The relativistic electron-electron interaction can be stringently tested by high-precision measurements of the gyromagnetic factor \((g\) factor\) of the valence electron bound in many-electron systems. Especially three-electron ions allow for a highly-sensitive test since they can be theoretically predicted to a high accuracy. To this end the \(g\) factor of the \(2s\) valence electron bound in lithiumlike silicon \(^{28}\text{Si}^{11+}\) has been determined with an uncertainty of \(\delta g/g = 1.1 \cdot 10^{-9}\) [1], which is the most precise \(g\) factor measurement of a three electron system to date.

The \(g\) factor measurement

For the \(g\) factor measurement a single ion was stored in a cryogenic triple Penning trap setup for several months [2]. To determine the \(g\) factor via

\[
g = \frac{2}{\nu_c} \frac{q}{M_{\text{ion}}} \frac{m_e}{e} \nu_L
\]

(1)

the Larmor frequency \(\nu_L\) and the free cyclotron frequency \(\nu_c\) of the ion have to be measured, while the mass of electron \(m_e\) and ion \(M_{\text{ion}}\) are known from other high-precision experiments. The free cyclotron frequency can be determined by measuring the three eigenfrequencies of the ion in a first Penning trap. Simultaneously, microwaves close to the expected Larmor frequency are irradiated into the trap to induce spin flips. To determine the spin orientation with the continuous Stern-Gerlach effect, the ion is transported to a second Penning trap, where a magnetic inhomogeneity couples the spin orientation to the axial motion. Comparing the spin orientation to the orientation determined in the last cycle reveals if a spin flip was successfully induced. After several hundred cycles the spin flip probability as a function of the measured frequency ratio \(\Gamma = \nu_L/\nu_c\) yields a \(g\) factor resonance as shown in Fig. 1.

We have recorded three resonances with different microwave powers to check for related systematic shifts. The experimental result \(g_{\text{exp}} = 2.000\,889\,889\,9(21)\) is in excellent agreement with the theoretical value \(g_{\text{exp}} = 2.000\,889\,909(51)\). The comparison between experimental and theoretical \(g\) factor confirms the many-electron contribution on the level of \(10^{-4}\), which is the most stringent test of relativistic many-electron calculations to date. Since the experimental value is by more than one order of magnitude more precise than the theoretical value, any improvement of the theoretical \(g\) factor will immediately improve this test.

Outlook

For highly sensitive tests of quantum electrodynamics with heavy ions the achievable theoretical precision is limited by unknown nuclear parameters. A measurement of both lithium- and hydrogenlike ions allows to cancel the contributions of the nuclear parameters to a large extent, hereby significantly increasing the stringency of the test [3]. Moreover, if combined with a measurement of the boronlike charge state, the fine structure constant \(\alpha\) can be determined with a comparable uncertainty as the current value [4].

Having finished the \(g\) factor measurement of lithiumlike silicon, a \(g\) factor measurement of hydrogenlike carbon was started, aiming for an improvement of the precision of the electron mass by one order of magnitude.

References

The goal of the present experiment is to access the quantum-electrodynamic (QED) contributions to the 1s binding energy in a heavy one-electron system in order to provide an accurate comparison with the most advanced QED calculations taking into account also two-photon exchange.

For this purpose the twin crystal-spectrometer assembly, Bi-FOCAL, operated in the FOcusing Compensated Asymmetric Laue geometry has been arranged for accurate x-ray spectroscopy at the ESR gas jet as schematically depicted in figure 1 [1]. Each spectrometer was equipped with one 2D position-sensitive Ge strip detector, F1 and F2. In May 2012, a major production run (E039) was conducted and the Lyman-α transitions of hydrogen-like Au$^{78+}$ were measured in high resolution via spectroscopy of the corresponding x rays located near 63 keV in the laboratory system. Bare gold ions were stored in the ESR at a velocity corresponding to $\beta \approx 0.47$ and the x rays were measured in coincidence with ions undergoing single-electron capture in the argon gas target and being deflected into a particle detector by the bending magnet downstream the gas jet. It could be demonstrated that the newly developed crystal optics in concert with the position sensitive detector can cope with the low count-rate situation encountered. Background could be effectively reduced, by proper shielding facilitated by the existence of a polychromatic focus and by making use of the time and energy resolving capabilities of our detectors.

Figure 1 shows two-dimensional images of the Lyman-α doublet of Au$^{78+}$ recorded with the two 2D Ge strip detectors: Bottom – without, top – with energy and time discrimination in effect.

Figure 2 shows two-dimensional images of the Lyman-α doublet of hydrogen like Au$^{78+}$ impressively revealing the low background when energy and time discrimination is in effect. The slanted lines observed are consonant with the underlying x-ray-optical design. This way spectral resolving power can be retained also for fast moving sources. Coming in pairs the x-ray optics provide Doppler cancellation capabilities. Data analysis is still in progress.

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Electron-impact Excitation of Hydrogenlike Uranium Ions


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Electron-impact excitation (EIE) of bound electrons is one of the most fundamental processes and leads to the specific formation of spectral lines. In particular, it is responsible for the vast majority of x-ray radiation produced in various kinds of plasmas, in high energy density physics experiments and at laboratory fusion devices. Relativistic and retardation effects are known to affect the EIE process through the generalized Breit interaction (GBI) [1, 2].

Up to now, electron beam ion traps (EBITs) have been the preferred tool for studying the EIE [3]. Due to the small electron-impact ionization and excitation cross sections for heavy highly-charged ions, the focus of most of these EBIT studies has been confined to relatively low-Z systems.

In this contribution, we present an experimental and theoretical study of the electron-impact excitation effects in hydrogen-like uranium in relativistic collisions with different gaseous targets. The experiment was conducted at the experimental storage ring ESR. Recent developments, such as the anti-coincidence mode [4] and new micro-droplet target development [5], have rendered such studies feasible. By performing measurements with different targets as well as with different collision energies, we were able to gain access to both; proton (nucleus) impact excitation (PIE) and electron impact excitation (EIE) processes in the relativistic collisions. The large fine-structure splitting in H-like uranium allowed us to unambiguously resolve excitation to different L-shell levels. By looking at the intensity ratios of (Lyα1/Lyα2) of the subsequent decay photons, we were able to clearly identify and study the effect of the electron-impact excitation in H-like uranium (see Fig. 1). Combined calculations which treat both processes, PIE and EIE, provide a good agreement with the experimental data. Moreover, our experimental results clearly demonstrate the importance of including the effect of the GBI in the EIE calculations.

![Figure 1: Experimental results (solid black squares) in comparison with theoretical predictions for Lyα1/Lyα2 ratios for the K-shell excitation of U91+ in collisions with N2 and H2 targets at 212.9 MeV/u. Solid blue circles show PIE results. Solid red triangles depict combined (PIE+EIE) calculations. In addition, the combined calculations are presented without inclusion of the GBI, by empty red triangles.](image-url)

References

Experimental Investigation of Double Coherent Resonance of Li-like Ar in Si-crystal

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\textbf{Introduction}

We report on the experimental investigation of double resonant coherent excitation of Li-like Ar ions in traversing a Si crystal. The experiment was performed at the HIMAC accelerator at the National Institute of Radiological Science in Chiba, Japan.

Single and double excitation of incoming Argon ions were detected by measuring the change in the yield of different charge states of the projectile after passing through a Si crystal of 10 micron thickness. The measurements have been performed for different crystal orientations by using a two-dimensional position sensitive Si-detector.

\textbf{Experiment}

By passing a target with a regular structure, ions can be excited when the frequency the of the field created by the atoms of the ordered structure matches the frequency of an electronic transition into the ion. The excited state will de-excite via ionization and photon emission. By measuring the charge state distribution, electron and x-ray spectra from the ions after traversing the target, different excitations modes can be identified with large precision. In the present experiment single and double excitations in Li-like ions were measured. The typical resonance spectrum is shown in the fig. 1 where the 2s to 3p transition is identified.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{2s-3p transition in Li-like Argon single excited in Si crystal.}
\end{figure}

\textbf{References}

Laser cooling of stored relativistic C\(^{3+}\) ions at the ESR

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After several years of planning [1], development [2], and tests [3], in August 2012 a new laser cooling experiment (E089) has been performed at the ESR. One essential goal of this beamtime was to demonstrate that the initially ‘hot’ ions can be collected inside the rf-bucket using just the laser, i.e. without changing the bucket frequency and without electron cooling. This scheme can namely be used to cool relativistic ion beams in future storage rings and synchrotrons, such as the HESR and SIS-100 at FAIR. A second goal was to demonstrate in vacuo optical detection of the UV-light (ca. 155 nm) emitted from the laser excited ions. Finally, we wanted to perform a systematic study of several relevant parameters [4]. This also required collecting data from many different recently installed ESR diagnostic systems, such as the resonant Schottky pick-up [5], the ionization profile monitor [6], and UV-photochanneltron detectors [3].

Laser cooling of relativistic ions in a storage ring can be performed using only one anti-collinear laser beam and a bunched ion beam. We wanted to demonstrate two cooling schemes: In the first scheme, the CW laser frequency is rapidly scanned over a large range, cooling all ions inside the bucket. The group of Th. Walther at the TU Darmstadt has therefore developed a fast scanning narrowband CW laser system, based on a seeded fiber amplifier (1028 nm) with two frequency doubling stages (514 and 257 nm) [7]. In the second scheme, a powerful pulsed laser system (broadband) is used to cool many velocity classes in one shot. Here, a sufficiently high repetition rate is important, since the laser pulses must hit the ion bunches, which have a revolution frequency of about 1 MHz, often enough. Such a laser system, based on a fs-oscillator, a fiber-coupled diodelaser, an Yb:YAG amplifier medium (1028 nm), and two frequency doubling stages to reach 257 nm, has been developed by the group of U. Schramm from HZDR in Dresden [8].

As in the two previous ESR laser cooling experiments (2004 and 2006), we have used \(^{12}\)C\(^{3+}\) ions with \(2s \rightarrow 2p\) cooling transitions and a kinetic energy of 122 MeV/u. Typically, about \(10^8\) ions were stored in the ESR for about 5 minutes. During the 8 days of beamtime, we were able to have a fully functional laser cooling setup. From the Schottky spectrum in figure 1 it can e.g. be seen that the CW laser slows down the ions (i.e. they obtain a lower frequency) as it is scanning through its range. Fluorescence from the laser excited ions has been recorded with the UV-photochanneltron detectors, made possible by the support from the group of G. Birkle at the TU Darmstadt. We have also observed that the laser cooling scheme can change the velocity of the stored carbon ions, even when electron cooling is trying to keep the ions at a fixed velocity. This clearly demonstrates the power of the method. Detailed analysis of the large amount of data is currently being carried out by the collaboration.

In parallel to studies at the ESR, similar studies will be started at the CSRe storage ring in Lanzhou, China. The group of X. Ma in Lanzhou has also intensively contributed to the success of the recent ESR beamtime. The laser and detector systems will soon be shipped to Lanzhou.

References


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‡Work supported by DAAD.
\(^{1}\)With ca. 10% of \(^{16}\)O\(^{4+}\) contamination from the ECR ion source.

Figure 1: Schottky spectrum (time vs. frequency) of a stored C\(^{3+}\) beam in the ESR. The electron cooler is off, the ion beam is not bunched, and the CW laser scans through 12 GHz in 10 s. (All lines drawn are to guide the eye.)
An all-solid-state based laser system for laser cooling of relativistic ion beams

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In 2004 and 2006 laser cooling experiments of relativistic $C^{3+}$ beams were performed at GSI using frequency doubled Argon-ion lasers [1]. The results of these experiments were promising, but were limited by the large linewidth and the severely limited tunability of the Ar-ion lasers. While Ar-ion lasers are still quite common with applications in areas such as spectroscopy, laser pumping, medical care and even light shows, they have a relatively low efficiency and high maintenance costs [2].

Within this research project, we successfully developed an alternative laser system far superior to the existing Ar-ion laser: it is a rugged, efficient all-solid-state based system with output wavelengths of 1028 nm, 514 nm and 257 nm. It provides high output power, narrow linewidth, wide and fast tunability and a near perfect Gaussian beam profile.

Figure 1: Schematic diagram of the system. ECDL: external cavity diode laser, FA: fiber amplifier, SHG: second harmonic generation, FHG: fourth harmonic generation, WLM: wavelength meter, FVC: frequency to voltage converter, PD: photo detector, PID: proportional-integral-derivative controller, +: signal adder, ∼: function generator

A schematic overview of our system is shown in Fig. 1. It mainly consists of a fiber amplifier seeded by an external cavity diode laser (ECDL). The output of this amplifier is frequency doubled and quadrupled in bow-tie built-up cavities using LBO and BBO crystals, respectively. The fiber amplifier delivers up to 15.3 W of optical power at 1028 nm. In Fig. 2 the output of the first cavity is plotted over the input power. We achieved nearly 5 W with a conversion efficiency of 57% at 514 nm. The second cavity delivered up to 180 mW of UV light with a conversion efficiency of 12%.

The system is stabilized to an absolute frequency using an offset lock on another identical ECDL (master), which itself is locked to a high-precision wavelength meter. By adding an arbitrary ramp from the function generator to the error signal of the offset lock, the seed ECDL of the fiber amplifier can be scanned with respect to the master ECDL. In the UV it was possible to scan 12 GHz in 10 ms. Mode hops were suppressed by a novel locking scheme developed in our group [3]. The offset lock is achieved by mixing small amounts of light of both ECDLs in a Y-fiber and observing the resulting beat signal with a fast photo detector. The beat frequency is divided by a factor of 1000 and fed into a frequency to voltage converter whose output serves as the error signal. By observing the beat signal of the two identical ECDLs, their linewidth was determined to

$$\Delta f \approx 3 \times 10^{-6}.$$  

In conclusion, we were able to replace the Argon-ion laser with a more versatile light source. During a beam time in August 2012 stable long term operation was successfully demonstrated. Another beam time in Lanzhou (China) is planned in 2013 and further experiments at FAIR are possible.

References

In vacuo detection of XUV photons at the ESR using a movable cathode system

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The Institut für Kernphysik in Münster is currently developing a system for in-vacuum detection of XUV photons in the wavelength range from < 10 nm up to about 250 nm. The system will be installed at the ESR and consists of a movable cathode plate with a central slit that can be positioned around the ion beam axis to catch photons emitted in the forward direction during the de-excitation of stored highly-charged ions. Secondary electrons emitted from the cathode will be guided by a system of ring electrodes to a multi-channel plate (MCP) detector placed inside the vacuum. A similar detection system for optical photons making use of a movable parabolic copper mirror and a photomultiplier outside the vacuum, has successfully been applied in the detection of the HFS transition in lithium-like bismuth in the LIBELLE experiment two years ago [1, 2]. There it was demonstrated, that the introduction of a suitable optical system at the beam position does not disturb the stored ions apart from a small loss in beam current during the movement of the system. Figure 1 displays the result of a tracking simulation produced with the SIMION [3] package. Five ring electrodes are placed between the cathode plate and the MCP, with the first electrode parallel to the cathode. The CF200 port into which the system can be retracted during injection of ions into the ESR actually acts as an additional sixth electrode on ground potential, but has been omitted from the figure for clarity. In the simulation, more than 75% of the secondary electrons emitted from the cathode plate are collected by the MCP.

The new detection system will be used for a measurement of the \(^{3}\!P_0-^{3}\!P_1\) splitting in beryllium-like krypton in an anti-collinear laser spectroscopy experiment at the ESR [4]. The meta-stable state \((1s^22s^2p)^{3}\!P_0\) (see figure 2) is populated during the production of the \(^{84}\!\text{Kr}\)\(^{32+}\) ions. For the excitation to the \((1s^22s^2p)^{3}\!P_1\) state, a laser-beam is injected anti-collinear to the ions which are stored at a velocity of \(\beta = 0.69\). Due to the Doppler shift, the required wavelength is red-shifted from 118 nm to 276 nm. The photons emitted during de-excitation to the ground state in the forward direction are in turn blue shifted to energies up to 170 eV.

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First imaging of cold magnesium ion clouds in SpecTrap

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In recent years, sympathetic cooling has been established as an important tool for the study of exciting quantum phenomena and applications, ranging from microwave quantum logic gates [1] to ultracold chemical reactions [2]. It is mostly used when other cooling methods such as Doppler laser cooling cannot be applied. This also holds for Highly Charged Ions (HCIs), which are the subject of our current investigations at SpecTrap. We will therefore exploit a cooling strategy based on laser cooled singly charged magnesium ions for cooling any species of HCIs down to the mK regime for high precision laser spectroscopy experiments.

