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EXPERIMENTAL ATOMIC PHYSICS IN HEAVY-ION STORAGE RINGS

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Abstract

This paper outlines the discussion which took place at the "round table" on experimental atomic physics in heavy-ion storage rings.

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1. Introduction

Although the concept of storage rings with cooling capability has been with us for some time, their application to atomic physics is a relatively new development. There are many advantages that these devices have over the conventional accelerator beam — stationary target arrangement. By circulating the beam in the ring, one is able to purify the beam of metastable states by allowing time for decay; to obtain an effectively high current; to obtain better emittance by phase space manipulation ("cooling"); and to utilize the same (and possibly expensive) particles passing through a thin target many times. Sometimes the thin target is unavoidable, as in the case of a free electron target of limited density, and sometimes the thin target is necessary for the experiment, as when one is searching for a small cross section event in the presence of large cross section events. An example would be the investigation of nuclear collisions which require very high energy resolution. Here, one cannot use a thick target in which the particle energy is degraded and straggled. Another example is the interference of sequential large cross section single-electron transfer events where one is searching for small cross section multiple-electron transfer events in a single collision.

Several complete workshops and a number of papers have centered on the use of cooled heavy-ion storage rings [1-6] in physical research, but since no such facility is yet in operation, we are restricted to the discussion of planned experiments. It is, however, noteworthy that the number of ideas being generated for the use of these facilities is constantly increasing. The most recent and, in a sense, most concrete of these meetings was held in

March 1987 in connection with the GSI project. Towards the end of 1986, GSI sent a call for proposals and letters of intent for experiments at SIS/ESR (Schwer-Ionen-Synchrotron/Experimentier-Speicher-Ring) to researchers and research institutes worldwide. The response was unexpectedly high: About 100 proposals and letters of intent demonstrated the great interest in the new facility. This facility consists of a heavy ion synchrotron SIS for acceleration of even the heaviest nuclei to at least 1 GeV/nucleon and of an experimental storage ring ESR. The storage ring will enable experiments with highly stripped and cooled heavy-ion beams. Electron and stochastic cooling, and under certain circumstances a combination of both cooling methods will be applied [4].

Several nuclear experiments proposed for the ESR are concerned with the investigation of exotic nuclei which will be produced by fragmentation or electromagnetic dissociation in a special fragment separator [7]. Of special interest are precise mass measurements using the ESR as mass separator and data on the nuclear structure of nuclei far from stability.

As in previous workshops, many of the atomic physics proposals are concerned with studies of the electron-ion interactions in the cooler section. Experimental data on radiative and dielectronic recombination, for example, are important under two aspects: spectroscopy of atomic states and diagnosis of the beams. The topic of several proposals is the precise measurements of binding energies in few-electron high Z ions using a fixed internal target. A systematic study over a large range of nuclear charges will provide insight in QED effects and electron-electron interactions in H^- , He^- , and Li^- like ions.

Last, but not least, were the proposals on the possibility of forming crystalline beams by extreme cooling of the ion beam. Such crystalline beams are predicted to have special properties because the lattice constants are orders-of-magnitudes larger than those of ordinary crystals.

During a one-hour discussion, it is clear that not all points can be covered. This panel discussion will include some notions on electron-ion and ion-ion interactions, several comments on precision spectroscopy, and some new notions on experiments at the interface between atomic and nuclear physics.

2. Electron-Ion Interactions

Much of the interest in electron-ion and ion-ion collisions comes from the area of high temperature plasmas such as exist in Stellar coronae, and magnetic and inertial fusion plasmas. The dynamics of such a plasma consists of interactions of ions A of charge $q+$ in state α with electrons and with other ions $B^{q'+}$: viz. for electron ion interactions

All the processes which release a photon result in a loss of stored energy from the plasma. Very little information has been available on these processes, especially recombination, because of the limited density of electron targets.

The electron beam "cooling section" of the storage ring offers an almost ideal system for the study of these processes. In this region a space-charge-limited electron beam will be merged with the stored ion beam, permitting the study of low relative energy electron-ion collisions at high laboratory energies. The advantages of working with high laboratory velocities and a ring configuration can be seen from the following considerations.

