Observation of super Coster–Kronig-pumped gain in Zn III

D. J. Walker, C. P. J. Barty, G. Y. Yin, J. F. Young, and S. E. Harris

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

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We report the observation of laser gain in the vacuum ultraviolet pumped by super Coster–Kronig decay. Using a 5-J, 300-psec pump pulse of 1064-nm radiation, we have observed gain on transitions in Zn III at 127.0, 130.6, and 131.9 nm with total gains of exp(2.4), exp(5.1), and exp(3.2), respectively. The large branching ratios of the rapid super Coster–Kronig decay into a small number of final levels makes high-efficiency operation possible.

The use of selective Auger decay to produce population inversion and gain in the soft-x-ray and ultraviolet spectral regions was proposed by McGuire[1] in 1975. The first successful experiments were performed by Kapteyn *et al.*[2] in 1986; in those experiments 55 J of 1064-nm pump energy was used to produce incoherent soft x rays, which photoionized Xe I. These atoms Auger decayed to Xe III to produce a gain of exp(7) at 109 nm. Experiments by Yin *et al.*[3] showed that comparable gains on this transition could be obtained with less than 1 J of pumping energy. Recently Sher *et al.*[4] used a traveling-wave geometry to obtain a small-signal gain of exp(40) and a saturated output energy of 20 μJ at 109 nm.

In this Letter we follow the proposal of Mendelsohn and Harris[5] to obtain gain by selective super Coster–Kronig decay of photoionization-pumped Zn I. A super Coster–Kronig decay process is a subclass of an Auger process in which the initial hole, the jumping electron, and the departing electron all occupy the same n shell. As a result, the decay rate is very fast (typically $>10^{15}$ sec^{-1}), and therefore the process dominates other Auger processes. In particular, the branching ratio to the upper level for the Zn system described here is 27%, while that to the lower laser level is <1%. For the 109-nm Xe system, the Auger decay rates to the upper and lower laser levels are about equal,[6] and an inversion results from the higher degeneracy of the lower level.

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The relevant energy levels of the Zn system are shown in Fig. 1. Photoionization of Zn I $3p^63d^{10}4s^2$ ground-level atoms by the x rays emitted by a laser-produced plasma results in the production of highly excited Zn II $3p^53d^{10}4s^2$ ions. These ions undergo rapid, selective, $3d$ shell super Coster–Kronig decay into levels of Zn III. Calculations[5,7] have shown that about 48% of this decay produces the Zn III $3p^63d^84s^2$ $^1G_4$ LS basis level. Configuration mixing of the Zn III $3d^84s^2$ configuration with the nearby Zn III $3d^94d$ configuration results in several levels of both configurations having significant components of the $3d^84s^2$ $^1G_4$ basis level. Thus they receive a large fraction of the super Coster–Kronig decay. The energy levels relevant to the transitions on which we have observed gain, and the branching ratios into them, are shown in Fig. 2. The level positions are from Ref. 8, and the branching ratios and gain cross sections are from Refs. 5 and 7.

Our experimental configuration, shown in Fig. 3, is similiar to that suggested by Harris *et al.*[9] and demonstrated by Caro *et al.*,[10] Silfvast *et al.*,[11] and Lundberg *et al.*[12] The 5-J, 300-psec, 1064-nm pump laser is focused by a 30-cm focal-length cylindrical lens, producing a focal line 28 mm long by ~100 μm wide. The beam passes through a 1.5 mm × 28 mm-long slotted aperture positioned 2 mm from, and parallel to, the solid Ta target in the Zn cell. This slot defines both the pumped volume and the volume observed by the detection system. The detection system consists of a 1-m normal-incidence vacuum monochromator followed by a p-terphenyl scintillator and a fast visible photomultiplier tube. The system has a total re-

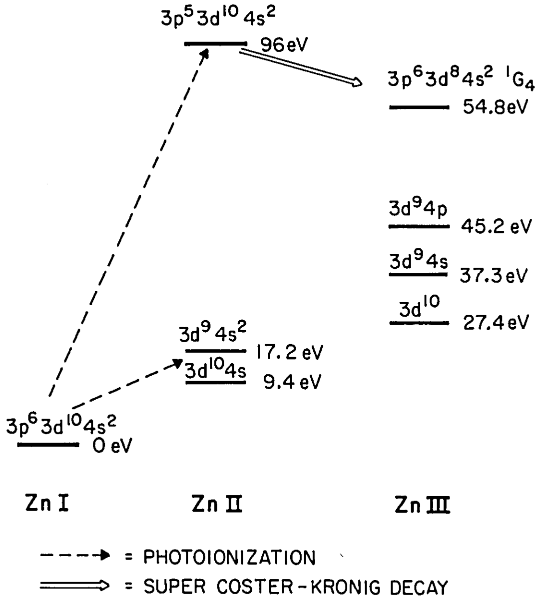

Fig. 1. Simplified energy-level diagram of Zn I, Zn II, and Zn III. The branching ratio into the Zn III $3d^84s^2$ $^1G_4$ level is 27%.

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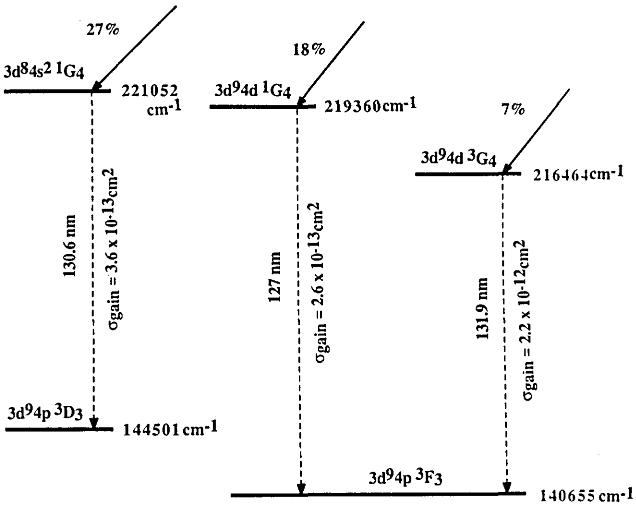

Fig. 2. Energy-level diagram of the transitions on which gain was observed.

