Multi-photon superradiance from a nuclear ensemble

Understanding the response of large collections of atoms to external stimuli, based on the response of a single atom, is one of the interesting and fundamental problems in physics. One class of such problems is the decay of two-level atoms. An early, and now famous, treatment of this was Dicke's theory of superradiance [1]. He showed that the decay time of a collection of two-level atoms was strongly affected both by the number of atoms and the number of photons in the system. Specifically, for the case when all the atoms are very close to each-other, he showed that a system of n_a atoms or nuclei of which n_γ are excited, decays at an enhanced rate given by

$$\frac{I}{I_0} = n_\gamma n_a \left(1 - \frac{n_\gamma - 1}{n_a}\right) \approx n_\gamma n_a$$

where I/I_0 is the rate relative to the decay rate, I_0, of single atom or nucleus in isolation, and the approximate equality holds for small numbers of photons, $n_\gamma \ll n_a$. More generally [1] the response to pulse excitation of a (slightly) extended collection of oscillators behaved similarly, with $I/I_0 \approx n_\gamma n_a$ (again $n_\gamma \ll n_a$) with, now, n_a replaced by a geometric factor that scales as a phased sum over atom positions. In both cases, the enhanced decay rate relative to the single photon case for the system, I_1, by a factor

$$\frac{I}{I_1} = n_\gamma \left(1 - \frac{n_\gamma - 1}{n_a}\right) \approx n_\gamma$$

This enhanced decay rate, relative to the one-photon response, is what we investigated.

Nuclear resonant scattering of synchrotron radiation [2] offers a body of techniques that can be used to investigate the change in lifetime of a collection of oscillators. Indeed, it has been well demonstrated that the time response of a collection of nuclei after single photon excitation is rather different than that of isolated nuclear decay, with, in many cases a faster response, often called “speed-up”, that is found to be in excellent agreement with calculations. But the dependence on the number of photons, n_γ in the system, has not been investigated. Here, unfortunately, synchrotron based experiments are not much help, as the number of photons per pulse in the nuclear resonance bandwidth is only extremely rarely larger than 1.

The SACLA Free Electron Laser provides pulses with enough intensity so that one can begin to investigate the nuclear multi-photon response, at least for small numbers (<100) of photons/pulse. In particular, we performed the first nuclear scattering experiment at a Free Electron Laser beamline SACLA **BL3** to investigate the multi-photon aspect of the response [3]. The setup, Fig. 1, used the pure nuclear (111) reflection in a highly enriched perfect crystal of iron borate, $^{57}FeBO_3$, to select only the nuclear scattered radiation from the beam. A typical scope trace of one of the stack of 4 APD detectors, showing 18 photons detected after a single pulse is given in

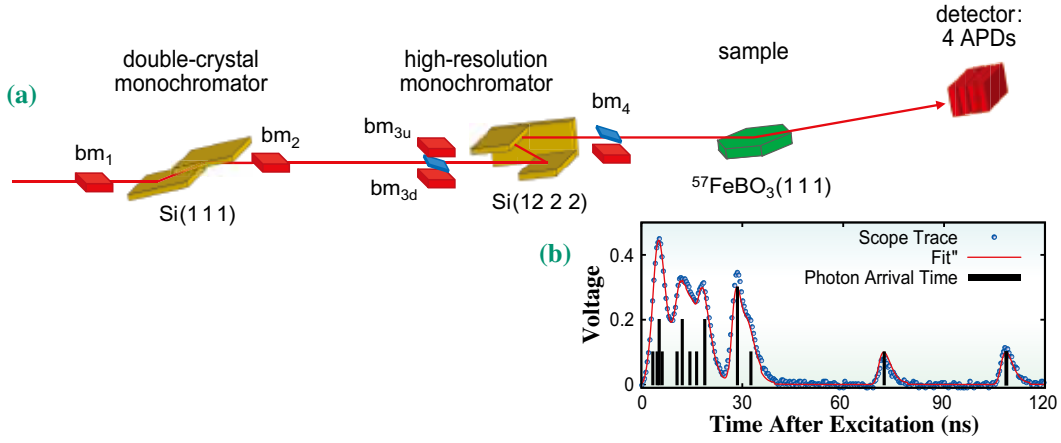

Fig. 1. **(a)** Experimental setup showing optical components, the sample, and beam intensity monitors (bm) and **(b)** scope trace of the response of the first diode after a pulse.

Fig. 1, confirming the multi-photon response. Figure 2 then shows an enhanced decay rate for the first photon observed as the number of detected photons increase, with the rate plotted in detail in the lower panel. One finds reasonably good agreement with the linear dependence expected from [1].

