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THE HEIDELBERG TEST STORAGE RING FOR HEAVY IONS
AND ITS USE FOR ATOMIC PHYSICS

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Abstract

A brief description of the Heavy-Ion Test Storage Ring (TSR) presently being built at the Max-Planck Institut in Heidelberg is given. It will be able to store ions injected from the tandem postaccelerator combination up to about 30 MeV/nucleon for a charge to mass ratio of 0.5. One of the main purposes of the TSR will be the study of electron cooling. Some atomic physics experiments are discussed using the electron cooling device which provides an electron-ion collision facility with good energy resolution and ion beams of high currents and low emittances. Here the possibilities for measurements of spontaneous and laser-induced radiative recombination and dielectronic recombination in the electron cooling section are discussed.

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MASTER*See*

1. Introduction

The Heavy-Ion Test Storage Ring (TSR) [1] presently under construction in the Max-Planck Institut in Heidelberg is an experimental research facility for accelerator, atomic, and nuclear physics. It will be closely coupled to the MP tandem - Postaccelerator from which the ions will be injected in the storage ring. Firstly, multiturn particle injection methods will be studied, which are necessary to fill the ring up to the given limits with ions. The next important task of this storage ring will be the cooling of the phase space distribution of the stored ions, e.g., by merging them with a low temperature electron beam [2], or by stochastic cooling [3]. For these studies electron cooling combined with stochastic precooling will be installed in the TSR.

The TSR will be located in a recently built hall attached to the accelerator building. In fig. 1 the layout of the TSR [1] with its main components is shown. With eight C-shaped 45° magnets AMX the deflection is obtained. This together with the quadrupoles QZX and sextupoles SZX defines the fourfold symmetry of the ring structure. The lattice is flexible enough so that zero dispersion can be chosen in two straight sections and at the same time it can be set to an adjustable value over a length of two meters in the other two straight sections. The large aperture of the ring elements matched with the values of the dispersion should allow a storage of beams at different charge states at the same time, called here multicharge state operation. A result of closed orbits from simulations [1] for iodine ions is shown in fig. 2. The difference in the charge states correspond to

momentum steps of $\Delta p/p = 0.02$. It is clear that this feature of the ring is very important in reducing the loss of particles by charge changing processes. It can, however, also be very valuable for accumulating, detecting, and storing charge changed ions which might even be prepared in a well-defined atomic state.

Losses of particles still occur, e.g., by scattering and energy loss in the residual gas or internal target, by electron capture in the dispersive straight sections, and if the charge state is out of the acceptance range given by the apertures. As lower limits for the beam lifetimes in the TSR due to capture in the residual gas of pressure $P < 10^{-11}$ Torr, we have estimated $10^2 - 10^3$ sec depending on the charge of the ion.

2. Electron Cooling

Electrons will be emitted from a hot cathode (1000 °C, 50 mm dia.) with a Pierce electrode immersed in a magnetic field [1,4]. A magnetic field of about 0.05 Tesla (T) will prevent the blowing up of the electron beam due to the initial transverse momentum and space charge repulsion. However, one gets a cyclotron motion of the electrons around the field axis. The electrons will be accelerated by five ring shaped anode electrodes which divide the negative potential of the cathode down to the ground potential of the drift region. The exact value of the magnetic field is strongly coupled with the geometry of the gun and the acceleration potential in order to keep the transverse electron temperature constant during acceleration. In this so called resonant acceleration mode the electrons perform one or

multiples of the cyclotron revolution up to the end of the acceleration region [4].

After bending the electrons in a toroidal field they overlap with the ion beam over a length of about 1.5 m. Then electron and ion beam are separated again by a toroidal magnetic field and the electron beam is dissipated in the collector after being decelerated. In table 1 more parameters of the ring and the electron beam are given.

