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Motivation

Novel ion production and manipulation techniques offer the opportunity to prepare a large variety of atomic systems „on demand“ with steadily growing efficiency. Any charge state for any stable element in the periodic table, at velocities ranging from the relativistic regime down to micro-Kelvin temperatures, can now be selectively produced and stored. By similar methods even atomic systems containing radioactive nuclei or exotic particles like positrons, muons or antiprotons can be made available for precision studies. MPIK groups are strongly involved in this flourishing field of atomic physics research. The activity is based on a unique combination of in-house facilities – the accelerators, the cooler-storage ring (TSR), the newly set-up electron beam ion trap (EBIT), and a slow positron source used for positronium research. Moreover, the MPIK participates in a variety of external activities – among others, the antiproton (ASACUSA) programme at CERN, the planned charge breeding of radioactive beams at TRIUMF and GSI, and the atomic physics research at the upcoming TESLA free-electron laser at DESY. Recently MPIK has also acquired a leading role in several key projects for the new Facility for Antiproton and Ion Research (FAIR) at GSI which will become a strong focus for future international activities.

Interest in all kind of ions, their electronic structure and dynamical behaviour, is fuelled by their large abundance in terrestrial (fusion) and astrophysical plasmas. In regions such as interstellar clouds, stellar coronae, supernova explosion remnants, accretion disks or active galactic nuclei, highly charged ions are of paramount importance for the characterisation of the energy balance, temperature, velocity distribution, and so on. The electronic structure of highly charged ions can even influence nuclear reaction pathways, as in the case of bound $\beta$-decay, and the nucleosynthesis through supernovae may be modified in this way.

The highly charged ions and the wide spectrum of other atomic species becoming available in the laboratory by these methods provide a testing ground for basic theoretical concepts ranging from fundamental symmetry laws in physics to relativistic many-body quantum systems and the quantum-electrodynamics (QED) in strong electric and magnetic fields. The main tools of investigation are precision spectroscopy in the optical and the X-ray domain, resonant electron collision processes and precision lifetime measurements. For example, precision spectroscopy of heavy one-electron systems can be applied to study so-far poorly understood nuclear properties like the magnetization or neutron distribution, and the charge radii of nuclei, completely unaffected by deficiencies in the understanding of the electronic structure. In the opposite limit, purely leptonic few-body systems, such as the negative positronium ion ($\text{Ps}^-$) investigated at the MPI-K, can sensitively probe the understanding of elementary interactions unperturbed by nuclear effects.

Instrumentation: The Cooler-Storage Ring (TSR) and a Trap for Ions at any Charge State (EBIT)

Two major facilities, the cooler-storage ring TSR and the newly installed electron beam ion trap and source (EBIT), provide a unique experimental backbone for all facets of ion research. They are equipped with latest instrumentation, such as the electron cooler and sensitive probes for ion beam analysis at the ring, high-resolution laser sources, fragmentation spectrometers, and precision spectroscopy tools at the ring as well as at the EBIT.
The cooler ring TSR makes beams of highly charged ions available for experiments at excellent beam quality and intensity. It is recognised as a prime facility world wide for high resolution, absolutely normalised electron-ion interaction studies. Very recently, pioneering the experimental techniques to be used at future ion facilities such as FAIR, the TSR has been the first facility to implement a novel ultra-cold high-precision electron target (Figure 1), along with a multi-purpose fragment imaging spectrometer, where stored ions can be collided with quasi-monoenergetic electrons at any chosen relative energy – from below a milli-electronvolt up to several kilo-electronvolts – while a separate electron cooler continuously ensures the optimal ion beam quality. The electron target employs advanced techniques to reach low internal electron beam temperatures; thus, a unique cryogenic electron source using a GaAs photocathode was taken into operation, reaching internal beam temperatures well below one milli-eV, up to an order of magnitude better than at any other similar device. Both atomic ion recombination and molecular ion fragmentation studies have already strongly profited from the new facility.

