The talk contained examples of recent atomic physics experiments with stored and cooled ion beams from different ion storage-ring facilities. Here, we first introduce the principles of storage rings and electron cooling. A whole class of experiments exploits the cold electron beams available in the electron coolers and electron targets of storage rings. The recombination experiments have applications in fusion and astrophysical plasmas. Dielectronic resonances at meV to eV energies are measured with a resolution and absolute accuracy to much below a meV. The measurements of these resonances provide a serious challenge to theories for describing correlation, relativistic, quantum electrodynamical effects, and isotope shifts in highly ionized ions. Experiments with internal targets in storage rings use the high luminosity of cooled MeV ions for collisions. First measurements demonstrate the resolution with a He RIMS apparatus (He gas-jet Target for Recoil Ion Momentum Spectroscopy) in Thomas-like electron-transfer processes by protons. An outlook into the future with the new Facility for Anti-proton and Ion Research (FAIR) and the Stored Particle Atomic Research Collaboration (SPARC) is given.

I. Introduction

Ion cooler storage rings were adopted from high energy and particle physics in the field of atomic and molecular physics, as unusual devices for spectroscopy and studies of collisions. The storage rings ASTRID at University Aarhus, CRYRING at Manne Siegbahn Laboratory, Stockholm, ESR at GSI, Darmstadt, TSR at Max-Planck Institut, Heidelberg, and CRS at IMP Lanzhou, that are schematically shown in Fig. 1, were built for having atomic, molecular or cluster ions rotating on a up to 100 meter circumference with high velocity, electro-magnetically confined. Now, after more then 15 years of operation of these rings, one may ask what has been achieved, what is presently being done, and which are the new directions?

In the talk, I concentrated on the applications of ion-cooler storage rings for atomic collision physics. In this subject, ion beam cooling plays a central role by providing both a high brilliance of the beam and luminosity in connection with a target. The storage capability is the prerequisite for cooling the ions by overlapping them with a beam of cold electrons (electron cooling) or a laser beam (laser cooling), or by correcting a displacement of their orbit deduced from a pick-up (stochastic cooling). It may sound like a paradox to cool an ion beam of GeV energy, but here, cooling means making the beam mono-energetic and reducing the angular divergence and geometrical size of the beam. Electron cooling [Poth1990] is the most universal applicable cooling in ion storage rings and it reaches for highly-charged ions a very high cooling force. One of the highlights that were achieved recently are ordered structures similar to a pearl string of the stored beam by electron cooling[Steck1996]. This occurs when the thermal energy of the ions becomes smaller than the Coulomb repulsion between them, then the ions cannot overcome the Coulomb barrier and do not pass each other, but are forced on a string[Hasse99]. This phase transition,
together with the capability of storing ions for extended time in the ring, allowed the observation of nuclear beta decay processes in real time in single ions[Litvinov2003]. A beta decay channel, such as the beta decay into a bound atomic state is only possible when the ion has a vacancy in the inner shell. It is forbidden in the neutral atom. This important process for the formation of elements during nucleosynthesis in stellar media was seen for the first time in the laboratory by storing the isotope in the ESR [F. Bosch in this issue].

Electron cooling opens up the possibilities to measure electron-ion collision processes with unprecedented resolution. In these collisions a number of interesting phenomena occur, with important applications in fusion and astrophysical plasmas. One of the fundamental collision processes is recombination, and can be seen as time-inverse of photo-ionization, auto-ionization, or electron-impact ionization. By observing recombination element abundances can be obtained, the velocity distribution of the electrons in the cooler but also in a plasma can be diagnosed. Indeed, in plasmas, much of the energy transport happens as electrons collide with ions. In such collisions, the ion can be excited or further ionized, or, the electron can be captured. Astrophysical objects are investigated through analysis of their radiation spectra [Ferland2003], and thus require accurate

Fig. 1 A view of the existing ion cooler storage rings using magnetic confinement, ASTRID at University Aarhus, CRYRING at Manne Siegbahn Laboratory, Stockholm, ESR at GSI, Darmstadt, TSR at Max-Planck Institut, Heidelberg, and CRS at IMP in Lanzhou, in an approximate scale.
knowledge of electron-ion recombination and electron-impact excitation as well as ionization. Recombination is an efficient mechanism for anti-hydrogen production in a trap filled with antiprotons and positrons. Finally, studies of electron-ion impact phenomena can be very useful for developing our understanding of the structure and decay modes in many electron systems. They can serve, e.g., as testing grounds for highly accurate calculations of energy levels in few-electron ions which require a proper treatment of relativistic, quantum electrodynamical, and correlation effects. Very recently the nuclear magnetization could be measured to a high accuracy through shifts of dielectronic recombination resonances in different isotopes of a highly charged ion. The electron cooler has been exploited for atomic ions over the whole atomic charge range, from protons to uranium ions, and with molecular ions of increasing complexity. Also negative ions were stored and collisions with electrons were investigated. Here we concentrate on electron-ion recombination. It will be shown how this process can be measured at cooler-storage rings with very high accuracy. This has advanced to the level of detecting the hyperfine-structure of ions and testing Quantum Electro-Dynamics (QED) by collisional spectroscopy.

