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GENERAL INFORMATION

This symposium is organized by the Stored Particles Atomic Physics Research Collaboration (SPARC) and the Atomic and Molecular Physics Division of the Portuguese Physical Society (Sociedade Portuguesa de Física). The SPARC collaboration has been formed to organize atomic physics experiments at the (FAIR) - Darmstadt, Germany, and aims to join expertise on atomic physics with highly charged ions at an international level.

This symposium will review the present status of the scientific, technical and financial issues of the SPARC collaboration and establish the forthcoming activities.

Organizing Committee

- José Paulo Santos (U. Nova Lisboa)
- Ana Costa (U. Lisboa)
- Pedro Amaro (U. Nova Lisboa)
- Mauro Guerra (U. Nova Lisboa)
- Thomas Stöhlker (GSI, Darmstadt)
- Reinhold Schuch (Alba Nova, Stockholm Universit).

Scientific Program

The scientific program will consist of Review Talks (50 minutes in length plus 10 minutes for discussion), Progress Reports (25 minutes in length plus 5 minutes for discussion), Short Progress Reports (15 minutes in length plus 5 minutes for discussion) and Posters.

Symposium Venue

The symposium venue will be at the Caparica Campus of the New University of Lisbon (Universidade Nova de Lisboa - UNL), near the Costa de Caparica, 15 kilometers south of Lisbon, which provides magnificent ocean views. It is only 20 minutes from Lisbon Airport, 10 minutes from the centre of Lisbon and 5 kilometers from the beaches at Costa de Caparica.

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10:45 - 11:00				
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REVIEWS

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R2	**A. Pálffy** (MPI, Heidelberg, Germany)	Nuclear effects in atomic transitions
R3	**R. Thompson** (Imperial College London, UK)	

Precision X-ray spectroscopy of highly-charged ions from low-energy ion sources

P. Indelicato

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Spectroscopy of highly-charged ions has been used for 3 decades to test QED in strong electromagnetic fields. It also has applications to plasma physics and astrophysics. Experiments evolved in two parallel lines:

- From beam-foil spectroscopy, with large Doppler shift and broadening-dominated uncertainties (~25 ppm at best) to storage ring experiments for very heavy elements with better control of the Doppler effect (using laboratory frame X-ray standards) (see, e.g., [1, 2])
- From spectroscopy based on highly charged ion sources using X-ray reference lines (typically from X-ray tubes) at NIST or Livermore (using and EBIT) to absolute energy measurements in Heidelberg (using an EBIT) [3] and Paris (using an Electron-Cyclotron Resonance Ion Source)

In the future, decelerated and stored beam at new facilities like HITRAP at GSI and FAIR, in the framework of the SPARC collaboration will allow access to relatively weak sources of highly charged ions at rest, up to bare uranium.

In this talk I will describes recent advances in absolute highly-charged ions X-ray transitions energy measurements in medium-*Z* ions, show preliminary results and describe difficulties to be overcome to get X-ray measurements of transitions like the 1s2s $^3S_1$-> $1s^2$ $^1S_0$ relativistic M1 transition in heliumlike Ar or the 1s 2s 2p ^2P_J->$1s^2$ 2s $^2S_{1/2}$ transition in lithiumlike Ar using a double-flat crystal spectrometer.

I will review the existing experiments, and present our future plans.

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Nuclear effects in atomic transitions

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Processes at the borderline between atomic and nuclear physics open the possibility to explore nuclear properties via experiments involving highly charged ions. Among these, nuclear excitation by electron transition and bound internal conversion have been recently observed experimentally [1,2]. The observation of the resonant process of nuclear excitation by electron capture (NEEC), in which a free electron is recombined into a bound atomic shell with the simultaneous excitation of the nucleus [3], continues to be a challenge for experiments with trapped or stored highly charged ions. NEEC is a process analogous to dielectronic recombination (DR), and when followed by the radiative decay of the nucleus, is a competing resonant channel of radiative recombination (RR). Similar to other resonant recombination channels, NEEC can occur in highly-ionized plasmas with heavy ions and, therefore, might have relevant applications in astrophysical processes.

In particular, effects of atomic vacancies on the nuclear lifetimes and population mechanisms of excited nuclear levels are addressed. NEEC into an excited electronic bound state for instance is followed by rapid x-ray emission and can lead to nuclear lifetime prolongation and an increase of the NEEC resonance strengths of up to two orders of magnitude [4]. We discuss applications of these effects for potential experimental observations of NEEC and to dense astrophysical plasmas.

NEEC can also act as an efficient nuclear excitation mechanism. Motivated by the need to identify efficient mechanisms that release on demand the energy stored in metastable nuclear states [5], isomer depletion via NEEC is investigated. A comparison with other depletion mechanisms shows that, among these, NEEC is the most efficient [6]. Finally, we discuss a potential experimental verification of our findings for the as yet unobserved NEEC at upcoming ion storage ring facilities.

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PROGRESS REPORTS

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PR2	**A. Wolf** (MPI, Germany)	Precision electron collision spectroscopy of highly charged ions
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Hyperfine structure in heavy ions: towards a test of QED in strong fields

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Investigations of the hyperfine splitting in highly charged ions give an access to a test of bound-state QED in the strongest electromagnetic field available for experimental study. To date, accurate measurements of the ground-state hyperfine structure were performed in several H-like heavy ions. An extension of such kind of experiments to highly charged Li-like ions will provide the possibility to investigate a specific difference between the corresponding values for H- and Li-like ions, where the uncertainty due to nuclear effects can be substantially reduced. Achievement of the required theoretical accuracy for the hyperfine structure in the case of Li-like ions is a very interesting and demanding challenge for theory.

A special attention is focused on one of the most difficult correction, namely, the screened QED correction in the presence of a magnetic field. The systematic description within the framework of QED perturbation theory allows one to account consistently for all the contributing diagrams to a given order. This crucial step has been achieved now and in the talk we report on current results of our rigorous evaluation of the complete gauge-invariant set of the screened one-loop QED corrections. As the most interesting application of these results towards tests of the magnetic sector of bound-state QED we present improved theoretical predictions for the specific difference between the ground-state hyperfine splitting values of H- and Li-like Bi ions. Perspectives for the reduction of remaining theoretical uncertainties are discussed.

Precision electron collision spectroscopy of highly charged ions

Andreas Wolf[1], Dmitry A. Orlov[1], Claude Krantz[1], Stefan Schippers[2], Dietrich Bernhardt[2], Alfred Müller[2], Michael Lestinsky[3,1], Michael Hahn[3], Oldrich Novotný [3,1], Daniel Wolf Savin[3], Fabrizio Ferro[4], and Eva Lindroth[4]

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Collisions between highly charged ions and electrons in merged electron beams have in recent work on ion storage rings been introduced as a precision tool for determining atomic properties. Photorecombination in these collisions displays a large number of resonances as a function of the electron energy, where the ion is excited while the incident electron is captured in a bound quantum state. This non-radiative process, highly sensitive on the interaction dynamics and the energies involved, is followed by photoemission. In precision electron collision spectroscopy at ion storage rings, the resonance energies in the total photorecombination cross section are measured by varying the electron impact energy at high resolution. With a photocathode electron target in the ion storage ring TSR, Heidelberg, resonances at energies down to 10 meV or even below were resolved. For Li-like scandium (Z=21) [1], these Rydberg-type resonances revealed the hyperfine splitting in the 2s level of the Li-like core. Moreover, their observation yielded the highest relative precision to-date on the absolute 2s-2p energy in any Li-like ion at intermediate or high nuclear charge Z. Nuclear charge radii were extracted from dielectronic recombination energies in a recent measurement on Li-like Nd ions (Z=60) [2] at the ESR ion storage ring at GSI, Darmstadt. In further measurements presently under analysis, low lying dielectronic resonances were measured with the photocathode electron target at the TSR for Be-like Ge (Z=32) [3] and B-like iron (Z=26) [4]. These measurements reveal detailed atomic structure information on the highly charged ions from the resonance energies, serving as a precision benchmark for high-accuracy calculations of partly filled electron shells and challenging high-precision atomic structure calculations on these systems. Highly accurate understanding of multi-electron atomic structure will considerably widen the range of those highly charged species which are suitable candidates for precision determinations of nuclear parameters. The results are reviewed and work in progress for some further interesting cases is reported.

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RMBPT studies of dielectronic recombination in Be-like ions

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A numerical code to treat three-open-shell electron systems with a Relativistic Many-Body Perturbation Theory (RMBPT) approach has been recently developed. We apply it to study the electron recombination on Be-like germanium Ge^{28+}, that was measured at TSR in Heidelberg with a 0.5 meV accuracy.

