LETTERS

PACS numbers: 42.55.Vc; 52.38.Ph; 36.40.Gk
DOI: 10.1070/QE2012v042n11ABEH015030

Generation of iodine L-shell X-rays under excitation of large CF_3I clusters by femtosecond laser radiation

V.M. Gordienko, M.S. Dzhidzhoev, I.A. Zhvaniya, A.V. Pribytkov, D.N. Trubnikov, D.O. Fedorov

Abstract. **The use of clusters of polyatomic molecules with a relatively low ionisation energy (~10 eV) is proposed for the efficient production of X-ray radiation. We have observed for the first time the generation of characteristic X-ray radiation due to L transitions in iodine atoms under the high-intensity femtosecond laser irradiation of molecular CF_3I clusters, which were a small admixture to Ar carrier gas. The X-ray conversion efficiency amounts to ~10^{-6} (for a yield of ~10^7 photons per pulse), which is an order of magnitude higher than the efficiency we obtained in the case of argon clusters under comparable conditions.**

Keywords: *femtosecond laser, molecular clusters, characteristic X-ray radiation.*

1. Introduction

In recent years, the generation of hard (above 2 keV) characteristic X-ray radiation arising from the interaction of high-intensity ($I > 10^{15}$ W cm^{-2}) femtosecond laser radiation with cluster targets has been the subject of vigorous investigations [1, 2]. The characteristic X-ray radiation of cluster nanoplasmas in the 2–4-keV range may be used in radiography [3], because the radiation of cluster nanoplasmas has a higher contrast in comparison with the X-ray radiation of high-temperature plasmas of solid-state targets. The X-ray radiation yield increases with increasing intensity and contrast of laser radiation as well as with increasing cluster size [4].

One method of producing large clusters for the efficient production of characteristic X-ray radiation involves the use of a mixture consisting of a clustering molecular gas (CO_2 [5], SF_6 [6]) and an atomic, relatively light carrier gas with a higher density. In this case, owing to the high heat capacity of the polyatomic molecules, which is due to the large number of their low-lying vibrational–rotational levels and their high heat of condensation, the use of carrier-gas atoms permits realising efficient thermalisation of the molecules, thereby fostering their higher-efficiency clusterisation. It is evident that the X-ray conversion efficiency also depends strongly on the electron density resulting from the initial ionisation of clusters by laser radiation. One would therefore expect that the electron nanoplasma density for the clusters of polyatomic molecules with a relatively low ionisation energy will be significantly higher than for atomic clusters of similar size usually used in experiments. Therefore, when the intensity at the leading edge of a laser pulse reaches the threshold intensity for the first ionisation potential, an elementary molecular cell defined by the Wigner–Seitz radius will contain significantly more electrons than an atomic one. The generation of characteristic X-ray radiation in the energy range above 2 keV induced by the interaction of femtosecond laser radiation with large molecular clusters has heretofore been studied only by the example of the processes involving K transitions in sulphur atoms (SF_6 clusters [6]).

In the present work we report the first-ever production of characteristic iodine L-shell X-rays generated under excitation of large CF_3I clusters by femtosecond laser radiation with an intensity $I \leqslant 10^{16}$ W cm^{-2}. The choice of the CF_3I molecular gas is underlain by the relatively low ionisation potential (~10 eV) of these molecules and the circumstance that the energy of the characteristic X-ray lines is near 4 keV (4 keV for the L_α line and 4.2 keV for the L_β line). The characteristic K line of argon corresponds to an energy of ~3 keV. That is why the X-ray yield data in the interaction of laser radiation with Argon clusters are conveniently used as reference data in the execution of comparison experiments. The authors of Ref. [7] observed the clustering of CF_3I molecules mixed with Ar in the 1:15 ratio for a total stagnation pressure of ~0.5 atm of a pulsed gas valve. Large molecular clusters would be expected to emerge in the higher-pressure gas mixture of this composition in the gas-dynamic expansion into vacuum. And this will also favour the efficient production of characteristic X-ray radiation.

In our experiments we used Ti:sapphire laser radiation [$\lambda \approx 810$ nm, $\tau_{min} = 60$ fs, $W \sim 5$ mJ, nanosecond energy contrast ratio ~10^6, 1-cm beam diameter), which was focused with a lens with a focal length $f = 20$ cm into a gas-cluster jet at a distance of 2 mm from the nozzle exit section. X-ray spectra were detected using an Amptek silicon pin diode with an energy resolution of ~200 eV. An X-ray photomultiplier tube was employed to measure the integral yield of X-ray photons with energies higher than 2 keV. The clusters were produced in the supersonic gas expansion through a conical nozzle in vacuum. The facility was described at length in Ref. [6]. The

V.M. Gordienko, M.S. Dzhidzhoev, I.A. Zhvaniya, D.O. Fedorov Department of Physics, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119991 Moscow, Russia; International Laser Centre, M. V. Lomonosov Moscow State University, Vorob'evy gory, 119991 Moscow, Russia; e-mail: gord@phys.msu.ru, djidjoevms@mail.ru, zhvania@mail.ru;
A.V. Pribytkov, D.N. Trubnikov. Department of Chemistry, M.V. Lomonosov Moscow State University, Vorob'evy gory, 119991 Moscow, Russia; International Laser Centre, M. V. Lomonosov Moscow State University, Vorob'evy gory, 119991 Moscow, Russia; e-mail: andkras@gmail.com, tdn@phys.chem.msu.ru

Received 23 October 2012
Kvantovaya Elektronika **42** (11) 957–958 (2012)
Translated by E.N. Ragozin

clusterisation of the gas was controlled by the Rayleigh scattering of the second harmonic of Q-switched Nd:YAG laser radiation.

