Dominant secondary nuclear photoexcitation with the XFEL

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Photon energies accessible with the new x-ray free-electron laser (XFEL) facilities open the way for the resonant driving of nuclear transitions. In particular, the high brilliance and coherence features of the XFEL light promise an increase in nuclear excitations in comparison to synchrotron radiation experiments. While in the latter experiments the electronic response only acted as background, the unique interaction between high-intensity XFEL pulses and matter can lead to new states, like cold, high-density plasmas [1] where secondary nuclear processes from the coupling to the atomic shell are rendered possible. In this work we show on the example of ^{93m}Mo isomer triggering that secondary nuclear excitation by electron capture (NEEC) can even dominate the direct resonant photoexcitation.

The idea of isomer triggering is to connect the metastable isomeric state to an above-lying level in order to release the stored excitation energy on demand [2]. The 6.85 h long-lived ^{93m}Mo isomer is particularly attractive for an XFEL-induced activation, since the 2.5 MeV excitation energy can be retrieved by a 4.85 keV triggering transition accessible by todays XFELs. In the subsequent decay cascade an outstandingly high energetic photon of 1 MeV can be used as distinct signature for the nuclear excitation. Moreover, in $^{93}_{41}$Nb(p,n)$^{93m}_{42}$Mo reactions, the isomers can be produced directly embedded into 1 μm thick niobium foils, providing high-density targets. Using, for instance, the LINAC proton beam at GSI a density of 10^{16} isomers/cm^3 can be achieved.

The direct light-nucleus coupling between the XFEL radiation and the Nb target foils can be described by the density matrix formalism using the semiclassical approach. Although the XFEL pulse is tuned on the 4.85 keV triggering transition, only a small fraction of the laser photons fulfill the nuclear resonance condition due to the large discrepancy between the laser width $\Gamma_{\rm XFEL}$ ($\sim$10 eV) and the nuclear transition width $\Gamma_{\rm n}$ ($\sim 10^{-7}$ eV). Taking this effective intensity reduction into account and considering laser parameters for the LCLS at SLAC a signal rate of 5.6×10^{-14} photons/s is obtained [3]. A further analysis shows that the nuclear photoexcitation is strongly suppressed by the poor temporal coherence of current XFEL facilities.

The nuclear excitation induced directly by the laser should be compared to its secondary electronic-processes-induced counterpart. The XFEL-induced plasma formation is governed by inner-shell photoionization and subsequent refilling by either radiative or Auger decay. Due to the fast and uniform heating process the plasma stays almost at solid-state density. After the irradiation of the sample, radiative and collisional processes lead to a fast thermalization among the electrons. In our scenario, we estimate an electron temperature T_e and density of 350 eV and 1.3×10^{24} cm^{-3}, respectively, and consider the plasma conditions to hold for 100 ps.

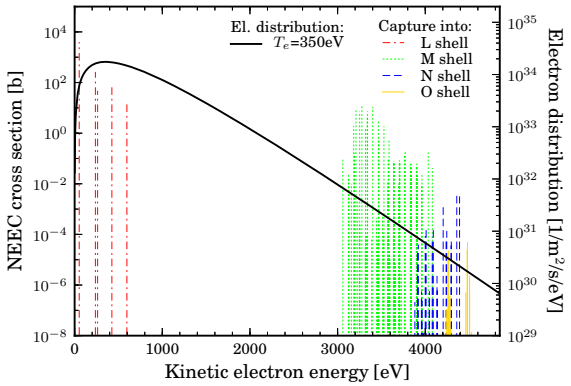

Figure 1: NEEC resonance cross sections (left axis) together with the electronic energy distribution (right axis).

In this environment, NEEC takes place on a longer time scale compared to the laser pulse duration. The total NEEC rate in the plasma relies on the available charge states and electron energies. As shown in Fig. 1, NEEC prefers the capture into deep vacancies. At T_e=350 eV, the L shell seems to provide the pivotal NEEC channels. However, the available charge states are limited to q=18+...30+ prohibiting the capture into the L shell. Nevertheless, a summation over all open resonance channels results in a NEEC-induced signal rate of 1.7×10^{-7} photons/s which is 6 orders of magnitude higher than the direct process [3]. Additionally, NEEC represents the more robust mechanism since it is less sensitive to the match between the photon frequency and the nuclear resonance condition.

References

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