The experimental apparatus, the preparation scheme, and first experimental results of laser cooled Mg\textsuperscript{+} are described in detail in [3]. In brief, singly charged magnesium ions are produced in an electron impact ion source and are subsequently transferred in bunches of 1–10 \( \mu s \) at an energy of 200 eV into a cylindrical Penning trap. By dynamically switching the trap electrodes it is possible to stack multiple ion bunches. The precise timing even allows isotope selective loading by this means. All experimental parameters, such as electrode or ion optic voltages, are controlled by our newly developed experimental control system, which was successfully tested in 2012.

After completion of the loading procedure, the ion cloud is efficiently cooled by 280 nm laser light irradiated in axial direction. For this purpose, a new seed laser was installed to provide more than 10 mW ultraviolet laser light after frequency quadrupling. A frequency stability of the seed laser of a few hundred kHz on a long-term scale was achieved by locking it to a high-precision wavemeter. Fluorescence detection of the scattered cooling light is performed in radial direction. During the cooling phase of approximately six seconds, the ionic sample undergoes a transition to a strongly coupled state. The rearrangement of the ion cloud becomes apparent in form of a precooling peak visible in the fluorescence spectra while scanning across the resonance [3]. Detailed analysis of the obtained fluorescence signal reveals an upper limit for the ion temperature of roughly 60 mK.

Usually, the laser frequency is tuned to the closed \( |3S_{1/2}, m_j = -1/2 \rangle \rightarrow |3P_{3/2}, -3/2 \rangle \) transition to ensure permanent cooling of the confined ionic ensemble. By observing the fluorescence signal, the lifetime of the magnesium ions in the trap was estimated. A single measurement of the lifetime shows that the ion cloud could be stored for 75 minutes without significant losses.

Additionally to the fluorescence detection with photomultiplier tubes, a UV-CCD camera was used to image the ion cloud. In figure 1 a sequence of four images of the laser cooled ion cloud is depicted. It shows a compression of the cloud during the cooling phase. By varying the trap voltages, precise control of the spatial position of the ion cloud was possible and even the manipulation of the ion cloud density might be possible using the rotating wall technique [4]. In future, an improvement of the imaging system will help us to study in more detail the ion dynamics of low-Z ions, HCIs and their mixtures in the Penning trap.

In summary, the experimental results show that we can prepare an ideal source of cold and dense singly charged magnesium ions, by optimizing the vacuum conditions, implementation of an experimental control system and optimizing the existing laser system. As soon as the beamline from the HITRAP facility to SpecTrap is finished, first high precision spectroscopy measurements on HCIs will be possible.

References

Controlled interaction of ions with high-intensity laser light

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We are currently preparing an experimental setup which features a Penning trap for preparation and control of suitable ion targets for irradiation with high-intensity laser light and study of subsequent reactions. Of particular interest is the detailed investigation of multiphoton-ionisation of confined particles by highly intense laser light. One important aspect is control over the confined particles’ mass, charge, density, localization and optimized overlap with the laser light by Penning trap techniques like the use of trap electrodes as ‘electrostatic tweezers’ and by application of a ‘rotating wall’, respectively. Also, the non-destructive detection of reaction products is a central property. The Penning trap setup is designed in a portable fashion, such that it can be attached to existing laser systems easily \cite{1}.

The interaction of highly intense radiation with matter and the corresponding non-linear effects have been subject of lively research, both theoretical and experimental, especially in the infrared and visible photon energy regimes. Laser systems capable of producing high intensities also at photon energies in the extreme ultra-violet (EUV) and (soft) X-ray regime open access to novel effects like non-linear Compton effects or simultaneous elastic and inelastic photon scattering, and allow multiphoton-ionisation experiments in a new domain. However, experiments have so far not been able to prepare and investigate well-defined particle ensembles and to non-destructively analyse the reaction products with high accuracy, nor were they able to select or prepare products for further studies in a well-defined way.

The particles (atomic or molecular ions) are confined in the Penning trap following in-trap production or capture of externally produced ions. Confined ions can be cooled, compressed, positioned and selected with respect to their mass and charge prior to laser irradiation. The reaction products are analysed by non-destructive methods and hence remain confined for further studies. Such measurements are, for example, able to determine cross sections for multiphoton-ionisation in an energy- and intensity-regime so far not or not sufficiently examined. Additionally, the created electrons may be extracted from the trap and analysed externally. Hence, the reaction energetics may be reconstructed as completely as possible.

Figure 1 shows an example of a multiphoton ionization study using these techniques: ions are dynamically loaded into the trap from external sources or produced in the trap by electron impact or laser ionization (A). One or more specific ion species are selected (B), these ions are then cooled, compressed by a rotating wall and positioned. Thus, the ion target is well-prepared for interaction with the high-intensity laser. During and following the laser interaction, the charge state evolution of the confined ions is monitored by FT-ICR-spectrometry (C and D). Specific product ions can be selected and remain stored for further use (E).

Ion positioning along the experimental axis has some interesting features when a focused laser is considered since it allows to determine the position of the focus with high resolution. At the same time, especially for strongly focused lasers, ion positions can be chosen such that the reaction takes place at different field intensities and thus allows a study of the reaction as a function of laser field intensity without the need to change laser parameters.

**References**

Access to the quadratic and cubic Zeeman effects at ARTEMIS

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We have conceived an experiment for laser-microwave double-resonance spectroscopy of highly charged ions in a Penning trap. Such spectroscopy allows a highly precise measurement of the Zeeman splittings of fine- and hyperfine-structure levels due to the magnetic field of the trap. We also have performed detailed calculations of the Zeeman effect in the framework of quantum electrodynamics of bound states as present in such highly charged ions. We find that apart from the linear Zeeman effect, also second- and third-order Zeeman effects contribute to the splittings on a level of $10^{-4}$ and $10^{-8}$, respectively, and hence are accessible to a determination within the achievable spectroscopic resolution of the currently prepared ARTEMIS experiment.

A quadratic contribution to the Zeeman effect has first been discovered by Segré and Jenkins in the 1930s. Since then, there have been numerous studies, both experimental and theoretical, of higher-order Zeeman contributions in atoms, molecules and singly charged ions in laboratory magnetic fields. Corresponding studies in observational astronomy have identified a quadratic Zeeman effect in abundant species like hydrogen and helium. Although highly charged ions are both abundant in the universe and readily accessible in laboratories, to our knowledge, no higher-order Zeeman effect in highly charged ions has been observed so far.

We are currently setting up a laser-microwave double-resonance spectroscopy experiment with highly charged ions in a Penning trap, which combines precise spectroscopy both of optical transitions and microwave Zeeman splittings \cite{1, 2}. The experiment aims at spectroscopic precision measurements of such energy level splittings and magnetic moments of bound electrons on the ppb level of accuracy and better. At the same time, it allows access to the nuclear magnetic moment in absence of diamagnetic shielding. For first tests, the $^{40}$Ar$^{13+}$ ion has been chosen. It has a spinless nucleus, such that only a fine structure is present. Similar measurements in hyperfine structures are to be performed with ions of higher charge states such as for example $^{207}$Pb$^{81+}$ and $^{209}$Bi$^{82+}$ as available to ARTEMIS within the framework of the HITRAP facility.

In an external magnetic field, the Zeeman effect lifts the degeneracy of energies within fine- and hyperfine-structure levels. For highly charged ions in magnetic fields of a few Tesla strength, the Zeeman splitting is well within the microwave domain and thus accessible for precision spectroscopy. In addition, in case of fine- and hyperfine-structure transitions, the strong scaling with $Z$ eventually shifts the corresponding energies into the laser-accessible region and thus makes them available for precision optical spectroscopy. Figure 1 schematically shows the Zeeman splitting of the $2^2P_J$ states of boron-like argon Ar$^{13+}$ in an external magnetic field with higher-order contributions to the Zeeman effect (not true to scale).

![Figure 1: Level scheme of the $2^2P_J$ states of boron-like argon Ar$^{13+}$ in an external magnetic field with higher-order contributions to the Zeeman effect (not true to scale).](image)

References

Versatile cold atom apparatus

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We present a compact apparatus that consists of a cold atomic target at the center of a high resolution recoil ion momentum spectrometer (RIMS) \cite{1} which will be implemented in the HITRAP beamline at GSI.

With our current setup densities of up to a few $10^{11}$ atoms/cm$^{-3}$ can be achieved. Therefore a dark spontaneous force optical trap \cite{2} loaded by a 2D MOT \cite{3} is used which not only overcomes the density limit of a normal magneto optical trap but also reduces loading times of the trap to as low as 300ms. This allows measurements of processes with very low probability such as multi electron charge transfer, which are otherwise disguised by the far more dominant single charge transfer channel. To resolve the dynamics of such processes a new recoil ion momentum spectrometer has been build (Fig. 1).

The whole setup has been tested using a pulsed laser beam. The inset of Fig. 1 shows the recoil ions' angular momentum distribution depending on the polarization of this pulsed laser. It can be clearly seen that the very small momentum transferred to the ion during the ionization process can be well resolved. The determined resolution of the recoil ions' momentum is 0.10 a.u. which is sufficient to study multiple charge transfer in highly charged ion – atom collisions. With these measurements also the target could be characterized in great detail and the use of the 2D MOT as an independent target has been explored \cite{4}.

As a next step the target will be upgraded by implementing a dipole trap where the atoms are trapped at the focus of a far detuned, intense laser beam. This technique allows the reach densities of some $10^{13}$ atoms/cm$^{-3}$ and by letting the warmest atoms evaporate from the trap a Bose-Einstein-Condensate (BEC) can be reached. This way a completely new target will be provided where not only the interactions between single atoms and ions but also collective effects which are only present in BECs can be investigated.

In addition, using a dipole trap allows to trap atoms without the use of a magnetic field which has several advantages. Firstly the trap can be run continuously whereas in the present setup the magnetic field as well as the MOT lasers have to be switched of several milliseconds before any recoil momentum can be measured with high accuracy. Secondly it is possible to state prepare the atoms in the dipole trap which makes it possible to explore the dependence of multiple charge transfer on the polarization of the target.

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Figure 1: MOTRIMS setup. The inlet shows the recoil ions' angular momentum distribution when atoms are photoionized with a pulsed laser beam. The two graphs correspond to the different polarizations of the laser.
Towards Precision Laser Spectroscopy of Forbidden Transitions in Highly-Charged Ions

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Introduction

The SPECTRAP experiment for the investigation of highly charged ions (HCI) at rest with methods of high-resolution laser spectroscopy is under development at GSI. The spectroscopic data can be used to test atomic structure and bound-state quantum electrodynamics (QED). Systematic measurements on several species of highly charged ions will be possible with up to three orders of magnitude better spectroscopic resolution than in former experiments [1]. Amongst others, related earlier measurements have been realized on bunches of $^{209}$Bi$^{82+}$ ions in the experimental storage ring ESR. The value of the transition wavelength was determined to be 243.87(4) nm in the lab-frame [2, 3]. For improved precision in the measurement the ions will be now be decelerated by the HITRAP-facility and cooled to liquid helium temperatures inside the SPECTRAP Penning trap.

Spectroscopic Apparatus

For spectroscopy on $^{209}$Bi$^{82+}$, the necessary laser system has to produce laser light with a power of several mW at 243.87 nm and a tuning range significantly larger than the standard deviation of 100 GHz of the previous measurement [2, 3]. In addition, the laser frequency should be stable to a precision and accuracy comparable to or below the expected Doppler-width of the transition of the ions inside the Penning trap which is expected to be approximately 30 MHz. For the generation of the light at the target wavelength we use a commercial frequency-quadrupled diode laser system. Through the successive frequency doubling we have access to laser fields at 244 nm, 488 nm and 976 nm. The light at 488 nm is used for frequency diagnostics on $^{130}$Te$_2$ vapour while the light at 976 nm is used for frequency stabilization to a cavity. Tuning of the output frequency with high precision is achieved via a tunable rf offset lock and coupling to the cavity.

For stabilization and frequency diagnostic, vapour of molecular tellurium $^{130}$Te$_2$ is used as spectroscopic reference. We recorded and analysed a set of resonances, delivering precise spectroscopic references on a continuous spectrum between 488.36 nm and 487.28 nm with an absolute accuracy of 3 MHz (one standard deviation). The data were compared to previous highly precise measurements of known tellurium features. The uncertainty of 3 MHz is caused by ambient pressure fluctuation and the limitations in the corresponding corrections. In a recent set of measurements, our absolute accuracy for some lines has been improved to 0.9 MHz.

To constitute a map of $^{130}$Te$_2$ vapour, we switch between the zero crossings of the 976 nm cavity signal for stabilization. We took two sets of measurements which were then combined to one final average. For analysis, Gaussian and Lorentzian profiles were fitted to the averaged ensemble map. Those features which could be correlated to the ones listed in [5] were assigned accordingly. Additionally, we took five measurements scanning the previously calibrated features from the literature with the cavity placed inside a vacuum chamber. Taking several runs on known tellurium references gives us the possibility to quantify our precision by calibrating each run to two features with known absolute frequency. Comparing our Doppler broadened lines to the ones in [5], we could confirm previous results [6], that the atlas delivers smaller values by an average offset of 65.8 MHz (Fig. 1). As a result, we now have a high-precision map of tellurium lines in the range of 488.36 nm and 487.28 nm and a table with over 900 spectroscopic references.

References

Production and diagnostics of spin-polarized heavy ions in the sequential two-electron radiative recombination *

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Within the last decades the radiative recombination (RR) by highly charged heavy ions remains the subject of intense theoretical and experimental research (see [1] and references therein). The RR is an effective tool for studying of the photoionization in the relativistic regime, which is not approachable directly at the present time. Moreover, the RR is interesting due to its sensitivity to the spin, relativistic and QED effects in the structure and dynamics of heavy atomic systems (see, e.g. [2, 3]).

In the recent years several experiments on researching the RR with polarized ion beams were proposed [4, 5]. Furthermore, it was proposed to use the RR into polarized H-like ions as the tool for beam spin diagnostic [6]. Information about the ion polarization is required for studying, for example, the parity nonconservation effects in highly charged ions or in heavy-ion collisions. But all of proposed experiments are hampered now by the lack of polarized ions.

In the present work we propose the method, that can be used for investigations of the RR into spin-polarized H-like ions. This approach is based on a subsequent capture of two electrons from two spatially separated targets by initial bare (finally He-like) ion and measurements of two emitted photons in coincidence. We choose the quantization axis (Z-axis) along the momentum \( p_1 \) of the incoming electron. After the capture of the first electron, a photon is emitted in the direction \( k_1 \), determined by polar angle \( \theta_1 \). It turns out that the relative magnetic sublevel population of the resulting H-like ion depends on \( \theta_1 \). Hence the properties of the second photon, emitted in the direction \( k_2 \) characterized by two angles \( (\theta_2, \varphi_2) \), should be also dependent on \( \theta_1 \).

The population of the intermediate H-like ion can be parameterized in terms of the polarization vector \( \mathbf{P} = (P_x, P_y, P_z) \). From the symmetry considerations in our case, when the photons, emitted in course of recombinaction of unpolarized electrons with bare ions, are observed in a particular setup, only single parameter \( P_y \) is non-zero [7].

Information about the polarization of the H-like ions can be obtained from the analysis of the linear polarization of the second recombination photons. From the practical viewpoint it is more convenient to use the polarization ellipse parameters \( P_L \) (the degree of linear polarization) and \( \chi_0 \) (the orientation of the principal axis with respect to the reaction plane) for the description of the x-ray linear polarization.

In Fig. 1, we display \( P_y \) as a function of \( \theta_1 \) and \( \chi_0 \) as a function of \( \theta_2 \) in the case of \( \varphi_2 = 90^\circ \). The calculations have been performed in the ion–rest frame for the incident projectile energy \( \varepsilon_i = 109.7 \text{ keV} \), which correspond to the projectile energy \( T_p = 200 \text{ MeV/u} \) in the laboratory frame. As one can see from the figure, the polarization of the H-like ions following RR is very sensitive to the geometry of the photon emission. For example, a very significant degree of polarization, \( P_y \sim 85\% \), can be achieved for those ions, whose production is accompanied by the photon emission under the angle \( \theta \simeq 150^\circ \). You can also see that \( \chi_0 \) shows strong dependence on the \( \theta_1 \) and, hence, on the degree of ion polarization. Thereby in the proposed scheme the characteristics of the first and the second RR photons are correlated through the spin states of intermediate H-like ions. Hence, using the proposed method we can "emulate" not only the production but also the diagnostics of heavy ion beams.