To achieve the desired v_r , a high v_i requires a high electron velocity, v_e , and for space-charge-limited beams $\rho(e) \propto v^{3/2}/v_e \propto v_e^2$. The rate R at which a process with cross section σ occurs in the merged beam is $R = \sigma (v_r/v_i) \rho(e) l \phi_i$, where v_r is the relative velocity, v_i is the ion velocity, $\rho(e)$ is the electron density, ϕ_i is the ion current, and l is the length of the overlapping beam region. For a given $\Delta p/p$ value, the ion current in the circulating beam at the Keil-Schnell stability limit $\phi_i \propto v_i^3/L$, where L is the ring's circumference. Since in most experiments $v_e \approx v_i$, we have

$$R \propto v_i^4 (l/L) .$$

The electron cooler for the Aarhus storage ring ASTRID is being built and tested at a beam line at the Aarhus EN tandem accelerator. Here, several merged beam single pass experiments with free electrons and ions are planned before the insertion of the "cooler" into ASTRID. Since the experimental setup is made in such a way that the electrons and the ions travel with

essential identical velocity, the experimental program focusses on low energy electron-ion collisions and, in particular, recombination processes. In order for an electron to recombine with an ion, a certain amount of excess energy must be taken away. In radiative recombination, the excess energy is carried away by a photon. In the process of collisional recombination, the energy is transferred to another free electron, and in dielectronic recombination, energy is taken up by bound electron of the ion. In the present experimental program, the Aarhus group plans to concentrate on radiative recombination and dielectronic recombination.

The theory of radiative recombination for bare ions was worked out a long time ago [9]. The cross section for radiative recombination is proportional to $1/E$ at low kinetic energy E of the electron. Thus, the rate of recombination is sensitive to the energy spread in the electron beam and, in fact, this dependence, which is known in the case of a fully stripped ion, will be utilized to determine the energy spread or temperature of the electron beam. Then cross section measurements can later be performed with non-fully stripped ions.

Another direct measure of the temperature of the electron beam can be obtained through observation of dielectronic recombination. This process is a resonant one and, thus, the width of the resonance can be related to the energy definition of the electron beam. The process of dielectronic recombination has been measured for a large number of ions, in particular, by the Oak Ridge group [10]. The energy resolution in these experiments has typically been around 3-5 eV. The Aarhus experiment aims at a resolution which is an order-of-magnitude better.

Finally, a study of laser stimulated radiative recombination is planned. The gain which one can achieve by the laser depends crucially on the state n to which the electron recombines. This gain is proportional to n^6 [11]. One possible reaction to study would be laser stimulated recombination to $H(n=11)$ in $H^+ + e^- + h\nu$ collisions. To this purpose, a CW CO_2 laser with $h\nu = 0.1$ eV will be used. The gain G is defined as the rate of stimulated recombination to state $n=11$ divided by the total rate of spontaneous recombinations to all n . We expect a gain $G=10$ with a laser power of 100 Watt.

At present, the electron gun, together with the magnetic coils (which provide the magnetic field that guides the electrons through the 1 m interaction region), is being assembled. The beam line is essentially ready for the measurements, and a pressure in the 10^{-12} Torr region has been obtained throughout the interaction region. The experimental program will start in the fall of 1987.

3. Ion-Ion Collisions

Another area relevant to plasmas which is in strong need of investigation is that of ion-ion collisions with multiply charged ions

and, in addition, since charge transfer can take place to excited states, radiative losses can occur. Two approaches utilizing rings have been suggested. At the electron storage ring (ESR) at GSI, two beams of slightly different (1%) p/q (e.g., U^{91+} and U^{92+}) can be made to cross at an angle

$\alpha \sim 0.1$ rad. the center-of-mass (CM) energy with this case is

$$E_{CM} = m_0 c^2 \beta^2 \gamma^2 (1/2 (1 - \cos \alpha) + (\Delta p/p \ 2\gamma)^2).$$

For beams at 500 MeV/nucleon, the collision energy can be varied between zero and 3.5 MeV/nucleon [12]. At HISTRAP at ORNL, the availability of two separate injection systems makes possible another interesting opportunity for the study of ion-ion collisions [5]. Here, one would inject an ion beam with a given M/q , where M is the mass of the ion having charge q , from the ECR-RFQ injector, accelerate it to a kinetic energy E , and then inject another ion species from the Holifield tandem. The condition for the simultaneous storage of two ion beams is (nonrelativistically)

