ENHANCEMENT EFFECTS ON ELECTRON-ION RECOMBINATION RATES

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Recombination of highly charged ions with electrons is studied by accelerator based merged-beams experiments. In most measurements excessively high recombination rates are observed at low relative energies which cannot be explained by ordinary radiative recombination. The enhanced rates lead to serious losses of ions during the electron cooling process in ion storage rings. Another type of rate enhancement, known from previous experiments on dielectronic recombination, is related to external fields in the electron-ion collision region. By introducing controlled electric fields in the cooler of a storage ring it has been possible for the first time to obtain quantitative results for effects of electric fields on dielectronic recombination of highly charged ions.

I. INTRODUCTION

When the first direct measurements of electron-ion recombination cross sections in colliding beams experiments became available, it was immediately noticed, that the experimental data exceeded the theoretical expectations for dielectronic recombination (DR) by large factors [1] . Theory soon provided an interpretation of the observations on the basis of Stark mixing of states in external electric fields [2]. The influence of well controlled fields on DR in a wide range of specified Rydberg states was experimentally studied for singly charged Mg^{+} ions [1]. However, prior to the present work no quantitative measurements with controlled external electric fields were reported for highly charged ions.

Few years after the first direct observation of DR, again an apparent deviation of measurements from theoretical expectations was reported [3]. In merged-beams experiments at very low electron-ion center-of-mass energies, the measured recombination rates were sometimes even more than a hundred times bigger than those calculated for radiative recombination (RR). This enhancement effect grossly increases with the ion charge state. It is observed in almost all experiments, but has not yet been quantitatively explained [4]. The present short contribution presents evidence for the role of DR on recombination rate enhancement effects.

II. FIELD EFFECTS

Study of DR is now committed almost entirely to ion storage rings. The quality of the data obtained using rings is emphatically higher than with any other technique [5]. An important issue in DR, however, remains to be clarified. The early measurements on Mg^{+} [6] demonstrated a clear dependence of DR cross sections for experimentally specified principle quantum numbers on known ambient electric fields in the collision region. The previous disagreement by factors 2-10 between theory and experiment [1] was resolved satisfactorily [7,8]. Nevertheless, there still remained some, possibly serious, discrepancies. Also, anomalous results in a first generation of merged beams experiments at ORNL [9] could be interpreted in terms of similar electric field mixing; though the fields in the collision region could only be estimated. Inclined beams experiments at Harvard [10] have attempted to resolve inconsistencies in the interpretation of results for Li-like ions obtained at ORNL, but the precision and scope of these experiments have left ambiguity. Effects of external electric fields on dielectronic recombination were also invoked in the interpretation of results obtained in a second generation of merged beams experiments. Examples are the studies on C^{3+} and O^{5+} [11], on N^{4+}, F^{6+} and S^{11+} [12], and on Ar^{15+} [13]. As in all other merged-beams measurements of cross sec-

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tions and rates for DR of ions carried out so far, however, the external electric fields were not experimentally controlled, leaving a free parameter for theory to adjust the calculated data to the experiments.

In general, the experimental basis for a detailed understanding of field effects on DR rests almost solely on one experiment on Mg^{+}. In particular, field effects on the recombination of highly charged ions have not been studied in detail so far and deserve special attention.

Quantitative investigations of field effects on DR require controlled fields in the electron-ion collision region. Since an electrostatic external electric field would corrupt the energy definition of the electrons, $\vec{E_c} = \vec{v} \times \vec{B}$ motional electric fields are the best choice for those studies ($\vec{v}$ is the ion velocity and $\vec{B}$ the flux density of the magnetic field). External motional electric fields can be introduced in the cooler of a storage ring by tilting the axis of the longitudinal magnetic field that guides the electron beam. An accurately known angle between the ion beam and the magnetic field lines facilitates the precise knowledge of the size of the external electric field experienced by the ions in the collision region.