Beam cooling results in an excellent definition of the interaction zone and collision parameters when crossing the stored beam with a gas-jet. This was used in studies of rare processes in ion-atom collisions, such as higher-order process in electron capture. Examples are shown in chapt. IV, where at CRYRING different electron capture channels were separated by means of a reaction microscope including a recoil-ion momentum spectrometer. Photon emission from the interaction of stored heavy ions with gas-target atoms were studied in details at ESR. Radiative electron capture is the ion-atom collision analog of radiative recombination in electron-ion collisions and as such the time inverse of direct photo-ionization. The polarization of X rays emitted in radiative electron capture by relativistic U ions was measured in the ESR [Tashenov2006]. The electron capture occurred in a jet gas target in the ring. This gas jet or the electron beam in the cooler was also used to populate atomic levels which then decay. Cooling reduces Doppler spread. With precision x-ray spectroscopy of Lyman alpha transitions in H-like U one aims at a test of QED in the regime of very strong electric fields [Gumberidze2004,2005].

One can also use storage rings effectively for observing the decay of long-lived unstable ions [Rostohar2001, Träbert1999]. The decay of certain long-lived unstable positive and negative ions was observed for times in the range of μsec to sec. Some negative ions, for example, only exist for an interval in the range of μsec to msec. Such times are usually too long to be measured accurately through observation of the decay during a single passage of such an ion beam, where 100 nsec observation times are typical. A storage ring, however, is like an infinitely long beam line.

Storage times from milliseconds to several days (depending on the electronic structure of the ions and the vacuum in the ring) have been achieved for high circulating ion currents. The future will be in new machines for even higher beam intensities, heavier ions with higher charges, storing and cooling of anti-particles, such as anti-protons or positrons. To reach that, a new international Facility for Anti-proton and Ion Research, FAIR, at GSI Darmstadt is planned, as described in section V. The facility will be a sophisticated system of synchrotrons and storage devices, equipped with novel instrumentation such as internal targets, merged beams, spectrometers and analysers, and with the capability to keep the ions in a wide range of energies, starting at the highly relativistic end, or to bring them to rest.
II. Electron Cooling and Photo Recombination

For electron cooling [Poth1990] a monoenergetic electron beam having the same velocity as the stored ions is merged with them over a length of 1 to 2 m. The electron beam is guided by a magnetic field. In the moving frame, this appears like mixing a hot gas of ions with a cold gas of electrons (illustrated in Fig. 2). Energy (heat) is exchanged between the ions and the low-temperature electrons by collisions as the ions pass through the electron cooler many million times as they circulate in the ring. Thus, at thermal equilibrium, the ion-beam temperature will be reduced from several million degrees to a few hundred degrees Kelvin.

Until recently, it was difficult to study reactions between free electrons and ions, with accurate control over their collision velocity. In addition to reaching narrow velocity distributions of the stored beam, electron cooling opened up new possibilities to study electron-ion collisions, particularly recombination with unprecedented resolution and luminosity. Another important device for collisions of electrons with highly-charged ions is the electron-beam ion trap (EBIT). There collision energies are in the keV to 100 keV regime, whereas in the storage ring collision energies from 0 to 100 eV were mostly investigated. There are several components which make collision studies in rings attractive in comparison to other techniques: (i) The electron beam required for cooling has excellent properties for electron-impact studies (low energy spread, low space charge potential etc.). (ii) Cooler storage rings provide clean experimental situations: where only one charge-state (q) component interacts. (iii) By cooling, the ion beam is compressed to a small diameter keeping its intensity, instead of collimating it. This gives a high luminosity for merged or crossed beam experiments (electrons, laser, gas-jet etc.). (iv) There is usually a low background from residual gas collisions due to the excellent vacuum conditions required for a storage device. (v) One can exploit ion storage for having metastable states or exited states in the beam decaying, before the experiment or to observe their decay rate. These are major points in using cooler storage rings in the field of atomic and molecular physics [Schuch2000, Larsson1995, Lindroth2003].

![Fig. 2 Schematics of cooling ions by electrons. (a) In the laboratory frame. (b) Electron velocity distribution in the rest frame of the ions.](image)

The electron beam in the cooler has excellent properties for electron-ion collision studies. The electrons are emitted from a heated electron gun with a temperature $T_C \approx 1100$ K. Acceleration reduces the longitudinal velocity component ($v_\parallel$; parameterized by a longitudinal temperature $T_\parallel$) by a large factor $T_\parallel = k T^2 / 4 E_e$, where $k$ is the Boltzmann constant and $E_e$ the electron energy. The effective value of $T_\parallel$ is, due to the so-called longitudinal-longitudinal relaxation [Aleksandrov1990], $T_\parallel = 1.6 e^2 n_e^{1/3} / (4 \pi e_0)$, in CRYRING, $T_\parallel \lesssim 10^{-4}$ eV/k, for a typical electron density $n_e = 10^{-7}$ cm$^{-3}$. Adiabatic expansion of the electron beam [Danared1994] by a factor of 100
reduces the transverse velocity component \( (v_\perp) \) of the electrons to \( T_\perp \sim 10^{-3} \text{ eV/k} \), parameterized by a transverse temperature \( T_\perp \). We have thus a flattened Maxwellian distribution \( f_e(v_{cm}, T_\parallel, T_\perp) \):

\[
f_e(v_{cm}, T_\parallel, T_\perp) = \left( \frac{m_e}{2\pi k} \right)^{\frac{3}{2}} \frac{1}{T_\perp \sqrt{T_\parallel}} \exp \left( -\frac{m_e v_\parallel^2}{2kT_\parallel} - \frac{m_e (v_\parallel - v_{cm})^2}{2kT_\perp} \right)
\]

where \( v_{cm} \) is derived from \( E_{cm} \) defined below.

