Photoionization of ions in arbitrary charge states by synchrotron radiation in an electron beam ion trap

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Abstract. Photoionization of ions in various charge states is studied with an electron beam ion trap at the synchrotron BESSY II. The ion target density achieved by this method, representing an increase of up to four orders of magnitude with respect to conventional techniques, gives unprecedented access to photoionization of highly charged ions at photon energies reaching the keV range. Data on near-threshold photoionization of \( \text{N}^{3+} \), \( \text{Ar}^{12+} \), \( \text{Fe}^{12+} \) combined with measurements on neutral gas targets in the same setup demonstrate the versatility of this technique and show both very good resolution and accuracy.

1. Introduction

Photoionization (PI) in the XUV and x-ray regime is a very important photoabsorption mechanism observed in astrophysical spectra, due to the high abundance of highly charged ions (HCIs) in the universe [1, 2, 3]. In addition to this direct relevance, the results of PI studies can be regarded as precise tools for the investigation of electronic structure of ions, allowing for a detailed characterization of ionization thresholds, autoionizing resonances, isotopic shifts, and fine structure [4]. This clearly highlights the importance of PI studies on HCIs.

Two techniques have been used for PI studies on ions during the last decades: dual laser produced plasma (DLPP) and merged-beam (MB) experiments [5]. DLPP is based on photoabsorption in a dense plasma containing ions in various charge states, which is generated by a strong laser pulse focused on a solid target. A synchronized second laser produced plasma acts as a pulsed, broadband soft x-ray light source. Investigation of HCIs is possible, however, not at very high accuracy, due to difficulties arising from limited reproducibility of both the light source and the absorbing plasma, as well as the transient nature and the strong density gradients of such plasmas and the need for time-resolved spectral diagnostic in the soft x-ray range. Additionally, absorption measurements are less sensitive than the detection of the ion produced by the PI process (photoion), as in MB experiments. There, a photon beam from a synchrotron is overlapped axially with an ion beam over a certain interaction region and a magnet separates the target ions from the photoions. Beam profile monitors measure both photon and ion beam density distributions and consequently allow for the determination of absolute cross sections with a typical accuracy of 20%. The MB method has become the experimental technique of choice for PI of ions in the last decade [6]. In spite of these advantages, the achievable area...
density of an ion beam is limited (up to $10^6$ cm$^{-2}$) and strongly decreases at higher charge states. Moreover, the ion beam may consist of a mixture of ions in the ground state and in excited metastable states, reducing the accuracy of inferred absolute cross sections.

Recently, a PI experiment on trapped ions demonstrated the viability of suppressing short lived metastable states [7]. After production, Xe$^{1+}$-ions were stored in a Penning trap for a time long enough so that excited species could decay before photon beam interaction. Photoions (Xe$^{2+}$) were detected by Fourier transform ion cyclotron resonance. However, the setup in its present form is restricted to targets of low charge state at low densities.

Here, we present the first results of PI studies in an electron beam ion trap (EBIT). This new technique allows for the irradiation of ions in arbitrary charge states at high area densities in the range of $10^{10}$ ions/cm$^2$, and utilizes photoion counting, leading to high accuracy and sensitivity. Additionally, this new approach offers all the possibilities of an ion trap, such as suppression of metastable states and control over the interaction time, which can be used to determine absolute cross section with no need for ion density measurements [8]. Thus, this technique combines the key advantages from methods utilized hitherto.

2. Setup
The concept for PI of ions in an EBIT with synchrotron radiation was first proposed two decades prior to this experiment by Church et al. [9], but has not been demonstrated up to now. Fig. 1 shows the main components of our setup, namely the EBIT (b) with the photon beam from a synchrotron (e) is adjusted with the aid of scintillation light from a retractable Ce:YAG crystal (c). The ion optics (f) guides extracted ions to the Wien filter for charge state separation and subsequent detection (d) on a position sensitive detector (PSD). For more details see text.
the overlap of the ion cloud and the photon beam (c).

An electron beam is emitted from a cathode on potential \( U_{\text{cath}} \), accelerated toward the trap region, consisting of ring-shaped electrodes on potential \( U_{\text{trap}} \) called drift tubes (DT), compressed and guided by a strong magnetic field and absorbed in a collector. Atoms or molecules can be injected at the trap center where they are ionized by electron impact and radially confined by the space charge of the electron beam. Axial confinement is governed by the application of adequate voltages to the DTs, resulting in a trapping region in the shape of a thin cylinder (50 mm in length, about 300 \( \mu \)m in diameter), well suited for an axial overlap with the photon beam.