The recombination spectrum shows a rich resonant structure below 1.7 eV. Most resonances are due to dielectronic recombination. They arise from the capture of a continuum electron into a 9lj Rydberg state, with the excitation of an electron belonging to the $1s^2(2s^2)\ ^1S_0$ Ge^{28+} core to $1s^2(2s2p)\ ^1P_1$, or from continuum electron capture into a 14lj Rydberg state alongside a core excitation to $1s^2(2s2p)\ ^3P_0$. In addition, two resonances arise from trielectronic recombination; the free electron is now captured into a 7lj Rydberg state involving the excitation of two core electrons to $1s^2(2p^2)\ ^1D_2$.

We used RMBPT in the all-orders formulation to calculate the 2-body term energies $(2s^2)\ ^1S_0$, $(2s2p)\ ^1P_1$, $(2s2p)\ ^3P_0$ and $(2p^2)\ ^1D_2$ of the Be-like target states, while full 3-body calculations were performed to second order.

Comparison between the experimental spectrum and our theoretical results will allow to extract of the $(2s^2)\ ^1S_0 – (2s2p)\ ^3P_0$ transition energy, that is presently unknown.

The status of the storage ring project at Lanzhou

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The cooler storage ring CSR project was launched in 2000 at the Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou. In 2007, the installation was completed and the commissioning of CSRs gained great success, a new highly precise generation of collision experiments will become accessible even for the heaviest ion species. Commissioning experiments of radiative recombination and mass measurement were performed.

The recombination experiments was carried out at the electron cooler of CSRm, the charge changed ions was monitored by a particle detector located down stream after the dipole magnet. In the present experiment, a plastic scintillator is employed as a particle detector. The first test experiment for radiative recombination was carried out at CSRm electron cooler with Ar^{18+} ions at energy of 21.44 Mev/u.

The CSRe can also be used as high-resolution mass analyzer, and the masses are determined from the precise measurement of their revolution frequencies. The CSRe was set to isochronous mode for commissioning run of mass measurement. The fragments of $A/q = 2$ from fragmentation of 368MeV ^{36}Ar projectile were measured by their revolution frequencies. The mass spectrum is shown in figure 4. A mass resolution $\Delta m/m$ was estimated to be 10^{-6}.

High precision spectroscopy planned in the CSRe at the internal target, and the density of internal target reached several 10^{12} atoms/cm^2. The laser cooling of heavy ion beams was initiated. An overview of the updated plans for experimental researches will be presented.

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Radiative Recombination Studies at ESR and NESR

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The radiative recombination (RR) is a fundamental process of interaction of ions with electrons reflecting a coupling of radiation with matter. In this process a free electron is captured into bound state of an ion with emission of a photon which carries out the energy difference between continuum and bound electron states. Radiative recombination was first discussed theoretically nearly a century ago, but experimental possibilities to study the recombination of an ions with free electrons were opened up with availability of storage rings equipped with electron coolers.

The radiative recombination processes have been studied at existing heavy ion cooler/storage ring facilities in last decade quite systematically for bare and few-electron ions. Most of the experiments were performed by detecting the recombined ions separated in a bending magnet of the ring using a particle detector. In particular, it has been demonstrated in these experiments that the measured recombination rates for very low relative electron energies substantially overestimate the theoretical predictions This, so called enhancement effect is still not fully understood theoretically. At the same time the x-ray radiative recombination experiments performed in the electron cooler of the ESR storage ring with Au^{79+} and U^{92+} ions demonstrated the importance to use the K-RR and Lyman x-ray lines to extract precisely the QED effects in high-Z ions such as the Lamb shift in H-like ions.

In the first state-selective x-ray studies of radiative recombination of U^{92+} ions with electrons performed for low electron energies at off-cooling condition we have demonstrated that the relativistic effects strongly influence the angular distribution of K-RR photons. Furthermore, we show that the measurements of the RR rate coefficients for low relative electron energies are very sensitive to study the angular distribution of RR photons as well as the velocity distribution of electrons in the electron cooler. Finally, it is demonstrated that fully relativistic description of the RR was necessary for reliable estimation of the RR enhancement. The observation of the enhancement for RR into K- and L-shell is new important finding in the studies of RR which opens new perspectives for detailed understanding of the RR process. Radiative recombination of high-Z ions with cooling electrons will be studied in the future FAIR facility within SPARC collaboration using the dedicated electron target installed in the NESR ring.

Electron screening effects in nuclear reactions, alpha and beta decays

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Strongly enhanced electron screening of the Coulomb barrier between reacting nuclei has been recently observed in low-energy reactions occurring in metallic environments [1-4]. Since the alpha and beta decay probabilities depend on the penetration through the Coulomb barrier analogously to nuclear reactions, one might expect a dependence of decay half-lives with the electron density of the medium.

An explanation of the large screening was suggested [1-2] based on the Debye plasma model applied to the quasi-free metallic electrons. This model is able to describe successfully the measured data. However, an improved theory is highly desirable to explain why the simple Debye model appears to work so well. Without such a theory, one may consider the debye model as a parametrization of the data, with an excellent predictive power.

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Photoionization of highly charged ions at relativistic intensities

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The starting point of all laser plasma physics is photoionization. While, at least at 800nm wavelength, solid experimental work has been done up to intensities of $\approx 10^{15}$W/cm^2, there is an amazing shortage in experimental data for higher intensities, in particular at strongly relativistic intensities. In addition, the few experiments actually performed were not highly differential, but rather restricted to a measurement of ion yield as a function of intensity. Profound theoretical modeling at relativistic intensities is available for single-electron dynamics only, while multiple ionization is treated in the framework of sequential ionization. The credibleness of this approach is already questionable to date and seems to be doomed once laser plasmas are generated by *few-cycle* Tera-Watt pulses. Under these conditions, heavier atoms may emit more photoelectrons than there are optical cycles or even half-cycles. This suggests that collective effects in the ionization dynamics will play such a crucial role that even the formation of laser plasmas is affected.

We discuss an entirely new approach for obtaining highly differential data on relativistic photoionization: The key problem of the electron signal produced by relativistic intensities drowning in electrons from background gas produced by much smaller intensities is dramatically reduced by using a fast ion beam. In case a sufficiently cold ion beam is used, one has the additional benefit that the electron sum momentum can be measured via the ``recoil" on the ions. To this end a position and time resolving detector will be used to measure the momentum and the charge state of the ions.

The use of an ion beam has additional advantages: It is possible to select the charge state of the ions *before* interaction with the laser. The effect of this manipulation of initial conditions can be investigated on the final charge state distribution as well as on the recoil on the ion. As the ion momentum is equivalent to the electron sum momentum, the method is sensitive to collective effects. Using an electron-beam ion trap (EBIT), it is possible to produce a sufficiently strong peak current of ions with such a high charge state that ionization even at highly relativistic intensities is not saturated. In this way, possible collective effects in the ionization dynamics can be clipped electron by electron.

Laser – cluster interaction: electron heating and production of HCI

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In laser-cluster interaction (see [1] for an overview), the ions and quasi-free electrons in the cluster form a "nano-plasma" of solid density. The electrons are efficiently heated by the combined fields of the laser and the surrounding particles [2,3]. Electron-impact ionization produces highly charged ions as well as inner-shell vacancies, which are at the origin of x-ray radiation. As a fraction of the electrons leaves the cluster, a net positive charge is left behind and the cluster begins to expand before disintegrating completely in a Coulomb explosion.

The measurement of the 3.1 keV characteristic K-shell x-ray radiation emitted from argon clusters [3] provides an excellent experimental tool to gain insight into the dynamics of the interaction on a very short time-scale, down to a few femtoseconds. Besides measurements of absolute fluorescence yields, high resolution x-ray spectroscopy gives also access to the charge state distribution of highly charged cluster ions emitting x-rays.

Due to the large number of atoms ($N > 10^4$) in a cluster, a full ab-initio simulation still seems impractical. We therefore opt for an open effective mean-field approach based on a Monte Carlo simulation, in which many-particle effects are included via stochastic processes. Simulations show that the x-ray yield is controlled by two factors: the number of emitting clusters and the number of x-rays emitted per cluster.

To investigate the competition between electron heating mechanisms and ionic motion (i.e. cluster expansion) the dependence of x-ray emission on the laser pulse duration has been studied. The influence of the expansion dynamics (ionic motion) is found to manifest itself strongly in the x-ray production for long pulse durations, but also in the evolution of the ionic charge state distributions (ionization of M- and L-shell). At constant pulse energy, we find that, whatever the cluster size, the competition between the growing number of x-rays produced per cluster and the decreasing number of emitting clusters is at the origin of the experimentally observed optimum pulse duration where the total x-ray yield is maximized. The predicted optimum duration is in very good agreement with the measurements and we thus rule out any resonance effect as the cause of this maximum in the present parameter range.