$$(E_1/E_2) = (M_2/M_1)(q_1/q_2)^2.$$

Within the merged beams, collisions would take place with relative energy

$$E_{rel} = k\mu (B\rho)^2 [(q_1/m_1) - (q_2/m_2)]^2,$$

where μ is the reduced mass and $B\rho$ the magnetic rigidity of the system. A continuous range of E_r is obtained by varying E_1 and suitably adjusting E_2 and B . For experiments of this type, such as those involving colliding beams, good emittance is necessary. Although the two beams are at different velocities, cooling can be achieved by changing the electron beam velocity to accommodate each beam separately. An example here is the injection of C^{13+} at 10.5 MeV (300 keV/nucleon) from the ECR-RFQ followed by acceleration up to 50 MeV; then a beam of C^{14+} at 58 MeV would be injected from the Holifield tandem. Here, the relative energy would be 24 keV. Injection

and acceleration of the Cl^{13+} to 297 MeV with the matched injection of Cl^{14+} at 345 MeV from the Holifield would lead to an E_{rel} of 930 keV.

4. Precision Spectroscopy of Highly Charged Ions

This is an area of great interest. With high Z hydrogen-like ions, one can probe ultra relativistic effects or extreme QED effects, or with ionic Rydberg states, one can probe at retardation forces. With helium-like (or Li-like) ions, investigations of the three-body problem in relativistic QED can be carried out.

The precision required to make meaningful new contributions in these areas is quite high and a list is given in Table 1.

Table 1

Area of Investigation	Required Precision in ppm
QED Second Order Terms (one body, two body)	1
Relativistic Effects	0.1 + 1
a. magnetic correlation	
b. relativistic correction to electron correlation	
c. retardation (+ correlation)	
Three-body Relativistic Effects	0.1 + 1
Parity Violation	$< 10^{-3}$
Multiple Rydberg States	100
Retardation Effects on Rydberg States (note here one needs much intensity)	10

Moreover, it should be pointed out that, although spectral standards in the visible and UV regions allow such precision, for multicharged ions where many of these transitions lie in the X-ray region, the presently available precision of standards is only ~ 1 ppm.

What is the present status of our knowledge? Although fully stripped ions up to uranium are now available, most work has been confined to low atomic numbers up to $Z \sim 18$ (e.g., S, Cl, Ar, Ti, ...). These ions are now available at almost any velocity in ion sources, as recoil ions, in Tokomaks, in the sun and from accelerators (beam foil). The present precision is a few ppm for $n = 2 \rightarrow n = 1$ or $\Delta n = 0$ ($n = 2$) transitions.

For heavier elements, there are very few experiments. At the "GANIL" facility in France, measurements have been made on Kr($Z = 36$) with a precision of ~ 10 ppm and Xe($Z = 54$) with a precision of ~ 100 ppm. At the Bevelac facility in California, 1 GeV/nucleon ($\beta = 0.8$) beams up to U^{92+} have been obtained. There have been some lifetime measurements but precision measurements have been obviated by large Doppler aberrations, large uncertainties in velocity and direction of the ions (poor emittance), and the combination of low intensity with small excitation cross sections.

In the future, more highly stripped high- Z ions will likely be produced at low energies in confined ion sources such as the electron cyclotron resonance sources (ECR) being developed at Grenoble, where Ar^{18+} has already been produced and in electron beam ion sources (EBIS) and electron beam ion traps (EBIT) where even higher- Z ions (e.g., totally stripped xenon have been reported).

Thus far, using high energy beams which have been decelerated has given the most precise results. But even here the potentialities are

limited by Liouville's theorem since the deceleration leads to an increased angular width which mitigates the Doppler width gain from deceleration. The angular width can be compensated by a high degree of mechanical collimation, but the attendant loss of intensity is very severe. Cooled stored beams offer great advantages here. The precise energies of the beam are known, and the emittance can be very highly refined at high energies by electron beam cooling before deceleration.

To perform such experiments, a beam of bare nuclei is formed, for example. The nuclei are allowed to capture an electron into an excited state from some target. The precision spectroscopy is then done on the radiative decay photons. For the highly charged ions in question, these photons are in the X-ray region.

A ring experiment could be carried out either with a decelerated cooled extracted beam passing through a thin gas target or with the stored beam at higher velocities. It is estimated that a precision in Lamb shift measurements of 10^{-4} may be possible using stored cooled beams [13].

5. Atomic Physics and Related Nuclear Physics

Some examples in this interdisciplinary area were proposed at the recent GSI workshop. Two are listed here.

