Resonance Laser Spectroscopy on Trapped Highly-Charged Ions using Soft X-Rays from FLASH

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Resonance laser spectroscopy is one of the most sensitive tools to study the precise structure of matter, i.e. of atoms and molecules. However, laser spectroscopy has been severely limited beyond the UV and especially the VUV region due to the lack of appropriate light sources. In particular, the atomic structure of heavier, simple few-electron systems was not accessible for this precision method. With the free electron laser in Hamburg, FLASH, the soft x-ray region is now widely opened to laser spectroscopy. Hence, also the precise structure of highly charged ions (HCIs) can be probed, provided enough species of proper HCIs can be supplied at the focus of a FLASH beamline.

Here we report on the first demonstration of resonance fluorescence laser spectroscopy by matching soft x-rays from the free electron laser (FLASH) together with HCIs provided in an EBIT (cf. [1]) especially developed in Heidelberg for this purpose, cf. Fig. 1. Critical difficulties resulting from very small excitation cross sections at those short wavelengths, several order of magnitudes weaker photon fluxes than in the visible, small radiation collection efficiencies, and the low achievable target densities of HCIs had to be overcome. As a first objective, the transition between the $1s^2 2s\ ^2S_{1/2}$ (ground) and $1s^2 2p\ ^2P_{1/2}$ (excited) states was investigated for Li-like iron Fe^{23+} ions. This transition is closely related to the Lamb shift in one-electron ions and is playing an important role in the formulation of few-electron QED in strong fields, c.f. [2,3]. Moreover, HCIs of iron are due to their relative large abundances key systems for investigating extraterrestrial or terrestrial plasmas.

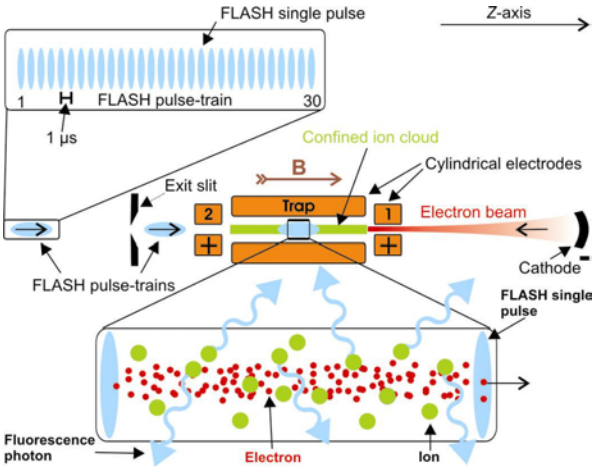

Figure 1: Matching of FLASH pulses with highly charged ions in the EBIT: Li-like Fe^{23+} ions (green) are produced and trapped by a 5 keV, 450 mA electron beam (red), compressed to 50 µm by a 6 T coaxial magnetic field B (brown). Soft x-rays (light blue) from FLASH at the PG2 monochromator beam line enter as pulse-trains (30 single pulses 20-80 fs long spaced by 1 µs) with a 5 Hz frequency (upper inset). They (lower inset) excite the Li-like Fe^{23+} ions, which emit fluorescence radiation – finally collected by x-ray mirrors and focused onto a microchannel plate detector for counting (both not depicted).

The experiment was performed in a single photon resonant absorption scheme, by tuning the laser over the $^2P_{1/2} \rightarrow {}^2S_{1/2}$ resonance around 48.6 eV and registering the resonant fluorescence photon

yield as a function of the laser wavelength. The lifetime of the excited level is only 0.55 ns, and its excitation results in immediate emission of fluorescence radiation. Fe^{23+} ions were produced in the EBIT by successive electron impact ionization of Fe atoms: Positive ions in the EBIT are confined radially by the negative space charge potential generated by the electron beam and longitudinally by appropriate potentials applied to the cylindrical trap electrodes. The trapped HCIs form a cylindrical cloud of 50 mm length and 200-300 µm diameter with a density of about 10^{10} ions/cm^3. The ion cloud was brought to overlap with the laser beam of FLASH at the focus of the scanning plane monochromator PG2, which had a comparable diameter (light blue in Fig. 1). As a compromise a resolution $E/\Delta E$ of about 2,000 at 48.6 eV photon energy was chosen for the monochromator yielding $3 \cdot 10^{12}$ photons/s.

A fraction of the fluorescence photons was collected by two cylindrical grazing incidence mirrors and focused onto the surface of a microchannel plate detector with an overall photon detection efficiency of ~10^{-4}. Photons are recorded in time coincidence with the FEL pulses as a function of the monochromator energy settings. The monochromator was repeatedly scanned between 48.53 eV and 48.71 eV in 5 meV wide steps, with 3 s integration time. Fig. 2 shows the photon yield as function of photon energy and arrival time, as well as the relevant projection onto the photon energy axis. Despite the time consuming overlap tuning a resonance signal containing about 370 true counts became clearly visible in the final half hour run. A Gaussian fit of the data (red curve in Fig. 2) yields a transition energy of (48.6127 ± 0.0011 $_{\text{stat.}}$ ± 0.0150 $_{\text{syst.}}$) eV.

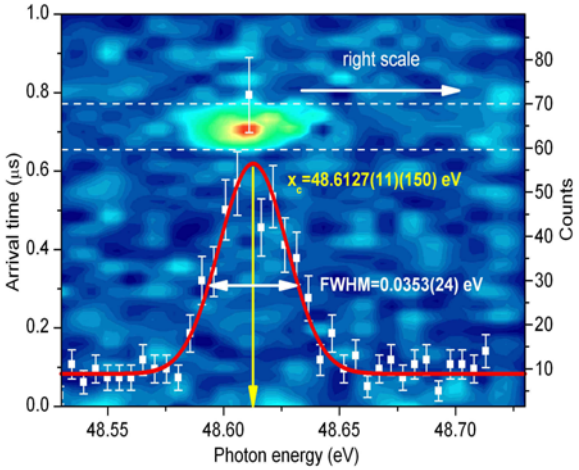

Figure 2: 2D plot of the fluorescence signal as a function of the photon arrival time relative to the FEL pulse (left y-axis, arbitrary offset) versus photon energy (x-axis) after 1987 s (smoothed data, 5 meV × 0.016 µs binning). Inset: Projection of the relevant band (white lines; white squares) onto the photon energy axis yielding the number of photons (right y-axis) as a function of the photon. Red line: Gaussian fit.

So far, the absolute value suffers under the preliminary calibration uncertainty (± 0.0150 eV) of the PG2 beamline monochromator. It will be reduced considerably by an adequate calibration of that instrument in the near future. However, the present statistical accuracy is already superior to the theoretical uncertainties and allows verifying the leading two-photon QED terms. Any further increase in experimental precision provides a systematic sensitivity improvement: namely, one additional photon in the QED graphs for any accuracy gain of $1/\alpha$ (≈ 137) – which seems quite feasible. Hence, so far uncalculated two-loop and higher order QED contributions, as well as model dependent nuclear-size and polarization effects will be revealed.

References

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