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Towards surface experiments at HITRAP

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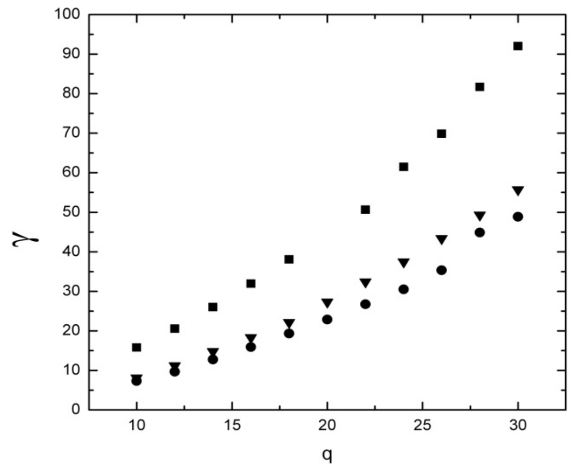
Among others, a multi-user surface physics set-up is being developed within the framework of the collaboration agreement between GSI and KVI/University of Groningen. The so called IISIS (Inelastic Ion Surface Interactions Set-up) is now being commissioned and tested at KVI. The whole experiment can be floated on high voltage allowing for the deceleration of the incoming highly charged ions to basically 0 eV. The five-element lens system necessary to focus the beam on target while decelerating has been tested successfully.

The multi-electron dynamics of slow highly charged ions on surfaces depends strongly on the electronic structure of the surface as is known from comparing metallic and insulating surfaces. Using thin films of metals on insulators or the other way around one may be able to study in a controlled manner the transition from insulator to conductor behavior by means of electron emission yields. For that reason IISIS is equipped with an electron statistics detector supplied by the TU Wien group and an e-beam evaporator to produce controllably thin films.



To test the experimental procedures and evaporator and detector systems we have started measurements on C60 films on a Au substrate. For this combination of thin film well established recipes exist.

The preliminary results of secondary electron yields for impact of multiply charged xenon ions on Au (squares), “bulk” C60 on Au (triangles), and 1 ML of C60 on Au (circles) are shown in the figure. It is clearly seen that a C60 film evaporated on a Au substrate reduces the number of emitted electrons as compared to a clean Au surface and that the effect depends on the thickness of the film. It will be very interesting to see whether the difference in electron yields between pure Au and C60 films continue to increase for higher ionic charge states and whether the difference between “bulk” C60 (several mono layers) and mono layer C60 films persists.

Precision *g*-factor measurement of the electron bound in highly-charged medium-heavy ions

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High-precision measurements of the magnetic moment of the electron bound in hydrogen-like and lithium-like ions can be used for testing state-of-the-art bound-state quantum electrodynamics (BS-QED) calculations. In the past relative experimental uncertainties as low as $5{\cdot}10^{-10}$ have been achieved on the g-factor of hydrogen-like carbon and oxygen [1]. Since the contribution of the BS-QED to the *g*-factor increases with the nuclear charge, experiments with medium-heavy ions allow for increasing the significance of these tests.

The current experiment is dedicated to the measurement of the *g*-factor of lithium-like and hydrogen-like silicon (Z=14) and calcium (Z=20) [2,3], respectively, to a relative precision $\delta g/g < 10^{-9}$. These measurements will be performed on a single ion trapped in a precision Penning-trap system. The quasi-simultaneous measurement of the free cyclotron frequency and the Larmor spin precession frequency allows for a magnetic field independent determination of the magnetic moment. The free cyclotron frequency is determined via the invariance theorem [4] by measuring all three trap eigenfrequencies. The axial frequency is measured directly using a superconduction tank circuit with attached ultra-low noise electronics, whereas the radial modes are detected indirectly via radiofrequency mediated mode coupling [5]. The Larmor frequency can be determined by detecting the spinflip probability as function of the excitation frequency. To this end the spin state can be detected in the so-called analysis trap by coupling the spin orientation to the axial eigenmode via a magnetic bottle field. The experiment is operated in a sealed environment at liquid helium temperature in order to reduce the electronic noise of the amplifiers and to allow for cooling of the ion motion and long storage times. First experimental results will be presented.

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Many-electron QED effects in the g factor of heavy ions

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High-precision determination of the fine structure constant α will become possible with both experimental and theoretical investigations of the g factor of highly charged ions. These investigations will also serve for testing of QED in a strong Coulomb field. In order to achieve the desired theoretical accuracy elaborate calculations of various QED and correlation effects should be accomplished. One of the largest contributions missing up to date is provided by the many-electron one-loop QED corrections. We present *ab initio* treatment of these corrections to the first order in 1/Z. The gauge-invariant set of the diagrams corresponding to the screened self-energy and vacuum-polarization corrections to the g factor has been evaluated in the framework of rigorous QED approach. As a result the uncertainty of the many-electron one-loop QED contribution to the g factor of lithiumlike lead $^{208}Pb^{79+}$ is reduced by an order of magnitude.

A new facility for trapping experiments with highly-charged ions

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A new facility for highly-charged ions (HCI) is being constructed at AlbaNova at Stockholm University (figure 1). The facility hosts the Stockholm electron beam ion trap (S-EBIT), the Penning trap mass spectrometer SMILETRAP II and a beam line for studies of HCI interaction with nanostructures. S-EBIT is presently being upgraded to increase the electron beam energy to allow for creating fully ionized elements up to Uranium. In the future, low charged ions from a CHORDIS source will be injected into S-EBIT for charge breeding increasing the number of available elements considerably. Fast ion extraction with time-of-flight (TOF) spectroscopy of charge changing processes in S-EBIT was developed. At the high-precision mass spectrometer SMILETRAP II cooling experiments with HCIs have been carried out. HCIs from S-EBIT were trapped in the cooler trap and their axial temperature was reduced to about room temperature by evaporative cooling. The axial energy was detected by excitation of coherent axial oscillation of the ions in the trap and TOF (figure 2). In order to assess the transverse temperature of the ions in the trap a time-resolving emittance meter was developed. Emittances of about 2 π mm mrad were measured for ions extracted from the cooler trap. The next step will be the injection of HCIs into the precision trap for mass measurements to the accuracy of below 10^{-9} for g-factor determinations of the bound electron and other applications.

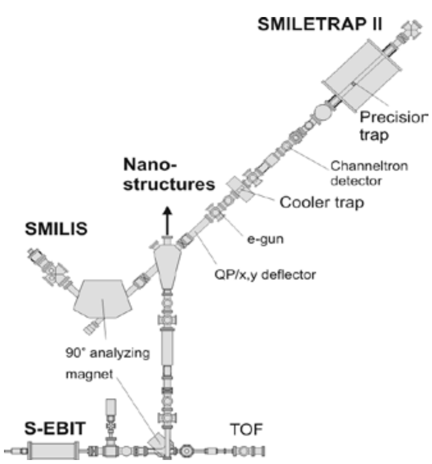

Figure 1 Outline of the facility for HCI at AlbaNova

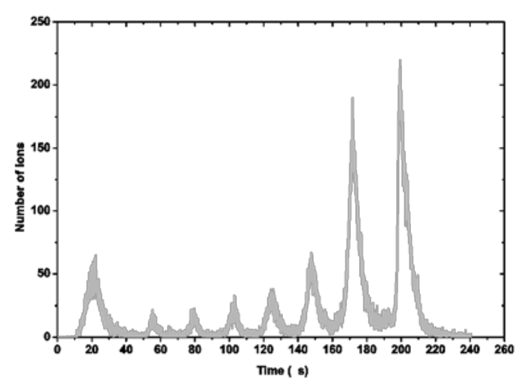

Figure 2 TOF of ions extracted from the cooler trap after excitation of a coherent axial motion.

News from the ESR storage ring

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In my talk I will give an overview of several experiments that were performed in 2008 and 2009 at GSI's Experimental Storage Ring (ESR) in Darmstadt. For instance, during the beamtimes in March, April, and May 2008, x-ray studies were performed at the internal target with the new cryogenic cluster-jet [1], which can generate high area-densities (~10^{13} particles/cm^2). The experiments were conducted with beams of Xe^{54+} and $U^{28,86,92+}$ ions and different target gasses. One goal was to determine the degree of linear polarization of the REC and Ly□ radiation emitted from these ion-atom collisions [2,3]. For this purpose, two novel Compton polarimeters were employed [4]. Our preliminary *K*-REC data for Xe^{54+} show that the degree of linear polarization can be almost 100%. Another important ESR experiment, which took place in February 2009, was a test of special relativity by means of laser spectroscopy of a $^{7}Li^{+}$ beam at 34% of the speed of light [5]. In 2008 and 2009 also parts (IH-LINAC, RFQ) of the new HITRAP facility [6] were being commissioned. In the end, I will also inform you about the latest modifications of the experimental stations at the ESR.