In CRYRING, such an electron beam of density \( n_e \) is merged with ions in a guiding magnetic field of 0.03 T over a length \( l \) of 1m. After cooling at \( E_e \), the electron energy can be changed by a certain amount \( \Delta E_e \) which results in a center-of-mass energy: \( E_{cm} \approx \Delta E_e^2 / 4E_e \). The exact relativistic expression is:

\[
E_{cm} = \sqrt{\left(E_e + E_i + m_e c^2 + m_e c^2 \right)^2 - \left(E_e^2 + 2m_e c^2 E_e + E_i^2 + 2m_e c^2 E_i \right)} - m_e c^2 - m_i c^2
\]

The energy resolution for measuring resonances with the electron cooler of a storage ring is determined by:

\[
\Delta E_{cm} = \sqrt{(\ln 2k_{\perp} T_\perp)^2 + 16 \ln 2k_{\perp}/T_{rel}}
\]

The ion velocity distribution can usually be neglected due to cooling and the mass reduction-factor \( m_e/m_i \). Examples of energy resolution that was obtained in recombination experiments will be discussed below.

One of the fundamental atomic processes investigated at these setups is recombination which is described here in short:

\[
Z^{q+} + ke^- \rightarrow Z^{(q-1)+} + (k-1)e^- + h\nu
\]

For radiative recombination (RR) the photon is emitted directly (\( k=1 \)). Dielectronic recombination (DR) is characterized by \( q<Z, k=1 \), and the emission of photons is from an intermediate doubly-excited state. In three-body recombination (TBR) a neighboring electron carries away recombination energy (\( k>1 \)). If \( Z \) represents a molecular ion (\( q=1 \)), dissociative recombination occurs with \( k=1 \).

In dielectronic recombination, a free electron can be captured by an ion containing a bound electron which takes up energy and is excited. This doubly excited state stabilizes by emitting photons. Due to energy conservation, this recombination occurs as a resonance when the electron velocity is changed relative to the ion velocity. The charge-changed ions by recombination in the electron cooler are detected after separation from the stored beam in a ring dipole-magnet. Fig. 3 shows these resonances for \( \text{N}^{4+} \) ions stored in CRYRING [Glans2001] and scanning the electron energy in the center of mass (CM) system from 0 to 10 eV.

Absolute recombination rate coefficients are determined from:
\[ \alpha_{\text{exp}} = \gamma^2 \frac{L}{l} \frac{R}{n_i n_i}, \quad (5) \]

where \( \gamma \) is the Lorentz factor, \( L/l \) is the ratio of ring diameter to interaction length, \( N_i \) is the number of stored ions, and \( R \) is the background corrected ion counting rate. At a vacuum of \( 10^{-11} \) torr, the electron capture background is mostly in the percent level. The systematic experimental uncertainty in these types of measurements is about 5% to 10%; where 1% to 10% comes from the absolute number of stored ions, and 5% from the effective interaction length. The recombined ions are separated from the stored beam by passing through a ring dipole-magnet. The motional electric field acting in the ion frame can thus field-ionize the electron which recombines into states above a certain quantum number \( n_e = \left(6.8 \times 10^8 (V/cm) q^3/v_i B\right)^{1/4} \) [Müller1986]. This effect is seen in Fig. 3 as a cut-off of resonances in Rydberg states at the series limit.

Radiative and dielectronic recombination processes are schematically depicted in Fig. 3 (left) with the energy levels of the initial ion (\( N^{4+} \)) and recombined ion (\( N^{3+} \)) on the same energy scale. When the electron collides with \( N^{4+} \) a certain amount of kinetic energy, \( E_{\text{cm}} \), is brought into the system. If the energy of the electron-ion system now matches a doubly excited state in \( N^{3+} \) it can transform into this state. Here the active bound electron is in 2s. The new state is a very short lived, autoionizing state, and in most cases it will decay back the same way it was formed. If a photon is emitted, however, the system may end up below the ionization limit of \( N^{3+} \) (thick arrow) and then dielectronic recombination is completed. In the RR process the system emits a photon and proceeds directly to a bound state of \( N^{3+} \).

