Inelastic scattering of neutrons in crystals by laser photons and excitons

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The cross section for the scattering of neutrons by photons increases sharply in crystals. Since a photon moving in a crystal (polariton), being a superposition of transverse photons and Coulomb excitations (optical phonons, excitons, etc), also sets into motion an accompanying subsystem of nuclei, the cross section for the scattering of neutrons by photons turns out to be proportional to the cross section for the scattering of neutrons by nuclei and to the force function of the phonons at the polariton frequency. Numerical estimates of the cross section of incoherent absorption of a photon by a neutron, carried out for the LiH crystal in the presence of intense electromagnetic radiation produced by a pulsed laser, point to the feasibility, in principle, of acting on neutron beams by laser radiation. An analogous dragging (superposition) effect takes place also for excitons. This circumstance is used to calculate the cross section of elastic neutron scattering by excitons; this cross section is proportional to the cross section for the scattering of neutrons by nuclei. The influence of laser radiation on neutron-induced nuclear reactions (radiative capture and threshold reactions) is also discussed.

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1. INTRODUCTION

It is known that in a vacuum the interaction of neutrons with photons is negligibly small. The situation is radically changed, however, on going to photons in strongly polarizable media, particularly in crystals. Since the photons in a crystal (polaritons) are mixtures (superpositions) of transverse photons and Coulomb excitations (optical phonons, excitons, etc.) the strong interaction of the neutrons with the nuclei causes the intensity of the neutron scattering by the photons to increase strongly. The most interesting here are the processes of inelastic neutron scattering, which are accompanied by changes in their energy by an amount equal to the photon energy.

As is clear even from purely qualitative considerations, the effectiveness of the scattering of neutrons by photons of frequency ω in a crystal should be proportional to the so-called phonon strength function $S(\omega)$, which is used in polariton theory and determines the fraction of the mechanical energy in a polariton, and is equal to the ratio of the squares of the amplitudes of the atom in the polariton and in the optical phonon. For example, for an isotropic medium with a dielectric constant

$$\varepsilon(\omega)=\varepsilon_\infty+\frac{(\varepsilon_0-\varepsilon_\infty)\Omega^2}{\Omega^2-\omega^2}$$

(ϵ_0 and ϵ_∞ are the low- and high-frequency values of $\epsilon(\omega)$ and Ω is the frequency of the optical phonon), $S(\omega)$ is given by

$$S(\omega)=\frac{\omega\Omega\omega_0^2/\varepsilon_\infty}{(\omega^2-\Omega^2)^2+\Omega^2\omega_0^2/\varepsilon_\infty}, \qquad (1)$$

where $\omega_0^2=\Omega^2(\epsilon_0-\epsilon_\infty)$.

The concept of the strength function $S(\omega)$ and relation (1) can, of course, be used also to describe the structure of the polariton in the region of exciton transitions (exciton strength function, in which case Ω is the frequency of the exciton transition) and turn out to be useful, since $S(\omega)$ arises in natural fashion in the theoretical description of the processes of inelastic polariton scattering by phonons in both the electronic and in the vibrational region of the spectrum. In particular, $S(\omega)$ determines the intensity of the Raman scattering of polaritons by phonons in the region of the long-wave edge of the exciton absorption band.[4] It enters also in the theory of Raman scattering of light by polaritons, and determines the intensity[3] as well as the width of the Raman scattering line[5,6].

In contrast to the aforementioned situation, we are interested here in the polariton spectrum region where its frequency is much larger than the frequency of the optical oscillation ($\omega \gg \Omega$). As seen from (1), in this region of the spectrum we have $S(\omega)\approx\Omega\omega_0^2/\epsilon_\infty\omega^3$, so that at $\Omega/\omega\approx 0.1$ the function $S(\omega)$ turns out to be of the order of 10^{-3} to 10^{-2}.

An analogous involvement effect, but due to intermolecular interaction, arises not only for polaritons but also for excitonic (electronic) excitations and, as will be shown below, can lead to inelastic scattering of the neutrons by excitons.