The Heidelberg electron beam ion trap and source (EBIT), shown in Figure 2, came into operation 2001, widely extending and complementing previous ion research at the MPIK. Based on the principles of the original EBIT developed in the late 1980s at the Lawrence Livermore National Laboratory, our EBIT follows a completely new concept. With a magnetic compression field of 9 T and an electron current of up to 750 mA at anticipated energies up to 300 keV, it is designed to produce all kind of highly charged ions up to bare uranium, to trap and cool them by evaporative or resistive cooling, and to extract them for precision spectroscopy or reaction dynamics studies.
Selected Results

**Quantum Interference during Photorecombination Processes.** The electron beam ion trap (EBIT) gives access to electron-ion photorecombination for ions in extreme charge states. Such measurements were recently performed with unprecedented accuracy for mercury ions in extreme charge states, \( \text{Hg}^{78+}\ldots^{75+} \), where the few remaining electrons correspond to helium(He)- up to boron(B)-like configurations. The capture of electrons by such ions is sensitively monitored in the EBIT by recording the emitted X-rays and the changes in the charge state balance in the trap, while the electron collision energy is set to well defined values (*Figure 3*). In experiments with Hg ions, at collision energies up to 75 keV, an energy spread of only 1/1000 relative to the collision energy was achieved. Beside the direct radiative recombination process, also intermediate excitations of the most strongly bound electrons are observed, where 1s electrons are promoted to the \( n = 2 \) or higher shells while the incident monoenergetic electron is captured – the so-called dielectronic recombination. Resonance energies for this process could be accurately determined on an absolute scale at the level of few eV. The analysis of the X-ray maps reveals impressive features of the quantum interference in the photorecombination, which can for the first time be analysed charge-state by charge-state in the KLL resonances of highly charged He- to B-like ions.

**Low-energy Dielectronic Recombination of Highly Charged Ions.** In many astrophysical plasmas most recombination occurs via dielectronic recombination, using a large manifold of different reaction pathways where a free electron of a particular “resonant” energy excites a bound electron and remains itself attached to the ion, forming a doubly excited quantum state. The ion storage ring TSR with its unique electron-ion interaction zone is particularly well suited to study such resonances at low and intermediate collision energies. Even for relatively simple electronic structures, the exact collision resonance energies often have a large influence on the average recombination rates and in many cases are not known reliably from theoretical predictions. For an astrophysically important system, the berylliumlike magnesium ion \( \text{Mg}^{8+} \), recent measurements at the TSR have revealed surprisingly strong capture resonances at low collision energies (*Figure 4*), where a small set of quantum states at collision energies as low as 20 milli-electronvolt turned out to be responsible for the dominant part of the electron-ion recombination rate. When studied at high energy resolution, low-energy dielectronic recombination resonances of this type
contain a wealth of information about the atomic structure of highly charged ions. The most recent measurements with the new electron target facility at the TSR indicate that the energy accuracy in such studies can be improved to the sub-millieu-electronvolt level (Figure 5), making low-energy dielectronic resonances a sensitive probe for excitation energies in highly charged few-electron systems, suitable to test QED contributions with accuracies on a per-mille level as well as hyperfine effects in the electronic level energies revealing properties of the atomic nucleus.

Figure 4: High-resolution measurement of dielectronic recombination (DR) via atomic resonances for Mg$^{8+}$ ions at the TSR (dots: measurement; full lines: resonances derived from the measurement; dashed line: calculated non-resonant radiative recombination (RR). The inset shows the experimentally derived DR rate coefficient (full line) as a function of the electron temperature with indicated ranges where Mg$^{8+}$ ions occur in astrophysical plasmas. At an electron temperature of 3 eV the DR rate is about a factor of 3 higher than non-resonant RR. The dashed lines indicate the effect on the DR rate if a theoretical prediction would miss the exact resonance energies by 0.1 eV, the typical range of accuracy presently achieved; predicted DR rates would hence be uncertain within a factor of about 3, while the experimental rate is accurate to ~20%.

Figure 5: Dielectronic recombination resonances of the lithium-like scandium ion Sc$^{18+}$. The overall energetic position of the resonance pattern (whose line spacings are well predictable) reveals the 2s-2p$^{3/2}$ excitation energy of Sc$^{18+}$ to which QED effects contribute about 0.2 eV. The new electron target facility and its cryogenic photocathode give access to the individual hyperfine structure components (lower diagram; preliminary data) predicted theoretically but not resolved in the previous measurements at TSR (upper diagram); this largely reduces the uncertainty of the extracted 2s-2p$^{3/2}$ excitation energy.
Few-body QED. The study of forbidden transitions in the optical region, among the strongest signatures of highly charged ions occurring in nature, has been continued at the Heidelberg EBIT, delivering not only the most precise wavelength values for any highly charged ion worldwide, with error bars well below 0.3 ppm (a twenty-fold improvement in comparison with prior work), but also allowing us to resolve for the first time their Zeeman splitting (Figure 6) with an accuracy high enough to test theory up to the QED contributions due to the electron anomalous magnetic moment (EAMM). At this precision, QED corrections to the atomic level energies in, e.g., Ar$^{13+}$ are four orders of magnitude larger than our experimental error bar. Moreover, the lifetime of the metastable state from which the forbidden Ar$^{13+}$ transitions arise has been determined with an accuracy of 0.1%, testing atomic structure calculations at a hitherto unaccessible level, being again sensitive to EAMM contributions. A collaboration with a leading theory group in this field now aims at disentangling the QED contributions from electron correlation effects. The development of a laser spectroscopic setup in our laboratory has been finished, and first tests of the system have already taken place; a large gain in accuracy is expected from this method.