From the calculated recombination cross sections, \( \sigma_{\text{RR}} \) and \( \sigma_{\text{DR}} \) for RR and DR, respectively, values of \( \alpha \) can be calculated for comparison with \( \alpha_{\text{exp}} \) by:

\[ \alpha_{\text{RR/DR}}(E_{\text{cm}}) = \int \sigma_{\text{RR/DR}}(E_{\text{cm}}) f_\perp \left(v_{\text{cm}}, v_\parallel, v_\perp \right) d^3v \quad (6) \]
The theoretical DR cross sections are obtained by using three different computational schemes: One method is based on Relativistic Many-Body Perturbation Theory (RMBPT) and is capable of meV accuracy for few electron systems (except for the QED effects) [Lindroth2003]. This method uses complex rotation to handle autoionizing states. The other two calculations use AUTOSTRUCTURE (AS) in LS-coupling, AS with Breit-Pauli approximation and R-matrix codes, respectively [Badnell1989, Zhang1997]. All these codes have advantages and disadvantages. Based on the comparison with the experimental spectra the quality of these theoretical methods can be discussed.

For the cross section for dielectronic recombination via single resonances, at energy $E_r$, more than the natural line width $\Gamma$ above threshold, one can write:

$$\sigma_{DR}(E_{cm}) = \frac{S}{2\pi} \cdot \frac{\Gamma}{(E_{cm} - E_r)^2 + \Gamma^2 / 4}$$  \hspace{1cm} (7)

where $S$ is the strength of the resonance:

$$S = \frac{\hbar}{k^2} \cdot \frac{A^a_{id} \cdot \sum_s A^r_{ds}}{A^a + \sum_s A^r_{ds}}$$  \hspace{1cm} (8)

With $g_d$ and $g_i$ being multiplicities of intermediate doubly-excited state and ion initial state, respectively. The electron wave number is $k_e$, and $A^a_{id}$ is the autoionization rate of the intermediate doubly-excited state giving $k_e$, $A^a$ is its total autoionization rate and $\sum_s A^r_{ds}$ its total radiative stabilization rate. Single DR resonances can thus be characterized by three parameters: $S$, $E_r$, and $\Gamma$. From many-body perturbation calculations combined with complex rotation for describing the autoionizing states, these three parameters are obtained. Other calculations, such as the AUTOSTRUCTURE code, or R-matrix treatment give so-called binned cross sections: $\sigma_{DR}(E_{cm}) \cdot \Delta E_{cm}$, where single resonances are not distinguished and the bin size $\Delta E_{cm}$ is chosen so narrow that $\sigma_{DR}(E_{cm})$ can be considered constant there. The AUTOSTRUCTURE code is based on the many-body Breit-Pauli approximation for the wavefunctions in intermediate coupling for low-n, and the high-n states are obtained by extrapolating radial wavefunctions assuming quantum defect theory.

II. 1. Recombination – Photo Ionization – Detailed Balance

Notice that RR as well as DR starts with a system of a free electron and an ion and ends with a system where the electron is bound to the ion and a photon has been emitted so it can be seen as time inverse of photo ionization. The only difference between the processes is the intermediate step present in the DR process. From first principles it can then be argued that RR and DR should be treated as one single process and that the division into two processes is artificial. In most practical cases the division into two processes is natural and practical. The reason is that RR and DR often contribute for rather different center of mass energies and that they prefer different final states. In principle interference effects should be observable in storage ring experiments but the effect could not be clearly identified experimentally [Schippers2002].
Photorecombination (PR) and photoionization (PI) can be directly compared with the principle of detailed balance on a state to state basis. From the photoionization cross section $\sigma_{i\rightarrow f}^{PI}$ from an initial state $i$ to a final state $f$ the photorecombination cross section $\sigma_{i\rightarrow f}^{PR}$ can be obtained in the following way:

$$\frac{\sigma_{PR}(E_{cm})}{\sigma_{PI}(E_{cm} + I_i)} = \frac{g_{PI}}{g_{PR}} \frac{(h \nu)^2}{2m_e c^2 E_{cm}}$$

(9)

Here $g_{PI}$ and $g_{PR}$ are the statistical weights of the different states. The photon energy $h \nu$ and the center of mass energy $E_{cm}$ between the free electron and the ion are related via $h \nu = E_{cm} + I_i$, where $I_i$ is the ionization potential of state $i$.

Fig. 4 The upper part shows PR data and the lower part data for PI [Müller2002]. For details see ref. [Müller2002].

A detailed comparison of a single doubly excited state has been done by Müller et al. [Müller2002] comparing a PR measurement of C$^{3+}$ at the TSR storage ring with a PI measurement of C$^{2+}$ (see Fig. 4). The 2p4d $^1P$ doubly excited state is populated in PR and PI. The resonance strength of the two measurements are $S_{PI} = 7.6 \times 10^{-22}$ cm$^2$eV for PI and $S_{PR} = 1.6 \times 10^{-20}$ cm$^2$eV for PR. The difference of more than two orders of magnitude is due to the fact that only a small fraction of PR via the 2p4d $^1P$ resonance is due to stabilization by a two-electron one-photon transition. Only this transition can be considered since the principle of detailed balance can only be applied on a state to state basis. Comparison of PR and PI measurements can thus help to extract information about the recombination via certain channels which are not separable in storage ring PR measurements.
II. 2. Plasma Recombination Rate Coefficient

