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ScienceDirect

Matter and Radiation at Extremes 1 (2016) 76–81

MATTER AND RADIATION AT EXTREMES

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Modeling the gain of inner-shell X-ray laser transitions in neon, argon, and copper driven by X-ray free electron laser radiation using photo-ionization and photo-excitation processes

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Received 31 August 2015; revised 6 November 2015; accepted 16 November 2015
Available online 11 December 2015

Abstract

Using an X-ray free electron laser (XFEL) at 960 eV to photo-ionize the 1s electron in neutral neon followed by lasing on the 2p-1s transition in singly-ionized neon, an inner-shell X-ray laser was demonstrated at 849 eV in singly-ionized neon gas several years ago. It took decades to demonstrate this scheme, because it required a very strong X-ray source that could photo-ionize the 1s (K shell) electron in neon on a timescale comparable to the intrinsic Auger lifetime in neon of 2 fs. In this paper, we model the neon inner shell X-ray laser under similar conditions to those used in the XFEL experiments at the SLAC Linac Coherent Light Source (LCLS), and show how we can improve the efficiency of the neon laser and reduce the drive requirements by tuning the XFEL to the 1s-3p transition in neutral neon in order to create gain on the 2p-1s line in neutral neon. We also show how the XFEL could be used to photo-ionize L-shell electrons to drive gain on $n = 3{-}2$ transitions in singly-ionized Ar and Cu plasmas. These bright, coherent, and monochromatic X-ray lasers may prove very useful for doing high-resolution spectroscopy and for studying non-linear process in the X-ray regime.

PACS Codes: 42.55.Vc; 41.60.Cr; 32.80.Aa; 32.30.-r

Keywords: Photo-pumping; X-ray free-electron laser; X-ray laser

1. Introduction

In the 1960's scientists at Bell Laboratories, Duguay and Rentzepis, proposed using photo-ionization to create an X-ray laser on the inner shell K-α line in sodium vapor [1]. A decade later in the 1970's Ray Elton [2] from the Naval Research Laboratory discussed the challenges of making quasi steady state inner-shell K-α lasers in Si, Ca, and Cu. In 2003 Lan and colleagues modeled XFEL radiation driving gain on the He-α and Ly-α lines in He [3,4]. In 2011 the dream of demonstrating an inner-shell X-ray laser was realized at the SLAC Linac Coherent Light Source (LCLS) when the X-ray free electron laser (XFEL) at 960 eV was used to photo-ionize the K-shell of neutral neon gas and create lasing at 849 eV in singly-ionized neon gas [5].

Another approach pursued in the 1970's for creating X-ray lasers was the idea of a resonantly photo-pumped laser where a strong emission line in one material could be used to photo-excite a transition in another material and create lasing. A classic example of this scheme is the Na-pumped Ne X-ray laser scheme proposed by Vinogradov and colleagues [6,7]. This scheme used the strong Na He-α line at 1127 eV to resonantly photo-pump the Ne He-γ line and lase at 53.7 eV (23.1 nm) on the 4f-3d transition in He-like Ne. This scheme

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Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

http://dx.doi.org/10.1016/j.mre.2015.12.001

was studied extensively and numerous experiments were done to try to demonstrate lasing and measure gain [8]. Weak gain [8] was inferred in several experiments. However the difficulty with this type of scheme was creating a sufficiently strong pump line. With the availability of strong XFEL sources, the pump line in the traditional photo-pumped schemes can be replaced with an XFEL that is tuned to the appropriate resonance. The resonant photo-pumped scheme selectively pumps a transition so it offers the potential for higher gain and lower drive intensity than the photo-ionization pumping.

In this paper we look at the advantages and challenges of using the XFEL to resonantly photo-pump the 1s-3p line in neutral neon as a mechanism for creating gain on the K-α line in Ne, and compare this with the photo-ionization pumping that has already been demonstrated. We show that with the use of a sufficiently short XFEL pulse (1-fs) the resonant photo-excitation could reduce the XFEL flux requirements by several orders of magnitude. We then look at how the inner-shell X-ray laser can be extended to lasing on L-shell transitions in Ar and Cu. For Ar we consider an XFEL pulse that photo-ionizes the 2p or 2s electrons and creates lasing on the 3s-2p or 3p-2s transitions. In the case of Cu we consider an XFEL pulse that photo-ionizes the 2p electron and creates lasing on the strong 3d-2p transitions near 1 keV.

