ATOMIC PHYSICS IN HEAVY-ION STORAGE RINGS

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Résumé - On donne une revue sur les principes des anneaux de stockage d'ions lourds. Les méthodes de refroidissement d'espace de phase sont brièvement discutées et les paramètres de faisceau d'anneau et d'accélérateur conventionnel sont comparés. Les expériences effectuées avec le faisceau d'antiprotons de l'anneau LEAR sont discutées comme exemple de l'une des premières expériences réalisées sur anneau en physique atomique. Les mesures de recombinaison dans les collisions ion-electron sont brièvement abordées, et les expériences probables de la première génération sont tabulées avec les références aux articles originaux. Afin de rendre cette revue plus claire et de mettre l'accent sur les aspects importants des faisceaux d'anneau, quelques unes des estimations sont plutôt grossières et le lecteur est invité à se référer aux publications citées pour un aperçu plus approfondi et plus précis.

Abstract - An overview is given of the principles of heavy-ion storage rings. Methods of phase-space cooling are briefly discussed, and ring-beam and conventional accelerator-beam parameters are compared. Experiments using the LEAR-ring antiproton beam are discussed as an example of one of the first ring experiments in atomic-collision physics. Measurements of recombination in ion-electron collisions are briefly touched upon, and likely first-generation experiments are listed with references to the original articles. In order to make this overview more clear and to stress the important aspects of ring beams, some of the estimates are rather crude, and the reader is referred to the cited articles for a deeper and more precise insight.

1 - INTRODUCTION

Storage rings were developed as a device for accumulating, cooling, and recycling expensive particles. The LEAR ring at CERN is a low-energy storage ring which has acted as an inspiration for several ring projects around the world. Of special interest to us are heavy-ion storage rings which are currently in operation, under construction, or in the form of more or less realistic projects.

A good description of the present situation concerning storage rings can be found in the proceedings from a Symposium on the Physics of Low-Energy Stored and Trapped Particles in Stockholm in 1987¹).

The present survey is to a great extent based on articles in Ref. 1. As examples of storage rings, I shall consider mainly what is called low-energy heavy-ion storage rings.

After a brief description of some technical aspects of storage rings, I shall mainly concentrate on the specific properties of stored ion beams and discuss in a broad sense some atomic-physics experiments which have been discussed amongst 'ring physicists'. Since I happen to have been involved in atomic-collisions experiments with antiprotons at the LEAR ring, this experiment will be touched upon as one example among others. Most of the ions created by atomic-collision physicists have lived only around 1 μ s. More than 90% have died after having led an empty life, and the remainder have normally experienced some excitement only once during their lifetime. It was therefore an obvious idea to store particularly expensive or rare particles. In order to realize this idea, some kind of phase-space cooling of the stored particles had to be performed²). Having come so far, it is obvious that also less expensive particles can with advantage be stored, cooled, and used in specially designed atomic-collision experiments. The key words describing beams in a storage ring are: relatively high beam intensity, high beam quality (low momentum spread), and long lifetimes of individual atoms.

2 - RING TECHNIQUE

In its simplest form, a storage ring consists of four 90° corner magnets (dipoles) and four straight sections (vacuum tubes) connecting the chambers in these magnets. On the next level, the ring has to be furnished also with flexible beam optics (quadrupoles, sextupoles) and equipment for phase-space cooling (stochastic, electron or laser cooling). To get ions in and to accelerate them after injection, the ring should also be equipped with a septum and kicker plus an rf cavity.

Most of the rings currently planned will be filled with ions from a conventional accelerator (typically a tandem accelerator), and the charge states and atomic species will be as delivered from the injector. The main differences between the injected and the stored beam is the long lifetime, the improved beam quality (low momentum spread), and the post-acceleration/deceleration or bunching (debunching) which can be done, if necessary.

To a first approximation, the low-energy heavy-ion storage rings are similar, and the building layout of ASTRID³) (the Aarhus Storage Ring Denmark) is shown in Fig. 1 as a representative example. Other similar ring projects are under way in Heidelberg⁴) (TSR), Stockholm⁵) (CRYRING) and Oak Ridge⁶) (HISTRAP). The ASTRID ring circumference is 40m, and the four straight sections will be used for (1) injection, (2) experimental setup, (3) injection kicker and rf cavity, and (4) electron cooling. The maximum bending power is 2 Tm, corresponding to a maximum momentum of ~600 MeV/c. The particle energies for some typical ions are listed in Table I.