5.1 Beta decay into bound final states

There is a still undiscovered mode of β^- -decay which must have played an important role during nuclear synthesis: The β^- -decay to bound final states of the electron [14]. Such a process is the conversion of a neutron to a proton, where the decay electron does not end up in a continuum state

but in an empty, strongly bound state of a highly ionized atom. Since in neutral atoms only weakly bound states with small probability densities at the nucleus are available, this process normally plays no role. However, it becomes important for atoms with small Q-values. If they become ionized, the β^- -decay probability drastically increases because of the enlarged Q-value by a transition of the decay electron to a strongly bound state. Thus, "normally" stable nuclei can become radioactive if their electrons are removed.

Three possible candidates have been considered for experiments [15]:

1. The β^- -decay of $^{163}\text{Dy}^{66+}$ to $^{163}\text{Ho}^{66+}$. With the decay electron bound into the K-shell, the decay constant is expected to be about $3 \times 10^{-7} \text{ sec}^{-1}$ [14].
2. The decay of $^{187}\text{Re}^{75}$ to the 10 keV excited $3/2^-$ -state of $^{187}\text{Os}^{75}$ by a first forbidden β^- -decay with a half life of 10 y [14]. Neutral ^{187}Re decays to the ground state of ^{187}Os by a second forbidden β^- decay with a half-life of 4×10^9 y, so that the decay constant will change by nine orders-of-magnitude just by stripping of all the electrons of the ^{187}Re nucleus.
3. The decay of $^{205}\text{Tl}^{81+}$ to the 2.3 keV excited state of $^{205}\text{Pb}^{81+}$ with a predicted half life of ~ 19 y [15].

It should be noted that the $^{187}\text{Re}^{75+}$ decay is of astrophysical interest and that the $^{205}\text{Tl}^{81+}$ decay can give data on neutrino-capture cross sections [15]. As a pilot experiment, it is planned to study the decay of $^{163}\text{Dy}^{66+}$, because ^{163}Dy is a stable isotope easily available as

source material and the calculated decay rate is rather high. The experiment is, in principle, rather simple: One stores fully-stripped ^{163}Dy ions for variable times in the ESR and measures for different storage times the ratio of $^{163}\text{Ho}^{66+}$ daughter nuclei to the number of stored $^{163}\text{Dy}^{66+}$ ions. From this storage-time dependent ratio, the decay constant can be extracted.

The investigation of the β -decay into bound states is a typical experiment for a storage ring like the ESR, because one needs highly-stripped heavy ions, rather long storage times, and a rather sophisticated method to separate the daughter nuclei from their mother nuclei [15]. This remark also holds true in some sense for the next experiment to be discussed.

5.2. Atomic binding energies from spectroscopy of conversion electrons

The idea to determine binding energies of inner-shell electrons from a spectroscopy of conversion electrons is as brilliant as it is simple [16]: If the excitation energy E_n of a nucleus is precisely known and if E_n is slightly larger than the binding energy E_a of the K-shell electron (for example in a H-like ion), then the energy of the conversion energy is very small compared to E_n . From the measurement of the kinetic energy E_c of the conversion electron, the 1s binding energy can be extracted with a rather large precision.

Such a situation is, for example, realized for $^{155}_{64}\text{Gd}$, where $E_n = (60010 \pm 1) \text{ eV}$ and $E_a(1s) = 59153 \text{ eV}$, thus $E_c = 857 \text{ eV}$ [17]. If E_c is measured with an accuracy $<10^{-3}$ (the Doppler-shift of the conversion electrons due to the high velocity of $^{155}\text{Gd}^{63+}$ stored in the ESR will favour the measurements), then the absolute uncertainty of $E_a(1s)$ will amount to

about $2 \times 10^{-5} E_a(1s)$. Such a precision should permit a test of QED corrections (the Lamb-shift of the $2s$ state is calculated to 86.9 eV [18]) to within $\sim 1.3\%$ accuracy.

A test experiment has been performed at the UNILAC 1983 [16] with 18 MeV/nucleon projectile energy. This attempt, however, suffered from a strong background of electrons which were produced during the penetration of the Gd projectiles through a $100 \mu\text{g}/\text{cm}^2$ Au foil which was used to excite the Gd nuclei. An improved version has been proposed for the ESR [17] in which H-like Gd ions and low Z target atoms for excitation should keep the background of electrons much smaller.

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