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PolarX-EBIT – A VERSATILE TOOL FOR RESONANT X-RAY SPECTROSCOPY

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Abstract

Resonant photo-excitation provides a direct tool for investigating electronic transitions in atoms and ions. By combining EBITs and ultrabrilliant x-ray sources this kind of spectroscopy became also available for highly charged ions. Here we present the PolarX-EBIT, a compact permanent-magnet EBIT built by the Max Planck Institute for Nuclear Physics and University Jena specifically for operation at synchrotron radiation light source facilities. It employs a novel off-axis electron gun, allowing the photon beam to pass through the trap and be made available for downstream setups. Additionally, it features fast-switching power supplies for charge breeding and background reduction schemes, a time-of-flight ion extraction beamline and large area SDD detectors. Multiple successful experiments have been performed in the soft and hard x-ray regimes at the light sources BESSY II and PETRA III, measuring transition energies, oscillator strengths, natural line widths, photoionization and population balance. Furthermore, narrow lines of He-like ions have also been used as a diagnostic tool for the spectral performance of the photon beamlines.

INTRODUCTION

Electronic transitions in highly charged ions are of great importance for astronomy and astrophysics, as most matter in the universe is in an ionized form. Observed in x rays, their transitions are often the only spectroscopic features. Furthermore the strong electric field involved makes transitions in highly charged ions much more sensitive to relativistic and QED effects. Consequently, extensive spectroscopy measurements have been performed in EBITs and other plasma sources using electron impact as excitation mechanism.

As shown with laser spectroscopy in the optical region, more precise measurements can be performed when the excitation is induced by a photon. This resonant process allows selective excitation of states and thus more control over the atomic system.

Resonant Spectroscopy

By overlapping an ion cloud with a monochromatized photon beam, electronic transitions in highly charged ions can be selectively excited. The subsequent radiative decay of the excited state is observed by x-ray detectors mounted perpendicular to the photon beam. Spectra are recorded by scanning the incoming photon beam energy. The spectral resolving power is determined by the monochromator and other elements of the beamline. With the brightness of current generation synchrotron radiation sources, measurement times can be significantly reduced compared to conventional grating spectrometers.

This principle was developed and successfully applied during multiple campaigns with the FLASH-EBIT of the Max Planck Institute for Nuclear Physics [1–5].

PolarX-EBIT

Based on these campaigns with the FLASH-EBIT an EBIT permanently installed at a synchrotron radiation source was proposed and funded by a BMBF project, named PolarX-EBIT. In a joint development with the PTB-EBIT, a new type of compact permanent-magnet EBITs was designed and built. The main parameters of these EBITs are described in [6]. The modifications made for operation as part of an x-ray beamline are described in the following.

Off-axis Gun

To facilitate a permanent installation at a synchrotron radiation beamline, it is essential that the EBIT does not block the beam, so that other experiments can be performed when the EBIT is not in use or simultaneously to an EBIT measurement. For this reason an off-axis electron gun was designed, leaving the central axis of the EBIT free to pass the x-ray beam through the apparatus. The cathode is mounted below the axis under a 22° angle (see. Fig. 1). To bend the electron beam back onto the axis the anode and focus electrodes are split in two parts each. This design is more susceptible to the applied voltages, but with careful tuning beam transmission rates larger than 95% and electron currents up to 30 mA can be obtained.

X-ray Detectors

The PolarX-EBIT can be equipped with two large area (80 mm^2 and 150 mm^2) silicon drift detectors. The design of the trap allows to mount the detectors close to the trap, so that they cover a large solid angle up to 1 sr. 500 nm thick aluminum foil is mounted in front of them to block visible and VUV light. The detectors are mounted perpendicular to the photon beam and to each other. The two orientations allow investigation of the angular distribution of the emitted

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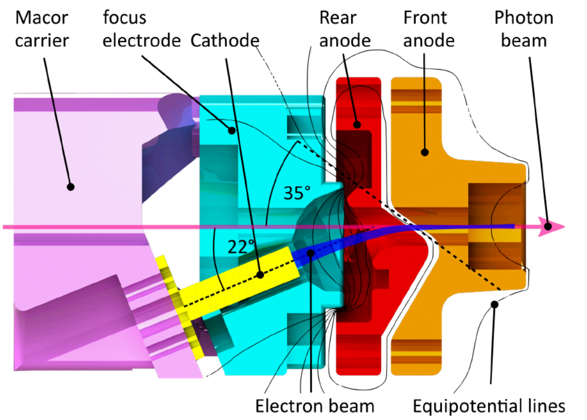

Figure 1: Layout of the off-axis gun. Figure taken from [6].

photons, which could be non-uniform if the ions are excited with polarized light.

