho}_1 - \vec{\rho}_2)] = 1$, etc.} the relative decrease of the absorption coefficient, neglecting the weak inelastic scattering by phonons, is determined by the relation (see, e.g.,[8])

$$\xi = 1 - \epsilon_0(\mathbf{K}) \exp\{-M(\mathbf{K})\}.$$

Here $\epsilon_0(\mathbf{K})$ is the ratio of the imaginary parts of the amplitudes for γ-quantum scattering by the electrons through the Bragg angle and through zero angle, respectively, and $M(\mathbf{K})$ is the usual Debye-Waller factor. Direct calculations (see, e.g.,[9,10]) show that for the energies typical of x-rays and for the minimal values of $|\mathbf{K}|$ the deviation of ϵ_0 from unity does not exceed 0.01. With increasing energy this difference will only decrease at fixed $|\mathbf{K}|$. As a result, the factor ξ is determined in practice by the value of $M(\mathbf{K})$. This makes it easy to estimate that at low temperatures ($T \ll \Theta_D$) the absorption coefficient decreases by a factor 20—100, as is indeed observed in experiment.

In view of the rapid growth of the absorption coefficient with increasing K [$M(\mathbf{K}) \sim K^2$; $1 - \epsilon_0$ also increases with K], only pair Bragg states with minimal $|\mathbf{K}|$ play an essential role in stimulated emission of γ quanta.

4. The use of the BE automatically separates a narrow angle interval for the γ-quantum propagation, $\sim 1''$ in the plane of the wave vectors $\mathbf{k}_1$ and $\mathbf{k}_2$ of the two waves. This plane itself can rotate about the vector $\mathbf{K}$, so that $\mathbf{k}_1$ and $\mathbf{k}_2$ generate conical surfaces with aperture angle $90 - \Theta_B$. The selectivity of the direction on these surfaces is already governed by the geometry of the crystal. Thus, an effective crystal may be a thin plate with crystalline planes (corresponding to a definite $\mathbf{K}$) perpendicular to the surface of the plate. The directions that are strongly singled out are then parallel to this surface.

5. The use of the BE presupposes the availability of a perfect crystal with a high concentration of excited nuclei. (We note that the requirement that the crystal be perfect comes close to the requirements that arise when narrow lines are used, see[11]). In the case of pulsed pumping by neutrons, the method of two-stage pumping may be particularly effective.[11] In this case it is precisely a crystal in the form of a thin plate provides us with a "thin crystal" for pumping and a "thick crystal" for the motion of the γ quanta through the active medium.

[1]V. I. Gol'danskiĭ and Yu. Kagan, Zh. Eksp. Teor. Fiz. 64, 90 (1973) [Sov. Phys.-JETP 37, 49 (1973)]; Usp. Fiz. Nauk 110, 445 (1973) [Sov. Phys.-Usp. 16, No. 4 (1974)].
[2]G. G. Borrman, Z. Physik 42, 157 (1942); 127, 297 (1950).
[3]G. C. Baldwin, in press, 1974.
[4]A. M. Afanas'ev and Yu. Kagan, Zh. Eksp. Teor. Fiz. 48, 327 (1965) [Sov. Phys.-JETP 21, 215 (1965)].
[5]Yu. Kagan and A. M. Afanas'ev, Mössbauer Spectroscopy and Its Applications, Proc. 1971 Vienna Panel, p. 143, Vienna, 1972.
[6]Yu. Kagan and A. M. Afanas'ev, Z. Naturforschung 28a, 1351 (1973).
[7]P. A. Aleksandrov and Yu. Kagan, Zh. Eksp. Teor. Fiz. 59, 1733 (1970) [Sov. Phys.-JETP 32, 942 (1971)].
[8]A. M. Afanas'ev and Yu. Kagan, Acta Cryst. A24, 163 (1967).
[9]H. Wagenfeld, Phys. Rev. 144, 216 (1966).
[10]G. Hildebrandt, J. D. Stephenson, and H. Wagenfeld, Z. Naturforsch. 28a, 588 (1973).
[11]V. I. Gol'danskiĭ, Yu. Kagan, and V. A. Namiot, ZhETF Pis. Red. 18, 61 (1973) [JETP Lett. 18, 34 (1973)].