In order to detect PI, ions from the trap are extracted through the collector, electrostatically deflected off the photon beam axis, charge separated by a Wien velocity filter, and finally counted on a position sensitive detector (PSD), cf. Fig. 1 (d). By variation of the photon energy, PI cross sections are investigated. Fig. 1 (f) shows the ion optics of the extraction beamline in more detail. Before the 90° deflection it is composed of four ring shaped electrodes. By cutting the third ring into four independent elements this assembly combines an einzel lens and a pair of deflection plates in a very compact design (steering lens). The electrostatic 90° ion deflector uses the principle of plane-parallel plates in the sense that the included angle of the incoming ion beam and the produced electric field is 45°. In contrast, the electrodes are not shaped as plates, but rather as two concentric cylinders in order to achieve significant astigmatism reduction. Focusing the ion beam on the entrance of the deflection unit leads to a double refocusing on the exit. Considering that spatial limitation demanded a bending radius of 20 mm the performance was satisfactory. Following deflection, a series of electrodes (including a second steering lens) and an adjustable aperture prepare the ion beam for charge-state separation by crossed electric and magnetic fields (Wien filter). Ions of a certain velocity will pass the Wien filter on a straight trajectory. The resolution can be adjusted by proportional scaling of the electric and magnetic field, which enables the simultaneous detection of target ions of any charge state \( q \) and corresponding photoions of charge state \( q + 1 \) on the PSD.

Obviously, the electron beam energy \( E_{\text{kin}}^e = e \cdot (U_{\text{trap}} - U_{\text{cath}}) \) has to be high enough to ensure target ion production. On the other hand, it is of crucial importance to stay below the ionization threshold \( E_{\text{th}} \) of the PI process under investigation \( E_{\text{kin}}^e \leq E_{\text{th}} \leq h\nu \), since otherwise electron impact ionization (EII) by typically \( j_e = 10^{21} \) electrons \( \text{s}^{-1} \text{cm}^{-2} \) would completely dominate the PI of typically \( \Phi = 10^{16} \) photons \( \text{s}^{-1} \text{cm}^{-2} \) (\( j_e \cdot \sigma_{\text{EII}} \gg \Phi \cdot \sigma_{\text{PI}} \)). In the case of Ar\(^{12+} \) this translates to \( E_{\text{th}}^{11+} \approx 619 \text{ eV} \leq E_{\text{kin}}^e \leq E_{\text{th}}^{12+} \approx 684 \text{ eV} \). The required fine tuning of the electron beam energy is easily achieved in an EBIT. However, even below the ionization threshold the signal does not completely vanish. This background is interpreted as EII of target ions in metastable states and other similar two step processes, resulting in the production of the next

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**Figure 2.** (color online) PI structures of \( \text{N}^{3+} \) by counting \( \text{N}^{4+} \) as a function of the photon energy. The ionization threshold for \( \text{N}^{3+} \) in the ground state at 77 eV is clearly visible. Resonant structures are due to the autoionization of doubly excited intermediate states (see labels). Features below the ground state ionization threshold are identified as PI of metastable \( \text{N}^{3+} \). Our measurement (top) is compared to a MB experiment (bottom) by Bizau et al. [13].
Figure 3. (color online) (a) PI resonances of atomic He (top) allowed for calibration of the N³⁺ data with 8 meV accuracy by comparison with experiments (bottom) by Domke et al. [14]. Resonances are labeled by the principal quantum number n of the outer electron of doubly excited autoionizing states. (b) The PhoBIS measurement on atomic Ne (bottom) is compared to theory (top) by Schulz et al. [16]. Resonances are labeled by the transitions to autoionizing states.

ionization stage. Efficient ion extraction requires the DTs to be on a certain minimal positive electrical potential $U_{\text{trap}}$, which determines the kinetic energy of the ion beam ($E_{\text{kin}} = q \cdot U_{\text{trap}}$). At low photon energies this demand contradicts the aforementioned requirements, as can be seen in Fig. 1 (a). The experiments presented herein achieve efficient ion extraction at an ion beam energy as low as 300 eV per unit charge. Therefore, measurements at photon energies above 350 eV were performed in a convenient continuous mode, while, at lower photon energies, target ion preparation and photoion detection had to be separated temporally in the form of a cyclic measurement procedure.

To guarantee a good overlap of the ion cloud and the photon beam, a retractable Ce:YAG crystal can be inserted into the trap center. The scintillation light caused by the impact of both the photon beam or the weakened electron beam, is imaged onto a CCD camera, via a mirror with a hole, which can be moved to the position of the electrostatic deflector, cf. Fig. 1 (c). The electron beam marks the position of the ion cloud. By these means, the overlap can be determined to 10 $\mu$m accuracy and adjusted accordingly by aligning the (1.5 tons) FLASH-EBIT with the help of setting screws. Furthermore, these precise measurements on the geometry of the overlap provide essential parameters for absolute cross section determinations.

3. Experimental results
The experiments were conducted during two campaigns at the Berliner Elektronen-Speicherring Gesellschaft f"ur Synchrotronstrahlung (BESSY II) using the transportable Heidelberg FLASH-EBIT [10], developed at the Max-Planck-Institut f"ur Kernphysik (MPI-K). The beamlines U125/2-SGM [11] and U49/2-PGM1 [12] covering photon energy ranges from 40 to 180 eV and from 85 to 1600 eV have been used. Both achieve maximal photon fluxes of approximately $10^{13}$ photons s⁻¹ at 100 mA ring current and 0.1% bandwidth.