Figure 6: The Zeeman components of the coronal line ArXIV at 6 T. The central wavelength of this forbidden M1 transition, 441.2559(1) nm, is the most accurately known of any highly charged ion, and contains a QED contribution of 0.3% of the total energy.

Precision Test of Special Relativity. High quality ion beams in storage rings are among the most sensitive probes presently available for testing the exact validity of time dilation as predicted by the theory of special relativity. In a recent TSR experiment the accuracy of such tests has been improved by about a factor of ten in comparison to older experiments employing different methods. For this purpose, the Doppler shifts for an optical resonance in $^7$Li$^+$ ions – circulating in the TSR at about 6.5% of the speed of light and interacting with parallel and antiparallel light – were measured with an accuracy of $1\times10^{-9}$ using laser saturation spectroscopy. By the comparison of these frequencies with the ions’ rest frame frequency, special relativity could be confirmed at a level of $|\alpha| < 2.2\times10^{-7}$ where $\alpha$ defines a possible modified time dilation factor as $\gamma_{\exp} = (1-\beta^2)^{-1/2+\alpha}$. The overall accuracy is presently limited both by the resonance frequency measurement as well as by the uncertainty of the $^7$Li$^+$ rest frame frequency.

The accuracy of the frequency measurement could meanwhile be improved to $2 \times 10^{-10}$. This will allow us to reduce also the present uncertainty of the $^7$Li$^+$ rest frame frequency by performing a second Doppler shift measurement with $^7$Li$^+$ ions at the lowest velocity possible at the TSR (3% of the speed of light). Ultimate sensitivity on $\alpha$ is then expected to be gained by extending the high-speed frontier. For this purpose, a measurement with $^7$Li$^+$ ions at 33% of the speed of light is presently being prepared at the Experimental Storage Ring of GSI, Darmstadt, with an improvement of the accuracy in $\alpha$ by a factor of 10 being well within reach.
Quantum Interference in Highly Charged Hg$^{75+\ldots 78+}$ ions


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We present experimental data on the quantum interference between direct and dielectronic recombination of highly charged mercury (Hg$^{75+\ldots 78+}$) ions in the KLL resonance region. The interference, observed for the first time for well-defined charge states in the Heidelberg EBIT, manifests itself in the asymmetry of line shapes, characterized by “Fano factors”, which have been determined with unprecedented precision for the most dominant charge states in the trap.

One of the most striking consequences of the wave-matter dualism is the appearance of quantum interference phenomena [1]. As a result, asymmetric resonance line profiles characterized by the so-called Fano factor are observed whenever resonant and non-resonant pathways interfere. We observe the interference between the radiative (direct) recombination and dielectronic (indirect) recombination of heavy highly charged ions collisions with free electrons. Our experiment confirms with improved accuracy an earlier observation carried out in the LLNL Super-EBIT [2] with uranium ions.

In the radiative recombination (RR), a free electron is captured into a vacant state of an ion emitting a photon. The dielectronic recombination (DR) is a resonant process where a free electron is captured and a bound electron is simultaneously excited. Later, the doubly excited intermediate state is stabilized via photon emission. At energies close to the DR resonances, it is not possible to know if the system has passed through the doubly excited state (DR) or if it went directly to the final state (RR). Both pathways are then indistinguishable and, therefore, quantum interference can occur.

