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X-ray laser implementation by means of a strong source of high-spin metastable atoms

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High-spin metastable atomic beams of high density and extremely small divergence can be produced by electron capture during grazing-angle scattering of ion beams at ferromagnetic surfaces. This can be used to generate a long-lived reservoir of Li $1s2s2p\ ^4P^0_{5/2}$ with enough density of metastables so that after laser-induced transfer to Li $1s2p^2\ ^2P$ strong lasing at 207 Å should occur. This novel technique can also be used to produce a variety of other metastables known as potential candidates for lasing at shorter wavelengths.

Sources of coherent radiation generated by stimulated emission have been produced over seven decades of the spectrum down to about 1000 Å. Among the many proposals[1,2] going beyond this limit, a mechanism proposed by Harris[2]—whereby a high population inversion is maintained by effectively depopulating the lower level—appears to be the closest to actual implementation. Crucial to Harris's proposal for an x-ray laser is the production of a high density (10^{12} atoms/cm^3) of Li $1s2s2p\ ^4P^0_{5/2}$ metastable atoms in a "geometrical" cylinder 0.05 cm in diameter and 300 cm long within the 6-μsec lifetime[3] of the $^4P^0_{5/2}$ level.

In this paper we report on a novel and unique technique for the production of large amounts of high-spin metastable atoms, e.g., Li $1s2s2p\ ^4P^0$, fulfilling all the (updated) requirements of Harris's proposal for a $\lambda = 207$-Å laser.

The fundamental process in the mechanism proposed here is the capture of spin-polarized electrons during grazing-angle surface reflection of intense ion beams at ferromagnetic single crystals. This method not only renders possible the realization of the metastable-state x-ray laser, but also opens a new and exciting field of research in atomic and surface physics by providing intense beams of polarized metastables whose polarization can be modulated. This is an advantage[4] which has already been met in spin-polarized electron experiments.[5,6]

Electron capture at solid surfaces. The deuteron one-electron capture technique has been used for many years to study the magnetic structure of surfaces.[7,8] Recently,[9] it has been shown that $D^- 1s^2$ is formed abundantly during specular reflection of D^+ ions at single-crystal nonmagnetic surfaces. This indicates that two-electron capture is also possible.[10] Moreover, when the surface is ferromagnetic, e.g., Ni(110), the production of $D^- 1s^2$ is strongly suppressed.[9] By measuring the negative current at short distances after surface reflection,[11] however, it has been found that the intensity increases considerably with decreasing distance to the surface. This negative charge might be due to electrons from a short-lived D^-. In fact, $D^- 2p^2\ ^3P$, which is the only[12] other bound (however unstable) state of D^-, is known to undergo radiative autoionization[13] with $\tau = 2 \times 10^{-9}$ sec. Thus, the surface reflection technique (SRT) utilizing magnetic surfaces favors the formation of high-spin metastables.

The same effect is expected to favor the production of high-spin metastable states in similar experiments with other ions. In particular this should apply to Li. In order to estimate the production yields we may use data taken from beam-foil (BF) experiments, where a variety of core-excited species are also produced. From BF data[14,15] it may be deduced[16] that 70-keV Li^+ ions through thin C foils yield about 20% of Li $1s2s2p\ ^4P^0$. The same experiments also yield 0.4% of core-excited Li^{-*} which is detected[17,18] through the $\lambda = 3490$ Å line corresponding to the transition $1s2p^3\ ^5S^0 \rightarrow 1s2s2p^2\ ^5P$. Analogous BF results are expected when Li^+ is replaced by Li^{2+}. Although BF and SRT yields may be comparable, the beam intensities which can easily be reached by SRT are many orders of magnitude larger, which is a crucial advantage for the actual realization of the x-ray laser.

By simply counting possible spin configurations one would expect that for a Li^{2+} incoming beam reflected at a fully magnetized surface, the yield of neutral Li $1s2s2p\ ^4P^0$ should be twice as large (40%), while the yield of Li^- $1s2s2p^2\ ^5P$ should be four times larger (1.6%).

In the following we discuss a general scheme for a metastable-state x-ray laser with particular quantitative attention given to the implementation of Harris's proposal.