An important feature of these processes is that their cross section, just like the cross section for neutron scattering by polaritons, is proportional to the cross section for the scattering of neutrons by nuclei. It is precisely this circumstance, and also the existing possibilities of using lasers and high-power neutron sources, which make the aforementioned processes of neutron scattering by excitons and polaritons interesting also for experimental purposes.

2. NEUTRON-POLARITON SCATTERING CROSS SECTION

We assume that an intense monochromatic wave (produced, say, by a laser) of polaritons with frequency ω, wave vector $\mathbf{k}$, and definite polarization propagates in an optically isotropic crystal. With respect to these polaritons we assume that they are the result of mixing of transverse photons with optical transverse phonons of frequency $\Omega(\mathbf{k})$. Let the laser produce in the entire crystal, in stationary fashion, n_p such polaritons. The doubly-differential cross section of the process of incoherent scattering of neutrons in the crystal, is due to the neutron scattering by the nuclei and proceeds with annihilation of one quasiparticle (phonon, polariton, or

exciton),[1)] is determined by the following expression[7]:

$$\sigma_-(\mathbf{p}'-\mathbf{p},E)=\frac{1}{8\pi^2\hbar^3}\frac{p'}{p}\sum_\gamma\sigma_{inc}^{(\gamma)}N^\gamma\int_{-\infty}^{+\infty}\langle(\mathbf{p}'-\mathbf{p})_i u_\gamma^i(t)\,(\mathbf{p}'-\mathbf{p})_j u_\gamma^j(0)\rangle e^{-i\omega t}\,dt, \quad (2)$$

where $\mathbf{p}$ and $\mathbf{p}'$ are the values of the neutron momentum before and after scattering; $E = \hbar\omega$ is the change of the neutron energy upon scattering; $\sigma_{inc}^{(\gamma)}$ is the cross section of the incoherent scattering of the neutrons by the bound nucleus numbered γ in the unit cell of the crystal; $\mathbf{u}_\gamma(t)$ is the displacement vector of the same nucleus, and N^γ is the total number of nuclei γ in the crystal.

Since in hydrogen-containing media, in which we shall be interested from now on, the value of $\sigma_{inc}^{(\gamma)}$ for the hydrogen nucleus greatly exceeds the corresponding cross sections for the other nuclei, we take into account in (2) only the scattering of the neutrons by the hydrogen nuclei. As is seen from (2), the calculation of the cross section of the inelastic neutron scattering by the photons reduces to a calculation of the correlation function under the integral sign in (2) under conditions when the phonon oscillator with frequency Ω is made to oscillate by polaritons of frequency ω.

When the thermal factor e^{-2W} is taken into account we obtain for the energy-integrated value of the cross section of neutron scattering accompanied by photon absorption

$$\bar{\sigma}_-(\mathbf{p}'-\mathbf{p},E)=\frac{1}{4\pi\hbar}\frac{p'}{p}\sigma_{inc}Ne^{-2W}|\mathbf{p}'-\mathbf{p}|^2\frac{n_p}{N}\frac{1}{2M\Omega}S(\omega)\cos^2\theta, \quad (3)$$

where M is the mass corresponding to the phonon oscillator with frequency Ω; θ is the angle between the directions of the electric field of the polariton and the vector $\mathbf{p}' - \mathbf{p}$. Consequently, the total cross section $\Sigma(E)$ of the process in question, integrated both over the energy and over all the directions of $\mathbf{p}'$, is given by

$$\Sigma(E)=\frac{1}{3}\frac{p'}{p}\sigma_{inc}ne^{-2W}\frac{m_n}{M}\frac{n_p}{n}\frac{\omega}{\Omega}S(\omega), \quad (4)$$

where m_n is the neutron mass and $n = N/V$ is the number of scattering nuclei per unit volume ($m_n = M$ for hydrogen).

The quantity $l_1 = (\sigma_{inc}ne^{-2W})^{-1}$ determines the average distance over which the neutron is scattered by a bound nucleus (for slow neutrons in hydrogen-containing media l_1 is of the order of several millimeters).