Many of the measured rate coefficients are of interest to plasma or astrophysical applications (see also N. Badnell and D. Savin this vol.). For some of the candidates such as Be, C, N, O, Ne, Si, Fe, and Ni in several charge states, accurate experimental data is now available. The measured rate coefficients become useful for these applications folding it with a Maxwellian temperature distribution (under the assumption that the peak width is very much narrower than the Maxwellian width):

\[
\alpha(T) = \frac{2\pi}{(\pi k T)^{3/2}} \int \alpha_{\exp} \sqrt{E_{cm}} e^{-\frac{E_{cm}}{k T}} dE_{cm}
\]  

(10)

As an example for such temperature dependent rate coefficients we show here the result [Fogle2005] for O\(^{4+}\) in figure 5. Emission lines from recombination of O\(^{4+}\) are observed, e.g., in planetary nebulae and used for temperature and abundance determination there, as well as in other astrophysical plasmas and in fusion plasma physics.

![Fig. 5 The RR and DR plasma recombination rate coefficients for O\(^{4+}\) [Fogle2005]. The thick solid curves represent RR only and the results for RR and DR extrapolated to the no-field limit. The dotted line in a) shows the calculation without the TR resonances. For explanation of the other symbols and lines see ref. [Fogle2005].](image)

One very interesting feature are the strong trielectronic recombination (TR) resonances at low energies. TR involves the excitation of two bound electrons while a free electron is captured into a \(nl\) state. In this case the \(2s^2\) electrons of the ground state of the beryllium-like oxygen ion are excited to the \(2p^2\) state. This has been observed first in a measurement with beryllium-like Cl ions at the TSR [Schnell2003]. Although the TR cross section is normally small compared to the DR cross section in the case of O\(^{4+}\) the contribution at small energies is dominating. This is due to the fact that the strength of a given resonance is inversely proportional to the incident electron energy.
The accuracy of determining the resonance energies in dielectronic recombination has reached unprecedented values in several experiments with ions from Be\(^+\) up to U\(^{89+}\) [Mohamed2002, Zong1997, Madzunkov2002, Brandau2003]. One calls this application of recombination at cooler storage rings Electron Collision Spectroscopy. Mostly Li-like, Na-like and Cu-like ions were studied due to their rather simple electronic structure with a tightly bound core and one loosely bound nl-electron. The recombination spectra contain a limited number of resonances, and the formed doubly excited states comprise a pseudo-two-electron system with two active electrons outside a closed shell. Therefore, the calculations may be performed with pure ab initio methods. Measurements of these resonances can thus serve as testing grounds for highly accurate calculations of energy levels in few electron ions which require, besides the binding to the nucleus, a proper relativistic treatment of the interactions between all the electrons and of the quantum electrodynamical corrections, and even the details of the interaction with the nucleus, i.e. the hyperfine interaction. The mutual overlap of the electronic wave functions with the atomic nucleus plays an increasingly important role for increasing Z. This can be used to obtain information about the nucleus with atomic physics experiments such as electron collision spectroscopy. The isotope shift has been measured recently for \(^{142}\)Nd\(^{57+}\) and \(^{150}\)Nd\(^{57+}\) at the ESR [Brandau2007].

For demonstrating the level of accuracy reached presently, and, also the variety of applications of these recombination measurements in physics, we selected Sc\(^{18+}\) and Pb\(^{53+}\) primary ions, which are Li-like and Cu-like, respectively.

For Sc\(^{18+}\), the recombination spectrum has been measured at the TSR [Lestinsky2007]. This ion is very favorable for doing precision spectroscopy because it has strong resonances below 100 meV. Due to the kinematics of merged beams experiments resonances at low energies (below ~100 meV) can be measured with extremely high precision. The TSR is also currently the only storage ring having an electron cooler and an electron target. This allows cooling throughout the measurement cycle, thus avoiding an increase of the temperature of the ion beam during the actual measurement. The permanent cooling also keeps the ion beam energy at a constant value allowing to obtain the electron ion center of mass energy with an even higher accuracy than previously possible. The electron beam temperatures achieved with a cryogenic photocathode were \(kT_\perp = 0.0011\) eV and \(kT_\parallel\) \(= 2.23 \times 10^{-5}\) eV. Fig. 6 shows the low energy DR of Sc\(^{18+}\). It is governed by the three narrow resonance terms \((2p_{3/2}10d_{5/2})_{J=4}\), \((2p_{3/2}10d_{3/2})_{J=2}\), and \((2p_{3/2}10d_{3/2})_{J=3}\) predicted to be at 29 meV, 34 meV, and 68 meV. Through the hyperfine structure of the \((1s^22s_{1/2})\) ground state with the levels \(F = 3\) and \(F = 4\) separated by about 6 meV each level produces two resonance groups \((J,F)\). These groups could clearly be identified and the value for the hyperfine splitting was found to be 0.00620(8) eV.