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Observation of Non-Exponential Orbital Electron Capture Decays of Hydrogen-Like 140Pr, 142Pm, and 122I Ions

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Beta decay of highly-charged nuclides has an immediate connection to stellar nucleosynthesis, where - at "temperatures" of some 10 keV - the atoms are highly ionized. The accelerator facility of GSI Darmstadt with the heavy ion synchrotron SIS coupled via the projectile fragment separator FRS to the cooler-storage ring ESR offers the unique opportunity to study the beta decay of highly ionized atoms. It is possible to produce, separate, and store for extended periods of time exotic nuclei with a well-defined number of bound electrons. Basic nuclear properties such as masses and lifetimes are measured by applying the mass- and time-resolved Schottky Mass Spectrometry (SMS). The change of the mass in a radioactive decay is evidenced by a corresponding correlated change of the revolution frequency. The area of the Schottky frequency peak is proportional to the number of stored ions and to the square of the atomic charge state, q². The SMS is sensitive to single stored ions with atomic charge states of about q>30. This allows us to precisely determine the fate of each stored ion. On this basis single particle decay-spectroscopy has been developed which allows for an unambiguous and background-free identification of a certain decay branch. Here we report on the first experiments which used time-resolved single-particle decay spectroscopy for studying the time evolution of two-body weak decays, i.e., EC and ßb of radioactive ions in the ESR. H-like 140Pr, 142Pm, 122I ions have been selected for these studies. These nuclei decay to stable daughter nuclei via either the three-body positron emission or the two-body EC-decay. These systems decay mainly by a single allowed Gamow-Teller (1+->0+) transition. The results of the experiment consist on a time modulation superimposed on top of the expected exponential decrease of the orbital electron capture branch. Interpretations of these interesting results will be discussed.

Resonance calculations with complex absorbing potentials: understanding spontaneous strong-field pair production

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Supercritical Dirac resonance parameters for quasistationary heavy-ion systems such as U-U and U-Cf were calculated on the basis of extrapolated analytic continuation methods within a discrete-variable representation (the mapped Fourier grid method) and compared with previous calculations [1]. The relevance of these results towards heavy-ion collisions at the Coulomb barrier was then explored by means of dynamical calculations [2].

In this talk we will try to accomplish two things. In the first part we will use the case of Schrödinger resonances to explain the complex absorbing potential method without a discrete-variable representation and its extrapolation to zero analytic continuation parameter. This work which is based on numerical ('exact') integration of the differential equation complements the usual matrix-representation point of view [3]. Work is currently under way to apply these ideas to multi-channel Dirac resonance calculations which are sensitive to more than just the monopole part of the interaction.

In the second part we will review the reasons for why supercritical Dirac resonances will be extremely difficult to observe even in bare U-U collisions. The complications arise from the shortness of the collision time as compared to the lifetime of the quasi-stationary supercritical resonance state. As known from previous work [4] the positron (and correlated electron) yield originating from spontaneous vacuum decay is broadly spread as a result of interactions during the second half of the collision. While the measurement of correlated processes (such as bound-free electron-positron production [2]) may result in a cleaner signal, substantial experimental challenges do remain.

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Electron cyclotron resonance ion source (ECRIS) ionic population modulation

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Analysis and interpretation of X-ray spectra emitted by highly charged ions in an ECRIS may be used as a tool to estimate the charge-state density ratios in the source plasma [1]. For that purpose, knowledge of the electron energy distribution in the plasma, as well as the most important processes leading to the creation and de-excitation of ionic excited states, is needed.

The rate of the number of events related to a process (excitation or ionization), averaged over the electron distribution energy, is defined by

$$\langle N_e \sigma_e v_e \rangle = N_e \int_{E_{\min}}^{\infty} f_e(E) v_e(E) \sigma(E) dE,$$

where $f_e(E)$ is the electron distribution energy, and $v_e(E)$ and $\sigma(E)$ are, respectively, the electron velocity, and the process cross section for electron energy E.

In this work we present a detailed calculation of inner-shell excitation and ionization cross sections, including double KL and triple KLL ionization, in the framework of the multi-configuration Dirac-Fock method assuming an electron energy distribution which is a linear combination of a Maxwellian distribution (90%), describing the cold electrons at the thermodynamical temperature (kT = 1 keV), and a non-Maxwellian distribution (10%), describing the hot electrons (KT = 20 keV) heated by electron cyclotron resonance [2].

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Electroluminescence in noble gases in rare-event detectors

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Since long [1,2] it has been known that secondary scintillation, also called electroluminescence, provides signals several orders of magnitude larger than the corresponding charge signals, with better energy resolution. Therefore, secondary scintillation readout is most suitable for experiments with very low event rates and/or high background levels, as are the $0\nu\beta\beta$ and dark matter search experiments, rather than the charge avalanche amplification signal [3]. This is the technique used in XENON, LUX, ZEPELIN and WARP direct dark matter search experiments and to be used in NEXT for neutrinoless double beta decay search.

This gave us the motivation to investigate the behaviour of the electroluminescence yield in Xe and Ar. We measured absolute yields of Xe [4] and Ar [5], around atmospheric pressure, using a straightforward method that makes use of only one experimental set-up, in opposition to the methods that had been used up to know. A VUV-sensitive large area avalanche photodiode (LAAPD) is used to detect, simultaneously, the secondary scintillation of a gas proportional scintillation counter (GPSC) and incident x-rays. The x-rays are used as a reference for determining the absolute number of VUV-photons impinging the LAAPD [6]. We have also measured, using the same technique, the Xe electroluminescence yield in the 2 to 10 bar range.

In addition, we have shown that the electroluminescence produced in the charge avalanches of micropattern electron multipliers is one to two orders of magnitude higher than that obtained in an uniform electric field, defined by parallel meshes [7]. This result can be important if other type of photosensors with lower gains, e.g. APDs, are to be used substituting for photomultipliers.

In this talk, we will review the results obtained for Xe and Ar electroluminescence yields and discuss their relevance for the different detectors used in WIMP and $0\nu\beta\beta$ decay search.

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Perspectives of Low-Energy Antiproton Physics at FLAIR

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The Facility for Antiproton and Ion Research FAIR at Darmstadt [1] will provide antiproton beams of intensities that are two orders of magnitude higher than currently available. Within the foreseen scheme, antiprotons can be decelerated to 30 MeV. The low-energy antiproton community has formed a users group to make use of this opportunity to create a next-generation low-energy antiproton facility called FLAIR. A letter of intent [2] and subsequent technical proposal [3] have been submitted for a new facility that goes far beyond the current Antiproton Decelerator at CERN by providing cooled antiproton beams using two storage rings of 300 keV and 20 keV minimum energy. The availability of low-emittance beams at these low energies will greatly enhance the density of antiprotons stopped in dilute gases or ion traps for precision spectroscopy. FLAIR will also provide slow extracted (i.e. continuous) beams of antiprotons, thereby enabling nuclear and particle physics type experiments which need coincidence techniques. A further opportunity will be the simultaneous availability of unstable nuclei at low energies, making it possible to use antiprotons as hadronic probes for nuclear structure by determining neutron halos or skins. An overview on the technical capabilities, experimental program and status of FLAIR will be given.

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Two-photon emission from few-electron heavy ions: Angle- and polarization-resolved studies

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For more than half a century, two-photon decay of few-electron ions and atoms has been explored intensively both, by theory and experiment. While, however, most investigations in the past dealt with light neutral atoms or low-*Z* ions, much of today interest is focused onto the high-*Z* region where the two-photon decay may serve as a sensitive probe of retardation, relativistic as well as quantum electrodynamical (QED) effects in extremely strong electromagnetic fields [1,2]. Apart from the detailed analysis of the total and energy-differential decay rates, these recent studies have also focused on the angular and polarization correlations between x-ray photons emitted from few-electron heavy ions [3]. In contrast to the total (i.e. summed over the angles and spin states) decay probabilities, the angle- and polarization-resolved properties usually appear to be more sensitive to relativistic and nondipole phenomena.

In this contribution, we review the recent theoretical progress in studying the angular and polarization correlations in the two-photon decay of high-*Z* few-electron ions. We pay special attention to the effects which arise from the higher non-dipole terms in the expansion of the electron-photon interaction as well as from the Dirac's negative continuum and interelectronic interaction phenomena. To investigate these effects detailed calculations have been performed for the angular correlation functions as well as (polarization) entanglement measures for the $2s_{1/2}$ - $1s_{1/2}$ and 1s2s S_0 - $1s^2$ S_0 transitions in the hydrogen- and helium-like heavy ions, correspondingly.

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Electron capture and ionization in ion-H_2O collisions using an anisotropic model potential

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Low energy electrons produced in ion-molecule collisions are often responsible of DNA strand breaking [1] in biological systems. In this context, the understanding of the interaction of highly charged ions present in common ionizing radiations with water molecules is essential.