TABLE I

H ⁺	50 keV - 175 MeV
Li ⁺	7 keV - 25 MeV
O ⁵⁺	80 keV - 270 MeV
Au ⁺	250 eV - 870 keV
Au ²⁰⁺	100 keV - 350 MeV

Fig.1. General building layout of the ASTRID facility.

Injection is done via an electrostatic septum and an electrostatic kicker placed opposite the septum. For ions from the low-energy injector (200-keV separator), single-turn injection will be used, whereas a combination of momentum stacking and multiturn injection is foreseen for beams injected from the tandem accelerator.

Two types of cooling methods are planned for ASTRID, namely laser and electron cooling. The laser, which will be used for the first experiments with laser cooling in the ring, is a cw-dye ring laser. In laser cooling, the photon recoil is used to change the velocities of the ring ions in a configuration where the ion and laser beams overlap. For special ions with a transition which matches the photon energy, the Doppler effect allows the selection of particles according to their velocities. Cooling is then achieved by frequency chirping the laser such that slow particles are accelerated, causing a reduction in the momentum spread of the ion beam. The electron cooler consists of an electron gun of the classical Pierce design and a 1m long solenoid for magnetic transport of the electrons. The electron energy is 100 eV - 2.5 keV, and the current goes from 1 to 55 mA (space-charge-limited current). The corresponding solenoid field is from 55 to 270 Gauss. Figure 2 shows a schematic draw-

Fig.2. Schematic drawing of the electron-cooling setup and of the electron motion in the magnetic guiding field. [Figure and caption adapted from Fig. 1 of A. Wolf, p. 55 in Ref. 1.].

ing of the electron-cooling setup and the electron motion in the guiding field. In electron cooling, energy is exchanged between the ions and the cold electrons via Coulomb interaction. The final momentum spread of the stored ions is determined by the cathode temperature of the electron gun and of the beam-heating mechanisms.

3 - RING BEAMS

If some sort of beam cooling is applied, the maximum intensity of a stored beam is normally determined by what is called space-charge effects. The space-charge limit to the number of ions stored in a ring is determined by the upper limit for the incoherent shift of betatron tunes caused by the space-charge forces. For ASTRID, a simple estimate of the maximum number of stored ions reads as

$$N = \frac{3 \times 10^5 E \text{ (keV)}}{q^2},$$

where E is the particle kinetic energy and q is the charge state. (For a more detailed discussion, the reader is referred to Ref. 7.)

In Table II, some examples of beam intensities based on the above equa-

TABLE II

E (MeV)	A	q	N	I	τ_c (sec)	τ_{cc} (sec)
0.1	7	1	3×10^7	0.2 μ A	200	500
230	16	5	3×10^9	2.6 mA	1.5	10^7
40	35	5	3×10^8	150 μ A	0.5	2×10^4
0.001	179	1	3×10^5	40 pA	10^7	10^4
20	179	20	1.5×10^7	5 μ A	2	8

tion are listed. It should be noted that the intensity gain over normal beams is noticeable only for the highest energies. Very little experimental work has been reported on heavy-ion cooling, but it is estimated that a relative momentum spread of around $\Delta p/p \approx 10^{-4} - 10^{-5}$ (which should be compared with $\Delta p/p = 10^{-4}$ for typical separator or tandem beams) can be obtained within a reasonable time with electron cooling, while laser cooling in the special cases where it can be applied is fast and can cool even further. The electron-cooling time scales as $A^2/(q^2 E)$, where A is the ion-mass number. Typical cooling times (τ_c) are shown in Table II.

Another interesting parameter is the time it takes to change the beam quality because of heating. The dominant mechanism is normally intrabeam scattering. If this time is longer than the cooling time, then beam heating can be compensated for by cooling, and the final ion temperature is determined from the balance between these two processes. Except for extremely low energies, a reasonable balance between the cooling time and the heating time can be obtained. A much more serious process is loss of the beam because of charge exchange in the rest gas ($\sim 10^{-12}$ torr). This process cannot be compensated for, and for multiply charged ions, capture is the process that determines the storage time. Examples of charge-changing times (τ_{cc}) are listed in Table II.