Since we are interested in the cross section of the considered process over the entire length l of the crystal in the direction of the neutron beam, we find by using (4) that when diffusion and the finite lifetime of the neutrons in the crystal are taken into account this cross section takes the form

$$\Sigma_{tot}(\omega)=\frac{1}{3}\frac{p'}{p}\frac{n_p}{n}\frac{\omega}{\Omega}S(\omega)\frac{L}{l_1}(1-e^{-l/L}), \quad (5)$$

where L is the neutron diffusion length in the crystal. We assume that the crystal thickness $l \gtrsim L$. Taking into account the expression for $S(\omega)$ in the considered frequency region ($\omega \gg \Omega$), we obtain for Σ_{tot}

$$\Sigma_{tot}=\frac{1}{3}\sqrt{\frac{\hbar\omega}{E_0}}\frac{n_p}{n}\left(\frac{\Omega}{\omega}\right)^2\frac{\varepsilon_0-\varepsilon_\infty}{\varepsilon_\infty}\frac{L}{l_1}, \quad (6)$$

where $E_0 \approx kT$ is the initial neutron energy ($E_0 \ll E = \hbar\omega$).

Of great importance in the estimate of the cross section is the ratio n_p/n. For cw lasers we have $n_p = U/\hbar\omega_p v$, where U is the power radiated by the laser and v is the velocity of the polaritons in the crystal. The presently available lasers deliver a continuous power of several kilowatts per cm^2sec, so that at $\hbar\omega \approx 0.2$–0.5 eV, $v \approx c/\sqrt{\varepsilon(\omega)}$, and $n \approx 5\times10^{22}$ nuclei/cm^3 we have $n_p/n \sim 10^{-10}$. Modern pulsed lasers, however, are capable of increasing this ratio to several hundredths or even more. But the pulse durations of such lasers, as is well known, is of the order of 10^{-9}–10^{-12} sec, i.e., much shorter than the pulses of the thermal neutrons from pulsed reactors. It is clear, however, that the best neutron utilization can be reached only under conditions when the pulsed laser is synchronized with the pulsed reactor so that the durations of the pulses and the distances between them coincide.

The thermal-neutron pulses from modern pulsed reactions are approximately 10^{-4} sec long, while the pulse repetition frequency can amount to several hertz or even less. What would be suitable for the synchronization with such a reactor is a pulsed laser, say, with a photon energy $\hbar\omega \sim 0.2$ eV, and capable of emitting during the pulse time $\tau = 0.5\times10^{-3}$ sec an energy $U \approx 10$ kJ (see, e.g.,[9]). For such a laser $n_p = U/\tau v\hbar\omega_p \approx 2\times10^{17}$ photons/cm^3, so that $n_p/n \approx 10^{-5}$ (the pulsed reactor can, of course be synchronized with an entire system of lasers that emit in sequence; concerning the operating conditions of the reactor see[10]).

The choice of the crystal dictates the following value in (6):

$$\beta=\frac{\Omega^2}{n}\frac{\varepsilon_0-\varepsilon_\infty}{\varepsilon_\infty}\frac{L}{l_1}.$$

Since

$$\Omega^2\frac{\varepsilon_0-\varepsilon_\infty}{\varepsilon_\infty}=\Omega_\parallel^2-\Omega_\perp^2,$$

where $\Omega_\parallel$ and $\Omega_\perp$ are the frequencies of the longitudinal and transverse oscillations, interest attaches to crystals having a large longitudinal-transverse splitting gap. A hydrogen-containing crystal with a large gap $\Omega_\parallel - \Omega_\perp$ is LiH ($\Omega_\parallel = 1130$ cm^{-1}, $\Omega_\perp = 590$ cm^{-1}).[11] We have in mind here a crystal based on the isotope Li^7, with low thermal-neutron absorption. For such a crystal we have $\beta \approx 2\times10^{-16}$ cm (Ω is the cm^{-1}).