Positioning System

The aperture of the gun and collector are just 4 mm in diameter, so precise alignment of the EBIT to the photon beam is important. This is achieved by a support frame with three feet, one front foot under the gun and two in the back, left and right of the collector. Each foot has a lifting spindle and is mounted on a translation stage, so the horizontal and vertical position, as well as pitch and yaw can be adjusted. All motions are motorized to allow remote control in radiation protected areas.

Electron Beam Energy Switching

For some measurements the electron-beam energy required to sufficiently produce the ion of interest is equal or larger than the transition energy probed. In this case the background created by electron impact excitation and radiative recombination overlaps the fluorescence signal, reducing the signal-to-noise ratio drastically. To circumvent this, an electron beam energy switching technique was implemented. The ions are charge bred at a high electron-beam energy, then the potentials of the trap electrodes are ramped down to a value causing no significant background. To avoid ion losses, ramping is performed with a sigmoidal shape while the trap depth is kept constant. At the low energy, the measurement can be performed. After a probing period, the energy is ramped up and the cycle starts again. Typical breeding and probing times are 0.1–1 s while the switching time is in the order of 10 ms.

Ion Extraction

To analyze the charge state distribution of the trapped ions, the PolarX-EBIT was equipped with a time-of-flight extraction beamline (see Fig. 2). It consists of an electrostatic 90° bender, a focusing lens and a channeltron detector. To extract the ions, the central trap electrode is instantaneously raised to 2 keV by a Behlke switch. By this the ions are kicked out of the trap and travel through the collector and the bender onto the channeltron, where the time-of-flight spectrum is acquired. From the time-of-flight, the charge-to-mass ratio can be determined. By observing changes in the charge state distribution, photoionization processes can be detected.

EXPERIMENTS

Since finishing construction in 2016 the PolarX-EBIT was successfully utilized for various measurement campaigns at different synchrotron radiation sources. During these experiments a lot of experience was gained. The installation and alignment of the EBIT can now be achieved within one day. Only a brief overview of the experiments can be given here, which are described in more detail in the referenced publications.

BESSY II

At the BESSY II beamline U49/2-PGM1 a gas cell was mounted behind the EBIT to simultaneously measure transitions of highly charged ions in the trap and O_2 photoionization. Using the K_δ, K_ϵ and K_ζ transitions in He-like N^{5+} to calibrate the photon beam energy, it was found that previous literature values of O_2 transitions were off by 450 meV [8]. Further gases were measured, proving the potential of highly charged ions as a reliable calibration source [9].

P04

Several beamtimes were performed at the soft x-ray beamline P04 of the PETRA III synchrotron radiation source at DESY. With its high photon flux and energy resolution it is ideally suited for resonance spectroscopy.

After initial measurements of the 3C/3D intensity ratio in neon-like iron [10], the signal-to-noise ratio could be greatly improved by the electron beam energy switching technique. Thus it was possible to measure the Lorentzian wings of those transitions. These accurate measurements for the first time yielded an intensity ratio in agreement with calculations. Furthermore, the natural linewidths of those lines could also be determined [11].

The extraction beamline was used to measure photoionization of Fe^{13+}, which was detected by the resulting Fe^{14+} photoions showing up in the time-of-flight spectra. Many transitions of the so-called unresolved transition array between 760 eV and 810 eV could be observed [7]. In addition to the Auger process, the radiative decay of the excited states was observed with the SDD detector which enables deductions about branching ratios.

As many lines of highly charged ions are much narrower than the ones usually found in neutral gases, they also provide a more precise diagnostic of the spectral line shape of the photon beam. Thus the strong w transitions of oxygen and neon were used to tune the P04 beamline [12].

P01

At the hard x-ray beamline P01 of PETRA III several beamtimes have been conducted with photon energies in the 6-15 keV range, investigating iron and krypton ions. As the charge states get higher, it becomes harder to produce

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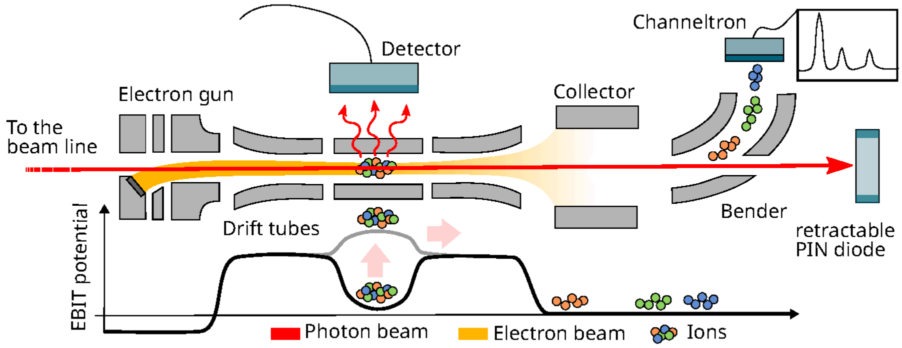

Figure 2: Scheme of the PolarX extraction principle. Figure taken from [7].

them with the electron beam current achievable with the off-axis gun. However, it was possible to measure K_α and K_β transitions in iron up to He-like Fe^{24+}. The high flux and resolving power of the P01 dual crystal monochromator allowed to measure transitions originating from metastable states in Fe^{22+} and Fe^{20+} [13]. Furthermore K_β transitions have been measured for several L-shell iron and krypton ions. For the latter the ^{57}Fe Mössbauer line at 14 412.497 eV was observed in parallel and used as a photon energy calibration reference.