Requirements for a 207-Å laser. After Harris's proposal,[2] and recent experimental[19,20] and theoretical[21,22] work on the laser-induced Li $1s2s2p\ ^4P^0 \rightarrow 1s2p^2\ ^2P$ transition, the last difficulty to implement the 207-Å laser is to achieve a metastable $1s2s2p\ ^4P^0_{5/2}$ density

$$N_m = 10^{12}(15\tau/\tau')(\Delta\nu'/\Delta\nu)$$
$$= 3\times 10^{12}\ \text{metastables/cm}^3\ , \qquad (1)$$

in a geometrical cylinder 0.05 cm in diameter and 300 cm long, and in a time of about 2 μsec. In Eq. (1), the parantheses enclose deviations from Harris's original estimate: the factor of 15 accounts[21] for an early overestimate of the oscillator strength for the $^4P^0 \rightarrow {}^2P$ transition; $\tau/\tau' = 0.3$ arises after the new and more accurate experimental[20] ($\tau' = 49 \pm 5$ psec) and theoretical[22] ($\tau' = 47 \pm 5$ psec) lifetime for Li $1s2p^2\ ^2P$ updating the value $\tau = 15$ psec used by Harris, whereas $\Delta\nu'/\Delta\nu$ accounts for any change in Doppler broadening from the value $\Delta\nu = 3.7\ \text{cm}^{-1}$ assumed by Harris. With our setup we estimate $\Delta\nu' = 2.2\ \text{cm}^{-1}$.

Experimental setup. (a) Neutral Li. A 2-A pulse of 70-keV Li^{2+} ions with a time duration of 2.15 μsec can be produced using specialized Li sources and a storage ring.[23] This pulse can be focused to an area of 0.0025 cm^2 before grazing at 0.57^0 a single-crystal Ni(110) ferromagnetic surface $1\times 5\ cm^2$ shown in Fig. 1. The reflected beam should contain at least 20% of Li $1s2s2p\ ^4P^0_{5/2}$.[24] Since the velocity of the particles at 70 keV is 1.4×10^8 cm/sec, the beam satisfies the required $N_m = 3\times 10^{12}$ metastables/cm^3 allowing for a 25% loss due to spontaneous decay of the metastables before action of the transfer laser. In this setup $\Delta\nu'$ is mainly caused by the dispersion in

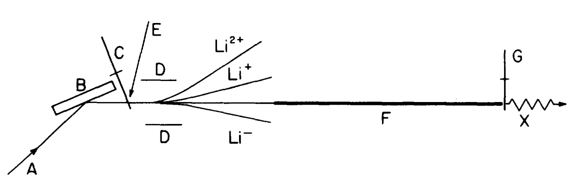

FIG. 1. Scheme of experimental setup. A: Li^{2+} beam from storage ring, B: magnetic single-crystal surface, C: synchronized punched rotating disk to drive transfer laser when laser medium is filled, D: deflecting plates, E: radiation from transfer laser, F: laser medium, G: synchronized punched rotating disk to stop lithium beam and to let out the x-ray laser radiation.

the particle velocities after surface reflection: we obtain $\Delta\nu' = 2.2\ \text{cm}^{-1}$ assuming a 140-eV energy width in the reflected beam.[25]

The 300-cm-long beam of Li $^4P^0_{5/2}$ must now be pumped into the $1s2p^2\ ^2P$ lasing state by a 30-psec pulse of a 5×10^{10}-W/cm^2 dye laser tuned to $\lambda = 2933$ Å [Doppler uncorrected $\lambda = 2952$ Å (Refs. 19 and 26)] as suggested by Harris,[2] see Fig. 2. To this end, it is necessary to intercalate a synchronized rotating punched disk which allows the transit of the metastable beam during the 2.15-μsec pulse, and which immediately afterwards reflects the 30-psec pulse of the 2933-Å transfer laser. A similar synchronized disk is placed at the end of the laser medium to allow for the clean exit of the 207-Å laser radiation whilst most of the lithium beam is stopped.