2. Modeling the inner-shell Ne laser

Fig. 1 shows the pumping mechanism used in the LCLS experiments that demonstrated lasing on the inner-shell neon laser. The XFEL beam is tuned above the K-edge of neutral Ne I and photo-ionizes the 1s electron. This creates an excited state of singly-ionized Ne II that has a missing 1s electron. This excited state can Auger decay to Ne III or lase to the ground state of Ne II by emitting an X-ray on the 2p-1s transition at 848.6 eV [9]. The experiment starts with a neon gas that is in the Ne I ground state. The lower laser state is initially unoccupied. The natural lifetime of the laser transition is 135 fs based on calculations done with the multi-configuration Dirac-Fock (MCDF) atomic physics code of Grant et al. [10] for similar transitions in Mg assuming the oscillator strength is the same for Ne. This is consistent with the Auger branching ratio of 98.2% calculated in the work of Aksela [11].

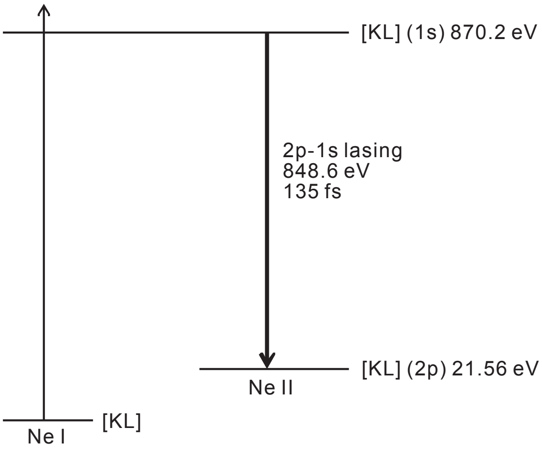

Fig. 1. Energy level diagram for the photo-ionization driven inner-shell neon X-ray laser showing lasing on the 2p-1s line at 848.6 eV in Ne II.

The notation [KL] signifies the fully occupied K shell, $1s^2$, and the L shell, $2s^22p^6$, configurations while the notation (1s) represents a 1s hole in the K shell and (2p) represents a 2p hole in the L shell. The challenge with this scheme is that the Auger lifetime of the upper laser state is 2.3 fs [11] so pumping this scheme requires a very short pulse duration in the fs regime. The Auger process is an auto-ionizing process that causes rapid ionization as one of the L-shell electrons fills the 1s hole while a second L-shell electron is ionized.

Fig. 2 shows the resonant photo-pumping mechanism for driving the inner-shell neon laser. In this case, the XFEL is tuned to the 1s-3p transition in Ne I at 867.63 eV [12] creating a large population in the [KL] (1s) 3p or $1s2s^22p^63p$ level. This level can then lase to the lower [KL] (2p) 3p or $1s^22s^22p^53p$ level by emitting X-rays on the 2p-1s transition centered at 848.96 eV. Because of the splitting in the lower level, there are 5 X-ray lines emitted that are spread over the energy range from 848.67 to 849.25 eV. We calculate the total gain by summing the gain of the 5 lines. The upper laser level has a similar Auger lifetime of 2.3 fs that implies a linewidth of 0.3 eV on the lasing transition. The linewidth, ΔE, equals $hA/2\pi$ where h is the Planck's constant and A is the inverse lifetime or destruction rate of the transition which is determined primarily by the Auger lifetime. The photo-excitation scheme also requires a short pulse drive because of the very short Auger lifetime. The difference between this scheme and the photo-ionization scheme is that lasing is now in neutral Ne I instead of Ne II. The lasing energies differ by about 0.4 eV. The potential advantage of this scheme is that the photo-excitation cross-section is about 18 Mb compared to 0.3 Mb for the photo-ionization scheme. In this paper we show how

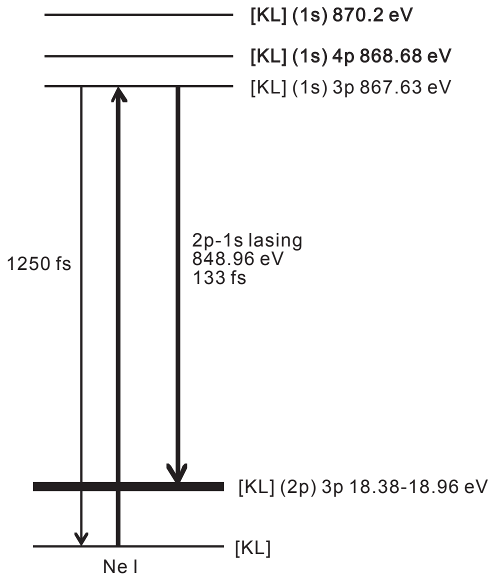

Fig. 2. Energy level diagram for the photo-excitation driven inner-shell neon X-ray laser showing lasing on the 2p-1s line at 848.96 eV in Ne I.