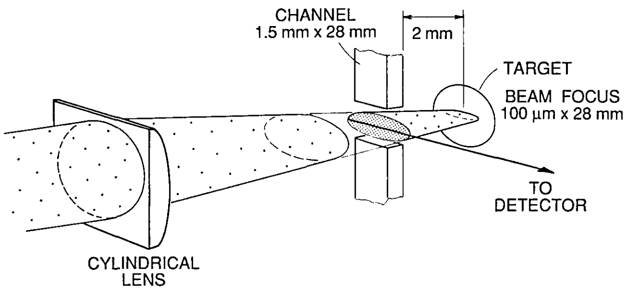

Fig. 3. Schematic of experimental configuration.

sponse time of about 5 nsec FWHM. The Zn cell is a heat-pipe oven with He buffer gas operating at about 500°C. Because the operating temperature is so close to the melting point of Zn, 418°C, the heat-pipe wicks are not effective in returning condensed Zn to the hot zone, and the cell has a tendency to deplete after about 1 h of operation. The Zn cell is separated from the spectrometer by a LiF window.

The gains of the Zn transitions were measured by blocking parts of the pump beam to vary the length of the pumping plasma and measuring the resulting output energy. The actual output beam of our laser is 32 mm in diameter, but 2 mm of each edge of the beam was permanently blocked to equalize the energy per unit area of different vertical strips of the beam. The measured energy as a function of plasma length was fitted to the theoretical frequency-integrated emission function of a line radiator, which can be approximated as[13]

$$E \propto \frac{[\exp(\alpha l) - 1]^{3/2}}{[\alpha l \exp(\alpha l)]^{1/2}}, \qquad (1)$$

where α is the gain per unit length and l is the length. The points on Fig. 4 are measured values of 130.6-nm energy, and the curve is the best fit of expression (1) to those points. In this case the fit indicates $\alpha = 1.7$ cm^{-1} and a total gain of exp(4.8). This method was used to determine all the gain values presented here. We estimate our minimum measurable gain to be about 0.7 cm^{-1}. The measured values varied about 20% from day to day, largely because of variations in the performance of the Zn cell.

Figure 5 shows that the gain at 130.6 nm maximizes at a Zn pressure of about 1.2 Torr. The decrease in gain at higher pressure is probably due to electron quenching of the upper-level population. In Zn I, the largest photoionization cross section is for the removal of a 3*d* electron, not a 3*p* electron.[14] Thus a large number of electrons are produced that are not involved in creating excited states but that can act to destroy the inversion by processes such as electron deexcitation or ionization of the upper level.

In addition to measuring the gain at 127.0, 130.6, and 131.9 nm, we also looked for gain at 130.3, 133.2, 135.9, and 136.3 nm, using the 1.2-Torr optimum pressure. These transitions have upper levels that are populated by super Coster–Kronig decay and could conceivably have gain. We did not observe gain above our minimum threshold at any of these wavelengths. We note that the 133.2-nm transition, which shares an

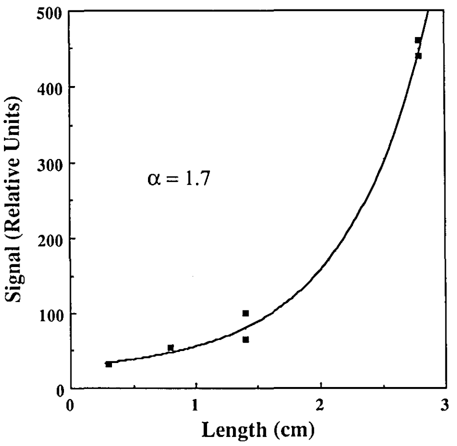

Fig. 4. Output energy at 130.6 nm as a function of pumped length for a plasma-producing laser energy of 5 J in a 300-psec pulse and Zn pressure of 1.2 Torr.

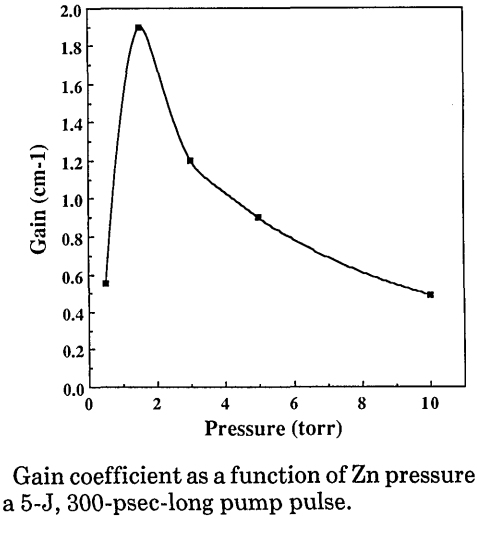

Fig. 5. Gain coefficient as a function of Zn pressure at 130.6 nm for a 5-J, 300-psec-long pump pulse.

upper level with the 130.6-nm transition, was predicted[5] to have the higher gain; we did not observe this to be the case.

In summary, using only several joules of laser energy, we have observed super Coster–Kronig-pumped gain on several transitions near 130 nm. As shorter-wavelength systems and deeper holes are reached, the high selectivity and ease of identification of the super Coster–Kronig process will make the process important not only for directly pumped systems but also for systems that are pumped by Auger cascade.

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