We shall assume below that we are scattering neutrons obtained with the aid of a moderator cooled to several dozen degrees ($E_0 \approx 10^{-3}$ eV). For LiH irradiated by the laser described above we obtain a cross section $\Sigma_{tot} = (2$–$4)\times10^{-7}$ cm^2. Thus, only a fraction $\approx10^{-7}$ of the total number of the thermal neutrons will acquire an energy on the order of one electron volt from the polariton by which they are scattered.

The energy spread of the scattered neutrons is determined by the corresponding spread of the thermal neutrons prior to the scattering and by the degree of monochromaticity of the laser beam. In experiments using a cooled moderator and a laser with good monochromaticity is is apparently possible to reduce the neutron energy scatter to $(10^{-2}$–$10^{-3})\hbar\omega$.

The number of scattered neutrons in the process under discussion is smaller by one or two orders of magnitude than the number of neutrons having the same degree of monochromaticity and an energy $E \approx 0.2$ eV, emitted by the reactor itself.[8] In each burst of the neutron source, the pulse of these fast neutrons lasts about 5×10^{-6} sec. On the other hand, the pulse of the neutrons of the same energy ($E \approx 0.2$ eV) scattered by

the polaritons will last, just as the pulse of the thermal neutrons, 10^{-4} sec. It appears therefore that it is possible to observe experimentally neutron scattering by photons, provided the initial pulse of the fast neutrons can be discriminated in some manner. With further increase of the power of pulsed lasers, and possibly if a more suitable material than LiH is used, the effectiveness of the process will undoubtedly be improved. It must also be necessary to bear in mind here the feasibility, in principle, of using not one laser but of several lasers operating in synchronism. There is also an interesting possibility of scattering the neutrons in the active medium of the solid-state laser itself, where the radiation fluxes, other conditions being equal, can be made larger by more than one order of magnitude.

The future will show to what extent the process considered above can serve as the basis of a competitive method of obtaining fast (resonant) monochromatic neutrons. We note here only that the use of lasers with tunable frequency makes it possible also to change the energy of the scattered neutrons. On the other hand, in media with a large coherent-scattering cross section it is possible to obtain not only monochromatic but also sharply directional beams of scattered neutrons.

We note in conclusion that neutron scattering by photons can take place of course, not only with absorption but also with production of a photon in the crystal. The cross section of this process will be determined also by formula (5), but the pulse ratio p'/p will be appreciably decreased. Therefore the cross section corresponding to photon production will be smaller by two or three orders than the cross section of the process considered above. In addition, processes in which a neutron absorbs a photon are possible, but accompanied by the production of one or several optical or acoustic phonons.

In the hydrogen-containing crystal LiH considered above, the contribution of the acoustic phonons to the neutron scattering, owing to the smallness of the ratio of the hydrogen and lithium masses, turns out to be smaller by more than one order of magnitude than the contribution from the optical oscillations.[12] On the other hand processes in which optical phonons take part turn out to be more significant. It can be shown, for example, that the integrated intensity of the absorption of a photon by a neutron, accompanied by production of n transverse optical phonons, is determined, disregarding the phonon dispersion, by the relation

$$\sigma_n=\sigma_0\left(\frac{m_{Li}}{m_H+m_{Li}}\right)^n\left(\frac{\omega-n\Omega}{\Omega}\right)^n\frac{1}{n!}\frac{3}{2n+3},$$

where m_H and m_{Li} are the masses of the hydrogen and lithium nuclei. If $\omega/\Omega = 10$, then the cross section of the processes first increases with increasing n, and then decreases rapidly. It is important that the width of the spectrum of the neutrons produced in processes with production of $n \neq 0$ phonons is larger than the width of the spectrum of the neutrons produced in a process with $n = 0$, by an amount equal to n bandwidths Δ of one phonon ($\Delta \approx 100$ cm^{-1} for LiH).

3. SCATTERING OF NEUTRONS BY EXCITONS

In this section we consider the process of inelastic scattering of neutrons by excitons. We are not interested here in the well-investigated magnetic scattering of of neutrons, which results from the interaction of neutrons with electrons, and take into account, just as in the preceding section, only the interaction of the neutrons with nuclei.