Figure 1 shows the intensity of Rayleigh scattering as a function of stagnation gas pressure in the pulsed valve. These dependences are approximated by power functions with exponents equal to 3.2 (for the CF_3I–Ar mixture) and 3 (for Ar), which testifies to efficient clustering [8]. However, the intensity of Rayleigh scattering by CF_3I clusters in the CF_3I–Ar mixture is much stronger than the corresponding intensity in pure argon. Since the intensity of Rayleigh scattering rises with increasing cluster size and density, and since the density of substance being clustered in mixtures is approximately one order of magnitude lower than in argon, the resultant molecular clusters, as expected, are bigger than the argon ones. Estimates made by Hagena formula [8] suggest that the size of the argon clusters is ~30 nm for comparable pressures. We found that the highest X-ray yield both for CF_3I and Ar clusters was achieved for a positively chirped laser pulse of about 300 fs focused at the front edge of the gas-cluster jet. To the laser radiation with a pulse duration of 300 fs there corresponded a radiation intensity of 2×10^{15} W cm^{-2} in a vacuum.

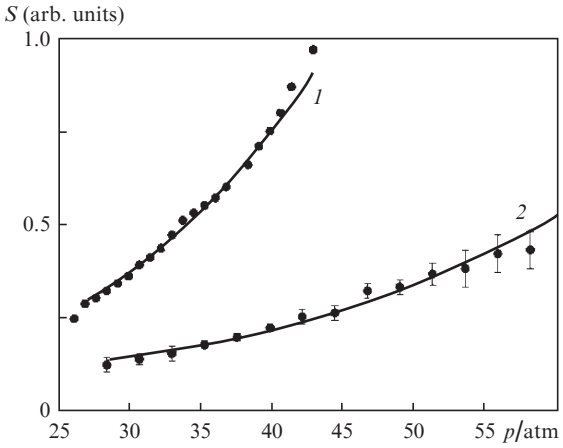

Figure 1. Intensity S of Rayleigh scattering in CF_3I–Ar (*1*) and Ar (*2*) cluster-gas jets as a function of stagnation gas pressure p in the valve. The curves are approximated by power laws.

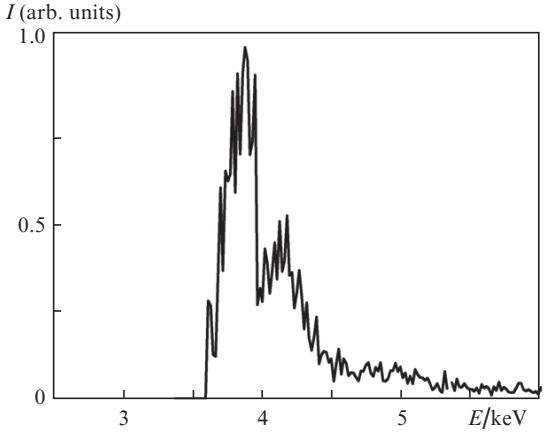

Figure 2. X-ray spectrum for CF_3I clusters.

Figure 2 shows the X-ray spectrum of CF_3I cluster emission. Low-energy spectral components were suppressed by 100-μm thick beryllium and 22-μm thick aluminium filter sets as well as by an air layer (8 cm). An approximation of the high-energy bremsstrahlung component with an exponential dependence permits the average electron energy in the cluster nanoplasma to be roughly estimated at ~1.2 keV. The contrast ratio (the ratio between the number of photons at the peak of the characteristic X-ray spectrum and the number of bremsstrahlung photons in this spectral range) is equal to ~10. The X-ray conversion efficiency amounts to ~10^{-6} (for a yield of ~10^7 photons per pulse), which is an order of magnitude higher than the efficiency we obtained in the case of argon clusters.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant Nos 11-02-00585 and 11-02-12197) and by the Ministry of Education and Science of the Russian Federation (Grant No. 8393).

References

1. Krainov V.P., Smirnov B.M., Smirnov M.B. *Usp. Fiz. Nauk*, **177**, 953 (2007) [*Phys. Usp.*, **50**, 907 (2007)].
2. Hayashi Y., Pirozhkov A.S., Kando M. *Opt. Lett.*, **36** (9), 1614 (2011).
3. Chen L.M., Kando M., Kotaki J.M., et al. *Appl. Phys. Lett.*, **90** (21), 211501 (2007).
4. Dorchies F., Caillaud T., Blasco F., et al. *Phys. Rev. E*, **71**, 066410 (2005).
5. Faenov A.Y., Fukuda Y., Pikuz T.A., et al. *J. Korean Phys. Soc.*, **56** (1), 279 (2010).
6. Gordienko V.M., Dzhidzhoev M.S., Zhvaniya I.A., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **91** (7), 355 (2010).
7. Apatin V.M., Kompanets V.O., Lokhman V.N., et al. *Pis'ma Zh. Eksp. Teor. Fiz.*, **94** (7), 610 (2011).
8. Ditmire T., Donnelly T., Rubenchik A.M., et al. *Phys. Rev. A*, **53** (5), 3379 (1996).