4 - PHYSICS IN STORAGE RINGS

4.1. Extracted Ion Beams

In the preceding paragraph, we listed the special characteristics of stored ion beams. It is natural to look at these when first-generation ring experiments are planned. The most striking property of a storage ring is the capability to accumulate rare particles. An example is the low-energy (down to 5 MeV) antiproton beam at the LEAR complex at CERN. In 1986, the first experiments on atomic single collisions between antiprotons, $\bar{p}$, and atoms were performed at the LEAR ring at CERN. These measurements showed that the cross sections for double ionization of He, Ne, and Ar in collisions with $\bar{p}$ are much larger than for equivelocity protons in the energy range 1-4 MeV. This experiment has stimulated a number of groups to discuss what can be learned from $p, \bar{p}$ and also e^+, e^- comparisons in atomic-collision physics.

In Fig. 3 are shown the results which started these attempts, together with our recent results on double ionization by positrons⁹). We have explained the $p/\bar{p}$ difference in terms of interference between the second-order double-ionization mechanisms, whereas McGuire¹⁰) suggests that

Fig.3. The ratio between double- and single-ionization cross sections for p^+ , p^- , e^+ , and e^- colliding with He.

interference between the shake-off and one of the second-order mechanisms would explain the data. Other models include the correlated motion of the two electrons. Numerical calculations, using the Forced-Impulse Method (Reading and Ford¹¹) or the Classical-Trajectory Monte-Carlo Method (Olson¹²), are in fair agreement with experimental results. Recently, a number of articles has discussed $p, \bar{p}$ differences in single ionization¹³⁻¹⁵). Olson and Gay¹⁵) pointed out that while differences in the single-ionization cross sections are small, large effects appear at 0.1-1 MeV energy when double- or even single-differential cross sections are measured. Figure 4 shows an example of such a difference at 200-keV projectile energy for He ionization, singly differential in ejection angle. Measurements of this type will be possible when monoenergetic $\bar{p}$ beams below 1 MeV will be available within a few years at the LEAR ring.

4.2. Electron-Ion Collisions

A large group of proposed experiments at the future ion storage rings

Fig.4. He single-ionization cross section singly differential in electron-ejection angle. Solid lines: CTMC calculations. [Figure and caption adapted from Fig. 2 of Ref. 15.]

are concerned with electron-ion interaction in either the electron cooler or in a similar device where the electron energy can be freely chosen. The most important processes in this connection are the so-called recombination processes. In their most general form, these processes can be written

↓

The cross section for radiative recombination (RR) into a given n state of a bare ion is given approximately by the expression¹⁶⁾

$$\sigma_n = 2.1 \times 10^{-21} [\text{cm}^2] \frac{E_{1s}^2}{n[E_{1s} + n^2 E] E},$$

where E_{1s} is the ground-state binding energy and E is the electron energy. Note that for $E_{1s} \gg n^2 E$, the cross section is proportional to q^2/nE , where q is the projectile charge state.

This capture process can be enhanced if continuum bound-state transitions are induced by applying a radiation field to the collision zone. The ratio $g(n)$ between the rate for spontaneous recombination to induced recombination is given by $g(n) = u(\nu)(B/A)$, where $u(\nu)$ is the spectral-energy density and A and B are the Einstein coefficients for spontaneous and induced recombination, respectively. With available laser-power values, $g \approx 500$ has been reported for realistic cases¹⁷).

For dielectronic recombination (DR), the cross section for recombination via a specified intermediate n, l state is¹⁸)

$$\sigma_{nl} = \frac{\pi(2l+1)a_0^2}{2E} \frac{\Gamma_r \Gamma_a}{[E - E_{nl}]^2 + \frac{1}{4}[\Gamma_r + \Gamma_a]^2},$$

where Γ_r and Γ_a are the radiation and autoionization decay rates, respectively. Recombination via such a state could be enhanced by induced transitions to some other state $n'l'$ with a smaller autoionization rate¹⁹). Even relatively weak lasers could have a noticeable effect in such cases, and calculations¹⁹) have shown that the cross section can be enhanced by a factor of ~ 3 for C^{5+} by applying a laser with a light intensity $\sim 10 \text{ MW/cm}^2$.

In ternary recombination, transfer of energy from one electron to another occurs, and therefore the rate scales as the electron density squared. It is also interesting to note that the rate for this process scales as $T^{-9/2}$ (T is the ion center-of-mass temperature of the electron beam), implying that TR becomes the dominating recombination mechanism at very low energies.

The various recombination processes and their laser-induced variants are explained graphically in Fig. 5.

An electron cooler is an ideal target for measurements of RR, DR, and TR. The experimental situation is the so-called merged-beam configuration, where a space-charge-limited electron beam is merged with the 'cold'-stored ion beam, permitting the study of low-energy electron-ion collisions at high laboratory energies. It will further be possible to let this interaction take place in a laser field and thus study laser-stimulated processes.