The velocity spread of the two particle beams can be characterized by two temperatures, T_i and T_e . In cooling conditions the average electron velocity $\langle u \rangle$ is equal to the average ion velocity $\langle v \rangle$. In this frame of reference the temperatures can be related to the spreads of the two velocities:

$$\Delta v = (2kT_i/m_i)^{1/2}, \quad \Delta u = (2kT_e/m_e)^{1/2}, \quad (1)$$

where m_i , and m_e are ion and electron mass, respectively. During cooling the ions transfer energy to the electrons (as their temperature is much higher than that of the electrons) and at thermal equilibrium their temperatures would be equal ($\Delta v = (m_e/m_i)^{1/2} \Delta u$). This would result in very small ion velocity spread if there were no beam heating processes like intra-beam scattering, target scattering, etc., but beam cooling is in equilibrium with heating, and this determines the final ion temperature.

From the cathode the electrons are emitted in all directions with a thermal energy spread kT of about 0.1 eV. Potential fluctuations due to mechanical inaccuracies and deformations of the hot cathode, the acceleration electrodes, and instabilities of the high-voltage power supply can cause

an additional energy spread. The final temperature should be in the order of ~ 0.2 eV. The compression of the longitudinal velocity spread by acceleration causes a flattened velocity distribution of the electrons.

$$\Delta E = kT_e = m_e u \Delta u, \quad \Delta u = kT_e / m_e u, \quad kT_e = (m_e / 2) \Delta u^2 = (kT_e)^2 / 4eU \quad (2)$$

Therefore the longitudinal temperature is for an acceleration voltage of some keV extremely small ($10^{-5} - 10^{-6}$ eV). However, the longitudinal energy of the electron beam also varies because of the potential from its space charge distribution. Thus an additional energy spread is introduced, determined by the size of the ion beam averaging over the electron beam. Still the longitudinal energy spread is after cooling, where the emittance of the beam shrinks enormously ($< 1 \pi$ mm mrad), much smaller than the transverse spread [5]. The energy spread of the beam is calculated to be of order $\Delta E/E \sim 10^{-4}$. It can reach values of order 10^{-5} depending on the number of particles stored, because this is responsible for the beam heating process of intra-beam scattering. The maximum number of ions which can be stored in the TSR were obtained by different criteria [6]:

- the critical change of the tune (betatron oscillations) of the machine by the space charge (Laslett tune shift).
- the stability of the phase space compressed beam with respect to external perturbations (Keil- Schnell criterium).

These give the maximum numbers of 10^9 to 10^{12} particles depending on the ion velocity, charge, and momentum spread.

Electron cooling has been tested successfully in the proton cooling experiments in the NAP-M at Novosibirsk [2], the ICE ring at CERN [7], and the Fermilab cooler. The cooling of heavy ions is new. One expects [5] much

larger cooling efficiencies with shorter cooling times (of order 0.1 sec.) compared to those with protons; however, this still needs to be verified experimentally. This will be one of crucial tests to be performed in the TSR.

One of the problems which could arise in electron cooling of heavy ions is a high recombination rate of ions with the electrons in the cooler and a loss of these ions from the ring. The radiative recombination with electrons has been observed already in the cooling experiments of protons and the effect has been used for electron beam diagnostics [7]. In heavy-ion cooling experiments the radiative recombination rates for bare ions should be orders of magnitude larger than for protons as the cross section increases like Z^2 (Z is the nuclear charge of the bare ion), and also other recombination channels like dielectronic recombination might become important in very special cases, for the cooling of few electron ions. These recombination processes, like radiative recombination, dielectronic recombination, electron-electron-collision induced recombination, are partly known and important roles in atomic-, plasma-, and astro-physics. There are still many open questions which can be addressed by experiments in the cooler because it is an excellent environment for their studies. In order to cool all stored charge states simultaneously, but also to reduce the loss due to recombination processes and to detect the recombined particles, the electron cooler is in a nondispersive section of the TSR.

3. Electron Ion Collision Experiments in the Cooler

Once the beam is cooled it is expected, that the electron beam velocity can be varied (if it is done fast enough compared to cooling times) from the

ion beam velocity for electron-ion collision experiments. The electron-collision energy is in the center-of-mass system, then:

$$E_r = (m_r/2)w^2 = (m_r/2) [(\vec{v} - \vec{u})/(1 - vu/c^2)]^2 \quad (3)$$

$m_r = m_e m_i / (m_e + m_i)$ is the reduced mass.