Figure 1: Component \( P_y \) of the polarization vector of H-like uranium ions \((Z = 92)\) as a function of first photon emission direction \( \theta_1 \) (left panel) and angle \( \chi_0 \) as a function of the emission angle of the second photon \( \theta_2 \) at \( \varphi_2 = 90^\circ \) (right panel). The calculations are performed in the ion–rest frame for the kinetic energy \( \varepsilon_i = 109.7 \text{ keV} \) of the incoming electron.

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Characterization of a Si(Li) Compton polarimeter for the hard x-ray regime, using synchrotron radiation.*

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Novel highly-segmented semiconductor detectors which combine a good detection efficiency, energy and time resolution, together with millimetre to sub-millimetre position sensitivity, represent a versatile tool for Compton polarimetry in the hard x-ray regime [1]. Such detection systems have recently been introduced for the investigation of radiative processes involving high-Z ions in collisions with gaseous matter at the storage ring ESR [2,3,4] as well as in electron-atom collisions at the TU Darmstadt [5].

In the present experiment, a novel Si(Li) Compton polarimeter [6], which was developed for experiments at the international FAIR facility, has been tested at the DESY PETRA III beamline P07-EH1. For this purpose, the detector was exposed to the synchrotron radiation. Since the synchrotron radiation is nearly 100% linearly polarized, we were able to test the detector performance as an x-ray polarimeter for photons in the hard x-ray regime.

Figure 1 shows the Si(Li) detector response to the incident synchrotron radiation. The monochromator of the beamline was set to 57.3 keV. The clearly visible line at 161.1 keV could be identified as the third harmonic. The broad structures at lower energies belong to recoil electrons of the Compton-scattered photons.

Figure 2 shows the position distribution of Compton scattered photons inside the Si(Li) detector crystal for 161.1 keV incident photons. The strong anisotropy indicates the high degree of linear polarization of the incident synchrotron radiation.

According to Klein-Nishina equation, the photons are scattered mostly perpendicular to the incident photon electric field vector (polarization axis). This is clearly reflected in the strong azimuthal anisotropy of Figure 2, which indicates a very high degree of linear polarization, typical for synchrotron radiation facilities. The degree of linear polarization as well as the polarization orientation of the incident radiation can be reconstructed applying a least-squares adjustment to the azimuthal scattering distribution [7].

We have acquired the Compton scattering data for different x-ray energies as well as different detector orientations. The evaluation is currently under way.

References

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Characterization of a novel setup for hard x-ray spectroscopy and polarimetry at very high fluxes

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X-ray spectroscopy is a powerful tool for the diagnosis of plasmas being produced in fusion devices, celestial objects and in the interaction of high-power lasers or ion beams with matter. It is also known that radiative processes like bremsstrahlung, radiative recombination and characteristic transitions occurring in plasmas may exhibit distinct anisotropic and polarization features. In general, an anisotropic plasma tends to produce polarized radiation, and by photon polarimetry and/or angular resolved measurements one can investigate the anisotropic, and thus non-thermal features of the plasma [1, 2].

While single photon spectroscopy up to roughly 20 keV can be performed using standard x-ray CCD cameras, precise studies in the hard x-ray regime are often hampered by the lack of adequate detector technology. This is due to extremely high fluxes in combination with low repetition rates being typically found at plasma sources which generate x-rays up to the MeV regime, e.g. high-power laser facilities. Here, the operation of standard unsegmented, large-volume detectors leads to photon pile-up in the detector or requires unrealistic long acquisition times in order to obtain single photon spectra. Thus, state-of-art studies of hard x-ray spectra originating from plasmas still rely on low-precision techniques like stacks of several filter materials in front of an image plate [3]. However, with the recent development of pixelated CdTe sensors equipped with the Timepix readout chip [4, 5], energy-resolving detectors have become available that combine a high granularity comparable to x-ray CCDs with the high-stopping power of a high-Z detector material.

In this report, we present a setup optimized for Compton spectroscopy and linear polarimetry of incident x-rays up to a few hundred keV based on such detector systems, see Fig. 1. Here, two 1 mm thick CdTe detectors with up to 256×256 pixels record the radiation which is Compton scattered within a low-Z target. Compton spectroscopy aims for the reconstruction of the incident x-ray spectrum from the spectral distribution of the scattered photons and is in particular well-suited for fluxes being too high to expose the detector directly to the incident radiation [6]. As for photon energies below about 1 MeV the Compton cross section varies only slightly, the efficiency and consequently the amount of flux reduction of the scattering setup is mainly determined by geometry, namely the solid angle covered by the CdTe detectors. Similarly, the spectral broadening due to the dependence of the scattered photon energy on the longitudinal Compton scattering angle $\vartheta$ can be adjusted.

Moreover, the degree of linear polarization $P_L$ of the incident radiation can be obtained by means of Compton polarimetry, which is based on the asymmetry of the scattered photon emission pattern with respect to the azimuthal scattering angle $\varphi$, see [7]. Assuming that the CdTe detectors are located at $0^\circ$ and $90^\circ$ with respect to the incident photon electric field vector, the linear polarization is given by $P_L = M(N_{0^\circ}-N_{90^\circ})/(N_{0^\circ}+N_{90^\circ})$, with $M$ denoting the modulation factor depending on the photon energy and the experimental setup. If the orientation of the polarization is unknown, this quantity can also be obtained by rotation the detectors around the scattering target.

Recently the setup from Fig. 1 was used in a test measurement at the PETRA III synchrotron facility at DESY where high-intensity, highly polarized photon beams between 50 and a few hundred keV were impinging on the scatter target. The analysis of the obtained data is still ongoing.

References


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Monte Carlo simulations of Compton polarimeter systems

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Compton polarimetry has proven to be a powerful tool to measure the linear polarization of hard x-rays. In the GSI atomic physics department, several measurements of this type have been carried out using a lithium-drifted silicon (Si(Li)) double-sided strip detector (DSSD) [1,2]. This device works well in a photon energy range of about 60 keV to 150 keV. An extension to higher energies can be achieved by using a heavier detector material. In this work, germanium DSSD has been simulated, using concepts from previous simulations of the same type [3]. For the low-energy region of about 20 keV to 80 keV, an entirely new concept for Compton polarimetry is proposed: the polarimeter consists of a low-Z cylindrical scatterer and - around it - a ring of individual high-Z absorber plates. Each of these plates is a high-resolution microcalorimeter which is a novel development of the "Magnetic Calorimeters" group in Heidelberg [4]. In this work, the efficiencies of both polarimeter systems have been investigated in Monte Carlo simulations using EGS5 [5]. In both cases, this quantity was given by the fraction of identified Compton events. Simulations were carried out for different polarimeter configurations and for different photon energies.

The geometry the germanium DSSD has always been chosen to be symmetric in x- and y-direction. Also, the strip width was fixed at 1 mm. The parameters varied were the number of strips (this number for each direction x and y) and the detector thickness (z-direction). First, results were obtained for a point-like (p) incidence in the center of the detector, then the incoming photons were spread over the detector area (s). Results are shown in figure 1.

For the microcalorimeter polarimeter, the following geometry has been considered: the scattering cylinder had a diameter and length of 1 mm. The area of the absorber plates (here: gold) facing the scatterer was 1 mm by 1 mm, the absorber thickness 0.2 mm. The radius of the absorber ring was derived from the requirement that one absorber covers the θ-range of 90° ± Δθ. The angular acceptance Δθ was chosen here according the number of absorbers to minimize the gaps between them. So far, three configurations have been simulated: 40 absorbers and Δθ = 3.5° with (1) a beryllium and (2) a carbon scatterer, and (3) 31 absorbers and Δθ = 5.8° with a carbon scatterer. Figure 2 shows the microcalorimeter simulation results.

References


Figure 1: DSSD results. Legend format: number of strips, detector thickness [cm], incidence spread (p=no, s=yes).

Figure 2: Microcalorimeter results. Legend format: scatterer material, number of absorbers.

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Direct mass measurement of $^{45}$Cr and its impact on Ca-Sc cycle in X-ray burst

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The experimental program on mass measurements of exotic nuclei has been continued at the storage ring CSRe in Lanzhou by addressing neutron-deficient $^{58}$Ni projectile fragments. Masses of $^{41}$Ti, $^{45}$Cr, $^{49}$Fe and $^{53}$Ni were measured by applying the isochronous mass spectrometry technique [1, 2]. Details of the experiment can be found in Ref. [3]. It turned out that the mass of $^{45}$Cr nucleus has an effect on the modelling of the astrophysical rapid proton capture process (rp-process) of nucleosynthesis in X-ray bursts.

In total 218 bare ions of $^{45}$Cr were collected, see Figure 1, and a statistical mass error of 16 keV was achieved for $^{45}$Cr. A special data analysis method was conducted to account for a possible contamination by a recently discovered isomeric state ($E_x = 107$ keV) [4], which resulted the final mass excess of $ME(45\text{Cr}) = -19515(35)$ keV.

Signal zone X-ray burst model [5] calculation was carried out to test the impacts of new masses on the rp-process. With our new mass value the matter flow through $^{43}$Ti could be constrained [6].

For a low $^{45}$Cr proton separation energy, $^{45}$Cr($\gamma,p$) reaction becomes effective, hampering the proton capture flow at $^{43}$Ti. As a result, a significant $\beta$-decay branch develops at $^{43}$Ti driving the reaction flow into $^{43}$Sc, which follows by a $^{43}$Sc($p,\alpha$)$^{40}$Ca reaction. Thus a so-called Ca-Sc cycle can be forms [7]. With our new $^{45}$Cr mass value, a p-capture on $^{44}$V becomes effective and a formation of a strong Ca-Sc cycle is practically excluded, see Figure 2.

Figure 2: Time integrated reaction flow through the Ca-Sc cycle during an X-ray burst as a function of $S_p(45\text{Cr})$. The graph spans the $3\sigma$ uncertainty of $S_p(45\text{Cr})$ in AME 2003. The thick black line limited by filled squares indicates the $1\sigma$ uncertainty of $S_p(45\text{Cr})$ in AME2003, while the thick red line limited by filled circles indicates the $1\sigma$ uncertainty when using the experimental data from this work. Taken from Ref. [6].

References

Direct mass measurement of $^{53}\text{Ni}$ and first test of IMME in fp-shell nuclei

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New mass measurements were conducted at the storage ring CSRe in Lanzhou, employing the isochronous mass spectrometry (IMS) technique [1, 2]. Nuclides of interest were produced in projectile fragmentation of $^{58}\text{Ni}$ primary beam. Masses of a series of short-lived neutron-deficient nuclides including $^{41}\text{Ti}$, $^{45}\text{Cr}$, $^{49}\text{Fe}$ and $^{53}\text{Ni}$ were measured with a typical mass uncertainty of 30 keV/c$^2$ [5]. The measured revolution time spectrum is illustrated in Figure 1.

![Figure 1: The revolution time spectrum of neutron-deficient $^{58}\text{Ni}$ projectile fragments. The insert shows the well-resolved peaks of $^{30}\text{S}$ and $^{45}\text{Cr}$ nuclei. Nuclei with masses determined in this experiment and those used as references are indicated with bold and italic letters, respectively. Adopted from Ref. [5].](image1)

New data enabled us to perform the first ever test of the Isobaric Multiple Mass Equation (IMME) in fp-shell nuclei [5]. Based on the concept of isospin symmetry, the states in nuclei can be classified according to the isospin quantum number $T$ with a projection $T_z=(N-Z)/2$.

Assuming the two-body nature for any charge-dependent effects and the Coulomb force between the nucleons, the masses of $2T+1$ members of an isobaric multiplet are related by the isobaric multiplet mass equation (IMME) [3, 4]. To test a possible deviation of the IMME from the predicted parabolic form, described by polynomial coefficients $a$, $b$ and $c$, an additional cubic term with coefficient $d$ can be considered.

Experimental $d$-coefficients obtained in this work are plotted in Figure 2 together with precision data on lighter nuclei, see Ref. [5] and references cited therein. A 3.5σ deviation from the parabolic shape is observed for $A=53$ isobaric multiplet, which is a striking result.

This large $d$ coefficient cannot be explained by either the existing or the new dedicated theoretical calculations of isospin mixing. If this breakdown of the IMME is confirmed by improved experimental data, both the new ground-state masses as well as the energies of the isobaric analog states, possible reasons, such as enhanced effects of isospin mixing and/or charge-dependent nuclear forces in the fp-shell, should be investigated.

![Figure 2: $d$ coefficients for the four $T=3/2$ isobaric multiplets in $pf$-shell (squares). Data for lighter nuclei (circles) are shown for comparison. Taken from Ref. [5].](image2)

References

A new particle detector manipulator for ESR, CRYRING and HESR*

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In a collaboration of GSI, EMMI and the universities Frankfurt and Giessen, a new particle detector manipulator for use at storage rings is presently being designed (Fig. 1). A central feature of this new device is that all detector installations can be completely retracted and can be separated from the ring vacuum using suitable translational motion devices and gate valves. With this design we obtain a high degree of flexibility that allows for easy and quick changes in the set-up between two experiments even with in-vacuum detectors. This new manipulator is ideally adapted to the high vacuum requirements (∼ 10−11 mbar) of storage rings such as the ESR, the CRYRING@GSI and the HESR. After opening for service, only the small volume of the bellow has to be heated and not the full ring sector. For the movement of the detector, both, a step motor for slow, fine-tunable movement of the full travel distance, and an additional pneumatic drive for fast short-distance travels (e.g. out/in during injection) are foreseen.

Installation of different modules offers a wide range of applications such as: (i) The use of detector pockets with metal-foil windows for detectors that cannot operate in the ultra-high vacuum of the ring. (ii) In-vacuum window-less detectors for atomic and nuclear collision studies at low ion energies. For example, such a low ion energy is favorable for precision x-ray spectroscopy (low Doppler shift) but also for nuclear reactions around the Coulomb barrier or around the Gamov window. (iii) Arbitrarily positionable scaper or slit systems. (iv) Thin-foil in-vacuum detectors for time-of-flight, particle tracking or even in-ring channeling experiments.

It is planned to have two prototype systems set up, tested and put into operation in the ESR’s first dipole magnets in the south and the north arc, respectively, by the end of 2013. Especially for the ESR, the present design allows for the installation of detectors in the dipole magnets (C-type). A special optional detector mount enables the placement of a detector in-vacuum on the inside of the ring. A first experiment envisaged at the ESR is the measurement of (p,γ) cross sections in inverse kinematics near or at astrophysically interesting energies for the p-process [1]. The p-process nucleosynthesis is responsible for the production of the rare, proton-rich heavy isotopes (p-nuclei) that cannot be made by neutron-induced processes. It occurs in supernovae, where (p,γ) and (γ,n) reactions modify the seed of s- and r- nuclei at high temperatures. A second immediate application with detectors in the ESR dipole magnets arises for atomic collision studies employing a permanently stochastically cooled ion beam. The electron cooler is then available as a full-time free-electron target for precision collision-spectroscopy experiments [2, 3]. For stochastic cooling the ion beam is stored on an orbit in the outside of the of the ring at a displacement of δp/p = ±1%. For this setting recombined ions hit the wall before the nominal particle detector positions in the scraper chambers [2]. Therefore, for cooler experiments with such ring settings a detector position inside the first dipole close to the exit of the magnet is required. Experiments with a stochastically cold beam open many new opportunities and significant enhancements over the standard measurement procedure at the cooler (cf. [2, 3]). With stochastic cooling beam losses due to cooling are essentially negligible and the beam lifetime in the ring is hours up to days. For example, this helps to make at least an order of magnitude more efficient use of expensive beams such as radioisotopes and additionally improves the duty cycle by a factor of 2-4. The technique also increases the available collision energy range from 0 up to 200 keV and appears ideally suited for lifetime studies via recombination resonances. As discussed in [4] it may also be a very important building brick towards experimental verification of the elusive process of nuclear excitation by electron capture (NEEC) [4].

References


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Construction of four position sensitive proportional counters for soft x-ray spectroscopy*

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Introduction: Two crystal spectrometers in a symmetrical set up have been demonstrated at the ESR yet for QED investigations on H, He and Li-like high Z ions. Position sensitive x-ray detectors have been used, a micro-strip germanium for high energy x-rays and CCD based detectors for the soft x-rays. CCD cameras for x-rays show sufficient energy and position but not time resolution according to the requirements (< 100 ns) of ongoing and future experiments within the SPARC collaboration. For these purposes four position sensitive proportional counters have been built.