CONCLUSION

The PolarX-EBIT has been successfully commissioned and used at various beamlines. The off-axis design has proven to be able to produce sufficient amounts of highly charged ions for resonance spectroscopy. It is a valuable addition to the experimental setup, allowing complementary measurements with the photon beam. With the charge-breeding scheme and ion extraction the range of addressable transitions could be extended. Furthermore the position and shape of transitions in highly charged ions have also been used as a diagnostic tool to improve the resolving power of the soft x-ray beamlines.

Following these pioneering works enabled by PolarX-EBIT, similar devices are currently under construction for the use at European XFEL, PAL-FEL, and Spring8.

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REFERENCES

[1] S. W. Epp *et al.*, "Soft X-Ray Laser Spectroscopy on Trapped Highly Charged Ions at FLASH," *Phys. Rev. Lett.*, vol. 98, p. 183 001, 18 May 2007. DOI: 10.1103/PhysRevLett.98.183001.

[2] M. C. Simon *et al.*, "Resonant and Near-Threshold Photoionization Cross Sections of Fe^{14+}," *Phys. Rev. Lett.*, vol. 105, no. 18, 183001, p. 183 001, Oct. 2010. DOI: 10.1103/PhysRevLett.105.183001.

[3] S. Bernitt *et al.*, "An unexpectedly low oscillator strength as the origin of the Fe XVII emission problem," *Nature*, vol. 492, no. 7428, pp. 225–228, Dec. 2012, ISSN: 1476-4687. DOI: 10.1038/nature11627.

[4] J. K. Rudolph *et al.*, "X-ray resonant photoexcitation: Linewidths and energies of $K\alpha$ transitions in highly charged fe ions," *Phys. Rev. Lett.*, vol. 111, p. 103 002, 10 Sep. 2013. DOI: 10.1103/PhysRevLett.111.103002.

[5] R. Steinbrügge *et al.*, "Absolute measurement of radiative and auger rates of $K-$shell$-$vacancy states in highly charged fe ions," *Phys. Rev. A*, vol. 91, p. 032 502, 3 Mar. 2015. DOI: 10.1103/PhysRevA.91.032502.

[6] P. Micke *et al.*, "The Heidelberg compact electron beam ion traps," *Rev. Sci. Instrum.*, vol. 89, no. 6, p. 063 109, 2018. DOI: 10.1063/1.5026961.

[7] M. Togawa, "Investigation of the M-shell unresolved transition array of aluminium-like iron using monochromatic soft x-ray synchrotron radiation," M.S. thesis, Ruprecht-Karls-Universität, Heidelberg, 2021. http://hdl.handle.net/21.11116/0000-0009-1029-7

[8] M. Leutenegger *et al.*, "High-Precision Determination of Oxygen K_α Transition Energy Excludes Incongruent Motion of Interstellar Oxygen," *Phys. Rev. Lett.*, vol. 125, p. 243 001, 24 2020. DOI: 10.1103/PhysRevLett.125.243001.

[9] J. Stierhof *et al.*, "A new benchmark of soft x-ray transition energies of Ne, CO_2, and SF_6: Paving a pathway towards ppm accuracy," *The European Physical Journal D*, vol. 76, no. 3, p. 38, Mar. 2022, ISSN: 1434-6079. DOI: 10.1140/epjd/s10053-022-00355-0.

[10] S. Kühn *et al.*, "High Resolution Photoexcitation Measurements Exacerbate the Long-Standing Fe XVII Oscillator Strength Problem," *Phys. Rev. Lett.*, vol. 124, p. 225 001, 22 Jun. 2020. DOI: 10.1103/PhysRevLett.124.225001.

[11] S. Kühn *et al.*, "Oscillator-strength ratio of two Fe XVII soft X-ray transitions essential for plasma diagnostics finally agrees with theory," 2022. https://arxiv.org/abs/2201.09070

[12] M. Hoesch *et al.*, "Highly Charged Ions for High-Resolution Soft X-ray Grating Monochromator Optimisation," in *presented at the 14th International Conference on Synchrotron Radiation Instrumentation (SRI), Hamburg, Germany*, 2022.

[13] R. Steinbrügge *et al.*, "X-ray Photoabsorption by Metastable Highly Charged Ions," *submitted for publication*, 2022.