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X-Ray Emission from Multi-Inner-Shell Excited States Produced by High-Intensity Short-Pulse X-Rays

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Abstract—We study the double inner-shell ionization produced by high-intensity short-pulse X-rays and the X-ray emission from doubly inner-shell excited states of Mg ($1s^22s^22p^43s^2$) and Xe ($1s^22s^22p^63s^23p^64s^24p^64d^85s^25p^6$). The intensity and pulse width dependence on the X-ray emission is studied.

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1. INTRODUCTION

Theoretical studies have predicted that high-intensity lasers make possible high-intensity short-pulse X-ray pulses with shorter wavelengths, such as via Larmor radiation [1–3] or radiation damping [4]. These X-rays may have many applications to the measurement of ultrafast processes in material and biological science [5–7] and as excitation sources for inner-shell ionization lasers [8–12]. In our previous paper [13, 14], we proposed the measurement of intensities and pulses of short-pulse X-ray sources through multi-X-ray absorption processes, that is, X-ray nonlinear optical processes. We found that the necessary atomic data for these measurements are mainly the threshold energies of inner-shell ionization (ΔE_{IES}) and double-inner-shell ionization (ΔE_{DIES}), photoionized cross sections, and the lifetime of inner-shell excited states, where ΔE_{IES} and ΔE_{DIES} are shown in [14, Fig. 1]. For the measurements, one needs to find a suitable target for the X-rays. Therefore, in this paper, we calculate the X-ray emission from the double inner-shell excited states (DIS) of $2p$ electrons of Mg ($1s^22s^22p^43s^2$) and $4d$ electrons of Xe ($1s^22s^22p^63s^23p^64s^24p^64d^85s^25p^6$) for various intensities and pulse widths of X-rays.

The table lists ΔE_{IES}, ΔE_{DIES}, the radiative transition probability (Ar), and autoionization rate (Aa) of the inner-shell excited state for the $2p$ electrons of Mg ($1s^22s^22p^53s^2$) and $4d$ electrons of Xe ($1s^22s^22p^63s^23p^64s^24p^64d^95s^25p^6$). The values of Ar and Aa have been calculated by [13, Eq. (10)] and Cowan's code [15]. We should note that the lifetime of Mg is much longer than that of Xe. The calculation method and the simulation models are the same as those of [13, 14]. Here, we assume that the population of the target is 1.

2. RESULTS AND DISCUSSIONS

Figures 1a and 1b show the X-ray number emitted from the double inner-shell excited states as a function of I for Mg and Xe, respectively. The X-ray pulse widths (τ) are treated as 10, 50, 100, and 500 fs. The X-ray numbers increase almost according to I^2 except for the X-ray intensity of 10^{14} W/cm^2, where the number seems to be saturated. The number of X-rays of Mg (Fig. 1a) is much larger than that of Xe (Fig. 1b) for all intensities and pulse widths. This may come from the branching ration of Ar with all decay processes ($Ar + Aa$), including the autoionization processes. The ratios are about 0.05 for Mg and 10^{-4} for Xe, respectively. Figure 2 shows the X-ray number as a function of τ for $I = 10^{12}$ W/cm^2. For Mg and Xe, the X-ray numbers

Atomic data for ΔE_{IIES} (eV), $\Delta E_{\mathrm{DEIES}}$ (eV), radiative transition probability (Ar), and autoionization rate (Aa) of the inner-shell excited state for the $2p$ electrons of Mg ($1s^22s^22p^53s^2$) and $4d$ electrons of Xe ($1s^22s^22p^63s^23p^64s^24p^64d^95s^25p^6$). The values of Ar and Aa have been calculated by [13, Eq. (10)]

	Mg	Xe
ΔE_{IES} (eV)	62	73
ΔE_{DIES} (eV)	88	89
Ar (1/s)	3.3E+09	1.3E+10
Aa (1/s)	7.9E+10	1.60E+14