Note that most of the pumping takes place at the ion source. The magnetic surface acts as a catalyst by providing a high concentration of spin-polarized electrons thus allowing for an efficient $Li^{2+} \rightarrow Li\ ^4P^0$ conversion.

(b) Core-excited negative lithium. As shown before, the yield of Li^{-*} is about 12 times smaller than the yield of Li $^4P^0_{5/2}$. However, Li^{-*} offers several distinct advantages, some of which cannot at present be precisely assessed but which, overall, could compensate the low yield: (i) Li^{-*} beams can be compressed and accelerated *after* surface scattering thus allowing for both the choice of the energy and the focusing of the Li^{2+} beam to obtain an optimal surface interaction with regard to Li^{-*} production. (ii) Li^{-*} can be separated electrostatically from the rest of the beam, providing a clean source of polar-

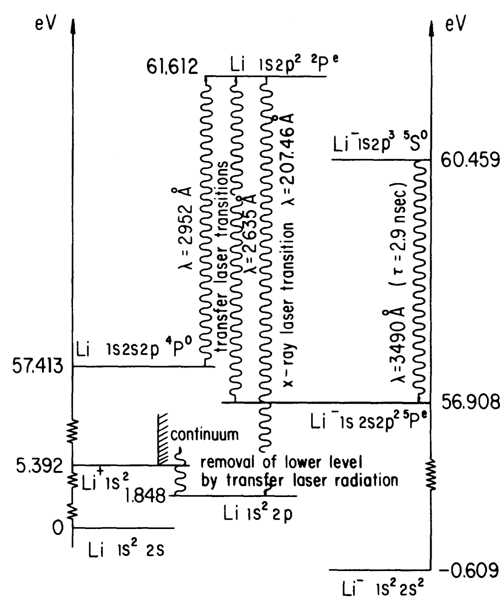

FIG. 2. Energy diagram of Li levels involved in the 207-Å laser (Refs. 26 and 27).

ized metastables; note that no mechanical device is needed to drive the pumping laser radiation along the laser medium. (iii) Since the final states of the lithium beam are charged ($Li^+ 1s^2$ and $Li^- {}^5P$), they can easily be removed from the direction of the 207-Å laser radiation. (iv) By changing the velocity of the Li^{-*} beam and by optionally reversing the course of the transfer laser, the x-ray laser can be tuned between 206.5 and 208.5 Å. (v) Due to the axial symmetry of the experimental arrangement and the charged character of the metastable reservoir, one can employ a plurality of Li ion sources and reflecting surfaces to obtain a much denser magnetically focused laser medium. In the case of Li^{-*} the wavelength of the transfer laser is 2623 Å [Doppler uncorrected $\lambda = 2635$ Å (Ref. 27)], corresponding to the photodissociation of the $Li^- {}^5P$ into Li $1s2p^2\,{}^2P$, see Fig. 2.

Further applications. More elaborated experimental arrangements involving more ion sources and reflecting surfaces can be conceived, especially when using high-charge isoelectronic metastables having shorter lifetimes. For example, $C^{3+}\,1s2s2p\,{}^4P^0_{5/2}$, which is a potential metastable candidate for inducing lasing action around 40 Å, autoionizes with $\tau = 0.09$ μsec.[28]

The development of metastable-state x-ray lasers for still shorter wavelengths will depend heavily on further progress in ion sources, and also on the discovery of alternative metastable states,[29] particularly in connection with tunable x-ray lasers. Finally, the surface reflection technique opens the possibility of obtaining intense high-energy beams of neutral particles collimated to a high degree, as required for controlled thermonuclear fusion. This is possible because SRT does not destroy[10] the focal properties of the incoming ions, it only facilitates neutralization.

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[23]Under these conditions, an ion source of 100 μA of Li^{2+} allows for a beam pulse every 50 msec.

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[25]After grazing reflection, the energy loss for beams of the energy we consider is about 2000 eV (Ref. 10). This may be interpreted in terms of a successive and independent production of about $n = 200$ plasmons of energy $\hbar\omega_p = 10$ eV each. In this simplified model the dispersion energy would then be $\hbar\omega_p\sqrt{n} = 140$ eV.

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