Mercury ions ranging from Hg$^{75+}$ to Hg$^{78+}$ were produced and trapped at the EBIT in Heidelberg [3]. Ionization takes place through successive collisions with an intense electron beam compressed with an 8 T magnetic field. The electron beam energy was scanned very slowly (37 V/s) across the KLL resonances (45-53 keV) in order to maintain the electron impact ionization in equilibrium with the recombination processes at each beam energy. In the experiment, both the photon and electron beam energies are simultaneously recorded for each event. After an appropriate data acquisition time, two-dimensional maps (photon energy vs. electron energy) of the photorecombination rate are obtained. By projecting specific regions of this map onto the electron beam energy axis, detailed information can be extracted (see Fig. 1).

In order to fit the asymmetric experimental data, we used a Fano profile function [4] convoluted with a normalized Gaussian distribution in order to account for the electron energy spread ($\approx$50 eV). The fit quality was tested with the $\chi^2$ over degrees-of-freedom (DoF) method. As clearly seen in Fig. 1, the observed and calculated asymmetry Fano factors including their signs are in good agreement with each other.

In conclusion, we have demonstrated experimentally the quantum interference between dielectronic and radiative recombination in highly charged mercury ions. The Fano factors for several well-resolved resonances have been determined with a relative error of 6%. The results show a good agreement with theoretical predictions obtained with the MCDF method [5]. It should also be pointed out that with our present technique absolute excitation energies in the range of 50 keV can be determined with an absolute experimental uncertainty as small as $\pm$ 5 eV.

References


The Zeeman splitting of M1 transitions in the ArXIV spectrum


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An observation of the Zeeman effect in the magnetic dipole (M1) coronal lines from highly charged Ar$^{13+}$ ions is reported. The splitting of spectral lines can be used to measure magnetic fields in tokamak plasmas [1, 2]. Various spectroscopic techniques used so far suffered from excessive thermal line broadening. In the present work, Ar$^{13+}$ ions are produced in an electron beam ion trap (EBIT) [3], and by a proper choice of the trap parameters (low electron current (20-50 mA), low axial trapping voltage (nominally 0-10 V) and strong magnetic field (6.82 T)) the Doppler width was reduced enough to observe the Zeeman splitting with an experimental FWHM of 0.035 nm at 442 nm.

In the weak-field limit, the Zeeman-splitting of an energy level is given by

$$\Delta E = g_J \mu_B B M$$  
(1)

where the $g_J$ is the Landé factor for total angular momentum J (in pure LS coupling), $\mu_B$ the Bohr magnetron, $B$ the magnetic field strength and $M$ the projection onto the z axis. In particular, in the $2s^22p \, ^2P_{1/2} \rightarrow ^2P_{3/2}$ transitions, the upper level (J=3/2) is split into four sublevels, while the lower level (J=1/2) is split into two. Thus, for the M1 transitions we expect six transition lines (anomalous Zeeman effect). For M1 transitions, the central components (\(\Delta M=0\)) are polarized perpendicularly to the field, while for E1 transitions the polarization is parallel to the field. The angular distribution of M1 radiation is identical with that of E1 radiation. However, they have opposite polarizations. For M1 radiation, the \(\Delta M=0\) transitions are \(\pi\)-components and the \(\Delta M=\pm 1\) are \(\sigma\)-components (see Fig. 1).

Tens of individually calibrated spectra were acquired with a grating spectrometer set at slightly varying grating angles each time, in order to sample the line profile and achieve excellent statistics. The relative intensities of the \(\pi\) and \(\sigma\)-components also depend of the grating polarization efficiency, which has been measured for the wave-lengths of interest. By using a polarizer we could select the \(\sigma\)-components (see Fig. 2a), and then by rotating it by 90°, the \(\pi\)-components (see Fig. 2b).

We have measured again, with high accuracy and in perfect agreement with previous measurements [5], the transition wavelength, obtaining \(\lambda = 441.2559(1)\) nm. Through the measured line splitting we determined the \(g_J\) of the upper (J=3/2) and lower (J=1/2) level of the 2s$^2$2p state as well. The experimental results of \(g_{3/2} = 1.331(1)\) and \(g_{1/2} = 0.655(3)\) can be compared with theoretical predictions, of 1.331665 and 0.664492, respectively. The discrepancy observed in the \(g_{1/2}\) factor seems significant, so further theoretical analysis is underway.

In conclusion, the Zeeman splitting and polarization of the M1 transitions of Ar$^{13+}$ ions have been observed in an electron beam ion trap, and the $g_J$ factors of the corresponding levels were determined experimentally for the first time.