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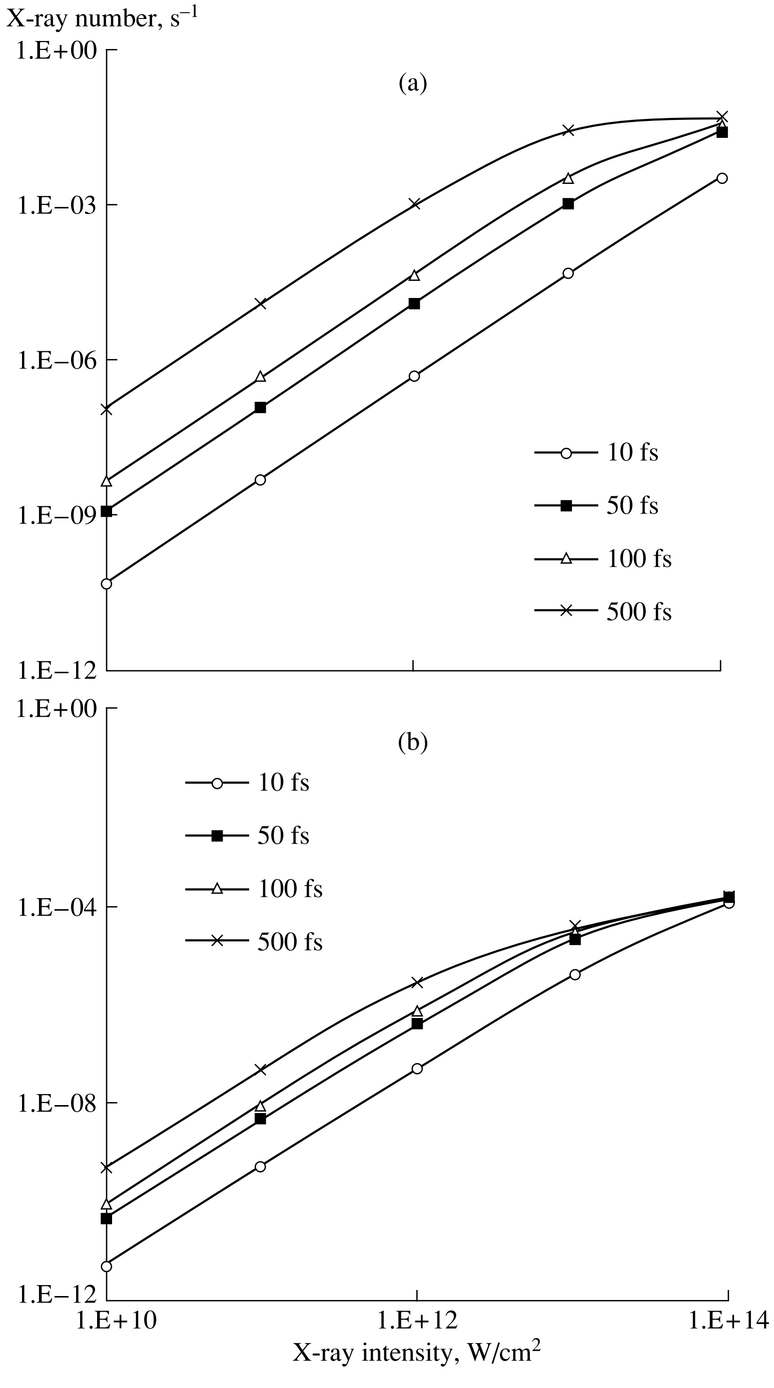

Fig. 1. X-ray number emitted from doubly inner-shell excited states vs. X-ray intensities for X-ray pulse widths of 10, 50, 100, and 500 fs: (a) $1s^22s^22p^43s^2$ of Mg and (b) $1s^22s^22p^63s^23p^64s^24p^64d^85s^25p^6$ of Xe are treated as doubly inner-shell excited states.

increase almost according to τ^2 and τ. This comes from the following fact. First, we consider the X-ray pulse as a pile of 10-fs X-ray pulses. The processes given in [12, Fig. 1] seldom take place in Xe because the lifetime of the inner-shell excited states is shorter than 10 fs. In this case, the X-rays are emitted separately for each 10-fs pulse. As a result, the X-ray number increases according to τ. On the other hand, in Mg, these processes always occur because the lifetime of the inner-shell excited state is much longer than 10 fs and increase the X-ray number. This may cause the X-ray number to increase according to about τ^2.