The term energies represent the difference of the \(2s_{1/2} \rightarrow 2p_{3/2}\) core excitation energy and the binding energy of the Rydberg electron. The latter can be calculated to a very high level of accuracy. This allowed to extract the \(2s_{1/2} \rightarrow 2p_{3/2}\) transition energy as 44.30943(20) eV with an accuracy of 4.6-ppm. Methods to obtain transition energies with high accuracy from DR measurements are described in detail in [Zong1997] and [Brandau2003].
In Pb$^{53+}$ it is a $4s_{1/2}$ to $4p_{1/2}$ excitation and simultaneous capture in an 18l-state, starting with $j=21/2$ that make the first resonance series. QED effects, such as self-energy and vacuum polarization, are substantial in this highly charged ion and contribute to the $4p_{1/2}-4s_{1/2}$ splitting with $\approx 2$ eV. A relativistic, but still hydrogen-like, determination of the 18l-states, shows that the doubly excited states due to $4p_{1/2}$ 18lj-configurations are spread out both below and above the ionization threshold and only those including the higher 18l-states can form resonances. With the RMBPT [Lindroth2001], starting from the Dirac-Fock approximation, adding contributions from core polarization, the energies of the n=18 electron is calculated. From a comparison with the measured spectrum the $4s_{1/2} - 4p_{1/2}$ energy splitting of 118.010(1) eV is found. This corresponds to a total contribution from QED corrections to the splitting of -2.044(1) eV which is in very good agreement with the value given by Blundell, of -2.05(1) eV (see ref. [Lindroth2001]).

At CRYRING it was possible to resolve and measure the hyperfine splitting by comparing the DR resonances of the two isotopes of the ions $^{207}$Pb$^{53+}$ and $^{208}$Pb$^{53+}$ [Schuch2005]. The difference between the recombination spectra of the two is mainly due to the hyperfine shifts of the F=0 and 1 states in $4s_{1/2}$ and $4p_{1/2}$ of $^{207}$Pb$^{53+}$. These energy shifts of the F=0 and 1 states in $4s_{1/2}$ and $4p_{1/2}$ were calculated (see ref. [Schuch2005]) to be -10.66 meV, and 3.55 meV, -3.524 meV, and 1.174 meV, respectively and found in reasonable agreement with the experiment.

These two experiments demonstrate the capabilities of storage ring experiments to extract data about the atomic nucleus from atomic physics experiments. This will be of great importance at the future FAIR facility (see section V) where exotic nuclei will be available.

Fig. 6 Sc$^{18+}$ recombination spectrum of the lowest resonances measured at the TSR [Lestinsky2007].
IV. Recoil-Ion Momentum Spectroscopy of Electron Capture

Fragmentation of atoms and molecules (by ionisation or dissociation) are very useful tools to understand the dynamical structure of atomic and molecular many-particle systems. In particular the dynamical electron-electron or multi-electron correlation in the initial and final states as well as during the reaction, are basic, unsolved problems in modern atomic and molecular physics. For the past 15 years the technique of Recoil-Ion-Momentum Spectroscopy (RIMS) has been developed to a very successful tool for atomic collision studies [Ali1992, Ullrich1997]. In recent years this techniques was implemented in ion-storage rings exploiting the boost in luminosity of cooled beam–internal target system. This allows studies of reactions of small cross sections so far not seen. Such a process is electron-capture at high velocity and transfer ionization (TI), where in an electron-capture reaction one electron is emitted into the continuum. These can occur via different mechanisms that involve higher-order interactions between the electrons and the nuclei. It is thus an interesting test case for descriptions of ‘correlations’ in the time dependent long–range interactions of atomic collisions. The high resolution momentum imaging of RIMS besides the spatial imaging of the reaction products allows reconstructing the reaction dynamics in until now unprecedented clarity, and is thus called a reaction-dynamics microscope. Together with the luminosity of a storage ring this allows to study reactions with tiny cross sections.

A gas jet-target is installed at CRYRING [Schmidt1999] and a He jet is crossed with a cooled proton beam reaching a luminosity of $10^{36}$ cm$^{-2}$s$^{-1}$. Here, we show examples where this set-up was used in studies of single electron capture (SC) and transfer ionization (TI) in fast p-He collisions. Both cross sections should decrease asymptotically with the beam velocity as $v^{-11}$. This high velocity regime could be tested, for the first time, with recoil momentum images at a storage ring [Schmidt02]. In the $v^{-11}$ regime SC is mediated by a very particular Thomas mechanism. Scattering of the electron (e) occurs first at the proton (P) then at the target nucleus (N) in such a way that e travels parallel to P with almost the same velocity and gets bound. Quantum mechanically the (P-e-N) scattering is described by higher-order interaction amplitudes. The projectile is scattered by $\theta = \sqrt{3} (m_e/2M_p)$ and the recoiling He$^+$ ion gets the transverse momentum $p_{\perp} = 0.5 M_p V_p$.

TI is a many-body process in electron capture [Briggs1979] where additionally to single capture, one target electron is simultaneously ionized. In the high velocity regime a Thomas mechanisms can occur that involves scattering between two target electrons and the incoming ion. In the (P-e-e) scattering the projectile deflects from an electron at $\theta = m_e/2M_p$ that e is scattered from a second electron in such a way that it travels parallel to P with almost the same velocity and gets bound. The electron that it scatters from is emitted near to 90°, it carries the momentum needed for the balance, first time observed in [Pálinkás1989]. The He$^{++}$ ion does not participate in this reaction, it does not get a recoil momentum [Mergel2001].