Construction of the Detectors: The detectors are of the backgammon type [H.F. Beyer at all, annual report 1985] where the positions signal is derived by charge division on a split cathode. The main components of the detectors are an anode frame with seven gold-plated tungsten wires with ~ 20 μm diameters, a backgammon cathode made as a printed circuit. The housing of the detector is made of a stainless steel (1.4301, non-magnetic) front plate and aluminium side and rear plates.

Figure 1: Exploded drawing of the detector chamber.

A beryllium foil 0.1mm thickness is used for the entrance window of 12 × 40 mm on the front plate.

| Active Area | 12 × 40 x 4 (mm) |
| Detection gas | 90% Argon+10% CO2 |
| Anode wires | Diameter ~20 μm |
| Windows sizes / material | 12×40 mm / beryllium |
| Window thickness | 0.1 μm |
| Cathode plate | Printed circuit board |
| Connector for HV supply | 50 ohms SHV |
| Valve and fittings for gas | Swagelok 316 WHL |
| Dimension of the housing | 105 x 130x 105 (mm) |

Table 1: Mechanical characteristics of the counter

Figure 2: Counter overview during first testing.

Figure 2 shows the pprincipal setup with the Fe-55 radiation source fixed at the entrance window during the very first tests of the counter’s function. An ORTEC EASY-MCA and a MC USB-1604 are also presented on the picture. The detector operates with an A/CO2 (90%/10%) mixture at one atmosphere.

Figure 3: Oscilloscope screen shot with anode signals, Ch0 after the preamplifier, Ch1 after the amplifier.

Testing of function and next steps:
The characterisation of the four counters concerning energy, time and position resolution is going on at the moment. A Fe-55 source and standard NIM electronic components are used. In the next step the counters could be integrated into the crystal spectrometer. Furthermore, the development of a new type 3D miniaturized Multi Tube Proportional Counter is planned for the next phase.

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Development of a VUV-VIS-Spectrometer for Target Characterisation

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Fluorescence Spectroscopy in the visible, ultraviolet and VUV spectral range is a powerful experimental technique for the investigation of quantum-mechanical interference and electron correlative processes in atoms, molecules, and their ions. Energy differences between the two involved levels of the radiative transitions can be determined accurately, the recorded fluorescence intensity is a measure for the population probability of the fluorescence transitions initial state and a polarization analysis enables an analysis of the population of the energetically degenerate magnetic sublevels.

Advantages of Fluorescence Spectrometry

In synchrotron radiation experiments fluorescence spectrometry has proven to be an outstanding tool due to its state selectivity. The possibility to determine energies of doubly excited states in rare gas atoms demonstrates this feature nicely. In these experiments energies of individual autoionizing Rydberg states of two-electron excitations were determined. The state specificity of the autoionization processes into particular final states (which have been the initial states of the fluorescence transitions) enabled an individual determination of Rydberg states energies, being completely impossible in absorption experiments due to the high density of all doubly excited Rydberg states contributing to the absorption signal [1]. An example of such an experiment is shown in Figure 1 for Rydberg series of Kr doubly excited states.

Figure 1: Dispersed fluorescence intensities from excited KrII 4s24p45s4P3/2 (a) and 4s24p55s4P3/2 (b) satellite states after photon excitation with energies around 28.55eV as well as the total photoion yield (c). Rydberg series of autoionizing two-electron resonances are clearly visible and can be distinguished.

Usage at Heavy-Ion Storage Rings

Fluorescence spectrometry used for the investigations of atomic or molecular ions formed after impact of heavy ions will be invaluable to conclude on the possible formation processes and on the involved electronic states. Also, a diagnosis of the ion beam itself after an impact in gaseous targets and foils is an intended aim of the project. Processes to be investigated will be radiative electron capture and dielectronic recombination.

Experimental setup and status of the project

The setup consists of a McPherson Model 225 1m-normal-incidence spectrometer that can be equipped with interchangeable diffraction gratings for the dispersion of the fluorescence radiation, each optimized for a different spectral range (VUV-VIS spectral range).

The detection of the photons is performed by 2-dimensional position- and time-resolving single-photon detectors that allow the simultaneous measurement of several fluorescence lines within a certain fluorescence wavelength range. Time resolution offers the option for lifetime or coincidence measurements.

Two detectors with wavelength ranges of 190nm to 700nm for the visible and 115nm to 300nm for the UV and VUV spectral range have been ordered from Quantar Technology and will be tested upon delivery. A third detector for the EUV spectral range from 30nm to 150nm will be assembled at the University of Kassel and also tested after completion.

Figure 2: Sketch of the spectrometer setup.

References


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Measurements of the Heavy Ion Stopping in X-ray heated low-density nanostructured targets


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Measurements of the enhanced ion energy loss in plasma compared to those in non-ionized matter have been carried out in the frame of the project U272. The plasma targets were produced via volumetric heating of CHO-foam layers (cellulose-triacetate-TAC; C_{12}H_{16}O_8) by soft X-rays. X-ray source with close to the Planckian spectral distribution was generated by irradiation of a gold cylindrical hohlraum with the PHELIX-laser at 0.54 μm, 150J, 1 ns, 5.10^{14} W/cm^2 [1]. 80% conversion of the laser energy into soft X-rays with T_{Planck} ~ 45eV has been reached. Hydrodynamic stable homogeneous plasma with electron density of n_e ~ 10^{21} cm^{-3} and 20-30 eV temperature is then produced in the state close to the thermodynamic equilibrium. This plasma is partially ionized and presented by He-like states of Carbon and Oxygen and fully ionized Hydrogen ions. Calculations of the 4.7 MeV/u Ti-ions energy loss on free and bound target electrons in dependence on plasma temperature/ionization degree (see Fig.1) have been done using a numerical code, described in [2].

![Figure 1](image1.png)

**Figure 1:** Expected energy loss of 240 MeV Ti-ions in a 1mm thick 2 mg/cm³ carbon–plasma layer in dependence on plasma temperature.

The experimental set-up for the plasma production and ion energy loss measurements was similar to those used in [3]. Plasma target was probed by Ti-ions with a variable delay between the laser pulse and the ion micro-bunch. The ion velocity after interaction with target was measured using Time of Flight method. The results are shown in Fig. 2. Comparison of the TOF data for vacuum and cold target conditions results into the time of flight difference of 6.9 ns. After interaction with plasma layer the ions reached the stop detector 2.8 ns later than in the case of the cold target, this corresponds to 1.4-times enhancement of the ion energy loss due interaction with free electrons in plasma. Energy loss of Ti-ions in plasma was measured for different time-delays and two plasma target densities, the results are presented in Fig. 3. At later times (>10ns) plasma temperature in the interaction region, placed 0.75mm apart from the hohlraum bottom, reached 20-30 eV and for both densities the enhancement of the ion energy loss is between 1.4 – 1.8 in accordance with [2]. The low enhancement factor at earlier times can be explained by lower plasma temperatures (see Fig.1) as a results of finite time needed for the heating process.

![Figure 2](image2.png)

**Figure 2:** Ti–ion beam micro-bunch structure measured in vacuum and after interaction with foam and plasma.

![Figure 3](image3.png)

**Figure 3:** Enhancement of the ion energy loss in plasma depending on the delay between the laser and ion pulses.

References:

Ion energy loss at maximum stopping power in a laser-generated plasma

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Ion stopping in plasma is relatively well-understood for projectile velocities much higher than the thermal velocity of plasma electrons (\(v_{\text{ion}}/v_{\text{th}} \gg 1\)), but large uncertainties remain for the region of maximum stopping power, where \(v_{\text{ion}}/v_{\text{th}} \approx 1\). This parameter region, of crucial importance for ICF, is very difficult to model theoretically \cite{1} and, to our knowledge, no experimental data exists in order to benchmark the existing theories and numerical codes. The purpose of this work, led in collaboration with the CEA and CELIA in France, is to carry out such measurements, and the first campaign was conducted in 2012.

100 \(\mu\text{g/cm}^2\) carbon foils were irradiated from both sides with frequency-doubled pulses from the PHELIX and nhelix laser systems, as in \cite{2}. The generated hot (200 eV) and dense (10\textsuperscript{20}–\textsuperscript{21} cm\textsuperscript{-3}) plasma has been well-characterized by using multi-frame interferometry \cite{3} and hydrodynamic simulations with the RALEF2D code \cite{4}, both approaches being consistent with each other \cite{2,3}. The plasma was fully ionized and ideal (coupling coefficient \(\Gamma \approx 0,01\)). The projectile energy was 0.5 MeV/u, and carbon ions were employed, as they are expected to be fully stripped in plasma in these conditions, according to Monte-Carlo calculations. In this way, no charge variation affects the stopping power and only the Coulomb logarithm of the interaction is expected to play a role. Theoretical calculations of the stopping power of C\textsuperscript{6+} in a fully ionized carbon plasma reveal discrepancies reaching 30\% between the various approaches.

The experimental setup is shown in Fig.1. The ions were decelerated to 0.5 MeV/u by using a graphite foil of 45\(\mu\text{m}\) thickness. This led to a beam straggling of 10\% in energy and \(1-2^\circ\) in angle, as calculated with the TRIM and Geant4 codes. The decelerating foil was positioned only 10 mm from the plasma target, allowing about 90\% of the ion beam to interact with a transversally homogeneous plasma according to TRIM and RALEF2D results, while keeping the foil outside of the laser beam path. To avoid the overlapping of consecutive ion beams, a time-of-flight distance of only 50 cm had to be used.

A new 15 \(\times\) 15 mm\textsuperscript{2} large and 13 \(\mu\text{m}\) thick polycrystalline CVD-diamond detector was therefore specially developed for the experiment, allowing to register 10\% of the beam. Due to their proximity to the plasma, the detector and the signal transmission line had to be properly shielded against X-rays and EMP. In particular, a 2 mg/cm\textsuperscript{2} gold foil on the beam path blocked most of direct X-rays without stopping the ions.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Experimental setup.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Energy loss as a function of time. 100\% corresponds to the energy loss in the solid foil.}
\end{figure}

First data was successfully gathered, and preliminary results are shown in Fig.2. An increase in energy loss in plasma of 34\% in relation to the cold target is observed.

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\end{itemize}

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Transport and focusing of laser-accelerated protons at Z6∗

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LIGHT

Irradiation of μm-thin foils with high-intensity laser pulses (> 10^{19} \text{W/cm}^2) became a reliable tool during the last decade for producing high-intensity proton bunches, providing up to 10^{14} protons in about a pico-second from a sub-millimeter source. However, the proton energy distribution is of an exponential shape with a currently achievable cut-off energy < 100 MeV (TNSA mechanism) and the beam is highly divergent with an energy-dependent envelope-divergence of up to 60 degrees. Thus, for most possible applications it is necessary to be able to capture and control these protons as well as select a specific energy. Therefore, the LIGHT collaboration (Laser Ion Generation, Handling and Transport) was formed, dedicated to investigate the possibilities of compact laser-driven ion sources for ions in the multi-MeV range. In this context, a lot of preparative work had been done at GSI in the last years and the most promising results could be obtained with small quadrupole magnets [1] and pulsed high-field solenoids [2, 3]. And since the commissioning of the PHELIX 100 TW beamline [4] some experiments could already move to the Z6 area, where now short-pulse laser technology and conventional accelerator infrastructure can be merged in a unique way.

pulsed high-field solenoid

The first experiment in 2012 for transport and focusing of laser-accelerated protons was done at the Z6 area, where PHELIX can deliver about 15 J of laser energy on target, exceeding 10^{19} W/cm^2. While the laser hits the front of the target, a 5–10 μm thin metal foil, the protons are accelerated targetnormal from the back side. The pulsed solenoid, placed 80 mm behind the target, is 150 mm long, has an open aperture of 40.5 mm diameter and can reach a maximum field of 10 T.

The magnetic field was adjusted to focus 4.5 MeV protons at 695 mm behind the solenoid (925 mm behind the target). The Detection of the proton beam in front of the solenoid and directly behind (still inside the targetchamber) showed the expected energy-dependent focusing and beam rotation. A proton focus could be reached inside the

Figure 1: Transverse focus profile of 4.5 MeV protons at nearly 1 m from source, produced with the pulsed high-field solenoid.

attached Z6 ion beamline at 695 mm behind the solenoid, containing 5 × 10^8 particles and with a spot size of 3 mm (FWHM).

The results are in good agreement with accompanying simulation studies, which are performed with CST particle studio and TraceWin.

permanent-magnetic quadrupole triplet

In a second experimental campaign in 2012, the transport and focusing of laser-accelerated protons could be tested in the PHELIX laserbay with a permanent-magnetic quadrupole triplet. Here, intensities of 5 × 10^{19} W/cm^2 were used with about 60 J laser energy on target; i.e. more particles are produced initially.

A sub-aperture of the full beam (40 mrad divergence) was transported through the triplet and at 630 mm distance to the source, 10 MeV protons were focused in a 3x6 mm (FWHM) spot size, containing up to 10^9 particles.

References

Ultra-thin foils for laser ion acceleration in the radiation-pressure regime

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Introduction

Recent developments by our and other groups on the mechanism of radiation-pressure driven acceleration of protons and heavy ions [1,2,3,4] emphasizes the strong dependence of the results on a very high laser contrast of $> 10^9$, as well as the development of suitable targets. Since a few years diamond-like-carbon (DLC) foils are an appropriate choice. The drawback is the low mechanical stability for foils having a thickness of just a few. We developed an alternative process using a polymer based film which is produced by vapor deposition. Test of the surface roughness as well as the mechanical stability show great advantage for this kind of material compared to normal DLC foil.

Setup

We use parylene, an industrial coating material which is hydrophobic and optical transparent [5]. Starting from a glass substrate which is wiped with a hydrophilic barrier layer (detergent) the polymer is attached by pyrolytic chemical vapor deposition (p-CVD) forming a homogeneous layer on all surfaces within the deposition chamber, see fig. 1.

![Fig. 1: Process of pyrolytic chemical vapour deposition (p-CVD) of parylene onto the glass substrates.](image)

After deposition the glass substrate is removed and stored in inert gas, allowing storage times of more than one year before mounting as a target. The foil can be flooded of the substrate by slowly casting in a bath of water and being attached to a target mount by adhesion, afterwards. For laser-acceleration experiments we used in previous experiments a 15nm thick foil attached on a special target mount (fig. 2a) creating more than 400 targets which can be used without opening the chamber in between shots. It was also possible to attach the foils self-supporting on very large apertures, up to 20mm, see fig. 2b.

![Fig. 2: a) Parylene foil attached to target mount used for laser-acceleration experiments. B) Self-supporting 15 nm foil freestanding on 20 mm aperture.](image)

Characterization

For a proper characterization we measured the thickness of each processed foil by ellipsometry, resulting in a thickness derivation of not more than 1nm at different positions of a large (150 x 100 mm) foil sample and a average thickness of 15nm. The mechanical stability of the parylene foil was compared to the stability of a DLC foil of the same thickness. Here 30 nm thick foils were used. For this purpose both foils were attached on TEM-grids creating small self-supporting samples. The force-distance relation was measured via nanoindentation using an atomic-force microscope (AFM). The measured elasticity of the parylene is 5 times higher than the one of the DLC, which explains the higher resistance against mechanical shock and temperature variation observed during hadling. Using AFM topography mode, we measured the surface roughness in addition. Both samples had more or less the same average roughness of $R_{DLC} = 5.7 \pm 0.9$ nm and $R_{Parylen} = 8.6 \pm 2.3$ nm.

References

X-ray Laser Developments at PHELIX

B. Ecker\textsuperscript{1,2}, B. Aurand\textsuperscript{2,3,4}, D. C. Hochhaus\textsuperscript{3,7}, P. Neumayer\textsuperscript{3}, B. Zielbauer\textsuperscript{1,4}, K. Cassou\textsuperscript{5}, S. Daboussi\textsuperscript{5}, O. Guilbaud\textsuperscript{5}, S. Kazamias\textsuperscript{5}, T. T. T. Le\textsuperscript{6}, E. Oliva\textsuperscript{6}, L. Li\textsuperscript{6}, H. Zhao\textsuperscript{8}, Q. Jin\textsuperscript{8}, D. Ros\textsuperscript{5}, P. Zeitoun\textsuperscript{6} and T. Kuehl\textsuperscript{2,4}

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Introduction

We report on results of a double-stage molybdenum x-ray laser experiment. The two targets were pumped using the double-pulse grazing incidence pumping technique, which includes travelling wave excitation for both the seed- and the amplifier-target.