The recombination rate of electrons with ions, derived from first principles, for a number of ions N hitting with the velocity $\vec{w}$ an electron target of density n_e is:

$$\Delta N = N \cdot p \cdot n_e \cdot w \cdot \sigma = N \cdot p \cdot n_e \cdot a \quad (4)$$

where a is the recombination coefficient, σ is the recombination cross section, and p is the fraction of the length of the overlap region to the ring circumference (in the TSR, $p = 0.027$).

For electrons and ions having a relative velocity $\vec{w}$ with a normalized distribution function $f(\vec{w})$, where $\int w f(\vec{w}) d^3 w = 1$

$$a = \int w^2 \sigma(w) f(\vec{w}) d^3 w. \quad (5)$$

Here we may distinguish between the components of transverse and longitudinal velocity, $w_\perp$ and $w_\parallel$, respectively. The value of $w_\perp$ is, after cooling, approximately equal to $\Delta u_\perp$, whereas $w_\parallel$ is determined by the change of the space charge potential over the beam size. For $f(\vec{w})$, we assume a Maxwell distribution.

$$f(w) = 1/(\pi^{3/2} \Delta u_\perp^2 \Delta u_\parallel) \exp\{-(w_\perp^2/\Delta u_\perp^2) - (w_\parallel^2/\Delta u_\parallel^2)\} \quad (6)$$

or, for an isotropic distribution ($kT = (m_e/2)\Delta u_\parallel^2 = (m_e/2)\Delta u_\perp^2$) relation

$$a = (m_e/(2\pi kT))^{3/2} \int dw \sigma(w) w^2 \exp(-m_e w^2/2kT) \quad (7)$$

4. Radiative Recombination

During cooling, radiative recombination of very highly-charged stored ions with cooling electrons ($Aq^+ + e^- \rightarrow A(q-1)^+ + h\nu$) is one of the most important charge changing processes in the ring. The electrons can be captured into certain bound states of the ions (binding energy E_b) thereby emitting a photon of energy:

$$E_\gamma = E_b + (m_e/2)w^2. \quad (8)$$

As the relativistic correction for ions in the TSR is small ($\beta = 0.1-0.2$) we restrict ourselves to a nonrelativistic treatment given by Bethe and Salpeter [8] for the radiative-recombination cross section into quantum state n of a bare ion of charge Z .

$$\sigma_{rr}^n = 2.11 \cdot 10^{-22} \text{ Ry}^2 Z^4 / n(\text{Ry } Z^2 + n^2 E_r) [\text{cm}^2] \quad (9)$$

where Ry is 13.6 eV, the Rydberg energy, and $E_r = (m_e/2)w^2$. This formula shows important features of radiative recombination: (1) the cross section peaks at $w \rightarrow 0$ and (2) for recombination into quantum states n with $\text{Ry } Z^2/n^2 \gg E_r$, the partial cross section varies with $1/n$, which gives ~30% into $1s$, 13% into $n=2$, 8% into $n=3$, and 6% into $n=4$.

Using the relations (7) and (9) Bell and Bell [9] derived the following formula for the total radiative recombination coefficient adopted here for bare heavy ions.

$$a_{rr} = 1.92 \cdot 10^{-13} [\text{cm}^3/\text{sec}] Z^2/kT [\ln(5.66/\sqrt{kT}) + 0.196 (kT)^{1/3}], \quad (10)$$

where kT is in eV. With the number of sulfur ions of 10^{10} expected to be stored in the TSR, a flattened electron distribution with $kT = 0.2$ eV, and using relations (4) and (10), the total-radiative recombination rate would be in this case about $3 \times 10^7 \text{ sec}^{-1}$. This shows that the beam lifetime due to this effect should be long compared to the cooling time, but of the same order as for capture from the residual gas. Therefore, it seems can be necessary to detune the electron velocity after cooling in order to increase the storage time.

The process of radiative recombination of bare ions should be quite well understood. However, there are, e.g., the following points which increases the interest in this process.