The high luminosity in the storage ring itself becomes a problem as it creates a high production rate of singly charged recoil ions from single ionization events. This process has a cross section, which exceeds that of SC and TI by up to nine orders of magnitude for our highest velocities of p-He. In order to overcome this problem a time-switched recoil-ion-momentum spectrometer was necessary to get SC and TI cross sections at high energies [Schmidt02]. Fig. 7 shows a schematics of the RIMS with the ion extraction potentials and the timing of the pulses.

As indicated in Fig. 7, when the transverse electric field is on, no ions can reach the detector, except in case of a hit of a H at the projectile detector. Then the field is switched off and recoil ions can be detected on the 2-dimensional position-sensitive Channelplate detector. Due to the high production rate of He$^+$ ions, also many random He$^+$ pass the deflector when it is off, besides those
coming from SC. Still they arrive later on the detector as they pick up less energy in the acceleration potential (see Fig. 7). In this way the very small TI and SC processes are well separated, and further, we separate by the momentum images (see Fig. 7, and below) its Thomas P-e-e and P-e-N parts from the kinematical contributions [Schmidt02].

Fig. 7 Schematics of the time-switched recoil-ion-momentum spectrometer applied to fast proton-He collisions. A transverse electric field is applied to the recoil ions so that they usually cannot reach the detector, except when a H⁰ hits the detector, then it is switched off and He¹⁺,²⁺ are detected on the 2-dimenional position-sensitive Channelplate detector [Schmidt02].

Neutral projectiles formed in electron transfer processes leave the ring and are detected by a position-sensitive microchannel-plate detector. The recoil ions hitting a second position-sensitive microchannel-plate detector serves as stop for a TDC, which stores the time-of-flight information yielding the recoil-ion charge-state distribution. The longitudinal recoil-ion momenta are deduced from the positions along the beam on the recoil detector (figure 7).

In figure 8 we show a time-of-flight spectrum recorded in the time-switched mode. The zero-point is the time of H⁰-detection. Before $t=4.2 \mu s$ only detector noise is observed, then there is an increase to a level set by random coincidences from double ionization (DI) events, on top of which the TI peak is seen at $t=4.6 \mu s$. At $t=5.2 \mu s$ the random level increases dramatically as the first He⁺ ions from single ionization (SI) reach the detector. The peak at $t=6.7 \mu s$ is due to single capture (SC) events. We distinguish between KTI and the Thomas p-e-e TI mechanism through their different recoil-ion-momenta along the projectile axis as deduced from the position distribution of the TI recoil ions. The inset a) in figure 8 shows the density of hits on the recoil-ion detector for a narrow time window around the SC peak. The maximum to the left is due to true SC events, whereas the wider peak is due to SI randoms. The inset b) shows the recoil-ions from TI. The structure to the left stems from the KTI process, whereas the distribution closer to the detector’s center is mainly the Thomas p-e-e scattering process with a small contribution from DI randoms.
Fig. 8 The right part of the figure shows the time-of-flight spectrum recorded in the time-switched mode with 2.5 MeV protons (from ref. [Schmidt02]). Note, the single capture (SC) peak rides on the large single ionization (SI) random level. Inset a) shows a contour plot of the recoil-positions recorded in coincidence with the SC peak. Inset b) is the equivalent picture for the TI peak, with indications of kinematical TI (KTI) and Thomas TI (TTI).

The conservation laws of energy and momentum lead to a well-defined longitudinal recoil momentum for a given $Q$-value of the process (in atomic units): $p_z = -q v_p / 2 - Q / v_p$ (1), where $v_p$ is the projectile velocity, $q$ is the number of transferred electrons and $Q$ is the change in total electronic binding energy. Fig 8a shows how randoms from SI are separated from true coincidences of SC in the longitudinal recoil momentum. In setting a coordinate system with z axis in beam direction, the momentum distribution in y direction can be directly read from images as Fig. 8a. The momentum distribution in x direction can be derived from ToF and the transverse recoil momentum distribution in Fig. 9 for SC in 7.5 MeV p-He collisions is obtained [Fischer2006]. In the center the dominant kinematical capture events and a ring around should be the Thomas scattering processes where a transverse momentum transfer to the recoiling nucleus is expected. From these events the differential capture cross section dependent on the projectile scattering angle can be derived directly. This is shown in Fig. 10 in comparison with data derived directly from projectile deflection (open circles) [Pedersen1983]. One can see directly the improvement in resolution of RIMS and statistical error in a storage ring experiment as compared to single beam passage [Pedersen1983, Vogt1986]. At higher velocity the Thomas peak should become more and more dominant. However, the total cross section decreases with a $v^{-11}$ velocity dependence, therefore, a measurement that was tried at 12.5 MeV [Fischer2006] show a relatively stronger Thomas peak, but also larger statistical error.
As seen from Fig 8 the events of transfer ionization in p-He collisions can be extracted as well. The total cross sections for this process are shown in figure 11 as function of proton energy together with the results of Mergel et al. and Shah and Gilbody (see ref. in [Schmidt02]) at lower proton velocities. The line in figure 11 has a slope corresponding to a $v^{-11}$ velocity dependence, consistent with the theoretical predictions (see ref. in [Schmidt02]) at high $v$. Note also that the present data for $v > 10v_0$ fall off much more rapidly with $v$ than the previous data for $v < 10v_0$ (see ref. in [Mergel2001]). The high-velocity cross sections for the Thomas p-e-e transfer ionization process are therefore consistent with a $v^{-11}$ scaling [Schmidt02].