The main motivation for X-ray laser (XRL) research at GSI is to perform spectroscopy experiments on highly-charged heavy-ions stored in the experimental storage ring (ESR) of the GSI accelerator facility\cite{1}. The first experiment of this kind will aim at measuring the 2s1/2 – 2p1/2 transition in Li-like ions. For ions of an atomic number between 50 (Sn) and 92 (U), this transition energy lies between 100 eV and 300 eV \cite{1}, which corresponds to wavelengths between 12 nm and 4 nm. Setting up the experiment in a way, where the XRL is counter propagating to the ion bunch, one can exploit the relativistic Doppler effect. The use of laser-pumped plasma XRL’s, with typical photon energy up to 100 eV \cite{2,3,3} can address the whole range of lithium-like ions for the lowest lying transitions The perspective for FAIR, given by the even higher ion velocities at HESR, opens a completely new range of experiments.

Experiment

![Fig. 1. Sketch of the experimental setup. A more detailed description is given in the text.](image)

A Mach-Zehnder like interferometer, which was implemented in the short-pulse frontend of the PHELIX laser, was used to create the chirped double-pulse structure required for the DGRIP scheme \cite{2}. After compression, the pulse duration of the two pulses was 200 ps (prepulse) and 2 ps (main pulse). Using the PHELIX pre-amplifier section, the total pump energy on the target amounted to 600 mJ, equally distributed between two individual pumping beams. Inside the target chamber, the two beams were focused in opposite direction onto the Mo slab target by two spherical mirrors, as illustrated in Fig. 1. The line foci were vertically separated by \sim 3 mm. The output of the lower XRL – the seed pulse - was focused into the upper – amplifying medium by a spherical XUV mirror.

Results

Seeded x-ray laser operation has been demonstrated, resulting in x-ray laser pulses of up to 240 nJ and 2 mrad \times 2 mrad divergence. The peak brilliance of the amplified x-ray laser of \num{4e23} photons/s/mm²/mrad² in \num{5e-5} relative bandwidth was more than two orders of magnitude larger compared to the original seed pulses. Figure 1 shows the typical beam patterns of the HH observed (filters: Zr and Ti) under (a) only He gas jet (valve stagnation pressure: 4000 mbar), (b) Ne 400 mbar jet, and (c) both gas jets for Ne 400-He 4000 mbar.

![Fig. 2: Beam quality of the seeded XRL showing 2 mrad \times 2 mrad divergence.](image)

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Hollow Beam creation with continuous diffractive phase mask at PHELIX*

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Overview

In the framework of the Laser Ion Generation Handling and Transport (LIGHT) project, the reduction of the divergence of the laser accelerated ions is a central issue. One solution relies on engineering the electron sheath used in standard laser-driven proton acceleration (target normal sheath acceleration, TNSA) for reducing the initial divergence of the ion beam. In 2012, we conducted an experimental campaign in which “donut” focal spot have been used to drive proton acceleration. From that we have found two interesting features:

- One sees a qualitative effect of the focal spot beam shape on the ion beam divergence as expected, and
- The energy cut-off in the proton spectrum was nearly higher when a donut focus was applied, although this resulted in contradiction with the scaling law of TNSA.

Report on the 2012 beamtime

During the beamtime, we did a first run on laser-ion acceleration with engineered beams. We also focused particularly on avoiding strong wavefront distortion in the laser amplifier (astigmatism) because we saw how crucial it is for that kind of experiment. In 2012 a new PHELIX off-axis parabolic mirror was installed and produced a good hollow focus profile during alignment. However, we found that the on-shot aberrations also strongly alter the beam quality. Therefore a bending mechanism was installed to the main-mirror 1 in the main amplifier of PHELIX to correct for the thermal aberrations happening on shot and measured with a wavefront sensor. Using this pre-compensation, the alignment- beam profile looks distorted but the on-shot profile looks more promising.

Results on ion acceleration with engineered laser beam

In total we had 29 successful high-energy experiment shots on gold foils with different thicknesses with and without hollow beam.

In comparison to a standard Gaussian beam (blue dots in Figure 1) the focal spot diameter of the hollow beam focus increases by a factor of about 2 and therefore the peak intensity drops nearly by a factor of 4. A troubling feature is that the maximum proton energy for the hollow beams (in red) does not depend on the laser intensity contrarily to what laser-ion acceleration scaling laws predict. For higher-order hollow beams (green dots), the focal spot was heavily distorted and resulted in a speckle-like energy distribution at low intensity. In this case a significant reduction of the proton energies was observed.

![Figure 1: Proton Energy dependency on laser intensity.](image1)

From an angular distribution stand-point, the proton beams created with the hollow laser beam clearly show a systematic trend to lower divergences and higher proton yields. Taking the more aberrated shots into account we observe other effects on the ion beam. Some type of shots with a hollow beam profile broke down to 2 similar strong focal spots shows a divergence reduction in only on dimension while other shots with the hollow beam phase on thick targets shows unexpected high proton energies.

3w on-shot focus diagnostics

We set up a new imaging diagnostic for measuring the laser focal spot on target during the shot [1]. The idea was to look at the relativistic oscillation plasma surface that generates harmonics. Then filter for only the 3w light that is specular reflected from the target surface and is linked directly to the laser focal spot and the TNSA source size. As the components were not available in the beginning of the experiment it was just installed in the last two days. Therefore there was not enough time for optimization of the diagnostic. We know that the imaging system was strongly affected by astigmatism (due to passing through a thick glass substrate). But still we can say that the source size was smaller than 80x80 µm² (Figure 2).

![Figure 2: on-shot focus in 3w.](image2)

References


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Amplification of high harmonic generation signal by double gas jet scheme

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Introduction

High-harmonic (HH) radiation due to nonlinear interaction of rare gas with an ultrashort, high intensity laser pulse has attracted a great deal of interest for various applications, such as, attosecond pulses \cite{1} and a seeding light for an X-ray free electron laser (XFEL) \cite{2}. On the other hand, we have observed X-ray parametric stimulated amplification of the HH emission for the first time \cite{3}. However, the output of the HH in high photon energy regime is still weak, so that practical applications are limited in some particular physical and chemical research. In order to increase the output energy and obtain much shorter wavelength radiation, a double gas jet method was used in this study. As a result, we succeeded in a significant enhancement of the HH output. Moreover, the appearance of a high intensity, hot spot emission was observed.

Experiment

The experiment was carried out at the JETI laser-system, delivering pulses of 200 mJ, 10 Hz in 26 fs, with a pulse contrast in the range of better than $10^6$. The beam was focused by a spherical mirror to an intensity of $< 5 \times 10^{15}$ W/cm\textsuperscript{2}. In order to enhance the HH lights, we employed a double gas jet scheme, in which the first gas was Ne as a seeder and the second jet (He) served as an amplifier. Both gases were supplied by electro-magnetic pulsed gas valves. An extreme ultraviolet (EUV) spectrometer was used to measure the HH spectra and their intensity distribution. The beam pattern of the HH was observed by a back-illuminated soft X-ray CCD camera, at which some appropriate filters (Ti and Zr) were inserted to select wavelength region and block the fundamental laser light.

Results

Fig. 1 shows the typical beam patterns of the HH observed under (a) only He gas jet (valve stagnation pressure: 4000 mbar), (b) Ne jet 400 mbar, and (c) both gas jets for Ne 400-He 4000 mbar.

The distance of the jets was set to $d=0$ mm. The figures are shown in the same color scale. As clearly seen, no HH was observed for only He gas jet, whereas by operating both jets the HH signal becomes higher by two times than that by only the Ne jet.

![Fig. 1: Two dimensional image of the high harmonic radiations for (a) only He jet (4000 mbar), (b) Ne (400 mbar), and (c) both jets operated. For comparison, the graphs are shown in the same color scale. Significant enhancement of the HH signal was obtained.](image_url)

On the other hand, the hot spot where the HH intensity is locally enhanced is obtained as shown in Fig. 2. The experimental conditions are as follows: stagnation pressures of Ne 250 mbar, He 4000 mbar, Zr-Ti filters, for various jet distances were used. The seed lights generated in Ne gas jet were amplified significantly at $d=0$ mm, which is similar with that in Fig. 1. However, in the case of the jet distances above $d=2$ mm, we obtain the intense spot radiation near the beam center. At optimal condition, we demonstrate that the gain coefficient at the hot spot, which is defined by the ratio of HH intensity with both gas jets to that of Ne one, is around 20.

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Supersonic radiation driven heat waves in foam target heated by X-rays

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A combined hohlraum-target concept have been investigated in order to gain a high degree of plasma homogeneity in experiment on the energy loss of heavy ions in ionized matter and approach plasma with a coupling parameter $\Gamma \sim 0.5-1$. In this scheme, low density mm-thick foam layers were heated by means of X-rays generated in the gold hohlraum. The application of low density CHO-foam layers for plasma production has demonstrated a very high hydrodynamic stability of the created plasma and its uniformity [1]. A wide verity of diagnostic methods has been applied for measurements on the thermal wave propagation, plasma opacities and plasma self-radiation.

In Hydrodynamic 1-D calculations, 2 mg/cc cellulose triacetate $C_{12}H_{16}O_{8}$ of 2 mm thickness was heated from the right side by an X-ray flux with the Planckian spectral distribution at temperature of 30 eV and 10 ns duration (experimental conditions), see Fig. 1. For radiation transport in the diffusion approximation $C_{12}H_{16}O_{8}$-opacities calculated in [2] have been used.

Figure 1: Propagation of the heating front through a 2 mm thick CHO-foam in time window from 1 to 10 ns.

Depending on the hohlraum spectra and foam density two different scenarios of a foam target heating by X-rays can be realized. If the mean photon pass in plasma is shorter than a plasma size, optically thick case, target heating occurs step by step (Fig. 1) via propagation of the radiation driven supersonic thermal waves. If created plasma is optically thin (low target density or more energetic spectra of photons due to higher hohlraum temperature) volumetric heating takes place.

Propagation of the radiation driven supersonic thermal waves has been observed experimentally using a pin-hole camera coupled to the 4-frame gated MCP (microchannel plate) [3] and imaging the CHO-foam at different times of the heating process. An exposition time for every frame, in experiment 3-5 ns, and time delay between two subsequent frames can be varied. Fig. 2 shows the geometry of the combined target (picture left), the MCP-cheep with four imaging areas (right) and a measured time history of the heat-front propagating from the cylindrical hohlraum into the foam (center).

Figure 2: 2-D image of the foam region heated to plasma by hohlraum x-rays in the regime of supersonic radiation-driven heat waves, measured at different times.

The supersonic heat wave velocity $V \sim \frac{T^{m+4}}{\rho^{\sim const}}$ (1) is a strong function of the plasma temperature $T$ (in our case $m \sim 3$) and doesn’t depend on plasma density for hydrodynamic stable plasmas ($\rho^{\sim const}$). After analyses of the radiation front position at different times one comes up with the averaged over the exposition time heat wave velocities and corresponding plasma temperatures.

- $V(1\,ns) = 1.2 \times 10^7\, cm / s \rightarrow T \sim 25\, eV$
- $V(4\,ns) = 8.3 \times 10^6\, cm / s \rightarrow T \sim 23\, eV$
- $V(7\,ns) = 4.0 \times 10^6\, cm / s \rightarrow T \sim 20\, eV$
- $V(10\,ns) = 1.4 \times 10^6\, cm / s \rightarrow T \sim 15\, eV$

In coming experiments this method will be applied for measurements of the plasma temperature in the time window of ion-plasma interaction.

References


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Comparison of measured time resolved hohlraum radiation temperature with data produced by RALEF II-Code

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For indirect homogeneous heating of low-Z triacetate-cellulose (TAC) foam targets, used in experiments on ion energy loss in plasma, a large (Ø > 1 mm) soft X-ray source with a Planckian equivalent radiative temperature of 30 to 50 eV is required. In this temperature region soft X-rays are effectively absorbed by low Z low density polymer layers. More energetic radiation above 1 keV passes through the 200 μg/cm² TAC-layer without attenuation giving no input into the process of foam heating.

The experiments have been supported by RALEF II simulations, made by S. Faik from University Frankfurt. One important data, the hohlraum temperature show a heating during the shot of the laser in the first ns, it leads to a peak temperature of about 70 eV. After some additional Nanoseconds the Temperature in the hohlraum is homogenized and stays nearly constant for a long (>10 ns) while (see figure 2a).

Figure 1a: The picture shows a scheme of the setup, with a view in the Au-Hohlraum from the same position as the X-ray-diode.
Figure 1b: The scheme shows the laser and the diode, using the same hole for heating and diagnostic.

The temperature in experiment was measured by X-ray-diodes. The X-ray-diodes are composed once of a carbon and second of an aluminium cathodes, a grid with and a filter. The combination of different filters allow measuring the absolute photon flux in different parts of the hohlraum spectrum and deduce a time-history of the hohlraum temperature radiation. dowrs for different wavelength (see Figure 2).

According to earlier experiments [1,2], we can assume a short time of 5-7 ns after the beginning of the laser pulse of X-ray imission and remission. After this homgenisa-

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References
Hard X-Ray backlighting for Warm Dense Matter at FAIR*

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FAIR opens new possibilities to study the fundamental properties of matter under extreme conditions. In experiments like HIHEX or LAPLAS [1] the Warm Dense Matter will be generated by high-energy, high-intensity ion beams heating large (mm²) high Z-targets (Al-Pb). For backlighting these targets, it is necessary to generate photons with energies in the keV-MeV range. Hard X-ray and Gamma sources can be generated by processes that occur during interaction of high intensity lasers with matter. When a laser pulse impacts onto the target, collective absorption mechanisms transfer up to 20% of the laser energy into hot electrons, which are accelerated to multi-keV and MeV energies. The deceleration of the hot electrons penetrating the target causes bremsstrahlung radiation. Attenuation and scattering of x-rays can be used to determine the electron plasma temperature and density[2]. The advantage of a hard x-ray generation using short-pulse lasers over a common x-ray tube is, that it gives the possibility to generate short bursts (fs-ps) of x-rays which provide the possibility to investigate a time history of dynamic processes in the plasma.

The experiment was carried out in the frame of the PHELIX - project P42. The applied laser parameters (E_L ≈ 150 J, τ_L = 500 fs, focal spot size of 15 - 20 μm) lead to the maximum intensity of 3 * 10¹⁹ W/cm². Ag foils (10-100μm) and Ag bulks (3mm) were used as targets. The experiment setup includes several pinhole cameras for spatial diagnostics, a single hit CCD for the measurement of Ag-Kα radiation, Hard X-ray Detectors (HXRD) for spectral diagnostics and a x-ray knife to determine the energy of hot electrons.

![Figure 1: comparison of calculated and measured IP-response](image)

The HXRD mainly consists of an image plate (IP), which is placed behind filters of different thicknesses (Pb 53-1807 μm). The x-ray absorption of the filter set takes place in accordance with the Lambert-Beer-Law I = I₀ * e⁻αρd, where d is the thickness of the filter, α is the attenuation coefficient of the filter material and ρ is the filter density. The bremsstrahlung spectrum will then be reconstructed using a fitting procedure in which a synthetic spectrum with a temperature of hot electrons, defined in a zero approximation by the laser intensity[3], is sent through the filter set. By varying the temperature of hot electrons, one tries to achieve the best agreement between theoretical and experimental data. Fig.1 shows the comparison of calculated and measured IP-responses in the laser shot at 2 * 10¹⁹ W/cm². The best fit is achieved for hot electron temperature of 1.5MeV. The x-ray knife diagnostic consists of a 500μm thick Au-plate placed between the target and an IP. Due to the bremsstrahlung, generated by hot electrons penetrating the target, this arrangement allows to obtain an 1-D image of the interaction region and to estimate the electron energy depending on the electron penetration depth in target.

![Figure 2: penetration depth of hot electrons in Ag](image)

Fig.2 shows that the hot electrons are stopped after 1455μm of propagation in silver target. A stopping range of ~1.5mm in Ag refers to electron energies of 2MeV. This is in good agreement with results of the HXRD-diagnostic.

For backlighting of the 4mm-thick LAPLAS target tamper [1] made from Nb or W, laser induced photons with energies above 0.5-1MeV, electrons >20MeV and protons >100MeV are required. The current progress in advanced laser driven sources will allow generating short, quasi-monochromatic bursts of protons, electrons, neutrons and coherent x- and gamma-rays of high energies.

References


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Melting of carbon under extreme conditions characterized by X-ray scattering

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Introduction

X-ray scattering is a very powerful technique to study warm dense matter which means materials around solid density and temperatures of from several thousand to several hundred thousand kelvins [1]. It gives the possibility for the direct measurement of plasma parameters like temperature, density of free electrons, degree of ionization and the microscopic structure of a warm dense matter sample. Therefore, X-ray scattering is a central diagnostics for all three upcoming plasma physics experiments at FAIR (HIHEX, LAPLAS, WDM) which aim for a precise characterization of warm dense matter [2]. Hence, the accumulation of experience with X-ray scattering experiments at GSI and using the laser system PHELIX as pulsed X-ray source of high brilliance is of major importance for the success of these future experiments at FAIR.