Defined transverse magnetic field components $B_\perp$ were applied to the electron-ion merging path in the cooler of the ion storage ring CRYRING in Stockholm by using the correction coils which normally serve for optimum adjustment of the electron and ion beam axes. Absolute rates for $\Delta n = 0$ DR of 10 MeV/u lithium-like Si^{11+} were measured for 9 different transverse magnetic fields $B_\perp$ between 0 and $4.2 \cdot 10^{-4}$ T corresponding to motional electric fields $E_c = vB_\perp$ between 0 and 183.1 V/cm [14]. Figure 1 shows one set of measured DR spectra taken in a single run with 5 different transverse magnetic fields. The data were taken in cycles covering one complete measurement of all these spectra at different values of $B_\perp$ using only one filling of the storage ring. Each cycle started with the injection of Si^{11+} ions into the ring from a 300 keV/u RFQ accelerator fed by the Stockholm cryogenic electron beam ion source CRYSIS. The ions were subsequently accelerated to 10 MeV/u by running the ring in synchrotron mode. After a cooling period the measurements were started, i.e. the rate of recombined ions detected with a solid state detector behind the first bending magnet downbeam from the cooler was recorded as a function of time. Shortly after the start, the cathode voltage of the cooler was switched away from cooling potential at 5.7 kV to about 6.5 kV and then slowly ramped down to 5.9 kV (in about 4 s). No additional magnetic field was applied to the cooler in this phase, so that a field-free DR spectrum (apart from the residual space-charge fields and small $\vec{v} \times \vec{B}$ fields due to the small angular spread of the ion beam) was measured in the range of the $\Delta n = 0$ resonances characterized by $e + (1s^2\,2s) \to (1s^2\,2pn\ell)$ with $n = 9, 10, \ldots$. After such a scan, covering about 25 eV in the electron-ion center-of-mass frame, the ion beam was cooled again for several seconds, the correction coils were set to produce a field $B_\perp = 1 \cdot 10^{-4}$ T and then a new scan was started. These scans were repeated with $B_\perp = 2, 3,$ and $4 \cdot 10^{-4}$ T so that 5 different spectra were measured during one filling of the ring. The remaining stored ions were then dumped and the whole cycle started over and was repeated for typically 1500 times in order to obtain the level of statistics shown in Fig.1.

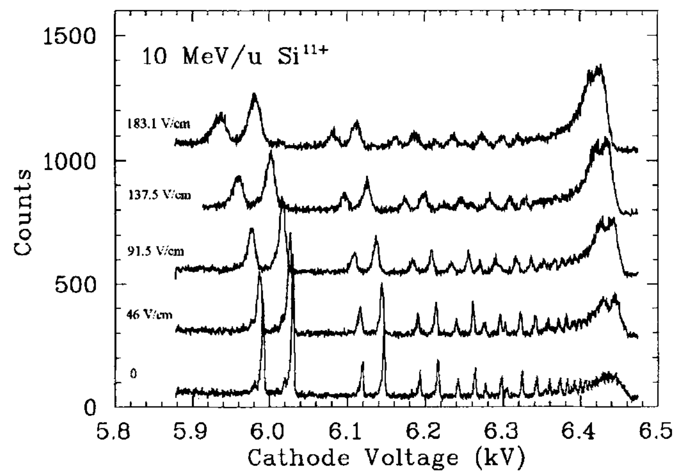

Figure 1. Measured relative rates for $\Delta n = 0$ dielectronic recombination of lithium-like Si^{11+} ions in the presence of imposed external electric fields E_c=0, 46, 91.5, 137.5, and 183.1 V/cm (from bottom to top). The spectra for increasing fields $E_c > 0$ are offset from the field-free spectrum by integer multiples of 200 counts. The abscissa is the electron laboratory acceleration voltage applied to the electron gun of the cooler at CRYRING.

The data displayed in Fig.1 are normalized to identical ion current, electron current and data-taking time so that they can be directly compared. Two features can be immediately recognized: (a) With increasing magnetic field the low-energy peaks are shifted to lower cathode voltages, i.e. to lower electron laboratory energies. The reason is that with increasing $B_\perp$ the electron beam is tilted with respect to the ion beam. With increasing angle between electron and ion beams the center-of-mass energy increases if the laboratory energy does not change. Since the resonances occur at fixed center-of-mass energies their position in the laboratory energy spectrum shifts downwards with increasing angle. (b) With increasing magnetic field the energy resolution of the measurements deteriorates. The reason for this is the increasing misalignment of the electron beam with respect to the ion beam. As a result, each ion probes an increasingly broader range of the electron-beam space charge potential distribution. However, even in the worst case, i.e. for the highest $B_\perp$, the energy spread is still of the order of only 0.4 eV for the $2p9\ell$ resonances. Thus, the relatively broad peak at the high-energy end of the spectrum is not very much influenced by the decreasing energy resolution: it is marginally broadened for the highest transverse magnetic fields used in this experiment. With this in mind, one can easily see that the size of this peak increases with the external electric field. In the peak, unresolved Rydberg states with $n > 20$ lump together and it is their contribution to the total DR rate which is subject to effects of the fields applied in this experiment. The dip on top of the peak is a result of the fine structure splitting of the $2p$ levels and the associated separated series limits of $2p_{1/2}n\ell$ and $2p_{3/2}n\ell$ Rydberg states. A detailed analysis of these experimental results with respect to the DR enhancement is presently underway.

III. RATE ENHANCEMENT AT COOLING

Before the construction of storage rings for heavy ions there was a major concern about recombination losses during the cooling by electrons. RR with its cross section diverging at zero energy was considered the beam lifetime limitation particularly for highly charged ions [15]. Regarding recombination losses due to dielectronic recombination (DR) near zero relative energy $E_{rel} = 0$ in the electron-ion collision system, a case study for Ar^{15+} ions was also carried out [16], but the results did not appear very threatening to storage and cooling of these ions.