References

High Precision X-ray Spectroscopy on H- and He-Like Argon Ions

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An electron beam ion trap (EBIT) is an ideal device for precision spectroscopy of highly charged ions, especially because of the high spectral purity, among other reasons. Due to the sequential nature of the ionisation and excitation processes in an EBIT, transitions are free of satellites, which leads to extremely symmetric line profiles. Hydrogenic ions trapped in an EBIT could be used to probe QED contributions, measure nuclear size effects, and establish new x-ray standards free of solid-state effects. However, for x-rays of few keV energy, currently only bolometers and crystal spectrometers can reach the needed accuracy.

The diverse existing crystal spectrometer types have different requirements concerning positioning and stability; when using flat crystals, it is vitally important to know the exact reflection position of the x-ray line on the crystal in order to be able to derive the Bragg angle from the measured crystal and detector angles. Usually, the reflection position is defined by collimating the incoming x-rays. A novel method of reflection position calibration not using any collimation has been introduced in the HD-EBIT flat crystal x-ray spectrometer [1], making it more suitable for experiments at low x-ray fluxes and eliminating numerous sources of error. In 2004, the first test measurements of transitions in highly charged argon ions have been performed and analyzed.

To test the novel method, the transition $1s^22p\;^1P_1 \rightarrow 1s^3\;^3S_0$ of He-like argon (commonly referred to as $w$-line) has been measured at the HD-EBIT with respect to the Lyman-$\alpha$ transition of H-like argon, which is presently known to a precision of 5 ppm [2]. In total almost 100 x-ray exposures at the expected Bragg angles (with small deviations to actively change the reflection position on the crystal) of the Lyman-$\alpha$ and $w$ transition have been acquired alternately, all of them preceded and followed by a visible light exposure. For each of these sets of spectra the relative position of the x-ray line to the visible light lines was obtained using appropriate fits. This information was plotted over the crystal angle at which the single spectra were acquired. From this plot the difference of Bragg angles of the two lines was extracted. With knowledge of this angular difference and using the literature-value of the Lyman-$\alpha$ transition wavelength, the energy of the $w$ transition was found to be $3139.539(22)$ eV, in good agreement with the literature value of $3139.552(37)$ eV measured by [3].

Figure 2: Sum of all Lyman-$\alpha$ spectra and Voigt fit. The small box is the same spectrum with a logarithmic ordinate.

The accuracy in the present measurement is limited by the knowledge of the reference line position and the statistical uncertainty, both contributing about 5 ppm to the total error. However, a previous measurement used to identify systematic error sources showed that the latter can be reduced to safely below 1 ppm. In the future, it is planned to extend the method from relative to absolute wavelength measurements. From our promising first results we expect that a precision approaching 1 ppm or better can be achieved which would make the EBIT the tool of choice to establish new x-ray standards.

References

Highly Accurate Lifetime Measurement of the Ar XIV $1s^22s^22p^2 \, ^2P_{3/2}^o$ Metastable Level at the Heidelberg Electron Beam Ion Trap.


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Accurate measurements of atomic transition energies and excited-state lifetimes are needed to improve our understanding of the atomic structure. Such information for fine-structure levels of highly charged ions (HCI), forbidden to decay via the electric-dipole (E1) interaction, besides of being of importance for the diagnostics of tenuous plasmas, are of great interest due to their sensitivity to quantum electro-dynamic (QED) effects.

Over the last few years, QED ab initio calculations in HCI have become increasingly accurate. These contributions to the energies of forbidden transitions such as Ar XIV $1s^22s^22p^2 \, ^2P_{3/2}^o - \, ^2P_{3/2}^o$ have been found to be as large as 0.2%. Transition energy measurements have been performed with a record-breaking accuracy beyond the ppm (part-per-million) level [1] deeply testing QED effects of a 160 ppm level. Measurements exposing QED effects to excited-state lifetimes are also essential. Lifetimes reveal non-averaged unique and direct information on the magnitude of the expansion coefficients in an individual basis of the atomic wavefunction, and hence, investigate and test an important but yet widely unexplored facet of current atomic theories.

Unfortunately, only a very few lifetimes in atomic physics are known to 1% accuracy or better. Accurate lifetime measurements still remain an important experimental challenge due to the difficulty of reaching a high statistical significance allowing us to efficiently control, understand, and model the time evolution of the ion (or atom) population under observation. The Electron Beam Ion Trap of the Max-Planck-Institut für Kernphysik (HD-EBIT) produces as well as confines HCIs and offers the possibility to significantly circumvent these problems by its large trap dimensions, and high light collection efficiency.