Experiment

After a first successful proof-of-principle experiment on X-ray scattering from shock-compressed matter at GSI in 2011 [3], an advanced campaign was performed in February/March 2012 at the Z6 experimental area. The aim was to investigate the microscopic structure of carbon at the melting regime around 100 GPa (=1 Mbar) pressure. The laser system nhelix with pulse energies of 65 J at 1064 nm and pulse durations of 10 ns was used for the compression of graphite samples. The ns-option of the PHELIX system at Z6 (150 J, 1 ns, 527 nm) was focused on a Ti foil and created enough X-rays of Ti-He-α line radiation (4.75 keV) for a successful X-ray scattering experiment. In fact, a conversion efficiency of up to $5 \times 10^{-3}$ could be achieved. The scattering angles were chosen to be 105° and 125° which ensures scattering in the non-collective regime (scattering on single electrons). Comparing the intensity of elastic scattering from tightly bound electrons to inelastic scattering from weakly bound electrons gives the possibility to determine an absolute value of the atomic/ionic structure factor $S_ii$ of the shocked samples (see figure 1). Density and pressure inside the shock wave could be characterized by a classical measurement of shock and particle velocity resulting in $3.9 \pm 0.2$ g/cm$^3$ and $145 \pm 17$ GPa for the 2012 campaign as well as $3.9 \pm 0.2$ g/cm$^3$ and $86 \pm 11$ GPa for the 2011 campaign.

Simulations and results

In addition to the experiment, DFT-MD simulations calculating the microscopic structure of possible carbon phases which might be present inside the laser-driven shock have been performed. Comparing the experimentally obtained structure factors to the simulations gives the definite result that liquid carbon is present inside the laser-driven shock in both experiments [4]. This is in fact the first direct measurement which proves the existence of the liquid phase in this density and pressure regime and can be used to test corresponding theoretical phase diagrams. Thus, a successful method to characterize phase transitions in warm dense matter has been developed. Concerning the carbon solid-liquid phase transition, more sophisticated experiments at the VULCAN laser are scheduled for February/March 2013 and high precision experiments at the LCLS facility are proposed for end of 2013.

References

S- and P-polarized reflectivities of strongly correlated plasma

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The experimental data from investigations of optical properties of a strongly correlated plasma is an important cornerstone to construct theoretical models for the description of warm dense matter. The analysis of the response of a dense plasma to electromagnetic waves of moderate intensity can be used as a tool to investigate the validity of the physical models describing the behavior of matter under extreme conditions, high temperatures and pressures.

The plasma created has transitive surfaces with a density profile. The research of the transitive layer of a explosively driven dense plasma can be carried out using the technique of inclined probing by polarized electromagnetic waves. Angular dependence of S- and P-polarized reflectivities at several wavelengths can be used in the integration of Maxwell equations to construct the spatial profile of the density of charge carriers. In this paper, we report new results of S- and P-polarized reflectivity measurements of a non-ideal plasma at ν\textsubscript{las} = 2.83·10\textsuperscript{14} s\textsuperscript{-1} (λ\textsubscript{las} = 1064 nm), ν\textsubscript{las} = 4.33·10\textsuperscript{14} s\textsuperscript{-1} (λ\textsubscript{las} = 694 nm) and ν\textsubscript{las} = 5.66·10\textsuperscript{14} s\textsuperscript{-1} (λ\textsubscript{las} = 532 nm).

To generate the non-ideal plasma, we used explosively driven shock waves which lead to compression and irreversible heating of xenon and to measure the dense xenon plasma polarized reflectivity index, a pulsed RUBY and YAG+KTP system with a four-channel pulse high-speed device for determination of the Stokes vector components was used [1]. The device allows to measure the intensity of the reflected laser beam for four azimuthal angles and was equipped with filters for selection of probing frequency.

In order to determine the thermodynamic parameters and composition of plasma suitable calculations have been carried out. Working with a grand canonical ensemble, virial corrections have been taken into account due to charge-charge interactions (Debye approximation). Short-range repulsion of heavy particles was considered within the framework of a soft sphere model [2-3].

In Figure 1, the experimental data and results of solving of Maxwell equations using the generalized Drude formula and the dynamical collision frequency in Born approximation [4] are shown. Results of calculations with layer temperature profile and ea-collisions as factor are shown in Figure 1 too.

**References**


Prototype of Real-time Hard X-ray Imaging System and Spectrometer

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Large scale (~mm), high-z targets are used in many laboratories as well as in the future FAIR in the research of warm dense matter and high energy density plasmas, and sub-GeV photon radiography is one important diagnostic. Besides sub-GeV photons, hard x-ray photons (E>100 keV) can also penetrate ~mm thick high-Z material, and such photons can be generated in the interaction of intense laser pulse with target, with conversion efficiency up to 10⁻⁴ and spot size as small as 10 μm [1,2]. This bremsstrahlung radiation then becomes another candidate for the above radiography. In many experiments, in-line or real-time diagnostic is necessary either due to long pump/vent time or high repetition rate of sources, which makes the popular image plate no longer useful. In this way, we are building a scintillator/screen-based hard x-ray imaging system to perform real-time imaging, and aiming to achieve ~10 ps temporal resolution, ~10 μm spatial resolution, ~1mm field of view for ~1mm thick high-Z targets. It should also work as a real-time x-ray spectrometer, working below 1 MeV.

The prototype is a point-projection, scintillator-based, lens-coupling, visible-ccd-measurement portable system. The scintillators/screen are LYSO, BGO and LANEX. In October 2012, the prototype was first tested in Phelix laser facility, compared with image-plate-based system. The laser parameters are ~100 Joules, ~picosecond, ~10 μm foci, intensity up to 10¹⁹ Wcm². The irradiated bremsstrahlung images the objects to scintillators/screen, and then the fluorescence from scintillator/screen is imaged by lens pair to pco ccd camera. For some shots, we mount copper and tantalum filters of various thickness to measure the spectra. Fig.1 shows that ~10 mm thick, middle/high-Z target can really be imaged in our condition. From other results and analysis, it is known that ~100 μm spatial resolution can be achieved on scintillator/screens, corresponding to 20 μm resolution on object with 5x magnification. And in the energy range 50 keV~1MeV, the system can achieve single-photon imaging, bypassing the detection capability of image plate. The x-ray spectra measured in the system fits with that of electron spectra measure by e-spec for energy range of 20~200 keV. By changing filters and thickness of scintillators, we will be able to measure energy spectra up to 1 MeV.

To better understand the system, we plan to do calibration with 5 keV radioactive source and 1~2 MeV DA-LINAC photon source, also Monte Carlo simulation of transport processes of high-energy photons in both filters and scintillators will be performed. Expensive fiber bundle coupling will also be utilized if we have enough funding. We hope to have better results in the next experiment.

Figure 1: Images of objects by LYSO-based system. Above: M4 nut (3 mm thick iron) and Tantalum layers (1 mm and 0.5 mm thick) with 1.5 mm through hole on 5 mm thick copper; Middle: 6-mm diameter Tantalum cylinder on 5 mm thick copper; Below: lineout of Tantalum cylinder.

References

Development of a high current gas discharge switch for the FAIR magnetic horn*

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The planned Facility for Antiproton and Ion Research (FAIR) is a new international accelerator laboratory at the GSI in Darmstadt, Germany. The main focus at this facility is aimed to heavy-ion research as well as protons and antiprotons colliding experiments. To produce these antiprotons (3 GeV), protons (29 GeV) will be aimed at a target (e.g. Copper). In order to focus these antiprotons for the storage in a synchrotron, a strong magnetic field will be applied by a so called magnetic horn. To generate the necessary high magnetic field for this application the designed stripline of the pulse forming network (PFN) has to handle a peak current of 400 kA with a pulse length of 20µs. Currently the only possibility to handle this amplitude is are mercury filled Ignitrons. Another application for high-power switches is the FAIR SIS injection and extraction magnets. The requirements for this switch are a hold-off voltage of about 80 kV and maximum currents of about 8 kA with a pulse length of a few µs.

The plasma physics working group at the University of Frankfurt develops a mercury free switch, which is able to replace the Ignitrons in the PFN of the magnetic horn. The challenge for the development of a switch for such high currents is to reduce the local electrode erosion. For that we propose a gas switch that generates an accelerated plasma to minimize the attrition.

The experimental setup of the switch consists of coaxial electrodes, similar to the geometry used for plasma focus devices [1]. To reach a high hold-off voltage, the setup is designed for the left hand side of the Paschen branch. One important feature of a high-voltage and high-current switch is the reliability for triggering. The main discharge between the coaxial electrode system will be initiated by a trigger predischarge. With an external triggering a gas breakdown is initiated at the outer electrodes and forms a conductive plasma sheath which penetrates through holes to the inner electrodes. After the ignition of the main discharge between the coaxial electrode system and due to the interaction of the induced radial magnetic field with the plasma, the gas discharge will be accelerated to the open end of the coaxial electrode system. This acceleration of the plasma sheet is due to the Lorentz force, which interacts with the discharge. It is given by:

$$\mathbf{F} = \int dV \mathbf{J} \times \mathbf{B}$$

Therefore the switch will be called a Lorentz Drift Switch (LDS). For already designed LDSs the maximum current is 33 kA with a current rise time of 15 kA/µs. As a working gas Nitrogen and Argon were used. For a further reduction of erosion and to provide enough charged particles for the current transport, several of these coaxial devices will be stacked together in a parallel, multiple electrode system. In order to synchronize the plasma sheets, the single tubes will be connected with each other across a vertical arrangement of boreholes at the outer electrodes. The following Fig. 1 shows a schematic drawing of the experimental set up of the first prototype of the multi-channel Lorentz Drift Switch.

Figure 1: Schematic drawing of a multi-channel LDS.

The designed multi-channel LDS is a low inductive, fast current, low pressure gas discharge switch. Due to the simple setup and the reduction of erosion we will introduce a low cost, and rugged high-current switch for applications in further high-energy experiments. With the introduced setup we hope to provide a real alternative for such high-current applications, when common Ignitrons were used at FAIR so far.

References


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Investigation of the parameters of a dense, inductively generated stripping plasma for the FAIR-Project

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As higher charge states are essential for short acceleration distances in modern facilities like FAIR, a screw-pinch plasma device is set up at the IAP Plasma physics group in the Goethe University Frankfurt. This screw-pinch device is set up as an alternative solution to the theta-pinch device and as possible alternative solution to the established stripping foils.

The objective of the experiment is the investigation of a new coil configuration, and the generation and maintenance of dense plasmas with different ignition parameters.

Figure 1 shows the configuration of the screw-pinch coils. This configuration consists of two coils, which are superimposed. The inner coil has 6 poloidal turns which are oriented along the Z-axis. The outer coil has 9 toroidal turns, which are in the XY-plane. The total inductance of the setup is L≈11 μH. The energy storage of the device consists of four capacitors with a capacitance of 25 μF each at a maximum charging voltage of 9300 V. The modular design of the capacitor bank can use capacitors single (25μF), parallel (50, 75, 100 μF) and in series (12,5 and 25 μF). A thyatron (TDI1-200k/25H) is used in order to switch the high voltage and current. The argon gas is used for the experiment.

Figure 2 shows a signal of the photodiode with a signal of a current curve. The photodiode signal is detected in the center of the recipient. The duration of the plasma discharge is about 500 μs, and is repeatedly compressed to a cylindrical shape. The duration of the compression phase is about 10 μs and the length of the discharge is 150 mm. The achieved average electron density of the plasma is 1,6⋅10^16 cm^-3. The maximum efficiency of the structure is achieved at a pressure of about 140 ± 20 Pa and is approximately η = 70% for frequency of 10 kHz (Capacitance 25 μF) and charging voltage 18 kV.

References

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Interaction of Ca\textsuperscript{10+} ion beam with a hydrogen theta-pincha plasma\textsuperscript{*}

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Introduction

The interaction of heavy ions with plasma is important for research in a field like warm dense matter (WDM), laboratory astrophysics and inertial confinement fusion (ICF), where the high repetition rate of ion-beam pulses are of an advantage as a driver. Also applications like using the plasma as an efficient beam-stripper are of importance with respect for the future Facility for Antiproton and Ion Research (FAIR).

Experiment

The Plasma Physics Group of the Goethe University in Frankfurt has developed and built a spherical Theta-pincha device [1, 2]. Different than in a Z-pincha, there is no need for electrodes in direct contact with the plasma.

Fig. 1 shows the set-up of the Theta pincha device. A spherical glass vessel is encircled by 7 segments of a copper coil. The coils together with a capacitor bank (37.5 \( \mu \) F) and a thyristor-stack [3] is part of a LRC electric circuit. At an operation voltage of 14 kV the stored energy in the capacitors is 3.7 kJ. Once triggered by the thyristor-stack, the energy will be released in the discharge in several milliseconds. The peak current in the circuit reaches up to 50 kA. Hydrogen is chosen as target gas in the vessel because hydrogen is easily fully ionized which is an advantage for obtaining a high charge state of the beam ions. The plasma is created by discharging the energy of the capacitor bank into the gas volume, which leads to an alternating strong current in the coil ionizing the gas and resulting also in a strong magnetic field compressing the plasma (pinch-effect). The Theta-pincha is differentially pumped over a two-stage aperture-system on both sides of the glass vessel, reducing the initial gas pressure of up to 1 mbar to the vacuum of 10\textsuperscript{-5} mbar of accelerator beam line the device is integrated in for measurements.

The interaction experiments were carried out at the Z6 experimental area of GSI. The Theta-pincha was integrated in the accelerator beam line, where a 3.6 MeV/u Calcium\textsuperscript{10+} pulsed ion beam with a 108 MHz frequency is provided, resulting in a time-structure with 9 ns distance between the micro beam-pulses, while the maximum duration of the macro-pulse is 5 ms. The ion-beam-pulse, triggering of the discharge and timing of diagnostic tools were synchronized by a high precision trigger system.

Results

Figure 2 shows the Ca-beam signal obtained by a stop detector, black curve. The blue curve is the light emission from the plasma which is detected by a photo diode. Here the beam micro pulse was 4 ms. During the first 100 \( \mu \) s, until the discharge is triggered, the beam is interacting with cold gas. Later when the hydrogen is ionized, visible in figure 2 by the start of the signal from the light emission (blue curve) the target is in the plasma state. The light emission is not constant but oscillating, following the oscillations in the discharge current. Fig. 2 also shows the transmission of the ion beam during the whole time of the plasma duration. The ion-beam signals show the same oscillating behaviour like the light emission, the pulse intensity increases even over the transmitted pulse intensity in cold gas and disappears at other times, this result depends probably from the time dependent magnetic field imaging the beam ions like a solenoid.

References


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First preparatory experiments on NEET at GSI


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Nuclear excitation by electronic transition (NEET) [1] designates a mechanism of nuclear excitation induced by a transition between two bound states of the atomic system. Depending on the considered element, the surrounding environment of different atomic configurations may influence the decay rates of isomeric states. This is supposed to be the case for 84Rb in a plasma environment [2]. As shown in Fig. 1, it is possible to excite a nucleus from an isomeric state to a higher state with different half-life. In 84Rb this transition is around 3.5 keV. The 84Rb isomeric state could be efficiently produced by the Unilac with a 76Ge(11B, 3n)84Rb reaction, alternatively with a 76Ge(12C, p3n)84Rb reaction. For an efficient NEET rate, high charge states (30-34+) are needed to have an efficient energy matching. Depending on different plasma models, especially for higher Z-elements the ionic structure depending on the temperature becomes hard to predict - LTE calculations suggest 300-400 eV, while non-LTE calculations suggest 2-3 keV to reach the desired ionization degrees.

To determine whether the PHELIX parameters available at Z6 in the long pulse option are sufficient to reach these high charge states, we did a first test run to record the spectra of a RbF target. Two spectrometers recorded time integrated spectra of the target and they were used in different configurations to observe different energy ranges. One was based on a HoPG crystal for high reflectivity, the other one was a Mica crystal for high spectral resolution.

The Phelix laser was used at an energy of 150 J(2ω) at a pulse length of 1.4 ns with a focus diameter of d=100 μm. This corresponds to an intensity of 1015 W/cm² on target. Additionally, we tried to increase the laser energy by using a pulse train of Phelix, each laser pulse at an energy of 150 J, but separated by 3-4 ns to fulfill the damage threshold criterions.