- the cross sections for radiative recombination into low n states of few electron ions, where, due to electron correlations, the formula derived for bare ions cannot be expected to be valid, are interesting for high temperature fusion and astrophysical plasmas.
- the measurement of the recombination photons with high resolution X-ray spectroscopy is of interest for the diagnosis of the cooling process (It allows the determination of the distribution function $f(w)$, and for direct measurement of $1s, 2s, \dots$ binding energies for atomic spectroscopy, e.g., the determination of the Lamb shift.

Here we want to discuss further the second point of high resolution X-ray spectroscopy. From relation (7), and (8) one obtains by substituting for w , $x = (E_\gamma - E_b)/kT_e$:

$$a_{rr}^n = 4(kT/2\pi m_e c^2)^{1/2} \int dx \theta(x) \sigma_{rr}^n(x) \cdot x \cdot \exp(-x), \quad (11)$$

with $\theta(x) \approx 1$ for $x > 0$, $\theta(x) = 0$ for $x < 0$, and

$$\sigma_{rr}^n(x) = 2.11 \cdot 10^{-22} [\text{cm}^2] n(E_b/kT)^2 / x(x + E_b/kT). \quad (12)$$

Since $E_b/kT \gg x$ for all relevant cases, one has:

$$da_{rr}^n/dE_\gamma = 10^{-11} [\text{cm}^3/\text{sec}] (kT/m_e c^2)^{1/2} [nE_b/(kT)^2] \exp(-x). \quad (13)$$

As an example the result of this formula is shown in Fig. 3 for S^{16+} ions recombining with electrons of kT 0.1 eV and 0.2 eV. Measuring such a spectrum from a cooler with an X-ray spectrometer gives directly the velocity distribution function. If one could measure at different angles with respect to the beam direction, longitudinal and vertical velocity distributions could even be determined. By measuring the spectra also precisely on an absolute energy scale the binding energies of the states into which recombination occurs like 1s, or 2s can be directly determined. These values are interesting for testing Q.E.D. effects.

5. Dielectronic Recombination

Whereas in radiative recombination the third body sharing energy and momentum is a photon, in dielectronic recombination [10] it is an electron bound in the ion. This process can be viewed as the time reversed Auger process. An electron in the cooler can recombine with the ion if the negative binding energy of an excited state plus the kinetic energy equals the excitation energy of a bound electron. For recombination to occur, the doubly excited state so produced must stabilize by emitting photons:

A well defined kinetic energy is required so that one must detune the electron velocity after cooling in contrast to the case of radiative recombination. A characteristic feature of dielectronic recombination is

sharp resonances in the recombined ion rate as a function of the relative energy between electrons and ions.

The only experiments on dielectronic recombination with multiply charged ions have been performed by Dittner et al. [11]. They have observed this process with ions as heavy as Cl^{6+} merged with a compressed, space-charge-limited, electron beam of about 10^9 cm^{-3} density and 5 eV resolution. In these experiments, due to the resolution and single passage $\Delta n = 0$ transition cross sections were measured, where single resonances could, however, not be resolved.

For storage ring experiments, the expected low emittance of the ion beam after cooling and the low temperature of the electron beam promise a high resolution in such a device. Together with the large current of the circulating beam, this should allow the observation of separated $\Delta n > 0$ resonances in the dielectronic recombination cross section σ_{dr} (see fig. 3). There an example of the dependence of σ_{dr} on the electron-ion relative energy is shown. This example was obtained [15] from the approximation of separated Breit Wigner resonances:

$$\sigma_{dr} = \pi(r_0^2 \omega Ry/E_r) [\Gamma_a \Gamma / ((E_0 - E_r)^2 + \Gamma^2/4)]$$

r_0 is the Bohr radius, E_0 is the resonance energy, Γ_a is the autoionization width, Γ is the total width of the state E_0 , and ω is the fluorescence yield.

The multicharge state operation of the TSR is essential for these types of experiments. It not only allows the measurement of resonances by

determining the fraction of charge changed beam as function of the electron velocity, but one also can accumulate and store recombined beam for use in further experiments. This could open a new field of precision spectroscopy of few electron ions for studies of, e.g., atomic structure, Q.E.D. effects, and parity violation in atoms. One could think of, e.g., having a laser beam crossed with this recombined ion beam in a dispersive part of the ring. As the closed orbit trajectories lead to well defined times (phases) for the photon-interaction amplitudes with a repetition rate of 10^6 sec^{-1} , coherence for certain transitions could exist. This would lead to strong interference patterns in the respective transition probabilities, similar to but much stronger than those seen in the Ramsey effect.