The interaction of neutrons or of other fast particles with nuclei leads to transitions in molecules or crystals when account is taken of the nonadiabaticity operator (see, e.g.,[13]). This operator, however, is under the indicated conditions not the only cause of the appearance of electronic transitions. We shall show below that electronic transitions of this type are possible in crystals by virtue of certain singularities, which arise already in the linear approximation, of the structure of the elementary excitations that are due to an effect of the type of mixing of molecular configurations in molecular crystals (see, e.g.,[2]).

To illustrate the foregoing, let us consider the simplest model of a dielectric, assuming that it has an exciton band (exciton energy $\epsilon(\mathbf{k})$, exciton wave vector $\mathbf{k}$, $B_{\mathbf{k}}^+$ and $B_{\mathbf{k}}$ are the exciton creation and annihilation operators) and an optical-phonon band (phonon frequency $\Omega(\mathbf{k})$, $b_{\mathbf{k}}^+$ and $b_{\mathbf{k}}$ are the phonon creation and annihilation operators). In the harmonic approximation the Hamiltonian for this model of the crystal is

$$\hat{H}=\sum_{\mathbf{k}}\varepsilon(\mathbf{k})B_{\mathbf{k}}^+B_{\mathbf{k}}+\sum_{\mathbf{k}}\hbar\Omega(\mathbf{k})b_{\mathbf{k}}^+b_{\mathbf{k}}+\sum_{\mathbf{k}}\Gamma(\mathbf{k})(B_{\mathbf{k}}^+ + B_{-\mathbf{k}})(b_{\mathbf{k}}+b_{-\mathbf{k}}^+), \tag{7}$$

where $\Gamma(\mathbf{k})$ is the energy of the exciton-phonon interaction. In the case, e.g., of a molecular crystal and for a dipole exciton and a dipole phonon, the energy $\Gamma(\mathbf{k})$ is governed by the dipole-dipole intermolecular interaction operator, so that its order of magnitude is $\Gamma(\mathbf{k}) \sim M_e M_{ph}/d^3$, where M_e and M_{ph} are the dipole moments of the transition in the molecule and correspond to the production of an electronic or vibrational excitation of the molecule. Consequently the value of $\Gamma(\mathbf{k})$, depending on the values of M_e and M_{ph}, can vary in a wide range, reaching values on the order of 500 cm^{-1} for intense dipole transitions (for example, at $M_e/e = 1$ Å, $M_{ph}/e = 0.5$ Å. and $d = 5$ Å we have $\Gamma(\mathbf{k}) \approx 500$ cm^{-1}; the value used here for M_{ph} can be obtained for optical phonons that correspond to proton oscillation), whereas $\epsilon(\mathbf{k}) \sim 10^4$—$5 \times 10^4$ cm^{-1} and $\hbar\Omega \sim 10^3$ cm^{-1}.

The Hamiltonian (7) can be diagonalized to take the form

$$\hat{H}=\sum_{\mathbf{k}}\tilde{\varepsilon}(\mathbf{k})\tilde{B}_{\mathbf{k}}^+\tilde{B}_{\mathbf{k}}+\sum_{\mathbf{k}}\hbar\tilde{\Omega}(\mathbf{k})\tilde{b}_{\mathbf{k}}^+\tilde{b}_{\mathbf{k}}. \tag{8}$$

Since $\Gamma(\mathbf{k}) \ll \tilde{\epsilon}(\mathbf{k})$, the new values of the exciton and phonon energies differ little from the old values in (7). More important for the question discussed here is the fact that after allowing for the mixing effect the exciton turn out to be superpositions of the electron and phonon states. Namely, inasmuch as in terms of the new variables the operator of the normal coordinate is

$$\xi_{\mathbf{k}}=\alpha\tilde{b}_{\mathbf{k}}+\dot{\alpha}\tilde{b}_{\mathbf{k}}^+ + \beta\tilde{B}_{\mathbf{k}}+\dot{\beta}\tilde{B}_{\mathbf{k}}^+,$$

where α and β are determined as a result of diagonalization of the Hamiltonian (7) (see[2]), this operator leads to transitions with exciton production, and this precisely ensures, that the neutron-nuclear interactions can excite these excitons.