The scene changed when unexpected high recombination rates at $E_{rel} = 0$ were observed in an experiment with 6.3 MeV/u U^{28+} ions employing a cold dense electron target at the linear accelerator UNILAC of the GSI in Darmstadt [3]. Within an energy range between 0 and roughly 1 meV the observed recombination rate dropped by a factor of 2 from about $2 \cdot 10^{-7}$ cm^{3}s^{-1}, while a realistic estimate of the RR rate yields approximately $1 \cdot 10^{-9}$ cm^{3}s^{-1} [4]. It was immediately recognized that the lifetime of a stored cooled beam of U^{28+} ions would only be seconds considering the normal density of electron coolers, and yet, this had not been widely noticed until after a series of experiments at the Low Energy Accumulator Ring LEAR at CERN in which Pb^{53+} ions were stored and cooled for preparation of further acceleration [17]. For $n_e = 4.4 \cdot 10^7$ cm^{-3} the beam lifetime was only 2 s which is intolerable for an efficient handling and acceleration of the ion beam.

While recombination rates for Pb^{53+} and its neighbouring charge states were determined only indirectly from life time measurements at LEAR, recently a special effort was made at the TSR [18] to investigate recombination of gold ions Au^{50+} which are isoelectronic with Pb^{53+}.

For the measurement of recombination spectra at low relative energies E_{rel} between electrons and ions in storage ring coolers, the effects of the cooling forces have to be considered. With fast switching between cooling- and scanning-energies together with time-resolved data taking the drag effects of the cooling forces on the ion beam can be corrected for. Figure 2 shows the recombination spectrum taken with Au^{50+} ions in the TSR. The ion energy was 3.6 MeV/u, close to the maximum possible at the accelerator facilities in Heidelberg for these heavy ions. The data are plotted on a double logarithmic scale in order to visualize the extremely sharp peak at $E_{rel} = 0$. Within approximately $4 \cdot 10^{-4}$ eV the recombination rate drops from its maximum which is as high as $1.8 \cdot 10^{-6}$ cm^3 s^{-1} to half this value. This is the highest recombination rate coefficient ever observed in merged beams experiments. The solid line in Fig.2 represents a calculation of the rate for RR based on the Bethe-Salpeter formula [19] which was modified by the corrections previously described by Andersen et al. [20]. The enhancement factor beyond the expectation of RR theory is about 60. At the electron density $n_e = 10^7$ cm^{-3} of the adiabatically expanded electron beam of the cooling device the lifetime of the circulating ion beam during electron cooling was only about 2 seconds with the settings of the present measurement.

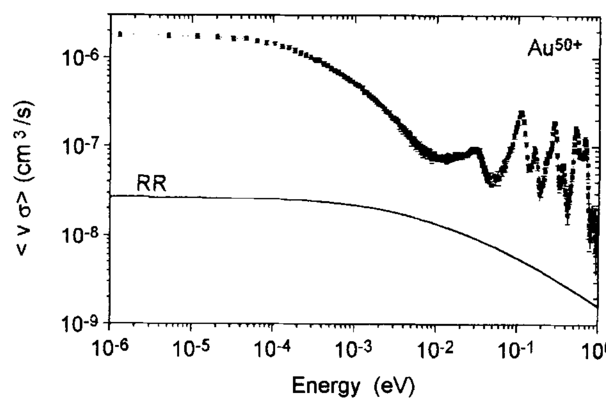

Figure 2. Recombination rates of electrons with 3.6 MeV/u Au^{50+} ions measured at the TSR as a function of the relative energy in the electron-ion center-of-mass frame. The curve denoted by RR is a calculation of the rate for radiative recombination. It agrees with the experimental rate observed at energies between 4 and 5 eV where no resonances appear to be present.

Apart from the recombination maximum at $E_{rel} = 0$ there are huge dielectronic recombination peaks. The one with the lowest energy is already at $E_{rel} = 30$ meV. The full width at half maximum of this resonance is only about 15 meV, which is the smallest width ever observed in electron collision experiments with multiply charged ions. The DR resonances are so densely spaced in energy that one can easily imagine strong resonance contributions also to the peak at zero energy. The DR resonance energy of an ion depends on the individual structure of this ion; hence, DR resonances of Au^{50+} may be fortuitously placed near $E_{rel} = 0$. One can then expect completely different recombination rates in isonuclear ions with different charge states and different electronic structure. Therefore, we also measured recombination rates of Au^{49+} and, indeed, the maximum recombination rate at $E_{rel} = 0$ is roughly a factor of 10 lower than that of Au^{50+}. DR resonances are not nearly as densely spaced as in Au^{50+} and probably are absent at $E_{rel} = 0$. Nevertheless, there is still a considerable enhancement (by about a factor of 4) of the measured rate beyond the expectations according to the theory for RR. A similar result is obtained with Au^{51+} ions. There, however, no obvious resonances are found at all at energies from 0 to 1 eV. In conclusion, excessive recombination losses during cooling in a storage ring can probably be avoided by proper choice of the ion charge state. Though, the phenomenon of enhanced recombination at low energies, also found for completely stripped ions which do not support DR, is not understood yet and needs further investigation.

IV. ACKNOWLEDGEMENTS

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