The high laboratory energy in these low-relative-energy experiments has many positive implications. The high-energy product ions are relatively easy to detect, the signal rate is proportional to the energy squared, and the energy resolution is inversely proportional to the square root of the energy. Further, since the outcome of the processes mentioned above is an ion with a lower charge state, the background in these experiments come from capture from the residual gas, and hence a high laboratory energy is a great advantage.

DR experiments with multiply charged ions were started at Oak Ridge some years ago²⁰). The energy resolution in these experiments ($\sim 5 \text{ eV}$) was insufficient to resolve individual DR resonances. At present, we have started DR experiments at Aarhus²¹), using the electron cooler for the

Fig.5. Diagram showing the principles in radiative recombination, dielectronic recombination, ternary recombination and their laser-stimulated variants.

storage ring at a beam line at our EN tandem accelerator. In these experiments, a relative energy resolution of less than 0.2 eV is obtained, and both individual DR resonances and radiative recombination are clearly separable.

In Fig. 6 is shown a model spectrum, visualizing the various processes mentioned in the present section.

With the development of cooled ion beams and extremely cold electron beams, which can be obtained from cold cathodes by photoionization²²), we can foresee high-resolution spectroscopy and extremely low-relative-energy experiments to be performed in storage rings in the near future.

4.3. Ion-Ion Collisions

Another type of ring experiments that have been suggested are ion-ion collisions. A survey of this field was given by Mowat at the Stockholm meeting²³). The most likely first-generation experiment is one suggested at the planned HISTRAP ring at Oak Ridge²⁴). The availability of two separate injection systems makes it possible to inject an ion beam with a given M/q , where M is the mass of the ion beam with charge q , then accelerate it to an energy E , and subsequently inject another beam with the same value of $\sqrt{EM/q}$. As an example, it will in this case be possible to

Fig.6. Model spectrum showing the expected recombination cross-section energy dependence. The various processes are shown in Fig. 5.

study collisions between Cl^{14+} and Cl^{13+} at relative energies ranging from 20 keV to 1 MeV. Both charge-transfer ionization and excitation can be studied in such collisions. Since the collision partners have high energies in the laboratory frame, one obtains the same advantages as mentioned previously when discussing electron experiments, such as more favourable detection conditions and less problems with charge-exchange on residual gas.

Several more special applications of storage rings have been suggested in the literature. Estimates by the Frankfurt group²⁵⁾ indicate that intensities of 10^9 bare recoil Ar ions per second would be produced from a 10^{11} atom/cm² target by 10^{10} iodine ions circulating at 8 MeV/amu. The Ar^{18+} ions could now be captured in an ion trap and act as a 'target' for an external accelerator. Or it could be used directly in collisions with another beam or an external target.

4.4. Laser-Ion Interactions

One of the more fundamental properties of the storage ring is the long lifetime of the ions. This implies that high-precision spectroscopy can

be performed. The nondestructive interaction of lasers with stored ions points directly towards experiments with long interaction times with cooled ions, resulting in narrow line widths.

One of the more spectacular possibilities with storage rings is crystallization of the ion beam. The coupling parameter Γ , which indicates the degree of coupling in the plasma, is given by the ratio between the potential and the thermal energy of the particles as measured in a moving frame. A high value of Γ corresponds to a strong coupling (solid state), whereas a low value corresponds to a weak coupling or gas phase. A phase transition around $\Gamma \approx 5$ is believed to be observed in the NAP-M proton ring in Novosibirsk²⁶, using electron cooling. A high Γ can be obtained by increasing the nuclear charge or by cooling the ions eventually by laser cooling. Several theoretical calculations on beam crystallization exist, and comprehensive reviews are given by, e.g., Rahman and Schiffer²⁷, and Poulsen²⁸). These crystals represent a new diluted form of matter, and the characterization of this form will most likely lead to a new understanding of basic properties such as plasma frequencies and phonon spectra in 'solids'.

5 - FINAL REMARKS

Storage rings add new dimensions to the Zoo of ion accelerators already in operation. The most important experiments which will be made with these machines are probably those which we cannot foresee with our traditional background. What I have tried here is to give nonspecialists a feeling for some of the more likely first-generation experiments with heavy-ion storage rings and for the exciting new fields in atomic physics that these devices have opened for us.

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