Without going into details of the elementary calculations, we present only the final result. Using the notation of the preceding section, we represent the total cross section of the process of incoherent excitation of an exciton with energy E in the form

$$\sigma_+(E)=\frac{1}{3}\frac{L}{l_1(E)}\frac{p'}{p}\frac{m_n}{M}\frac{1}{N}\sum_{\mathbf{k}}\frac{4\hbar\tilde{\Omega}(\mathbf{k})\Gamma^2(\mathbf{k})}{[\tilde{\varepsilon}(\mathbf{k})]^3}\delta(E-\tilde{\varepsilon}(\mathbf{k})). \quad (9)$$

Formally this expression differs from the analogous expression for the cross section for the excitation of the optical phonon by a factor $4\hbar\Omega\Gamma^2/\tilde{\epsilon}^2 \approx 10^{-3}-10^{-1}$, which is exactly what determines the relative smallness of the effect.[2)] Going over in (9) from summation over $\mathbf{k}$ to integration and introducing the normalized density of states g(E) in the exciton band, we obtain

$$\sigma_+(E)=\frac{1}{3}\frac{l}{l_1(E)}\frac{p'}{p}\frac{m_n}{M}\frac{4\hbar\tilde{\Omega}(E)\Gamma^2(E)}{E^3}g(E), \quad (10)$$

where $\tilde{\Omega}(E)$ and $\Gamma^2(E)$ are the values of $\tilde{\Omega}(\mathbf{k})$ and $\Gamma^2(\mathbf{k})$ averaged over $\mathbf{k}$ on the surface $\tilde{\epsilon}(\mathbf{k}) = E$.

Thus, a study of the inelastic scattering by excitons can be used in principle to find the density of states in the exciton band; it is necessary to know here, from some other considerations, also the dependence of $\Gamma^2(E)$ and $\tilde{\Omega}(E)$ on E. Since the power of the presently produced neutron sources is constantly increasing, the study of the here-discussed exciton band structure, using neutron scattering, may turn out to be timely from the experiment point of view.

We note that M. A. Krivoglaz, in connection with the question discussed here, called our attention to his article (with Kashcheev, see[13]), where they dealt with the possibility of inelastic neutron scattering by electronic excitations of impurity centers. It was proposed to raise the electrons to the excited state by heating, and inelastic processes with participation of neutrons turned out to be possible as a result of electron-phonon interaction in the impurity center. The difference between the situation considered in this section and that discussed in[13] is connected mainly with the specifics of the exciton-phonon interaction, which leads, for intense dipole excitons and optical phonons and for small values of the ratio $\hbar\tilde{\Omega}/\tilde{\epsilon}(\mathbf{k})$, to scattering cross sections that are larger by more than one order of magnitude than those obtained in[13].

4. EFFECT OF LASER RADIATION ON NUCLEAR REACTIONS WITH PARTICIPATION OF NEUTRONS (CAPTURE OF SLOW NEUTRONS AND THRESHOLD REACTIONS)

We consider first the effect of laser radiation on the radiative capture of neutrons in the resonance region of the spectrum of the excited states of a compound nucleus.[3)] The effect of the lattice vibrations on the radiative-capture probability was considered by Lamb[14] (see also[15]). The relation obtained for neutrons of energy E is

$$\omega(E)=|M_c M_\gamma|^2\sum_{\{n_s'\}}|(\{n_s^0\}|e^{i\mathbf{pu}/\hbar}|\{n_s'\})|^2 \times\left(\left[E-E_0+\sum_s\hbar\omega_s(n_s^0-n_s')\right]^2+\Gamma^2/4\right)^{-1}, \quad (11)$$

where the aggregate of the quantum numbers $\{n_S^0\}$ characterizes the initial state of the lattice, $\{n_S'\}$ characterizes the state of the lattice in the intermediate state, E_0 is the resonance energy, Γ is its width, $\mathbf{p}$ is the neutron momentum, $\mathbf{u}$ is the displacement operator of the nucleus on which the neutron is captured, and M_C and M_γ are matrix elements corresponding to neutron capture and γ-quantum emission by a free nucleus (for details see[15]).