3.1. Low photon energies (pulsed measurement): N⁴⁺
Be-like nitrogen N³⁺ with a PI threshold and near-threshold resonances in the optimal photon energy range of the beamline U125/2-SGM was chosen for the test experiment at the first campaign in 2008. The cyclic measurement procedure mentioned above had to be utilized at these low photon energies. The trap was on ground potential during the production of N³⁺-ions
Figure 4. (color online) PI of ions in charge state $q=12$ demonstrate the ability to access HClIs by the EBIT based method. (a) PI threshold of $\text{Ar}^{12+}$ at 683.93 eV, obtained by a fit to the $\text{Ar}^{13+}$-signal. The strong background signal below the ionization edge is mainly caused by residual gas ions with close lying charge-to-mass ratios ($\text{O}^{5+}$, $\text{C}^{4+}$). (b) Near-threshold PI of $\text{Fe}^{12+}$ revealing two significant resonances at 362.6 eV and 370.0 eV.

with an electron beam energy of only 50 eV. After 4 s the electron beam was turned off and the trap potential was raised to a level suitable for efficient ion extraction (500 V). During this step the ions were confined in the magnetic trapping mode [15]. The photon beam continuously irradiated the ion cloud and the photon energy was raised stepwise after each cycle. Fig. 2 shows the observed PI features. Good agreement with MB experiments was found. However, the proportion of metastable ions in the EBIT experiment is significantly lower, due to the photon interaction period without electron beam. The photon energy scale was calibrated by PI of neutral He, as described in the next section.

3.2. Photon Beam Ion Source (PhoBIS)
The setup for PI of ions in an EBIT can easily be used also to measure PI of neutral atoms or molecules. For this purpose, the electron beam is turned off and the photon beam directly interacts with neutral gas injected at high densities (compared to normal EBIT operation) to the trap center. The produced photoions can be extracted and counted on the PSD. Similar measurements have been reported by Kravis et al. [8], who introduced the acronym PhoBIS. We operated the FLASH-EBIT in the PhoBIS mode for photon energy calibration purposes and measured PI of neutral He and Ne as plotted in Fig. 3 (a) and (b) respectively. A calibration accuracy of 8 meV could easily be achieved by comparing to results from dedicated He PI experiments by Domke et al. [14]. PI of Ne produced an energetically well defined ion beam at suitable count rates for the PSD, which was ideal for optimization of ion extraction conditions without electron beam. Furthermore, the demonstration of PhoBIS mode proves that the EBIT-based PI setup allows direct comparison of atoms, ions, and HClIs (ions of arbitrary charge states) in a single setup. Valuable insight into electronic correlations can be expected, e.g., by comparing K-shell PI of atomic Ne and highly charged Ne-ions. Additionally, this type of experiment could establish new calibration standards at high photon energies, as theory is more accurate on few electron systems.

3.3. High photon energies (continuous measurement): $\text{Ar}^{12+}$, $\text{Fe}^{12+}$
High photon energies available during the second campaign in early 2009 allowed for investigation of significantly higher charge states in the more convenient continuous mode, i.e. target ion production, photon beam interaction and ion extraction were steadily running, while the
photon energy was stepwise increased. Thresholds and PI resonances of Ar\textsuperscript{q+} (q=8,10,12) and Fe\textsuperscript{q+} (q=12,14) at photon energies from 350 to 1200 eV were obtained. Most extensive studies were carried out on Ar\textsuperscript{12+} and Fe\textsuperscript{14+} and separate publications addressing these systems are in preparation. Here, results on Ar\textsuperscript{12+} and Fe\textsuperscript{12+} are presented. Fig. 4 (a) shows the threshold of Ar\textsuperscript{12+} at 683.93 (0.19) (0.42) eV (values in brackets give statistical and calibration errors respectively). This is the highest PI threshold energy tested experimentally by photons and disagrees significantly with literature (NIST: 685.9 eV [17]). For Fe\textsuperscript{12+}, near-threshold resonances were found at 362.6 (0.3) eV and 370.0 (0.3) eV, cf. Fig. 4 (b). Unambiguous identification of the associated transitions by comparison with available theoretical values was not possible to the best of our knowledge. Further accurate experimental tests on PI of HCIs are clearly needed for guidance of theory.

4. Outlook
The experiments presented herein clearly demonstrate the viability of EBIT based PI studies at synchrotron facilities, ranging from neutral systems up to HCIs. Moreover, several key technical advantages from other methods are combined in such a setup. Beyond access to HCIs, found in both astrophysical and laboratory-based fusion plasmas, an ion trap offers control over metastable species and interaction times, introducing a promising alternative approach toward the determination of absolute cross sections. Such a test measurement has been performed on Fe\textsuperscript{14+} and will be published elsewhere (submitted to PRL). Furthermore, very good accuracy in the determination of PI features has already been reached by the use of undulator beamlines and the detection of photoions. In an improved apparatus the remarkably high target ion area density of typically $10^{10}$ ions/cm\textsuperscript{2} should lead to a significantly increased sensitivity down to the few kbarn range. These advantages strengthen the case for the deployment of permanent EBITs at synchrotron facilities.

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