It turns out that the enhanced decay rate with increasing photon number is well explained by a statistical model, something that is not obvious from Dicke's treatment. Very simply, if one considers the probability distribution for the emission of a photon after the pulse to be given, in a small photon number limit, by $f(t)$, and then one considers a large number of photons placed into that distribution, then rather naturally, the time to the first photon is reduced, so the observed initial decay rate is enhanced. This is easy to see, either from Monte-Carlo simulations, or the analytic approach of [3]. Notably, the decay of the entire energy in the system keeps the shape of the single photon response, $f(t)$, (Fig. 3) so, when the number of photons in the system is not too large ($n_\gamma \ll n_a$), the time response, in the sense of the decay of the total energy in the system, not just the time to the first photon, still can be calculated using the usual formalism for nuclear scattering. This then also opens the door to single-shot hyperfine spectroscopy [3].

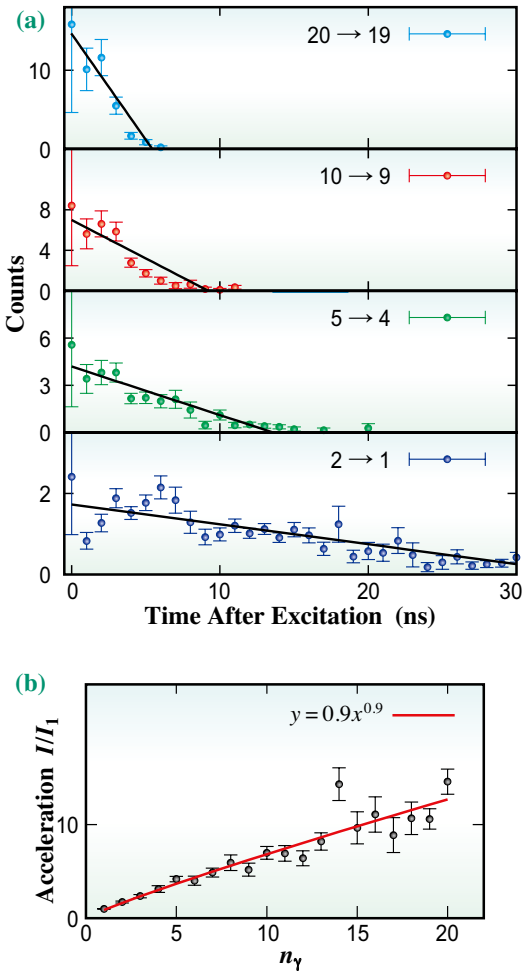

Fig. 2. **(a)** I/I_1 for different numbers of total detected photons. **(b)** Decay rate *versus* photon number.

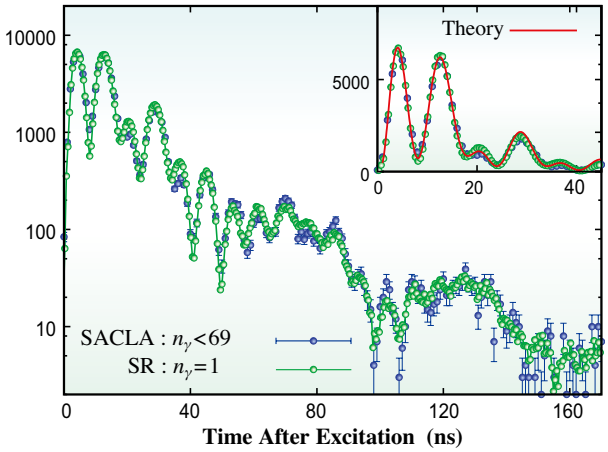

Fig. 3. Comparison of the time response for a multi-photon excitation at SACLA and the single photon excitation at a storage ring. The inset shows both data sets and a theory curve.

Alfred Q. R. Baron[a,*] and Aleksandr I. Chumakov[b]

[a] RIKEN SPring-8 Center
[b] European Synchrotron Radiation Facility (ESRF), France

*Email: Baron@spring8.or.jp

References

[1] R.H. Dicke: Phys. Rev. **93** (1954) 99.
[2] E. Gerdau and H. de Waard: Hyperfine Interact. **123-125** (2000).
[3] *A.I. Chumakov, A.Q.R. Baron, I. Sergueev, C. Strohm, O. Leupold, Y. Shvyd'ko, G.V. Smirnov, R. Rüffer, Y. Inubushi, M. Yabashi, K. Tono, T. Kudo and T. Ishikawa: Nat. Phys.* ***14*** *(2017) 261.*