Observation of extreme ultraviolet superfluorescence from helium atoms ionised and excited using soft x-ray free-electron laser pulses

J R Harries[1]*, H Iwayama[2]†, S Kuma[3]‡, M Iizawa[4], N Suzuki[4], Y Azuma[4], I Inoue[5], S Owada[6], T Togashi[6], and E Shigemasa[2]

[1]QST, SPring-8, Kouto 1-1-1, Sayo, Hyogo 679-5148, Japan,
[2]UVSOR/SOKENDAI, National Institutes of Natural Sciences, Okazaki, Aichi 444-8585, Japan,
[3]RIKEN, Saitama 351-0198, Japan, [4]Sophia University, Kioicho 7-1, Chiyoda, Tokyo 102-8554, Japan
[5]RIKEN, Kouto 1-1-1, Sayo, Hyogo 679-5198 Japan, [6]JASRI, Kouto 1-1-1, Sayo, Hyogo 679-5198 Japan

Synopsis We have studied the propagation of free-electron laser pulses at a wavelength of 24.3 nm through a dense sample of helium gas. Ionisation and resonant excitation leads to strong population of the He^+ $4p$ state, and the resulting superfluorescence, yoked superfluorescence, and free-induction decay were observed experimentally. Numerical simulations using the Maxwell-Liouville equations were used to interpret the observations.

Free-electron laser (FEL) pulses can be used to create instantaneously an extremely dense sample of ions. Here [1] we pass FEL pulses at a wavelength of 24.3 nm through helium gas at a number density of around $2 \times 10^{23}\,\mathrm{m}^{-3}$. Essentially all of the atoms along the optical path are ionised. The wavelength chosen is resonant with the ionic $1s$-$4p$ transition, leading to a high density of excited ions in the $4p$ state created within 100 fs. The density was high enough to result in superfluorescent emission on the $4p$-$3s$ transition at a wavelength of 469 nm, observed as bright blue flashes (see figure, and also previous work in neutral helium [2]). Using a fast photodiode, we determined that the emitted pulses had widths and delays with respect to the FEL pulse of the order of picoseconds, with the delay ranging from a few ps up to around 100 ps depending on number density. A 1/(number density) scaling was seen, confirming that the emission was superfluorescence. Using a grazing-incidence spectrometer, intense, highly-directional emission was also observed at wavelenghts of 164 nm, 30.4 nm and 25.4 nm, corresponding to the $3s$-$2p$, $2p$-$1s$, and $3p$-$1s$ transitions. Notably, no emission was observed at 121.5 nm ($4p$-$2s$), which in spontaneous emission should be three times more likely to occur than $4p$-$3s$. While the temporal pulse widths of these emissions could not be confirmed, their high intensity and strong directionality strongly suggest that superfluoresence also occurs on the $3s$-$2p$ and $2p$-$1s$ transitions. Since no population inversion can be expected on the $2p$-$1s$ transition, this is only possible if the initial excitation imparts sufficient coherence between the $1s$ and $4p$ states, resulting in *yoked* superfluorescence [3] on the $3s$-$2p$-$1s$ route. These conclusions are supported by detailed semiclassical simulations using the Maxwell-Liouville equations beyond the rotating-wave equation and including all 16 ionic levels with $n \leq 4$.

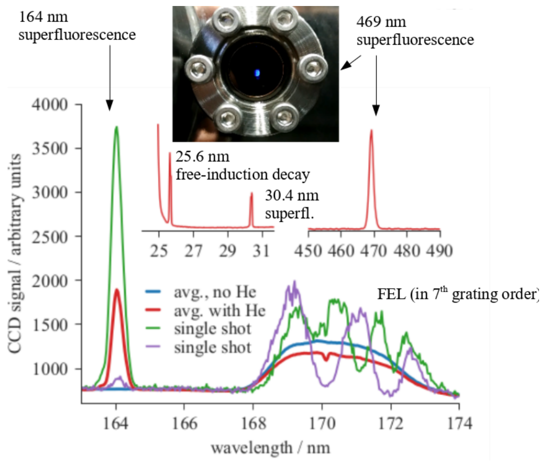

Figure: Intense, directional emission was observed at 469 nm ($4p$-$3s$ superfluorescence), 164 nm (3s-$2p$, superfluorescence), 30.4 nm ($2p$-$1s$, superfluorsecence yoked to $3s$-$2p$), and 25.6 nm ($3p$-$1s$ free-induction decay).

References

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*E-mail: harries@spring8.or.jp
†E-mail: iwayama@ims.ac.jp
‡E-mail: susumu.kuma@riken.jp