We recommend choosing the target according to the X-rays. Namely, if the X-ray pulse is long, one should choose a target whose inner-shell excited state has a

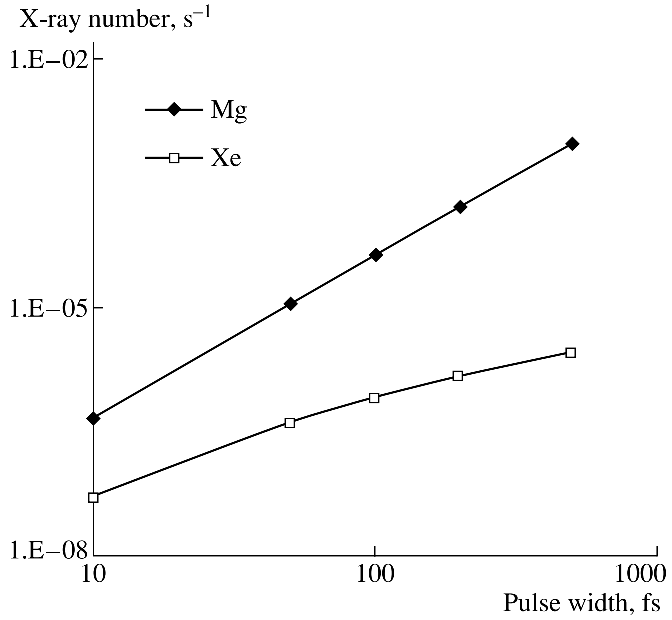

Fig. 2. X-ray number emitted from doubly inner-shell excited states vs. X-ray pulse widths for an X-ray intensity of 10^{12} W/cm^2. The same doubly inner-shell excited states as those in Figs. 1 are employed.

long lifetime, such as Mg. One should also consider the fact that the pulse measurement becomes difficult if the X-ray pulse is comparable to or shorter than the lifetime, as mentioned in [14].

3. CONCLUSION

The X-ray numbers emitted from double inner-shell excited states increase according to I^2 for the case of relatively low X-ray intensities, where I is the X-ray intensity. The number of X-rays of Mg is much larger than that of Xe for all intensities and pulse widths. Furthermore, the X-ray number increases according to about τ^2 and τ for Mg and Xe, respectively, where τ is the pulse width. This may be a result of the lifetime of the inner-shell excited states.

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REFERENCES

1. Y. Ueshima, Y. Kishimoto, A. Sasaki, and T. Tajima, Laser Part. Beams **17**, 45 (1999).
2. K. Lee, Y. H. Cha, M. S. Shin, *et al.*, Phys. Rev. E **67**, 026502 (2003).
3. K. Lee, Y. H. Cha, M. S. Shin, *et al.*, Opt. Express **11**, 309 (2003).
4. A. Zhidkov, J. Koga, A. Sasaki, and M. Uesaka, Phys. Rev. Lett. **88**, 185 002 (2002).
5. T. Guo, C. R. Petruck, R. Jimenez, *et al.*, Proc. SPIE **3157**, 84 (1997).
6. H. Kandori, H. Sasabe, K. Nakanishi, *et al.*, J. Am. Chem. Soc. **118**, 320 (1996).
7. S. Akimoto, S. Takaichi, T. Ogata, *et al.*, Chem. Phys. Lett. **260**, 147 (1996).
8. K. Moribayashi, A. Sasaki, and T. Tajima, Phys. Rev. A **58**, 2007 (1998).
9. K. Moribayashi, A. Sasaki, and T. Tajima, Phys. Rev. A **59**, 2732 (1999).
10. H. C. Kapteyn, Appl. Opt. **31**, 4391 (1992).
11. S. J. Moon, D. C. Eder, and G. L. Strobel, AIP Conf. Proc. **332**, 262 (1994).
12. D. Kim, S. H. Son, J. H. Kim, *et al.*, Phys. Rev. A **63**, 023806 (2001).
13. K. Moribayashi, T. Kagawa, and D. E. Kim, J. Phys. B **37**, 4119 (2004).
14. K. Moribayashi, T. Kagawa, and D. E. Kim, J. Phys. B **38**, 2187 (2005).
15. R. D. Cowan, J. Opt. Soc. Am. **58**, 808 (1968).