The lifetime of the metastable $1s^22s^22p^2 \, ^2P_{3/2}^o$ level of boronlike Ar XIV was measured to be 9.573(4)(5) ms (stat)(syst) by monitoring its temporal decay to its ground state $^2P_{1/2}^o$ through a magnetic-dipole (MI) optical transition at 441.2559(1) nm [1] (see Fig.1). Achieving an unprecedented 0.1% accuracy level, this measurement is 17 times more precise than a previous one at the Lawrence Livermore National Laboratory (LL) EBIT of 9.70(15) ms [2] and, thus, is the most accurate ever performed in multiply charged ions.

As seen in Fig.2, the result shows a discrepancy of about 3σ with the most recent theoretical predictions, corrected by the accurate experimental $^2P_{1/2}^o - ^2P_{3/2}^o$ transition wavelength and with the previously-neglected contribution of the free electron anomalous magnetic moment included.

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Laser Spectroscopy of Highly-Charged Ions in the EBIT

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A setup for high resolution laser spectroscopy of highly charged ions has been installed and tested at the Heidelberg electron beam ion trap (EBIT). Heavy ions with few (or even only one electron) are ideal systems to investigate relativistic and nuclear size effects as well as quantum-electrodynamics (QED) in strong fields and to test the corresponding models. Particularly interesting are the hyperfine transitions in the ground state of heavy hydrogenic ions which have been already investigated in storage rings by means of laser spectroscopy and in EBITs with spontaneous emission spectroscopy[1, 2]. These studies have fuelled intense discussions on the contributions of the nuclear magnetization distribution and QED effects to the observed transition wavelengths.

The hydrogenlike ground state hyperfine splitting energy is given by[3]

$$\Delta E^{(1s)} = \frac{4}{3} \alpha (\alpha Z)^3 \frac{\mu}{\mu_N} \frac{m_e e^2}{I} \times \left\{ A^{(1s)}(1 - \delta^{(1s)})(1 - \epsilon^{(1s)}) + \chi^{(1s)} \right\}$$

with $\mu/\mu_N$ the nuclear magnetic dipole moment, $I$ the nuclear spin, $A^{(1s)}$ the relativistic correction, $\delta$ the correction for the nuclear charge distribution (Breit-Rosenthal effect), $\epsilon$ the correction for the nuclear magnetisation distribution (Bohr-Weisskopf effect) and $\chi$ the radiative (QED) correction. Because of the strong scaling with the nuclear charge $Z$ ($\Delta E^{(1s)} \sim Z^3$) the hyperfine splitting energy for $Z \geq 60$ is boosted into the optical region and therefore becomes accessible for laser spectroscopy. Furthermore, the transition probability for dipole forbidden transitions increases as well leading to lifetimes of the upper hyperfine level in the order of ms (compared with $1.1 \times 10^7$ years in the case of hydrogen).

The combination of an EBIT and a tunable laser provides very appropriate conditions for high-precision studies on trapped highly charged ions. The laser system consists of a 100 Hz pulsed Nd:YAG laser (9 ns, 325 mJ at 1064 nm, 120 mJ at 532 nm) that is used to pump a tunable dye laser. A spectral range from 350-800 nm into the UV region. Locking the laser wavelength to a frequency stabilized HeNe-Laser that is part of the laser system an absolute wavelength stability of 5 ppm is achieved. Calibration is done by optogalvanic spectroscopy (OGS) where well known optical lines of singly charged gaslike ions occurring in a discharge from a hollow cathode lamp are used.

A schematic overview of the experimental setup is given in Fig. 1. The laser beam is superimposed axially upon the trapped ion cloud by means of off-axis parabolic mirrors mounted inside a complex UHV vacuum chamber. Adjustments of the laser beam to optimize the overlap with the ion cloud can be done fully from the outside of the vacuum system. The fluorescence detection system uses a cooled photomultiplier tube (PMT) that is located approximatelly 1 m away from the EBIT in order to not be affected by the magnetic field. A polished aluminum light guide in combination with a narrow-bandwith interference filter collects the optical fluorescence photons and guides them towards the detector. In order to prevent scattered light from the laser pulse produced in the drift tube region to saturate the photon detector an optical chopper is placed between the light guide and the PMT. The pulsed laser will excite the ions stored in the magnetic trapping mode[4] after cyclically turning off the electron beam. After excitation, excited levels will decay into their ground state within a few milliseconds, according to their long lifetimes.

