Molecular Imaging and Plasma Formation

Robin Santra

Center for Free-Electron Laser Science, DESY, 22607 Hamburg, Germany
and
Department of Physics, Universität Hamburg, 20355 Hamburg, Germany

One of the key opportunities offered by the development of x-ray free-electron lasers is the determination, at atomic resolution, of the three-dimensional structure of biologically relevant macromolecules [1]. The basic idea underlying molecular imaging using x-ray free-electron lasers is the "diffract-and-destroy" concept: Since at a photon energy of 10 keV or so (corresponding to a potential spatial resolution near 1 Å), the x-ray absorption cross section per carbon atom is higher by an order of magnitude than the x-ray elastic scattering cross section, radiation damage is unavoidable in x-ray diffractive imaging. However, if one uses an x-ray pulse that is sufficiently short, then in a single shot an x-ray scattering pattern may be obtained that is practically unaffected by atomic displacements triggered by ionization events during the x-ray pulse. What cannot be eliminated in this way is the impact of the *electronic* damage on the x-ray scattering patterns. The diffract-and-destroy method goes hand in hand with the formation of a nanoplasma within just a few femtoseconds.

Theory, therefore, plays an important role in the development of this new imaging technique: A quantitative understanding is required of the damage processes occurring during the exposure of a molecule to an ultraintense, ultrafast x-ray pulse. In this talk, I will present progress we have made in order to address this challenge. One tool we have developed, XMDYN [2], is a molecular-dynamics code that utilizes *ab-initio* atomic electronic-structure information, computed on the fly, within a Monte-Carlo framework. XMDYN has been successfully tested through experiments at LCLS [3] and SACLA [4]. XMDYN is part of a powerful start-to-end simulation framework for single-particle imaging at the European XFEL [5, 6].

Recently, we have taken first steps towards a full ab-initio framework for simulating high-intensity x-ray–matter interactions [7, 8]. Our new XMOLECULE software solves the polyatomic quantum-mechanical electronic-structure problem for every electronic state arising during the exposure of a molecule to a strong x-ray pulse. From this information, electronic transition rates (such as Auger decay rates) are computed on the fly, and the associated rate equations are integrated utilizing a Monte-Carlo method. XMOLECULE played a key role in a recent LCLS experiment on iodomethane, in which hard x-rays focused to a peak intensity exceeding 10^{19} W/cm^2 produced the highest charge states ever formed using light [9]. Not only did XMOLECULE correctly predict the charge-state distribution observed, but it also helped identify a new molecular ionization enhancement mechanism based on intramolecular charge transfer.

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