In this work, we study electron capture and ionization in collisions of H^+, He^{2+} and C^{6+} with H_2O molecules at energies from 20 keV/amu to 10 MeV/amu. To simulate a water molecule, we describe the interaction of the active electron with the H_2O^+ ionic core by means of a three-center model potential. Using this potential, we set up four microcanonical distributions with the energies corresponding to the four valence molecular orbitals ($2a_1$, $1b_2$, $3a_1$ and $1b_1$) of H_2O.

Single capture, single ionization and electron production cross sections are calculated by applying a CTMC treatment [2], continuing our experience in previous studies [3,4]. Many electron cross sections are obtained from one-electron results by employing the independent event model (IEVM) [5]. We have considered 12 trajectory orientations of the projectile with respect to the molecule in order to obtain orientation-average cross sections.

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SHORT PROGRESS REPORTS

SPR1	**D. Ursescu** (INFLPR, Romania)	X-ray lasers for ions spectroscopy
SPR2	**H. Hetzheim** (MPI, Germany)	Ionization dynamics in laser-driven hydrogen-like ions
SPR3	**D. Schneider** (LLNL, USA)	
SPR4	**G. Weber** (GSI, Germany)	Linear polarization and angular distribution of Lyman-α_1 radiation in H-like uranium
SPR5	**D. Thorn** (EMMI/GSI, Germany)	Precision K-shell Spectroscopy of Highly Charged Heavy Ions Using X-ray Calorimeter Spectrometers

X-ray lasers for ions spectroscopy

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X-ray lasers (XRL) for in ring ions spectroscopy experiments [1] were developing fast in the recent years. With the introduction of grazing incidence pumping method [2,3], the needed pump energy for XRL was dramatically reduced down to about 1 J or less in total and the repetition rate of such laser systems increased to 10 Hz. This progress made available such XUV coherent sources in smaller labs. Having such a source at FAIR should be straight forward, providing reasonable funding is available.

In order to obtain accurate measurements of various transition energies, one has to characterize the spectral properties of such x-ray laser system. There are only few papers concerning the emission line width of the x-ray laser. The claim is that due to the gain narrowing, the relative laser line width goes down in the 10^{-5} range [4]. However, in this case we show that the isotopic composition of the x-ray laser plasma becomes important in two ways, due to the mass shift which might influence the lasing transition energy. First, there is an increased possibility that the lasing emision contains several lasing lines corresponding to the isotopes in the XRL plasma, endangering the quality of the spectroscopic measurements. Such lasing lines should all be contained in a narow relative spectral range, of the order of 10^{-4}, and as a consequence they could not be observed up to now in experiments where typical spectral resolving power is about 10^{3}. Second, the presence of several isotopes in the XRL plasma could provide a strong negative effect on the eficiency of the lasing in the plasma. In this case, there are several different populations of ions in the XRL plasma which are producing gain in a certain electron density region (with the typical density 10^{20} cm^{-3}). As a consequence, the “doping” of the plasma is significantly diluted and this produces a low lasing eficiency.

Using isotopic pure targets would help to overcome both these effects. Experimental investigation of these aspects is on the way at 15 TW TEWALAS laser facility at INFLPR comissioned in May 2009..

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Ionization dynamics in laser-driven hydrogen-like ions

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The fields of ultra strong laser pulses provide insights into the fascinating realm of laser-matter interaction. The next generation of such laser pulses is envisaged to reach peak intensities of the order of 10^{26}W/cm^2. The measurement of these highly relativistic fields is experimentally very challenging. A sensitive method is presented to determine the intensities of ultra strong and ultra short laser pulses by measuring the ionization probability of hydrogen-like ions in the over-the-barrier regime [1]. It allows us to measure intensities in the range of 10^{18}W/cm^2 – 10^{26}W/cm^2. We numerically investigate the ionization dynamics of hydrogen-like ions by three-dimensional relativistic Monte Carlo simulations and the solution of the Dirac equation. Especially, the influence of basic laser parameters like the frequency, pulse length and shape on the ionization fraction is analyzed [2].

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Linear polarization and angular distribution of Lyman-α_1 radiation in H-like uranium

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In energetic ion-atom collisions radiative electron capture (REC) into the $2p_{3/2}$ state of a H-like ion leads to a non-statistical population of the magnetic sublevels. This alignment results in an anisotropic distribution of the emitted Lyman-α_1 (Ly-α_1) radiation, which is characterized by the parameter β_A. For H-like uranium it was previously shown that the M2 branch of the transition into the ground state gives rise to a significant modification of the angular distribution, namely a 28% increase in the alignment parameter as compared to the pure E1 decay channel, even so it only contributes by about 1% to the total transition rate [1]. In addition, calculations predict that the same effect should lead to a significant decrease of the degree of linear polarization of the Ly-α_1 radiation [2]. The recent development of energy, time and position sensitive X-ray detectors, which can be used as efficient Compton polarimeters, now allows for measurements of the linear polarization of X-rays in the energy region above 50 keV [3].

The present experiment was performed at the internal gasjet target of the ESR storage ring at GSI, Darmstadt by interacting bare uranium ions at an energy of 96.6 MeV/u with H_2 molecules. The emitted photons were detected by an array of standard solid state X-ray detectors, located at 60°, 90°, 120° and 150°, and two 2D μ-strip X-ray detectors, located at 35° and 90° with respect to the ion beam axis. While the standard X-ray detectors were used to obtain the angular distribution of the emitted radiation, the 2D detectors were used to measure the linear polarization. Each of the two measurements lead to an independent determination for the anisotropy parameter β_A, and consequently probe our understanding of the atomic structure at high-Z as well as the REC process.

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Precision K-shell Spectroscopy of Highly Charged Heavy Ions Using X-ray Calorimeter Spectrometers

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Much work has been done in the last 60 years to test the theory of quantum electrodynamics (QED). Recently, attention has shifted to producing QED theories that include higher order terms and multiple electrons in the strong field of a heavy nucleolus [1,2]. The precise knowledge of the K-shell energy levels (or K-shell transition energies) is required to benchmark these new theories. However, detection of K-shell transitions from highly charged heavy ions to the required precision to test these new QED calculations is not possible with the current crop of x-ray detectors. Crystal spectrometers have been shown to be able to fully resolve the K-shell spectra of elements up to krypton, and in turn, to make precise measurements which can guide quantum electrodynamics calculations. But, above a photon energy of 15 keV, the efficiency of crystal spectrometers makes it difficult (if not impossible) to measure hard x-rays (in all but the highest count rate sources) with enough statistical certainty to make a precise determination of the K-shell transition energies possible. On the other hand, solid-state detectors like high purity germanium (HPGe) detectors are used to measure harder x-rays and have shown much success in producing precise measurements for elements up to uranium [3,4]. However, solid-state detectors suffer from low resolving powers and can no longer be used to guide the latest QED theories.

Thermal based detection systems such as x-ray calorimeters promise to bridge the gap between high-resolution and high-quantum efficiency in the hard x-ray regime [5,6]. Here we present a series of measurements of the K-shell spectrum from highly charged Pr and Xe ions recorded with x-ray calorimeter spectrometers designed and built at NASA/GSFC. Furthermore, the potential to use x-ray calorimeters within the SPARC program at the future FAIR facility to make precision spectroscopic measurements will be discussed.

The measurements presented here were performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by NASA Astronomy and Physics Research and Analysis Program (APRA) grants to LLNL and NASA/GSFC.

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POSTER COMMUNICATIONS

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P17	M. Vogel, W. Quint, W. Nörtershäuser and R.C. Thompson	Precision spectroscopy of confined highly-charged ions
P18	M. Guerra, F. Parente and J. P. Santos	Modified-binary-encounter-Bethe model for ionization of neutral atoms by electron impact

Investigations on Dresden EBIS/T systems as charge breeders

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Charge breeding is an important part of experiments for which, primarily, only low charged ions are available but the use of higher charge state ions is favored. Since linear acceleration is proportional to the charge state q of an ion and circular acceleration scales as q^2, the use of a charge breeder substantially increases the viability of proposed experiments with exotic nuclei accelerated to the Coulomb barrier and above [1]. Charge breeding of radioactive as well as non-radioactive ion beams is also relevant for high-precision mass measurements using Penning traps, where the accuracy is directly proportional to the charge state of the investigated ion [2] [3].

Electron beam ion sources or traps (EBIS/T), in general, are well suited as charge breeding devices for many applications. Their high electron beam densities guarantee short ionization times. Due to the small trap region and the low temperature of the plasma in which ions are produced, the emittance of the ion beams provided by EBIS/T is low. Therefore, when placed in combination with accelerators, ion losses are minimal. In addition to these advantages, which all EBIS/T systems have in common, the concept of the warm Dresden EBIS/T type of ion sources features an excellent resource efficiency as well as a compact and transportable design.