In the presence of a flux of photons of frequency ω, the relation (11) retains the same form; it is only necessary to describe the lattice vibrations in a more general manner, namely, to take into account the retarded interaction and to include among the lattice oscillators also the photons in the crystal (polaritons).

Assuming the polariton flux to be intense enough, we take into account only their contribution in (11); however, we confine ourselves to the linear terms in the expansion of the exponential $\exp[i\mathbf{p}\cdot\mathbf{u}/\hbar]$ in powers of $\mathbf{u}$. In this approximation we have

$$\omega(E)=\omega_0(E)+|M_c M_\gamma|^2\frac{E}{\hbar\Omega}\frac{m_n}{M}\frac{n_p}{n}S(\omega) \times\left[\frac{1}{(E-E_0-\hbar\omega)^2+\Gamma^2/4}+\frac{1}{(E-E_0+\hbar\omega)^2+\Gamma^2/4}\right], \quad (12)$$

where $\omega_0(E)$ is the radiative-capture probability in the absence of laser radiation, and m_n and M are the masses of the neutron and nucleus, respectively. From (12) it follows that the capture process can be made resonant with the aid of a laser. If $E > E_0$, this calls for the light-quantum energy $\hbar\omega$ to be equal to $E - E_0$; to the contrary, if $E < E_0$, then the resonance takes place at $\hbar\omega = E_0 - E$. Since $E_0 \sim 1$ eV and $\Gamma \sim 0.05$ eV, the ratio of the resonant and nonresonant contributions to $\omega(E)$ is given by

$$\alpha\equiv\frac{4E}{\hbar\omega}\frac{\Omega^2(\varepsilon_0-\varepsilon_\infty)}{\omega^2\varepsilon_\infty}\frac{n_p}{n}\left(\frac{E_0}{\Gamma}\right)^2\frac{m_n}{M}.$$

At

$$\frac{E}{\hbar\omega}=\frac{\Omega}{\omega}=\frac{m_n}{M}=0.1,\quad \frac{E_0}{\Gamma}=30,\quad \frac{\varepsilon_0-\varepsilon_\infty}{\varepsilon_\infty}=3$$

we have $\alpha = n_p/n$, i.e., it is determined entirely by the ratio of the photon density to the density of the nuclei. In pulsed lasers this ratio can be made large enough. It is not clear whether the produced γ quanta can be observed, inasmuch as the number of these quanta in each pulse is small in comparison with the background.

In connection with the question discussed, great interest can apparently be attached to threshold reactions using neutrons with $E < E_1$, where E_1 is the threshold energy, but $E + \hbar\omega > E_1$.

In this case there should be on background, and the yield of the reaction is determined entirely by the effect of the laser radiation. This seemingly more interesting possibility of obtaining pulses of nuclear particles calls, however, for a special discussion.

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Note added in proof (25 June 1975). In connection with estimates of the effectiveness of the process considered in Sec. 2, the NH_4Cl crystal may also be promising, since its protons have high optical-oscillation frequencies ($\Omega_\perp = 3122$ cm^{-1}; $\Omega_\parallel = 3159$ cm^{-1}). The contribution of the optical oscillations to the quantity $W(E_0, E)$, which determines the Debye-Waller factor and enters in formulas (3) and (4), will be smaller for this crystal.

[1)] Processes with absorption of several quasiparticles can be treated analogously.

[2)]To be sure, in the case of scattering by an optical phonon it is necessary to choose in place of L the crystal thickness $l \lesssim l_1$, so that actually the smallness of the effect is given by the values $10^{-2}-10^{-3}$.

[3)]Under the conditions of the Mössbauer effect, the statements made below apply also to γ-quantum capture.

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