6. Laser Induced Recombination

As we have discussed above, the partial recombination cross section varies like $1/n$ which means that a very small fraction recombines into high n -states. It has been proposed [13] to merge a laser beam simultaneously with electron and ion beams. A laser photon can stimulate radiative recombination into a state E_b if it fits within the level width to the energy described by relation (8). The enhancement factor for stimulated radiative recombination is:

$$G = g(\nu) (B_{if}/A_{if})(a_{rr}^n(\Gamma)/a_{rr}), \quad (13)$$

$$\text{where } a_{rr}^n(\Gamma) = \int_{\Delta\omega} d^3w f(w) w c_{rr}^n(w) \exp\{-w_{\perp}^2/\Delta u_{\perp}^2 + w_{\parallel}^2/\Delta u_{\parallel}^2\}$$

and $\Delta\omega = (\Gamma/mu)$, Γ is the combined spectral width of the light field and the

final bound state. The spectral energy density of the laser $g(\nu)$ can be written as:

$$g(\nu) = (P/c) A \Delta\nu,$$

and here P is the laser power, A the geometrical area, $\Delta\nu$ the laser bandwidth. Since $A_{if} = 8\pi h\nu^3/c^3 B_{if}$ by the Einstein relation, one gets for G from relation (11) a value of about 2 for $n=30$ of S^{15+} and a laser power of about 10 MW/cm^2 (pulsed). With a total pulse length per sec of presently available lasers, $\Delta t = 10^{-5} \text{ sec}$, one has from a total radiative recombination rate of $3 \times 10^7 \text{ sec}^{-1}$ an induced rate of 600 sec^{-1} . This rate is not very large, however, as the TSR has multicharge state operation one can store these lower-lying Rydberg ions. An estimation of the field ionization limits show that the depopulation due to this effect should be small. By a fine adjustment of the ion velocity the laser recombined beam could be synchronized with the laser pulses in the cooler. This would allow the build up of a pulsed beam of Rydberg ions, which would be separated from the primary beam in the dispersive sections of the ring.

7. Time Plan and Summary

At present the magnets are assembled and might be finished by the end of 1986; the first beam could be injected by end of 1987. 87. Electron cooling is in preparation with a test stand for optimizing the gun and collector, and it should be installed in 1988. For future atomic physics experiments which could be done with the TSR only a few selected topics concerning electron ion collisions were presented. Not only the whole field

of nuclear physics, but also atomic spectroscopy, ion-atom, and ion-ion collisions have not been considered. Most important are new areas in physics which are not yet known and might be stimulated by these new machines, e.g., the case of crystallization of extremely cold stored particles [14,15].

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Table 1

Beam Length	Energy Range	Current	Particles	Quality	Magnetic Field
Electron $\lambda = 1.5\text{m}$	2.5 - 65 keV	0.3 - 2.1A	10^8 cm^{-3}	0.2 eV, 50 mm ϕ	0.05 - 0.2 T
Ion C = 55m	5 - 30 Mev/nucleon	<1 A	10^{10}	< π mm mrad	<1.5 T

Figure Captions

- Fig. 1. A plan of the TSR ring with the main components [1]: Electron cooler, AMX deflection magnets, QDX and QFX quadrupole lenses, SFX and SDX sextupole lenses, HF1 stacking cavity, ES1 electrostatic septum, MS magnetic septum.
- Fig. 2. Simulation of the multicharge state operation of the TSR by closed orbits for iodine particles with momentum deviation $\Delta p/p = 0.02$ [1].
- Fig. 3. The spectral distribution of photons from radiative recombination of electrons with temperatures $kT = 0.1$ eV and 0.2 eV into the $1s$ state of S^{16+} ions.
- Fig. 4. Cross sections for dielectronic recombination of KLL - and KLM type with S^{15+} ions as function of relative energy between electrons and ions [12].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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