In this work, we present studies of the characteristics of Dresden EBIS/T devices as charge breeders. We have investigated the injection of externally produced, singly charged Au ions both theoretically and experimentally. Further on, results of emittance and brightness measurements using a pepper-pot emittance meter are shown. Based on these facts, the viability of the sources for specific applications is discussed.

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Investigation of the photoionization behaviour of NO

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NO is a free radical which can be routinely obtained in the gas-phase in suitably high number densities for spectroscopic study [1].

An investigation of the photoionization behaviour of NO radical has been made in the gas-phase using angle resolved photoelectron spectroscopy (PES) and constant ionic state (CIS) measurements. The CIS and PES measurements were performed at Elettra synchrotron.

The observation of resonant structure in the CIS spectrum enables identification and characterization of Rydberg series associated with the neutral excited states. Recording photoelectron spectra at these resonant photon energies usually allows the photoelectron band envelopes to be extended providing more information on the ionic states [2].

A summary of the results obtained on highly excited states of NO radical will be presented.

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Pulsed gas-jet target for HITRAP facility

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HITRAP is an ion trap facility for heavy highly charged ions at GSI [1, 2]. HITRAP uses the Experimental Storage Ring ESR for beam cooling and deceleration to 4 MeV/u and decelerates it further to 6 keV/u. A Penning trap allows for ions accumulation and cooling to low temperatures. Low emittance beam from the HITRAP facility is delivered to a large variety of atomic physics experiments.

With this novel technique of deceleration, trapping and cooling of highly charged ions (HCI), atomic physics studies on slow HCI up to uranium U^{92+} interacting with photons, atoms, molecules, clusters, and surfaces will become possible.

One of the experimental setups will be dedicated to studies of low-energy highly charged ions collisions with light atoms. This setup requires a high quality gas target, with small interaction region and very good vacuum conditions. Based on detailed simulations of gas dynamics performed by the Petersburg group, a project of pulsed supersonic jet target was prepared. Proposed concept allows for a precise setup of target geometry in order to optimize beam-target interaction region. A multi stage differential pumping system guarantees optimal vacuum conditions in the HITRAP beam line.

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Correlated radiative double electron capture (RDEC) in collision of 38 MeV bare oxygen ions with carbon target

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Radiative double electron capture (RDEC) is a one-step process where two target electrons are captured into the bound states of the projectile, e.g. into an empty K-shell, and the energy excess is released as a single photon. Here, the first experimental confirmation of the process is presented.

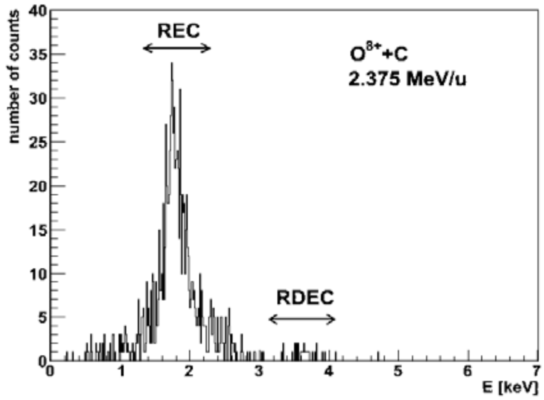

Fig 1: Preliminary X-ray spectra for 38 and 30 MeV beams. Structure consistent with RDEC is clearly visible.

The choice of the collision system used in the experiment was based on the latest theoretical calculations of the RDEC cross section [1, 2, 3] which predicted enhancement of this process in low energy systems.

The experiment was conducted at Western Michigan University using the tandem Van de Graaff Accelerator. Bare oxygen ions at the energy of a few MeV/u were collided with a thin carbon target. Emitted X-rays were detected with a Si(Li) detector positioned at 90^0 to the beam direction and were registered in coincidence with ions which captured one or two electrons. Obtained cross sections are in a fair agreement with theoretical calculations.

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Impact parameter dependence of radiative electron capture in relativistic ion–atom collisions

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Radiative electron capture (REC) is one of the main processes occurring in ion–atom collisions. During recent years it has been very well studied both theoretically and experimentally. (See Ref. [1] for the review and further references).

We offer an approach which allows theoretical investigation of the impact parameter dependence of REC within wide region of the relativistic collision energies. In framework of this approach we perform investigations of impact parameter dependence of various characteristics of REC, such as the differential cross-section and polarization of the emitted X-rays.

With the help of this approach we perform also the calculation of various two-step processes. For example in [2] such calculations have been performed for electron-positron pair creation accompanied by REC or non-radiative electron capture.

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X-ray spectra in laser-produced plasmas of Pb

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Hard X-ray spectra from laser produced plasmas have been subject of extensive research in the last years. This is due to their importance in what concerns alternative energy sources and atomic, plasma and materials physics research, including astrophysics [1].

Seely *et al.* reported on X-ray spectra from laser produced plasmas obtained when planar foils of U and Pb were bombarded with a total energy of about 12 kJ at the OMEGA laser facility in Rochester [2].

In this work we use the multiconfiguration Dirac-Fock method to generate a preliminary theoretical L-shell X-ray spectrum for highly charged Pb ions and compare it with the reported experimental data in order to obtain the charge state distribution in the plasma.

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A test of Lorentz invariance
Laser spectroscopy on a fast $^7Li^+$ beam stored at the ESR

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In Ives-Stilwell-type experiments, fast ions with an accurately known transition frequency are used as moving clocks, and time dilation as well as the velocity are derived from the simultaneous laser-spectroscopic measurements of the Doppler shifts with and against the direction of motion. In order to accurately measure these Doppler shifts, the Doppler broadening caused by the ions' velocity distribution needs to be overcome. We performed laser spectroscopy on $^7Li^+$ ions in the $2s^3S_1$ metastable state at the GSI in Darmstadt. The ions were stored in the Experimental Storage Ring (ESR) at a velocity of 0.338c, and optical-optical double resonance spectroscopy on a closed Λ-type three-level system was performed with two laser beams propagating parallel and antiparallel, respectively, to the ions. The used laser setup (shown in Fig. 1 left) allows for a frequency accuracy of $\Delta\nu/\nu < 10^{-9}$ by stabilizing the lasers to atomic and molecular references. Analyzing the emerging fluorescence signal (Fig. 1 right) and taking all statistic and systematic uncertainties into account, the current experiment sets an upper bound on hypothetical deviations from the predictions of special relativity of the order 7×10^{-8}, which is comparable to the so far leading experiment [1], but an improvement of this limit by an order of magnitude seems to be feasible in future measurements.

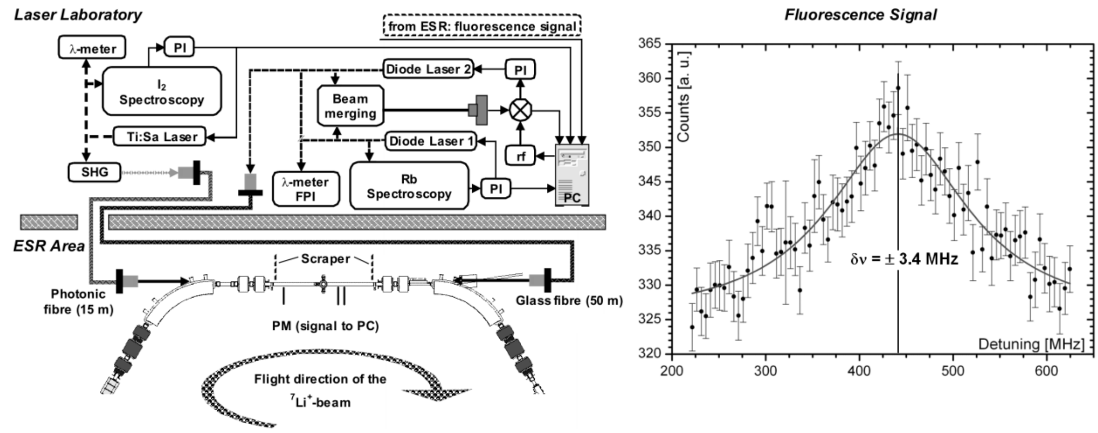

Figure 1: Left: Experimental setup (PI: proportional-integral controller, PM: photomultiplier, SHG: second harmonic generator, rf: radio-frequency source, FPI: Fabry-Perot interferometer). Right: example signal from optical-optical Λ-type spectroscopy.

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Feasibility of an imaging detector for heavy ions based on polycrystalline CVD-diamond

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We propose to develop a diamond-based position-sensitive detector, optimized for heavy ions with energies ranging from 4 MeV/u up to 150 MeV/u. Such a device is needed for spectroscopy and collision dynamic studies in interactions of highly charged heavy ions with solid state targets as well as for beam profiling and intensity monitoring at the present GSI facility and for the future FAIR/SPARC experiments. The difficulty in realization of such a device is due to the large amount of energy deposited by ions into the detector bulk, which dramatically reduces the detector life time.

