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Nuclear Instruments and Methods in Physics Research B 235 (2005) 408–413

NIM B
Beam Interactions with Materials & Atoms

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Physical parameter dependence of the X-ray generation in intense laser–cluster interaction

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Abstract

Studies on laser–cluster interaction performed on the LUCA facility (French acronym for Ultra Short Tunable Laser, CEA Saclay) allow to observe the production of hard X-rays in the 1–5 keV range when rare gas clusters of nanometer sizes are heated by strong optical fields ($F > 10^9$ V/cm). First complete quantitative measurements of absolute photon emission yields, as well as of charge state distributions of ionic species with inner shell vacancies have been performed as a function of several physical parameters governing the interaction. Our measurements give rise to fundamental results like an optimum heating time and an intensity threshold in the X-ray production. These data provide direct insight into the interaction dynamics and into the heating processes involved.

PACS: 36.40.−c; 52.50.Jm; 34.80.Kw; 52.70.La

Keywords: X-rays; Laser; Ionization; Clusters; Argon; Xenon

1. Introduction

The interaction of high intensity ultra short laser pulses with matter has received considerable attention in the last few years since the appearance of the CPA (Chirp Pulse Amplification) technique. The matter behavior under such extreme conditions has opened new fields of investigation with, for instance, the generation of high order harmonics, the acceleration of heavy particles, or the development of bright X-ray sources. The possibility to generate intense and short hard X-ray pulses with clusters or solids as target is a particular subject of interest for potential applications. The optimization of such sources demands however knowledge of mechanisms involved during laser–matter interaction, what can be reached through specific studies dedicated to fundamental aspects.

The use of atomic nanometer clusters gives several advantages. Clusters constitute renewable

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doi:10.1016/j.nimb.2005.03.215

targets free of debris, contrary to solid targets. The energy coupling between radiation and clusters is very efficient due, in particular, to their local density close to the solid one ($\sim 10^{22}$ cm^{-3}). Their size much lower than the laser wavelength and slightly below the skin depth allows to assume that the electric field inside the cluster is uniform. Moreover, they offer the opportunity of observing well separated nanoplasmas: usually the mean atomic density does not exceed 10^{17} cm^{-3} leading to inter-cluster distances larger than 1 μm. Therefore, they form simple systems for the study of laser–matter interaction experimentally and theoretically.

Early studies have shown that clusters under strong laser fields ($F > 10^9$ V/cm) generate multicharged ions reaching MeV [1], hot electrons up to few keV [2] and keV X-ray photons [3,4]. Different theories have been developed to explain the experimental features observed in the high laser intensity regime [5–7]. These first results boost the field and numerous kind of investigations have been made; a recent review is presented in [8]. The mechanisms responsible for the laser energy absorption are still not completely understood and give rise to controversy. Special attention has been paid to the nanoplasma model proposed by Ditmire et al. [5], which offers a complete scenario of the interaction, taking into account ionization, heating (through inverse Bremstrahllung and laser electric field) and explosion processes simultaneously. As an example, new theoretical implementation has been recently proposed by Megi et al. [9] showing the importance of electrons–surface collisions in the heating process and so far neglected. On another side, recent experimental results [10–12] on ion and/or electron angular distributions show, besides a disagreement with previous measurements [1], an anisotropy of the emission, which is not account for within the nanoplasma model [5]. All of these studies related to ion or electron emission are connected to both the dynamics of the induced plasma and the cluster explosion.

So far, most of the studies on X-ray emission have been mainly limited to qualitative observations. Very few systematic measurements with the parameters influencing the X-ray production have been realized. Moreover, simulations are still needed to explain the production of ions *with inner shell vacancies* responsible for the strong hard X-ray generation. Thus, our goal is to understand how electrons initially produced by Optical Field Ionization with a few eV can reach enough energy (up to a few keV) to generate inner shell ionization through inelastic electron–ion collisions. KeV X-rays are studied from rare-gas clusters ($(\mathrm{Ar})_n$, $(\mathrm{Kr})_n$ and $(\mathrm{Xe})_n$ clusters with n between 10^3 and 10^6 atoms/cluster) irradiated with intense ($I \sim 10^{14}$–10^{17} W/cm^2) infrared and blue laser pulses. Variation of the pulse duration in the 50–2000 fs range was available for infrared light. The observed X-rays are emitted by highly charged ions: for example, from Ar^{12+} to Ar^{16+} with K vacancies [13,14] in the case of Ar clusters and Xe^{q+} ($q \geqslant 24$) with L vacancies in the case of xenon [15]. Since the lifetime of excited levels produced is rather short for highly charged ions (down to 15 fs in the case of $\mathrm{Ar}^{16+}(^1P_1)$), the emitted X-rays allow to probe the heating mechanisms on a very short time scale (some fs). We have performed quantitative studies on the evolution of absolute photon emission yields and complete charge state distributions with different physical parameters governing the interaction; namely intensity, polarization, pulse duration and wavelength of the laser, size and density of the clusters. These studies, made under well-controlled conditions, allow to determine the sensitivity of the X-ray production upon these physical parameters and, consequently, to find conditions for optimization. They give rise, as well, to fundamental results, which will provide information on the dynamics of the interaction and on the heating processes involved. Scaling laws with the laser intensity and the cluster size have already been presented in [13,14]. With Xe clusters, we have also shown [15] that the X-ray yield does not follow a λ^{-6} law as stated in [16]. Furthermore, we have demonstrated that the charge state distribution of Xe ions strongly depends on the laser wavelength [15], while no difference has been observed for Ar clusters. In this paper, the work presented emphasizes our results on the laser intensity dependence showing evidence of a threshold in the X-ray production. In addition, we discuss the