Some of the spectra recorded with the HoPG spectrometer are shown in Fig. 2. They do not show dramatic differences when the energy is increased, however the overall amount of x-rays is increased.

The analysis of the spectra in detail is still ongoing. The difficulty is that there are no experimental data and only limited theoretical calculations available for Rb plasmas to compare them to. The results of a first analysis indicate that we observed charge-states in the range of 25-27+, which would be a bit too low for our experiment. However we intend to continue our efforts into this direction.

To specifically analyze the corona of the target to see, whether the undercritical part reaches a sufficiently high temperature and charge states to perform a final experiment at GSI to observe and measure the NEET rate of 84Rb in a plasma.

References

The $g$ factor of highly charged ions is an excellent instrument for probing bound-state QED effects in the presence of a magnetic field, and, moreover, gives access to an accurate determination of fundamental physical constants and nuclear parameters. Few-electron ions are of particular interest: On the one hand, apart from to one-electron QED effects they provide an excellent possibility to probe also many-electron QED corrections. On the other hand, simultaneous investigations of one- and few-electron ions allow us to construct specific differences, where the uncertainty originating from the lack of knowledge of the nuclear properties can be almost eliminated. Studying of a specific difference of the $g$ factors of H- and B-like ions [1] can provide an independent determination of the fine structure constant in the domain of strong external field.

The high-precision measurement of the $g$ factor has been recently accomplished for Li-like $^{28}$Si$^{11+}$ [2]. The measurement for B-like $^{40}$Ar$^{13+}$ is already in preparation in the framework of the ARTEMIS project [3]. Here we report on recent progress in the theoretical predictions for these systems.

The theoretical contributions to the $g$ factor of Li-like ions can be split into one-electron and many-electron parts, respectively. The former are similar to the corresponding corrections to the $g$ factor in H-like ions. The latter, which define the difference between the $g$ factors of H- and Li-like ions, are mainly due to screened QED-radiative and the interelectronic-interaction corrections. Until now, the interelectronic-interaction contributions have mainly determined the total theoretical uncertainty of the $g$ factor of Li-like ions for all values of $Z$. Recently, we have performed the rigorous QED evaluation of the two-photon exchange corrections to the $g$ factor [2, 4], and, thus, improved the total theoretical accuracy for the $g$ factor of $^{28}$Si$^{11+}$ by almost a factor of 2. A comparison of the experimental value $g_{\text{exp}}^{(2)}[2s] = 2.0008898899(21)$ with the corresponding theoretical prediction $g_{\text{th}}^{(2)}[2s] = 2.0008899095(51)$ allows to probe the two-photon exchange correction on a level of about 1%. This provides the most stringent test of many-electron QED effects in the presence of a magnetic field.

The ARTEMIS project will implement the laser-microwave double resonance spectroscopy to measure with ppb accuracy the Zeeman splittings of both ground state $\langle 1s \rangle^2 (2s)^2 2p_{1/2}$ and first excited state $\langle 1s \rangle^2 (2s)^2 2p_{3/2}$ in boron-like argon [3]. Recently, we have performed accurate QED calculations of the $g$ factor of these states [5]. The $1/Z$-term of the interelectronic interaction is calculated within the rigorous QED approach. For the ground state the higher-order contributions are evaluated within the large-scale configuration-interaction method with the Dirac-Fock and Dirac-Fock-Sturm basis functions (CI-DFS). The one-loop self-energy correction for $P_j$-states is calculated employing the Kohn-Sham potential, that partly takes into account the screening effect. The higher-order (two-loop) QED effects are accounted for to zeroth order in $\alpha Z$. The recoil correction is evaluated to first order in $m/M$, also with the Kohn-Sham screening potential. The present results $g_{\text{th}}[2p_{1/2}] = 0.663647(1)$ and $g_{\text{th}}[2p_{3/2}] = 1.332285(3)$ are in agreement with those reported in Ref. [6] and are by order of magnitude more precise.

We also considered the effects of second- and third-order in the magnetic field, which can be expressed in the following way: $\Delta E_A^{(2)}(B) = \langle g\rangle^2 (M_j)(\mu_0 B)^2/2(\alpha e^2)$ and $\Delta E_A^{(3)}(B) = \langle g\rangle^3 (M_j)(\mu_0 B)^3/3(\alpha e^2)^2$, where $\mu_0$ is the Bohr magneton and $m$ is the electron mass. Accordingly, the results for $g_j^{(2)}$ and $g_j^{(3)}$ for B-like Ar are obtained as:

\[
g_j^{(2)}(\pm 1/2) = -39.5 \times 10^3, \quad g_j^{(3)}(\pm 1/2) = \pm 2.5 \times 10^9, \\
g_j^{(2)}(\pm 3/2) = 41.0 \times 10^3, \quad g_j^{(3)}(\pm 3/2) = \mp 2.5 \times 10^9, \\
g_j^{(2)}(\mp 3/2) = 1.0 \times 10^3, \quad g_j^{(3)}(\mp 3/2) = \pm 5.7 \times 10^3.
\]

The ARTEMIS experimental setup implies the presence of a magnetic field of about 7 Tesla. This leads to the relative contribution of the quadratic effect $|\Delta E_A^{(2)}/\Delta E_A^{(1)}| = 0.9 \times 10^{-4}$ for the $2p_{1/2}$ state and $0.5 \times 10^{-4}$ for the $2p_{3/2}$ state. The relative contribution of the cubic effect yields $|\Delta E_A^{(3)}/\Delta E_A^{(1)}| = 4.7 \times 10^{-9}$ for the $2p_{1/2}$ state and $2.3 \times 10^{-9}$ for the $2p_{3/2}$ state. Therefore, the second- and third-order contributions can clearly be disregarded at the anticipated ppb-level of accuracy. The above results are closely related to recent experimental investigations [3], where details on the measurement procedure and the identification of higher-order effects can be found.

References

Parity nonconservation effects in the dielectronic recombination of polarized electrons with heavy He-like ions

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Parity nonconservation (PNC) experiments with heavy few-electron ions can provide new possibilities for tests of the Standard Model in the low-energy regime\cite{1,2}. In contrast to neutral atoms, the atomic structure of heavy few-electron ions can be calculated to a high accuracy. To date, various schemes\cite{3,4,5,6,7,8,9} for PNC measurements in highly-charged ions were suggested. Here we report on recent studies of the PNC effect in the dielectronic recombination of polarized electrons with He-like ions.

The enhancement of PNC-effect in atomic systems takes place for close-lying opposite-parity levels. As such levels, we consider the $\left(1s^2s_0\right)_{1/2}$ and $\left(1s^2p_{1/2}\right)_{0}\left(ns\right)_{1/2}$ states, which are found to be close for $4 \leq n \leq 7$, $Z \sim 60$, and $Z \sim 90$, where $n$ is the principal quantum number of the third electron and $Z$ is the nuclear charge number. The related energy differences are listed in Table 1.

Table 1: The energy difference $E_{\left(1s^2p_{1/2}\right)_0\left(ns\right)_{1/2}} - E_{\left(1s^2s_0\right)_{1/2}}$ in eV, for the values of $Z$ and $n$, which seem to be the most promising for enhancement of the PNC effect.

<table>
<thead>
<tr>
<th>$Z$</th>
<th>$n=4$</th>
<th>$n=5$</th>
<th>$n=6$</th>
<th>$n=7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>54</td>
<td>-0.489(35)</td>
<td>-0.787(34)</td>
<td>-1.21(4)</td>
<td>-1.47(4)</td>
</tr>
<tr>
<td>60</td>
<td>3.49(6)</td>
<td>1.42(6)</td>
<td>-0.222(56)</td>
<td>-0.376(56)</td>
</tr>
<tr>
<td>62</td>
<td>3.90(6)</td>
<td>1.66(6)</td>
<td>0.818(64)</td>
<td>-0.103(64)</td>
</tr>
<tr>
<td>64</td>
<td>4.40(7)</td>
<td>2.06(7)</td>
<td>1.14(7)</td>
<td>0.699(74)</td>
</tr>
<tr>
<td>88</td>
<td>9.17(30)</td>
<td>5.34(29)</td>
<td>3.86(29)</td>
<td>3.17(29)</td>
</tr>
<tr>
<td>90</td>
<td>8.27(47)</td>
<td>4.13(47)</td>
<td>2.51(47)</td>
<td>1.75(47)</td>
</tr>
<tr>
<td>92</td>
<td>6.69(27)</td>
<td>2.97(28)</td>
<td>-1.07(28)</td>
<td>-1.60(28)</td>
</tr>
</tbody>
</table>

We consider the process of the dielectronic recombination of a polarized electron with a heavy He-like ion, being originally in the ground state, into the doubly-excited $d_1 = \left(1s^2p_{1/2}\right)_0\left(ns\right)_{1/2}$ and $d_2 = \left(1s^2s_0\right)_{1/2}$ states. In order to evaluate the PNC effect, we consider the cross section without the PNC effect, $\sigma_0 = \left(\sigma_{1/2} + \sigma_{-1/2}\right)/2$, and the P-violating contribution, $\sigma_{\text{PNC}} = \left(\sigma_{1/2} - \sigma_{-1/2}\right)/2$, where $\sigma_{\pm 1/2}$ are the cross sections for the $\pm 1/2$ helicity (spin projection onto the electron momentum direction) of the incident electron, respectively.

In the process under investigation, the most pronounced PNC effect is expected in the uranium ($Z = 92$) ion, when the energy of the incident electron tuned in resonance with $\left(1s^2p_{1/2}\right)_0\left(6s\right)_{1/2}$ state. The corresponding behaviour of $\sigma_{\text{PNC}}$ as a function of the energy of the incident electron is presented in Fig. 1. In this case the PNC asymmetry, $\left|\sigma_{\text{PNC}}/\sigma_0\right|$, reaches a value of about $1.5 \times 10^{-5}$. The analogous process of the dielectronic recombination of polarized electrons with the H-like ions at $Z < 60$ was studied by Gribakin et al.\cite{10} in Ref. \cite{10}. The PNC asymmetry of that process was found to amount of about $5 \times 10^{-9}$, which is by several orders of magnitude smaller than the effect as we have reported here.

Figure 1: PNC cross section of the dielectronic recombination process into the states $\left(1s^2p_{1/2}\right)_0\left(6s\right)_{1/2}$ and $\left(1s^2s_0\right)_{1/2}$ for $Z = 92$. The difference $E_i - E_{\left(1s^2p_{1/2}\right)_0\left(6s\right)_{1/2}}$ determines uniquely the energy of the incident electron.

References

Parity–violating transitions in beryllium–like ions

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Parity–violation (PV) phenomena in highly–charged ions currently attract much attention (see e.g. [1, 2]). In particular, many studies are focused on the mixing between opposite–parity atomic levels caused by the weak electron–nucleus interaction. A number of proposals have been made to detect such a mixing and, hence, to explore the basic parameters of the electroweak theory. Most of theses proposals have dealt up to now with the near–degenerate 1s2s and 1s2p1/2 states of helium–like heavy ions for which the PV effects are significantly enhanced. In the high–Z domain, however, the lifetimes of such singly–excited states are shorter than τ ~ 10−10 seconds which makes the observation of the parity–violating phenomena in two–electron systems rather challenging. During the recent years, therefore, particular interest has been given to other few–electron species whose long–lived levels might be mixed by the weak interaction.

Owing to their shell structure, beryllium–like heavy ions may provide an alternative and promising tool for studying atomic PV phenomena. For the case of zero nuclear spin, the first excited state of these ions, 1s2 2s2p3P0, can decay to the 1s2 2s2 1S0 ground level solely by the strongly suppressed two–photon E1M1 emission and, hence, has a lifetime of the order of seconds. Moreover, the energy splitting between these two levels does not exceed 260 eV even for the heaviest ions, thus leading to a rather remarkable 1s0−3P1 parity–violating mixing [3]. To observe such a mixing, we have recently proposed to utilize the source of the coherent extreme ultraviolet (EUV) radiation and to induce a single–photon transition between the metastable 1s2 2s2p3P0 and short–lived 1s2 2s2p3P1 levels [4]. Since the 3P0 state has a small PV–admixture of the ground state, such an absorption can proceed not only via the allowed M1 but also the parity–violating E1 channel (see Fig. 1).

The interference between the M1 and PV–E1 excitation channels becomes “visible” if the 1s2 2s2p3P0 → 1s2 2s2p3P1 transition is induced by the circularly polarized light. In this case the photoexcitation cross section reads as [4]:

σλ = σM1 (1 + λec),

where λ = ±1 for the right– and left–hand polarization, σM1 describes the leading, parity–preserved 3P0 → 3P1 magnetic dipole channel, and the so–called asymmetry coefficient ε is given by:

ε = 2ηPV ⟨1s2 2s2p3P1 || E1 || 1s2 2s2 1S0⟩ ⟨1s2 2s2p3P1 || M1 || 1s2 2s2p3P0⟩. (2)

In this expression, ⟨... || E1, M1 || ...⟩ are the reduced matrix elements for the 1S0 → 3P1 (E1) and 3P0 → 3P1 (M1) transitions, and the parameter ηPV describes the PV mixing between the 1S0 and 3P0 states.

The asymmetry parameter ε is the physical observable in the proposed experiment. It can be determined by inducing the 1s2 2s2p3P0 → 1s2 2s2p3P1 transition separately with left– and right– circularly polarized light and by recording then the intensity difference of the x–rays from the decay of the 3P1 state. Since these intensities are proportional to the photo–excitation cross sections (1), Iλ(3P1 → 1S0) ~ σλ, we can find:

ε = I+ - I- / I+ + I-. (3)

In order to provide an estimate of this asymmetry parameter, detailed calculations have been performed within the framework of the multi–configuration Dirac–Fock (MCDF) approach [4]. Based on these calculations, we argue that the most suitable candidate for the experimental realization of the proposed scheme is beryllium–like uranium U88+. For this ion, the PV–mixing between the 1s2 2s2p3P0 and 1s2 2s2 1S0 states gives rise to ηPV = −1.0 × 10−6 and the asymmetry parameter ε = 3.1 × 10−7.

References
Relativistic calculations of charge transfer probabilities in heavy-ion collisions using the basis set of cubic Hermite splines


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Low-energy heavy-ion collisions provide a unique opportunity to test quantum electrodynamics effects in supercritical electromagnetic fields [1]. The investigation of related phenomena requires first the development suitable numerical methods for solving the two-center time-dependent Dirac equation in the external electromagnetic field generated by the colliding heavy ions. In previous works we developed a numerical method using the basis of atomic-like Dirac-Fock-Sturm orbitals [2, 3], which allows us to calculate charge transfer and electron excitation probabilities in ion-ion and ion-atom collisions.

Here we report on an alternative approach for the treatment of exact two-center Dirac problem based on utilizing the finite basis set of cubic Hermite splines on a two-dimensional uniform lattice. Previously, the Hermite splines have been employed for relativistic calculations of electron excitation probabilities within the monopole approximation [4]. An advantage of this basis set is, that only adjacent Hermite splines overlap. Accordingly, the Hamiltonian and overlap matrix are sparse. Moreover, since the overlapping area is small, the matrix elements can be obtained by numerical integration at a smaller number of points. The Dirac equation is solved in the reference frame which rotates together with the internuclear axis. It allows using the two-dimensional lattice instead of a three-dimensional one. The influence of the rotational couplings is taken into account by the inclusion of the states with different projection of the total angular momentum into the basis set. The time-dependent Dirac equation is solved by expansion of evolution operator into the Taylor series.

At first, collisions of a bare nucleus $^{92+}$ (projectile) with one-electron ion $^{91+}$ (1s) (target) were considered. The target is considered to be at rest, while the projectile moves along a straight-line trajectory with a constant velocity. Charge transfer probabilities were calculated at the projectile energy $E = 6$ MeV/u for a wide range of the impact parameters $b$. The calculations were performed including several channels with different projection of the total angular momentum onto the internuclear axis. In the case of one channel the rotation of the internuclear axis is not taken into account. The results of calculations are shown in Fig. 1. As one can see from Fig. 1, the six channel results are in a good agreement with the corresponding values of Ref. [2]. We observed that four channels are quite sufficient to describe the charge transfer process. Since for impact parameter $b < 600$ fm the one-channel results differ significantly from those including six channels, we can conclude that the influence of the rotational coupling due to the rotation of the internuclear axis becomes essential for small values of $b$.

We plan to extend the developed method to describe ionization and pair-creation processes in heavy-ion collisions. The negative-energy Dirac continuum will be considered to be fully occupied by electrons. The amplitudes of corresponding processes will be calculated utilizing many-body techniques as described in [5, 6]. We expect that this work will be required for the future experiments at GSI and FAIR.