To make use of the full beam intensity available at the future NESR, a fast, radiation hard device is needed as projectile detector. Also, to increase the efficiency of the measurements, the simultaneous detection, with 100% efficiency of many different projectile charge states separated in a magnetic field, is strongly desirable, i.e. the future detector active area should be at least 30 cm^2 large.

The present work was devoted to basic investigations related to the response of the diamond material to the irradiation with low-energy heavy ions, in order to find out the limits of its functionality and the material quality to be used in the future.

The intrinsic properties of this relatively new material (polycrystalline chemical vapour deposited diamond) are very promising for radiation detection, but his structural peculiarities require some specific investigations before proceeding to the realization of an imaging detector prototype.

For this, diamond probes with different structure and different thicknesses have been irradiated with heavy ions (C, N, S, Ni, Xe, Pb and U) at energies around 11 MeV/u and 50 Mev/u. The measurements were focused on the correlation between the amount of energy deposited into the detector, the charge collection properties and the structure of the diamond.

We analyzed the pulse height distribution of the signals created into the test detectors concluding about the detection efficiency and time stability, limit on the count rate capability and possible radiation damage effects.

The performed measurements indicate that the detector performance strongly depends on the correlation between the detector thickness, the particle range into the detector (i.e. the particle energy) and the material quality.

These observations are now used for the realization of a 2D position sensitive detector prototype, on a 25x25 mm^2 polycrystalline diamond substrate.

Angular and polarization correlations in two-photon transitions of hydrogenlike ions

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During the last decades entanglement and polarization studies on the two-photon emission from excited ions and atoms have attracted particular interest both in theory and in experiment [1,2]. While most of the studies carried out so far have been performed for low-Z systems, nowadays interest is focused on the relativistic regime. For example, in the future two-photon polarization measurements are likely to be carried out at GSI facility in Darmstadt. In order to provide theoretical support for these experiments, we developed a general relativistic description of correlated two-photon emission based on density matrix formalism [3]. With this unique tool, we explore relativistic and high order multipole effects on properties of two-photon transitions in hydrogenlike ions. To study these effects, detailed calculations are performed on polarization and angular correlations and entanglement measures for 2S to 1S transitions in neutral hydrogen as well as hydrogenlike Xenon and Uranium. For the decay of 2S metastable state of low Z ions, moreover, we obtain a non-relativistic form of the two-photon spin density matrix. Validity of such an approximation, which allows analytical evaluation of the angular and polarization properties, will be also discussed in our presentation.

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The status of the HITRAP project

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Heavy, highly-charged ions at very low, well defined energy are ideal systems for a number of precision experiments in different fields of physics.

At the GSI accelerator complex, using the universal linear accelerator UNILAC and the synchrotron SIS, highly-charged ions up to U92+ are produced by stripping off all electrons passing a 400 MeV/u beam through a gold foil. The HITRAP facility is built to decelerate the ions to almost rest and to provide them to the experiments [1]. In a first step, the ions are decelerated in the experimental storage ring ESR [2] from 400 to 4 MeV/u accompanied with stochastic and electron cooling to keep the emittance small. After that, an interdigital H-type (IH) structure and a radiofrequency quadrupole (RFQ) structure, both are operated in inverse, decelerate the ions from 4 MeV/u to 0.5 MeV/u and then further to 6 keV/u. The major components have been installed and are taken into operation. A number of tests and simulations have been performed and decelerated ions at 0.5 MeV/u have been detected [3].

The emittance of the incoming beam was measured and yields 3.7 π mm mrad for 90% of the beam. This is slightly higher than the 2.2 π mm mrad assumed in transverse beam dynamics calculations and requires refined calculations of the transverse optics.

The cooler Penning trap is assembled in the moment to be installed in the immediate future. An electron source to feed the trap with electrons needed for cooling has been designed and built based on a photo cathode covered with Cesium driven by an ultraviolet flash lamp. Most components for the transfer line to the experiments arrived meanwhile at GSI and are ready for installation, so that the beam line to the second floor, which connects to the SPARC-EBIT and the experiment beam line, can be installed and tested off-line with the EBIT within this year.

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Studies on the characteristic emission following inner-shell ionization of sodium-like ions by linearly polarized light

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The inner-shell photoionization of target ions leads to the emission of x-ray photons which have an anisotropic angular distribution as well as a nonzero linear polarization. Such polarization studies are of great importance for the diagnostics of high-temperature laboratory and astrophysical plasmas [1]. Until now, most of the experimental and theoretical studies of the x-ray polarization have dealt with the *electron-ion* collisions. Much less attention, in contrast, has been paid previously to analyze the polarization of x-ray lines following inner-shell photoionization of highly charged ions. A first step towards a polarization study was carried out by Inal *et al* [2] who performed calculations for the $2p^5 3s \rightarrow 2p^6$ radiative transitions following inner-shell photoionization of the $2p$ electron of the sodium-like iron Fe^{15+} and uranium U^{81+} ions. In this past work, the incident radiation was taken to be unpolarized. However, in the light of ongoing experimental studies on photoionized plasmas produced by polarized x-ray radiation from a Z-pinch, most recent interest would be to study the spin (or polarization) states of the subsequently emitted photons in dependence on the polarization of the incident radiation.

In this contribution, we apply density matrix theory to analyze the linear polarization of characteristic x-ray photons following the inner-shell ionization of highly charged ions by polarized beam of incident photons [3]. Such polarization studies require the knowledge of alignment parameters of the excited ionic state. These alignment parameters allow further the evaluation of polarization Stokes parameters for the characteristic x-ray radiation. We have performed detailed polarization calculations for the two electric dipole transitions $2p^5 3s\ ^1P_1 \rightarrow 2p^6\ ^1S_0$ and $2p^5 3s\ ^3P_1 \rightarrow 2p^6\ ^1S_0$ and one magnetic quadrupole transition $2p^5 3s\ ^3P_2 \rightarrow 2p^6\ ^1S_0$ in sodium-like iron Fe^{15+} and uranium U^{81+} ions. For these ions we found that the incoming polarized light leads to the enhancement in the degree of linear polarization of the subsequently emitted photon. We hope that, such a study would be helpful in analyzing the future polarization experiments which have become feasible owing to the progress in the set up of intensive light sources and x–ray detector techniques.

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Annihilation of protonium by charged particle impact

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The protonium $(Pn = p\bar{p})$, the bound state of a proton with an antiproton, receives particular interest both from experimental and theoretical points of view [1]. Pn is formed in highly excited excited states, when a low-energy antiproton collides with atomic or molecular hydrogen, where the antiproton the heavy "electron" substitute the electron. Based on the matching of energy levels, Pn's are produced in quantum states, where the principal (*n*) and angular momentum (*l*) quantum numbers, take large values (*n* = 30-60 and *l* >> 1) [2].

In this work we analyze the mechanism of annihilation of Pn induced by charged particle impact within the frame of close-coupling treatment. These calculations reveal that the energy dependence of the annihilation cross sections and the decay mechanisms differ considerably for each initial state of the Pn [3]. Scaling properties of the annihilation cross sections are discussed, which might be useful in planning experimental studies, when one considers the wide range of parameters that can affect the process of annihilation, including the charge and the velocity of the projectiles or the initial quantum numbers, etc..

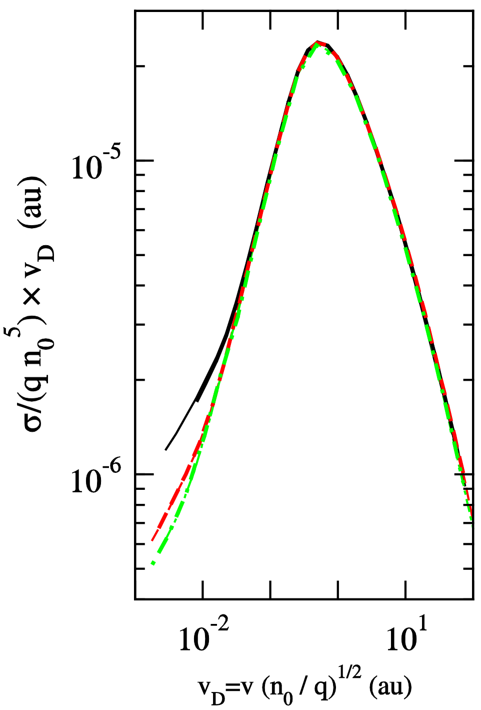

Figure: Scaled annihilation cross sections as functions of the scaled velocity for the X^{q+}+Pn(n_0,l_0 = 1) collisions evaluated in the close-coupling approximation. Solid line (n_0=10), dashed line (n_0=20), dot-dashed line (n_0=40). Thin (thick) lines are for q=1 (q=2).

