

POSSIBILITY OF OCCURRENCE OF "PHOTON CASCADE" IN EPR LINE WING SATURATION

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Experimental investigations [1, 2] have shown that pulsed saturation of paramagnetic crystals at a frequency somewhat different from the spin-transition frequency leads to a cascade-like increase of the number of phonons. The maximum temperature of the "hot phonons" reached in this case 8000°K. We show in the present article that a "photon cascade" can occur upon saturation of the EPR line wing, and we obtain the optimal conditions under which this effect can be observed.

The theory of the "phonon cascade" effect was developed in a paper [2] devoted to the derivation and investigation of a system of kinetic equations describing energy exchange between the Zeeman, dipole-dipole, and phonon subsystems, on the one hand, and a thermostat on the other. It was always assumed (see, for example, [3, 4]) that incoherent emission of photons by the spin system does not disturb the equilibrium between the radiation field and the thermostat (the resonator walls). However, when the rate of energy exchange between the spins and the photons exceeds the rate of energy exchange between photons and the thermostat (resonator walls), the "bottleneck" in the energy flow between the spins and the thermostat is the channel between the photons and the thermostat. If the photons are gathered into a separate subsystem, then the kinetic equation for the occupation numbers of the photons will be similar to the equation obtained in [2] for the photons. We write down a system of kinetic equations describing the behavior of the spin system and of the photons immediately after the action of the saturating pulse terminates. The kinetic equation for the average number of photons n is obtained by assuming that in the absence of spin-photon interaction n tends exponentially to its equilibrium value n_0 with a time constant τ_{ph} . For photons located in a resonator whose natural frequency ω differs from the frequency of the saturating pulse, the dependence of the energy density on the frequency is described by a Lorentz function, having a half-width at half the height $\omega/4\pi Q$, where Q is the figure of merit of the resonator. The lifetime of the photons whose frequency is sufficiently close to ω can be expressed in the form $\tau_{ph} = \omega/4\pi Q$. Assuming that the phonons are in equilibrium with the thermostat, we obtain the following system of kinetic equations

$$\begin{cases} -\frac{dx}{dt} = \frac{1}{r_{sph}} \left[(z+1) \left(x + \frac{\omega - \omega_0}{\omega_0} y \right) - 1 \right] + \frac{x-1}{r_{sl}}, \\ -\frac{dy}{dt} = \frac{1}{r_{sph}} \frac{(\omega - \omega_0)\omega_0}{\omega_L^2} \left[(z+1) \left(x + \frac{\omega - \omega_0}{\omega_0} y \right) - 1 \right] + \frac{\Delta^2 y}{\omega_L^2 r_{sl}}, \\ -\frac{dz}{dt} = \frac{\sigma_{phot}}{r_{ph}} \left[(z+1) \left(x + \frac{\omega - \omega_0}{\omega_0} y \right) - 1 \right] + \frac{z}{r_{ph}}. \end{cases} \quad (1)$$

Here $x = T/T_S$, $y = T/T_{SS}$, $z = (n - n_0)/n_0$; T_S , T_{SS} , and T are the temperature of the Zeeman, dipole-dipole subsystems and of the thermostat, respectively, ω_0 is the spin-transition frequency, and ω_L^2 is the mean square of the local field. The probability of a spin transition with induced emission of a photon of frequency ω , when the radiation field is in thermal equilibrium with the resonator walls is equal to

$$\tau_{sph}^{-1} = \frac{2\pi^2}{\hbar V} (g\beta)^2 \omega f(\omega - \omega_0) \frac{kT}{\hbar \omega_0}, \quad (2)$$

where g is the g -factor, $f(\omega - \omega_0)$ is the normalized form function of the unsaturated EPR line, and V is the resonator volume. The parameter σ_{phot} , which is the ratio of the rate of exchange of energy between the spins on the photons to the rate of exchange of energy between the photons and the thermostat, will be called the photon "bottleneck" factor

$$\sigma_{phot} = \frac{\pi N Q}{3} S(S+1) \frac{(g\beta)^2 \omega f(\omega - \omega_0)}{kT}, \quad (3)$$

where S is the effective spin of the paramagnetic ion, N is the number of paramagnetic ions per unit volume. For a crystal with $N = 10^{21}$, $S = 1/2$, $g = 2$, EPR line width $\Delta = 3 \times 10^8$ Hz, and at $\omega_0/2\pi = 10^{10}$ Hz, $T = 1.5^\circ\text{K}$, and $Q = 10^3$ we obtain the estimate $\sigma_{phot} \sim 10^2$.

Thus, the singularities observed in the behavior of the phonon subsystem ("phonon cascade") should be observed also in the behavior of the photon subsystem. If $\sigma_{phot}/\sigma_{ph} \gg 1$, where σ_{ph} is the phonon "bottleneck" factor, then the effect of the "photon cascade" prevails over the phonon emission. The ratio of the photon and phonon "bottleneck" factors can be represented in the form

$$\sigma_{phot}/\sigma_{ph} = \frac{2\pi Q}{\hbar v^2 \ell} (g\beta)^2 \omega^2 \frac{kT}{\hbar \omega_0} \tau_{sl}, \quad (4)$$

where τ_{sl} is the spin-lattice relaxation time, v the speed of sound in the crystal, and ℓ the linear dimension of the crystal. For the example given above, $\sigma_{phot}/\sigma_{ph} \sim 1.2 \times 10^3 \tau_{sl}$ ($v = 10^5$ cm/sec, $\ell = 1$ cm).

It follows from the foregoing estimates that observation of the "photon cascade" effect is feasible in principle. This effect should be sought in crystals with sufficiently long spin-lattice relaxation times ($\tau_{sl} > 10^{-2}$) and at high paramagnetic-ion concentrations ($N > 10^{20}$).

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