The setup successfully passed initial tests and adjustments under ion trapping conditions (using the M1 $2s2p^3P_{1/2} - 2p^3P_{3/2}$ transition of ArXIV with $\tau \sim 10$ ms) and will now be optimized to further reduce scattered light which has up to now hindered the detection of the fluorescence signal.

References
Two new electron beam ion traps (EBITs) are currently under construction in the EBIT group at the MPI-K. The first one, called TITAN-EBIT, will be an essential part of the Penning trap mass spectrometer TITAN (Triumf’s Ion Trap for Atomic and Nuclear science) [1], located at ISAC/TRIUMF in Vancouver, Canada. At ISAC (isotope separator and accelerator) radionuclides are produced through spallation and fission reactions induced by high energetic protons impinging into thick targets. The atomic through spallation and fission reactions induced by high energetic protons impinging into thick targets. The atomic
masses of the radionuclides will be determined by measuring the cyclotron frequency \( \nu_c = (q \cdot B)/(2\pi \cdot m) \) of the corresponding ion with charge \( q \) and mass \( m \) as it gyrates in a magnetic field of strength \( B \) in a Penning trap. The relative accuracy of the frequency measurement is given by the following relation:

\[
\frac{\Delta \nu}{\nu} \propto \frac{m}{T_{ex} q B \sqrt{N}}. \tag{1}
\]

with \( T_{ex} \) being the radiofrequency excitation time and \( N \) the number of trapped ions. Increasing \( q \) (or \( B \), which is limited to \( \approx 20 \) T due to technical reasons) can enhance the relative accuracy. By using higher charge states a specific desired accuracy can be reached with shorter excitation times and smaller count rates than in the case of singly charged ions. Since both, the amount of ions and their nuclear half-life (i.e. measurement time) are limiting factors in investigating radionuclides, charge breeding in an EBIT will allow to extend highly accurate mass measurements in regions further away from the valley of \( \beta \)-stability.

The second apparatus, called TESLA-EBIT, is intended to be operated at the free electron VUV laser test facility (TTF) at DESY in Hamburg, but also on synchrotron beam-lines. Laser spectroscopy on highly charged ions, a field which is widely unexplored and only few data exist, will be extended into the VUV range and x-ray energies. Here the TESLA-EBIT will profit from the relatively large photo excitation cross sections and the excellent energy resolution of the primary photon beams. The first experiments the electronic structure of Li-like highly charged ions will be explored with an accuracy not yet achieved by other means.

The electron beam in each of the two new EBITs is produced with a thermionic cathode and then electrostatically accelerated and injected into a strong magnetic field. Here the electrons are radially confined by the Lorentz force, and the beam is compressed as the magnetic field strength increases. The magnetic field of 6 T is generated by a cryogen-free superconducting magnet operating at 3.5 K. The electron beam acceleration voltage will be variable up to 80 kV, and a beam current of 5 A is envisaged. With these parameters a compression of the electron beam down to 150 \( \mu \)m is expected. The confinement of such an amount of negative electric charge provides a space charge potential, which is more than 5 kV deep. This space charge potential confines the ions radially. Axial confinement is accomplished by applying appropriate potentials to the trap electrodes. Whilst trapped in the dense electron beam, the ions undergo further ionization through successive electron impact processes. To obtain highly charged ions in charge states such as e.g. \( \text{Xe}^{44+} \), typical ionization times are in the order of 10 to 50 ms, depending mainly on the amount of residual gas atoms giving rise to recombination.

Figure 1 shows a schematic overview of the TITAN-EBIT. The radionuclides enter the EBIT as cooled bunches of singly charged ions, in the figure from the left side through the collector. The extraction after charge breeding takes place along the same path but in the opposite direction. The extraction and the transport to the Penning trap will be accomplished by means of floatable drift tubes and pulsed cavities (not shown in the figure).

The TESLA-EBIT requires a high current as well, in order to increase the number of trapped ions. Despite of its size, the device is designed to be easily transportable, which is an important requirement for the EBIT to operate at varying locations and photon beam lines. Seven diagnostic ports will facilitate the simultaneous use of several spectrometers and fluorescence photon detectors in the spectral ranges of interest.

The design of all mechanical parts is completed with very few exceptions, and the devices are currently being assembled. Stable operation at high electron beam currents is foreseen for the year 2005, as well as first off-line tests of ion injection and extraction.

References