Figure presents the annihilation cross sections (σ), scaled according according to the dipole scaling rule, versus the impact velocity (*v*) for the X^{q+} Pn (n_0, l_0 = 1) collisions.

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Laser-Microwave Double-Resonance Spectroscopy in a Penning Trap for g-Factor Measurements on Highly Charged Ions

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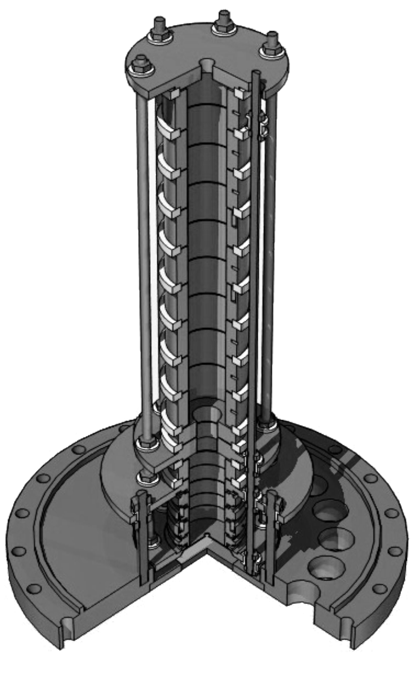
Precise determination of bound-electron g-factors in heavy highly-charged ions (e.g. Bi^{82+}, U^{91+}) provides a stringent test of bound-state QED in extreme fields. The H-like and Li-like heavy ions, produced at GSI and slowed down at the HITRAP facility [1], will be loaded into a half-open cylindrical Penning trap and confined at cryogenic temperatures. With a laser-microwave double-resonance technique [2] we can then probe microwave transitions between Zeeman sub-levels of the hyperfine structure in such ions. From this the ionic g-factors g_F can be measured with high accuracy. Both the electronic g-factor g_J and the nuclear g-factor g_I can be determined from a single experiment. This experiment will be a novel method to measure the g-factor of the bound electron.



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Evaluation of two-photon decay rates using a B-polynomials basis set

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Two-photon transitions in hydrogen and hydrogen-like ions are under investigation since Göppert-Mayer presented her theoretical formalism in 1931 [1].

Finite basis sets for Dirac equation have been applied for evaluating many-body sums in both atomic physics [2, 3] and quantum chemistry [4].

We discuss the influence of the basis sets used to produce the spectrum of the Dirac equation for the bound states of hydrogen-like systems in the two-photon total decay rate transitions, by comparing the results obtained with the B-splines [5] and B-polynomial [6] basis sets.

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HITRAP - a facility for experiments on heavy highly charged ions and on antiprotons

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HITRAP is an ion trap facility for heavy highly charged ions at GSI [1]. Ion beams with low emittance will be delivered to a large variety of atomic physics experiments. For the most ambitious case, uranium U^{92+}, we expect to load the cooler trap every 10 seconds with 10^5 ions.

With this novel technique of deceleration, trapping and cooling of highly charged ions, atomic physics studies on slow highly charged ions up to uranium U^{92+} interacting with photons, atoms, molecules, clusters, and surfaces will become possible. In addition to collision studies, high-accuracy atomic physics experiments on trapped or slow HCI will be a significant part of the atomic physics programme of the HITRAP facility [2]. Sensitive tests of quantum electrodynamics (QED) for bound electrons in the strongest electromagnetic fields available in the laboratory for extended periods of time will be performed by measuring the g-factor of the bound electron [3], the binding energies of a single or of few electrons including the Lamb shift, or the hyperfine structure (HFS) of a stable isotope of an element in different high charge states with utmost accuracy [4].
At the future FAIR Project, HITRAP will be an integral part of the collaborations SPARC (Stored Particles Atomic Physics Research Collaboration) and FLAIR (Facility for Low-energy Antiproton and Ion Research). The HITRAP facility at FLAIR/SPARC can be equally well used for HCI and antiprotons to bring them down to sub-thermal energies.

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Transportable MOTRIMS setup as a high precision target for heavily charged ions and femtosecond pulses

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We plan to investigate coherence effects in multiple charge transfer between neutral atoms and highly charged ions. A transportable high density dark SPOT [1] for Rb atoms, equipped with a recoil ion momentum spectroscopy (RIMS) detector [2] will be used in conjunction with the highly charged ion beam facilities at the GSI. Due to the low thermal spread of the target atoms, the recoil ion momentum can be measured with very high accuracy. We present details of the experimental setup.

In a recent experiment we have investigated the formation of ultracold molecules by femtosecond laser pulses in a pump-probe scheme [3]. Previous experiments [4, 5] have only managed to dissociate molecules by femtosecond pulses, whereas now active photoassociation is observed. A shaped pump pulse excites a collision pair of laser cooled rubidium atoms to a bound molecular state below the $5s5p_{1/2}$ asymptote, from where the molecule is ionized by a time-delayed probe pulse. The photoassociation signal shows oscillatory dynamics between the electronic molecular states coupled by the pump pulse, caused by coherent interactions of the molecular electronic dipole with the electric field of the pump pulse. The experimental findings are in excellent agreement with simulations where the time-dependent Schrödinger equation has been solved numerically using a mapped-fourier-grid-hamiltonian algorithm.

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Precision spectroscopy of confined highly-charged ions

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Confinement of ions in traps is most often motivated by the extended times available for investigations and the possibility to cool the trapped ions' motions nearly to rest, thus avoiding Doppler shifts and line broadening. However, specific properties of the confinement itself may also be used for studies of intrinsic ion properties. We discuss a set of possibilities for high-precision spectroscopy of forbidden transitions in highly charged ions confined in a Penning trap. Such measurements make stringent tests of bound-state QED calculations possible and allow access to fundamental quantities such as the fine structure constant and nuclear properties of the ions.

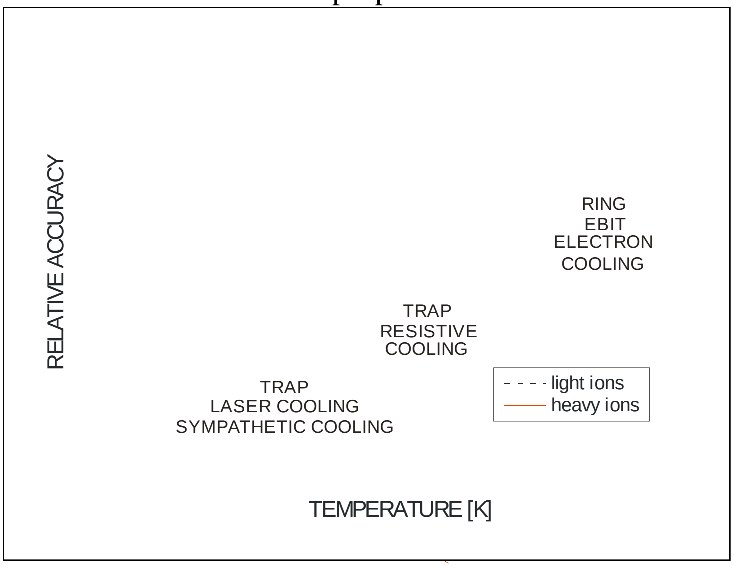

Figure: Relative accuracies of spectroscopic investigations depending on the confined ions' motional temperatures and experimental concepts.

The presented concepts comprise "classical" in-trap spectroscopy [1], laser-microwave double-resonance spectroscopy [2] and radiofrequency spectroscopy of optical transitions without optical detection ("blind spectrscopy") [3]. We present them in the order of the extent to which they make use of specific properties of the confinement other than just the localization of the ions. This is at the same time the order of increasing precision, from relative uncertainties of about 10^{-7} to below 10^{-10}.

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Modified-binary-encounter-Bethe model for ionization of neutral atoms by electron impact

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A theoretical model, free of adjustable or fitted parameters, was presented by Kim and Rudd [1] for the calculation of electron impact cross sections of atoms. This model, which was labelled Binary-Encounter-Bethe (BEB) model, combined the binary encounter theory with the dipole interaction of the Bethe theory for fast incident electrons. An extension of the BEB model was later performed in order to be used at relativistic incident energies, and was labelled RBEB. A review of the binary-encounter theory showed that some features, not included on the BEB/RBEB model, could result in significant changes in the shape and intensity of the cross section curves.

The role of the Burgess denominator [2] on the scaling of the first Born theories has been investigated [3], and a study of its impact on the calculation of BEB/RBEB electron impact cross sections has been done. Several open- and closed-shell atoms were studied, from K- and L-Shell ionization to total ionization cross sections.

In this work we propose a modified expression of the BEB theory that takes into account the modified Burgess denominator, as well as the phase shifts of the quantum-mechanical differential cross sections [4]. The range of the electron-electron interaction in direct ionization was also studied, since it is one of the main features of the modified denominator.

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