# Coherent phonons generated by stimulated emission in ruby

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## *Experiments*

Coherent phonons are generated by stimulated emission over the one-phonon transition connecting a population-inverted two-level system in dilute ruby (500 at.ppm $Cr^{3+}$ in $Al_2O_3$) [1]. Figure 1 shows the relevant part of the Zeeman-split level diagram of $Cr^{3+}$. The two-level system chosen is the $\bar{E}(^2E)$ Kramers doublet at an optical distance of 14430 $cm^{-1}$ above the $^4A_2$ ground multiplet, and the initial inversion is achieved by direct transient optical pumping. The doublet levels are separated to a distance of 1.68 $cm^{-1}$ by a magnetic field of 3.48 T at an angle of 65° from the $c$ axis. The subsequent stimulated emission invokes an enhanced decay over the one-phonon transition, which is accessible to measurement via suitable Zeeman components of the luminescence to the ground multiplet. At the highest initial inversions attained, decay times of order 0.2 μs are observed. By comparison, the spin-lattice relaxation time at the prevailing temperature of 1.4 K amounts to $T_1$ = 0.67 ms, so that phonon occupations in excess of $10^3$ are reached.

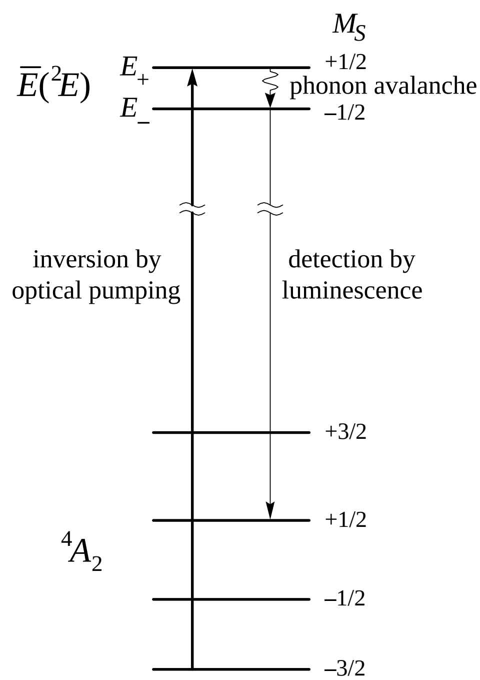


Figure 1. Level diagram.

## *Bloch equations vs rate equations*

The coherence of the generated phonons is established by comparing the experimental results for a series of initial upper-level populations with the theoretical predictions from (*a*) rate equations and (*b*) Bloch equations [1]:

(*a*) Rate equations are the traditional, yet inherently *incoherent*, treatment of nonequilibrium phonons in dynamic equilibrium with a "spin" system. In the present case, they govern the populations of the $\bar{E}(^2E)$ doublet levels on the one hand and the occupations of the resonant phonon modes on the other. However, rate equations, even with reasonable extensions, proved unable to provide a physically acceptable description of the experimental results.

(*b*) To arrive at a *coherent* description, we derived a set of Bloch equations, *i.e.*, a set of first-order differential equations for the motion of the spin Bloch vector and the acoustic waves. The starting point is a Hamiltonian in which the acoustic waves couple with the *transverse* components of the Bloch vector. The Bloch description turns out to be far superior and to excellently account for the experiments. Note that this finding has implications for the way phonon-bottleneck situations have traditionally been handled.

## *References*

[1] L. G. Tilstra, A. F. M. Arts, H. W. de Wijn, Phys. Rev. B **68**, 144302 (2003).