Manipulation of Nuclear $\gamma$-Ray Superradiance

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Superradiance [1], i.e., collective spontaneous emission from an ensemble of atoms or nuclei is interesting both for fundamental reasons, and for potential applications. Telltale signs of superradiance are a speedup of emission compared to the natural excited-state lifetime and, in the case of a sample larger than the wavelength, directional emission. Speedup is due to the multitude of potential absorption-emission pathways through multiple atoms/nuclei in the ensemble, and occurs even in the case of a single-photon excitation. Directionality is due to “storage” of the phase of the incident wave at the location of each potentially excited atom, so that it is present at re-emission [2, 3].

The present work is a proposal on how the emission direction can be changed through spatial control of the dynamic-phase evolution of the nuclei in the ensemble, as shown in Fig. 1. One possible way of doing so is to run a current pulse through a thin wire next to the sample to produce a spatially inhomogeneous, transient magnetic field lasting much less than the excited-state lifetime. Through hyperfine energy-level shifts, this leads to spatially inhomogeneous dynamic-phase evolution in the potentially excited nuclei. This differential dynamic-phase evolution happens only during the presence of the magnetic field - thereafter the phases stored in the ensemble are reset to new values given by the time integral of the magnetic field. With $^{57}$Fe as the resonant nucleus, magnetic fields of the order of 10 Tesla lasting for 10 ns, and field gradients of the order of 1 Tesla per micron would be required for directional changes of 100 $\mu$radians. This angular separation is sufficient for further separation with crystal x-ray optics. These high magnetic fields may seem outlandish at first, but they are well within the realm of the possible. For example, fields of 50 Tesla for about 30 ns within a micron-sized volume have been demonstrated using a microcoil and kA currents switched by a laser-triggered spark gap [4].

For a clean re-direction of the emission, a spatially linearly variable magnetic field would be required. This is not provided by a simple wire, but can be achieved with the help of multiple wires in a three-dimensional assembly. Other emission patterns can be programmed as well, such as emission towards a focus. Especially in conjunction with magnetically switched optical thickness (the “spectral scooper”, [5]), this idea can be applied to solve the prompt-pulse problem of time-domain nuclear-resonance spectroscopy where detectors tend to get blinded by the huge out-of-resonance part of the excitation pulse: the re-directed resonant pulse is not unnecessarily intense and makes detectors see the early times of the resonant decay.

![Figure 1: A micron-sized wire carrying a 10-ns, kA current pulse produces a magnetic field that drops off in the transverse direction (left). This leads to a differential dynamic-phase evolution and re-direction of any subsequent emission (center). An application would be a clean separation of on-resonant from off-resonant radiation in time-domain nuclear-resonance spectroscopy.](image)

References