From photoionization it is known that when an electron is instantaneously removed from the He ground state, the other electron finds itself in a superposition of bound and continuum He$^+$ eigenstates. Åberg calculated the amplitude for the continuum contribution and found (see ref. in [Schmidt02]) a 1.66 % probability for shake-off ($\rightarrow$He$^{2+}$+2e$^-$). With the new data for high velocity protons, we can look into the shake-off concept for describing the probability for removing the ‘second’ electron from He if the first electron is removed suddenly by capture. Figure 12 shows the ratio of TI to the total capture cross section as a function of the proton velocity (in atomic units $v_0$) showing also results from other groups at lower velocity. In the single pass [Mergel2001] and CRYRING experiments [Schmidt02] Thomas TI was isolated and in Fig 12 the $\sigma_{KI}/(\sigma_{SC}+\sigma_{TI})$ ratios are shown as open symbols. The $v>10v_0$ data show a decrease with increasing velocities in contrast to the trend for $v<10v_0$ seen in previous experiments. The probability for emission of the second electron following electron transfer approaches the shake-off limit 1.66 % (see ref. in [Schmidt02]).
Fig. 12. The ratios of TI to total electron capture (Š Shah and Gilbody, [Mergel2001], ref.[Schmidt02]) and the ratio of the kinematical transfer ionization process (KTI) to the total capture ([Mergel2001], ref.[Schmidt02]) as function of the projectile velocity. Expected shake-off limit 1.66 %.

Fig. 11. The total TI (Š Shah and Gilbody, [Mergel et al.], ref.[Schmidt02]), and Thomas p-e-e TI ([Mergel2001], ref.[Schmidt02]) cross sections as functions of the projectile velocity. The line through the present Thomas p-e-e TI data points (O) has a slope corresponding to a $v^{-11}$ velocity dependence.

V Outlook

As we have seen, ion cooler rings are excellent instruments for collision studies, opening important details of many-body quantum-dynamics and of highly accurate spectroscopy in few-electron atomic systems. A future milestone will be the international Facility for Antiproton and Ion Research (FAIR) that is going to be built in the next 8 years at GSI Darmstadt, Germany. That facility, although with the main emphasis on particle and nuclear physics, will offer new and challenging opportunities for atomic collision physics and related fields. Fig. 13 gives an overview of the planned facility. The envisioned program [SPARC, Stöhlker2005] of the atomic physics research collaboration SPARC (Stored Particle Atomic Research Collaboration, http://www-linux.gsi.de/~sparc) exploits almost all the key features of FAIR at different sites of it, as indicated in Fig. 13: Ions from rest up to the relativistic energies; ion species from anti-protons up to bare uranium and radioactive nuclei; targets that range from intense photon fluxes to cold electrons and atoms up to nano-structures.

SPARC intends studies in two major research areas: collision dynamics in strong electro-magnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area heavy ions will be used for a wide range of collision studies. In the extremely short, relativistically enhanced field pulses, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitudes and breakdowns of perturbative
approximations for pair production are expected. The detection methods of reaction microscopes will give the momentum of all fragments when atoms or molecules are disintegrating in strong field pulses of the ions. This allows exploring regimes of multi-photon processes that are still far from being reached with high-power lasers. For medium energies, the New Experimental Storage Ring NESR, a "second-generation" ESR, and the low-energy ring LSR, with optimized features and novel installations such as an ultra-cold electron target will be exploited for collision studies. Here, fundamental atomic processes can be investigated for cooled heavy-ions at well defined charge state interacting with photons, electrons and atoms. These studies can even be extended to the low-energy where the atomic interactions are dominated by strong perturbations and quasi- molecular effects.

The other class of experiments will focus on structure studies of selected highly-charged ion species, a field that is still largely unexplored; with determinations of properties of stable and unstable nuclei by atomic physics techniques on the one hand, and precision tests of QED and fundamental interactions in extremely strong electromagnetic fields on the other hand. Different complementary approaches will be used such as relativistic Doppler boosts of optical or X-UV laser photons to the X-ray regime, or coherent radiation by channeling of relativistic ions, or electron-ion recombination, or electron and photon spectroscopy that gives hitherto unreachable accuracies. These transitions can also be used to laser-cool the relativistic heavy ions to extremely low temperature, which could lead to a breakthrough in accelerator technology. Another important scenario for this class of experiments will be slowing-down ions or anti-protons into the Facility for Low energy Anti-proton and Ion Research (FLAIR) where they can be stored and cooled in the LSR and USR and finally in the Penning ion trap facilities of HITRAP. This scenario will enable high-accuracy experiments in the realm of atomic and nuclear physics, as well as highly-sensitive tests of the Standard Model.

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