Quantum control of nuclei with coherent x-ray light

Adriana Pálffy, Wen-Te Liao, Jörg Evers and Christoph H. Keitel

Max Planck Institute for Nuclear Physics, Heidelberg, Germany
email: palffy@mpi-hd.mpg.de

Coherent control of nuclear excitations would be a powerful tool for preparation and detection in nuclear physics, especially for the release of energy stored in long-lived nuclear excited states. In atomic quantum optics, visible lasers made a number of schemes to control matter via coherent light possible, such as laser cooling, optical pumping and stimulated Raman adiabatic passage (STIRAP). Unfortunately, in nuclei the energies of the excited levels can reach tens of MeV and the interaction rates of nuclei with the electromagnetic field are much smaller than the ones of atoms. Coherent control of nuclei is therefore expected to be less efficient than in the case of visible coherent light and require x-ray lasers with high intensities.

Nuclear quantum optics

To bridge the gap between photon and nuclear transition energies, often above the energy limits of present x-ray coherent sources, a key proposal is the use of accelerated target nuclei [1]. Using this scenario, the direct interaction of a x-ray free electron laser (XFEL) with a simple two-level nuclear system is investigated. Unlike in atomic quantum optics, for nuclei also nuclear transitions of higher multipolarity can be driven by super-intense lasers, providing a variety of suitable nuclear transitions for coherent schemes apart of the few available $E1$ transitions [2].

Nuclear STIRAP

Inspired by atomic quantum optics techniques, we investigate the possibility of coherent nuclear population transfer between two ground states in the Λ-level scheme showed in Figure 1(a) using two overlapping coherent x-ray light beams in a STIRAP setup [3]. The main question is under which conditions and parameters is control of nuclear states possible. We show that a truly coherent XFEL such as the future XFEL-Oscillator (XFEL-O) [4] or seeded XFEL [5] to provide both probe and Stokes laser fields, together with acceleration of the target nuclei to achieve the resonance condition, allow for significant coherent nuclear population transfer at intensities few orders of magnitude larger than the present designed values. Unlike in nuclear forward scattering (NFS) where spatial coherence is required, the most important prerequisite for nuclear STIRAP is the *temporal* coherence of the x-ray laser.

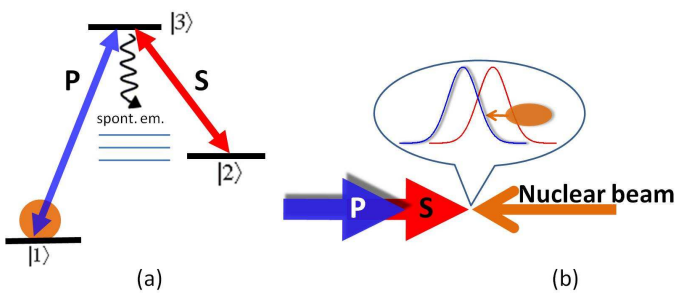

Figure 1: (a) The nuclear Λ scheme. The initial nuclear population is concentrated in state $|1\rangle$. The pump laser P drives the transition $|1\rangle \rightarrow |3\rangle$, and the Stokes laser S drives the transition $|2\rangle \rightarrow |3\rangle$. The upper state $|3\rangle$ decays also to other states through spontaneous emission, and the direct transition $|1\rangle \rightarrow |2\rangle$ does not occur. (b) Two partially overlapping and copropagating x-ray laser pulses P (pump) and S (Stokes) interact with relativistically accelerated nuclei. The Doppler effect ensures that both nuclear transitions are in one-photon resonance with the laser pulses.

Coherent control of cooperative branching ratio

While nuclear STIRAP requires further upgrades of XFEL facilities partially still under construction, a different aspect of coherent control has been already achieved more than a decade ago in NFS of x-ray light. The coherent cooperative decay of nuclei excited by x-ray light (in this case monochromatized synchrotron radiation) in NFS can be switched on and off by changing the direction of the hyperfine field in a magnetic sample [6]. We show that using this switching technique, one can steer the nuclear x-ray pumping and nuclear dynamics in NFS involving a nuclear Λ three-level system in which only one of the transitions is driven by x-ray radiation. In single nuclei, the final state populations and the pumping performance would be governed by the constant branching ratio of the excited state populated by the x-ray pulse. However, in ensembles of nuclei, cooperative excitation and decay leads to a greatly modified nuclear dynamics, which we characterize by a time-dependent cooperative branching ratio [7]. Coherent control of the cooperative decay renders the steering of the cooperative branching ratio possible. For realistic NFS parameters, we find that the control efficiency is limited not by the intensity of light (as in the case of nuclear STIRAP) but rather by the short time range of the coherent decay, i.e. by the nuclear exciton properties.

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