References

Relativistic calculations of inner-shell atomic processes in low-energy ion-atom collisions


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In the recent work [1] we developed a relativistic method for evaluation of charge-transfer and electron-excitation processes in low-energy ion-atom collisions. Here we report on a recent application of this method for the evaluation of K-shell-vacancy production and K-K-shell charge transfer probabilities versus the impact parameters in low-energy collisions of H-like ions with neutral atoms. The calculations are performed for systems already studied experimentally and theoretically [2, 3, 4, 5], as well as for systems, which will be investigated experimentally at GSI and FAIR (Darmstadt) in the near future [6].

The method of calculations is based on the independent particle model, where the many-particle Hamiltonian \( \hat{H} \) is approximated by a sum of effective single-particle Hamiltonians \( \hat{H}_{\text{eff}} = \sum \hat{H}_{\text{eff}} \) reducing the electron many-particle problem to a set of single-particle equations. The latter is solved by means of the coupled-channel approach with atomic-like Dirac-Fock-Sturm orbitals [1], localized at the ions (atoms). The solutions of these equations allow one to describe the many-electron collision dynamics. The Dirac-Kohn-Sham Hamiltonians with the exchange-correlation potential taken in the Perdew-Zunger parametrization [7] are used as effective single-particle Hamiltonians.

In our calculations the projectile (H-like ion) moves along a straight line with a constant velocity and the target (neutral atom) is fixed. Only the 1s electron of the target is considered as the active electron and participates in excitation and charge-transfer processes, while the electrons of the target provide a screening potential. In Fig. 1 we present the results of the calculations for the Ne – F\(^{8+}\)(1s) collision at the projectile energy 525 keV/u. We note that both curves have the same oscillatory behavior. The K-shell-vacancy production is mainly determined by the K-K-shell charge transfer. At small impact parameters the contribution from the charge-transfer excitation into the 2s, 2p, and higher vacant states of the projectile become also important. The related calculations of the K-shell-vacancy production are performed for the Xe – Xe\(^{53+}\)(1s) collision at the projectile energy of 5.9 MeV/u in the relativistic and nonrelativistic limits. As one can see from Fig. 2 the role of the relativistic effects is rather strong. We note that both curves have the same oscillatory behavior but the nonrelativistic curve is shifted toward larger impact parameters.

In our further investigation we plan to continue investigation of inner-shell electron processes in low-energy ion-atom collisions. Special attention will be paid to the many-particle effects.

References

Magnetic interactions and retardation in the electron emission from highly-charged ions

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X-ray studies from multiple and highly charged ions have been found a unique tool for exploring the electron-electron (e-e) and electron-photon interactions in the presence of strong fields [1]. The x-ray spectroscopy of such systems have demonstrated for a long time that accurate energies and cross sections are obtained only if, apart from the static Coulomb repulsion among the electrons, the magnetic interactions and retardation as well as leading quantum-electrodynamical effects are taken into account. In contrast to the spectroscopy of hard x-rays, however, much less is known about relativistic interactions among the electrons affect their emission and, hence, the dynamics of electrons in strong fields.

To obtain further insight into the strong-field dynamics of electrons, we re-analyzed the excitation and autoionization of highly charged ions with the goal to separate the magnetic and retardation contributions to the e-e interaction from the static Coulomb repulsion. A remarkable change in the electron angular distribution due to the relativistic terms in the e-e interaction was found especially for the autoionization of (initially) beryllium-like projectiles, following a $1s \rightarrow 2p_{3/2}$ Coulomb excitation in collision with some target nuclei. In this process, the angular distribution of the emitted electron is given by

$$W(\theta) \propto 1 + \sum_{k=2,4,...} A_k(\alpha_r, J_r) f_k(\alpha_r, J_r, \alpha_f J_f) P_k(\cos \theta),$$

where $A_k(\alpha_r, J_r)$ characterizes the alignment of the intermediate state after the excitation, $\theta$ is the polar angle with regard to the beam direction and where the $f_k(\alpha_r, J_r, \alpha_f J_f)$ are characteristic functions that describe the dynamics of the autoionization. The function $f_k$ in this distribution merely depends on the (reduced) matrix elements of the (frequency-dependent) e-e interaction

$$V = V_{\text{Coulomb}} + V_{\text{Breit}}$$

that comprises both, the instantaneous Coulomb repulsion and the (so-called) Breit interaction, i.e. the magnetic and retardation contributions.

For the excitation-autoionization process via the $1s^22s^2p_{3/2}^2P_2$ resonance, a diminished (electron) emission in forward direction as well as oscillations in the electron angular distribution due to the magnetic and retarded interactions are predicted especially for the electron emission into the $1s^22s^2S_1/2$ ground and $1s^22p^2P_{1/2}$ excited levels of the finally lithium-like ions. This emission pattern is in strong contrast to a pure Coulomb repulsion between the bound and the outgoing electrons. For example, Figure 1 displays the angular distribution of electrons emitted in the $1s^22s^2p_{3/2}^2P_2 - 1s^22s^2S_{1/2}$ (left panel) and $1s^22s^2p_{3/2}^2P_2 - 1s^22p^2P_{1/2}$ (right panel) autoionization of $^{88+}$ projectile ions with energy $T_p = 5 \text{ MeV}/u$.

In conclusion, the proposed excitation-autoionization process can be observed at existing storage rings and will provide novel insight into the dynamics of electrons in strong fields. The most simple signatures of the relativistic contributions to the e-e interaction in high-Z ions is the reduced electron emission in forward direction ($\theta < 5^\circ$) as well as the double-peak structure in the expected angular distribution; these signatures arise especially at low projectile energies $< 10 \text{ MeV}/u$ and for beryllium-like ions with nuclear charge $Z > 70$. The electron angular distribution from such projectiles can be analyzed with present-day electron spectrometers and provide complementary information about the electron dynamics in strong fields that is not accessible from x-ray spectra alone.

References

Excitation of autoionizing states of helium-like ions by scattering of high-energy particles

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Two-electron excitations of atoms and ions induced by impact of charged particles and photons are fundamental processes, which have been studied since decades. Along with double ionization and ionization accompanied by simultaneous excitation, double excitation is caused by the interelectronic interaction. Accordingly, the cross sections of these processes turn out to be extremely sensitive to the quality of which dynamic correlations are taken into account. This allows one to test different theoretical approaches. In experiments, the neutral helium atom is preferably used as a target, since it is the simplest multielectron system. Helium-like ions with moderate values of nuclear charge $Z$ are even more attractive for investigation of correlated processes, since the corresponding cross sections exhibit a universal scaling behavior. However, such processes are rather rare. Their cross sections decrease rapidly with increasing $Z$ values.

In a most recent paper [1], we have studied two-electron excitations of helium-like ions into the two lower autoionizing $2s^2(^1S)$ and $2p^2(^1S)$ states (in the following denoted, for simplicity, by numbers 1 and 2, respectively) by collisions with high-energy electrons and photons. The calculations are performed analytically within the framework of non-relativistic perturbation theory with respect to the interelectronic interaction. The atomic targets are assumed to be characterized by the small parameters $1/Z \ll 1$ and $\alpha Z \ll 1$, where $\alpha$ is the fine-structure constant. The Auger widths of the levels are equal to $\Gamma_1 = 0.226$ eV and $\Gamma_2 = 0.011$ eV.

In high-energy non-relativistic domain characterized by $3/2 \ll \varepsilon \ll 2(\alpha Z)^{-2}$, the total cross section can be cast into the following scaling form ($\hbar = 1$, $c = 1$) [1]:

$$\sigma^{**} = \frac{\sigma_0}{Z^6 \varepsilon} B(\varepsilon), \quad B(\varepsilon) = \int_{x_1}^{x_2} Q(x) dx,$$

(1)

where $\sigma_0 = \pi a_0^2 = 87.974$ Mb and $a_0 = 1/(\hbar c)$ is the Bohr radius. The limits of integration over the dimensionless momentum transfer $x$ are given by $x_1 = 9/(4x_2)$ and $x_2 = (\sqrt{\varepsilon} + \sqrt{\varepsilon - 3/2})^2$, respectively. The dimensionless energy $\varepsilon$ is related to the asymptotic velocity $v$ of projectile according to $\varepsilon = v^2/(\alpha Z)^2$.

The universal functions $Q(x)$ and $B(\varepsilon)$ are independent of the values of $Z$. The excitation process is characterized by a rather small momentum transfer $x \lesssim 4$ (see Fig. 1). The scalings $B(\varepsilon)$ are saturated already at $\varepsilon \gtrsim 10$. For the lower autoionizing states, the asymptotic high-energy limits amount to the values $B_1 = 0.0231$ and $B_2 = 0.0072$.

Then for fast projectiles ($\varepsilon \gg 3/2$), the total cross sections have a simple scaling behavior like $\sigma^{**} \sim \varepsilon^{-1}$, which is similar to that for single-electron excitations $1s \rightarrow ns \ [2]$. Note, that in this case, the formula (1) can also be employed for collisions with heavy charged particles, which are nevertheless much lighter than the atomic nucleus of target. If the charge number of the incident particle is equal to $\pm z$ (in units of the elementary charge $e$), then the cross section should be multiplied by the factor $z^2$. Although $\Gamma_2 \ll \Gamma_1$, both the autoionizing $2s^2(^1S)$ and $2p^2(^1S)$ levels can be efficiently excited by high-energy particle scattering.

![Figure 1: The universal functions $Q(x)$ and $B(\varepsilon)$: solid line, $2s^2(^1S)$ state; dotted line, $2p^2(^1S)$ state.](image)

References


High-temperature plasma of Ge generated by the PHELIX laser

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Certain nuclear transitions, accompanied by release of large amounts of energy, can be induced by appropriate atomic resonances. One potential candidate is an isomeric state of 84Rb, whose γ-decay could be initiated by resonant ns → 2s transitions in strongly (z_{ion} > 27) ionized Rb atoms [1]. The required degree of ionization could be achieved by heating the medium, where the 84Rb isomers are created, with the PHELIX laser at GSI. Since the Rb isomers are expected to be created in the 76Ge(12C,p3n)84Rb reaction, i.e. by irradiating Ge with a carbon beam, it is the Ge plasma where one should demonstrate the ability to achieve the necessary temperatures under laser irradiation.

Here we present the results of RALEF-2D [2] simulations of a 4 μm thick Ge foil, irradiated normally by a λ = 532 nm laser pulse of 150 J over a focal spot of radius r_f = 100 μm; the 1.4-ns long pulse was ramped with 0.2-ns linear rise and fall intervals. As a preliminary step, spectral opacities and the equation of state of Ge in the approximation of local thermodynamic equilibrium (LTE) were generated with the THERMOS code [3]. The RALEF runs were performed in the newly developed axial rz mode of the radiation transport, which was treated with 22 spectral groups and the S_{12} angular quadrature.

The calculated 2D temperature distribution in the Ge plasma shortly after the middle of the laser pulse (t = 0.8 ns) is displayed in Fig. 1. The corresponding 1D profiles along the laser-beam axis are shown in Fig. 2. The laser heated plasma consists of two distinct zones: a low-density hot corona behind the critical surface, whose temperature reaches T_{max} ≈ 1.3 keV, and a radiation-driven heat wave before the critical surface with a relatively high density of ρ ≈ 0.1–0.2 g/cc, where the matter and radiation temperatures are practically equal and lie in the range T ≈ T_r ≈ 100–150 eV. The whole structure is dominated by x-ray energy transport: our simulation indicates that about 70% of the absorbed laser energy escapes the target in the form of keV-range x-rays. The calculated time- and space-integrated emission spectrum (in the direction opposite to the laser beam) is shown in Fig. 3.

References

Radiation-hydrodynamic simulations of foams heated by hohlraum radiation

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Undergoing experiments at GSI use a cylindrical hohlraum target irradiated by the PHELIX laser for the indirect x-ray heating of a carbon foam to create a homogeneously ionized plasma state for measurements of the ion stopping power [1]. Simulations with the newly developed code RALEF-2D [2] have been performed to investigate the dynamics of the hohlraum and of the plasma [3]. Figure 1a shows the lateral cut of the simulated Cartesian (x, y) configuration which extends to infinity along the z-axis.

The RALEF-2D code solves the one-fluid one-temperature hydrodynamic equations in two spatial dimensions on a multi-block structured quadrilateral grid by a second-order Godunov-type numerical scheme using the ALE approach. Thermal conduction, radiation transport, and laser energy deposition by means of inverse bremsstrahlung absorption have been implemented within the unified symmetric semi-implicit approach with respect to time discretization. The applied EOS, thermal conductivity, and spectral opacities were provided by the THERMOS code. In combination with the Planckian source function, this involves that the radiation transport is treated in the LTE approximation.

The frequency-doubled PHELIX laser pulse in the experiment has a pulse duration of 1.4 ns with a total energy of 180 J, which corresponds to 122.8 J/mm after conversion to the simulated 2D case. In the simulation, the radiative transfer equation was solved for 7 spectral opacity groups and for 960 discrete ray directions over the entire 4π solid angle. The spatial laser intensity profile was approximated by a Gaussian curve with a FWHM of 0.2 mm.

The calculated x-ray hohlraum spectrum close to the end of the laser pulse (Figure 1b) shows a highly non-Planckian spectrum, which mimics the spectral opacity profile of carbon. The matter and radiation temperatures at the center of the hohlraum equilibrate to ≈ 31 eV at t = 3 ns. For times t > 7 ns a thin and dense filament of shock-compressed gold plasma is formed and stays close to the hohlraum center due to the collision of the expanding clouds of the ablated material from both hohlraum walls.

For a large portion of the hohlraum radiation emitted during the laser pulse the carbon foam with the initial mean density \( \rho_C = 2.0 \text{ mg/cm}^3 \) has an optical thickness of ≈ 1. For this reason the carbon foam is practically instantaneously heated by a flash of x-rays from the laser spot over the entire foam volume to an average temperature of \( T \approx 30 \text{ eV} \), varying by about a factor 4 across a distance of 1 mm. After the laser pulse, the plasma temperature relaxes while the x-ray heating from the hohlraum continues. At \( t = 14 \text{ ns} \) (Figure 1c) the dynamics of the carbon plasma is dominated by lateral expansion and by a shock wave propagating from the Cu-C interface. Nevertheless, the simulations show that the time and space variations of such key parameters as the column mass density along the ion trajectories and the plasma ionization degree (\( Z \approx 3.9 \) at \( T \approx 30 \text{ eV} \)) over the ion beam aperture remain sufficiently small for the measurements in the range 3 ns ≲ t ≲ 10 ns.

References
Study of Materials at Negative Pressures Using Picosecond Laser Pulses

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In the present work, the dynamic strength of Al, Pb, Cu, and Ta was studied by the method of generation of shock waves under the action of laser pulses of 70 ps duration. The use of such short pulse make it possible to realize in these experiments strain rates exceeding $10^{12}$ s$^{-1}$. We used a neodymium glass laser of the Kamerton-T facility in GPI RAS. The basic radiation was transformed to the second harmonic with the wavelength of 0.527 µm and the laser pulse energy of 2.5 J. Irradiated spot on a target surface was of 0.2 to 0.8 mm in diameter. Then the maximum energy density of the laser radiation flux in the focal area was $6.2 \times 10^{11}$ W/cm$^2$; the ablation pressure was about 1.35 TPa. Targets made of Al, Pb, Cu, and Ta had the form of plates 50 to 100 µm thick.

In our study, we have used an approach [1] that has allowed us to determine the strain rate and the spall strength of the material. This approach is based on both the measurement of the spallation depth after the laser-pulse action on the target and the subsequent numerical simulation of the shock-wave process in the matter under study.

For calculations, we used a numerical code [2], which is based on the hydrodynamic equations solving on the Courant–Isaacson–Rees scheme. Equations of state for the materials in question were taken from [3].

Figure 1 presents the obtained in this work spall strength values for Al versus the strain rate. Data from previous experiments [4–9] are also shown.

The data obtained under conditions of laser action on the target with pulse duration of 70 ps show that, at moderate amplitudes of shock loading, spall strength values are in agreement with the known functional dependencies of the strength upon the rate of deformation. With greater loading pressure (data set 4 in figure 1), there is a sharp growth of spall strength, that indicates the strengthening of the material as a result of loading. The registered growth of spall strength of aluminum is connected with the fact that, in the experiments, the increase of the rate of deformation was achieved not only by shortening of the pulse duration, but also by the increase of the amplitude of loading. The latter increase leads to hardening of the material under study. In this case, defects, which cause the premature spallation of the material, may be disappeared.

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