Recombination measurements at low energies with $Au^{49+,50+,51+}$ at the TSR

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Recombination of Au^{49+}, Au^{50+}, and Au^{51+} ions has been studied at the TSR. With Au^{50+} ions a storage lifetime of only 2 to 4 s was observed with the magnetically expanded electron beam of the cooler at a density of $n_e = 10^7$ cm^{-3}. This short storage time is a consequence of the highest recombination rate coefficient ever observed with an atomic ion ($1.8 \cdot 10^{-6}$ cm^3 s^{-1} at zero relative energy $E_{rel} = 0$ between electrons and ions). At about 30 meV a huge dielectronic recombination resonance is found with a record small width of only about 15 meV. Such resonances fortuitously occurring near $E_{rel} = 0$ are probably the main reason for the enhanced recombination rates observed with Au^{50+}, with Pb^{53+} (in a recent experiment at LEAR) as well as with other complex ions. For Au^{49+} and Au^{51+} the recombination rates are smaller by an order of magnitude.

1. Introduction

Before the construction of storage rings for heavy ions there was a major concern about recombination losses during the cooling by electrons. Radiative recombination with its cross section diverging at zero energy was considered the beam lifetime limitation particularly for highly charged ions. Also three-body recombination and collisional radiative recombination were considered [1] but the low electron beam temperatures presently achieved at storage rings had not been anticipated at that time,

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so that the higher-order recombination mechanisms were supposed to be less important. Regarding recombination losses due to dielectronic recombination (DR) near zero relative energy $E_{\rm rel} = 0$ in the electron-ion collision system, a case study for Ar^{15+} ions was also carried out [2], but the results did not appear very threatening to storage and cooling of these ions.

The scene changed when unexpectedly high recombination rates at $E_{\rm rel} = 0$ 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 [3,4]. Within an energy range between 0 and roughly 1 meV the observed recombination rate dropped from about $2 \cdot 10^{-7}$ $\text{cm}^3\,\text{s}^{-1}$ to half this maximum value. The electron density was $n_{\rm e} = 4 \cdot 10^8$ cm^{-3}. 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 [5,6]. From the observed lifetimes of the beam during cooling at different electron densities a total recombination rate coefficient of $6.0 \cdot 10^{-7}$ $\text{cm}^3\,\text{s}^{-1}$ was inferred. For $n_{\rm e} = 4.4 \cdot 10^7$ cm^{-3} the beam lifetime was reduced to only 2 s, which is intolerable for an efficient handling and acceleration of the ion beam. Fortunately, the neighbouring charge states $Pb^{52+,54+,55+}$ behave quite differently and provide sufficient time for cooling without extensive beam losses [7].

While the recombination rate for Pb^{53+} and its neighbouring charge states was determined only indirectly at LEAR, recently a special effort was made at the TSR to investigate by direct detection of the recombination products the similarly charged gold ions $Au^{49+,50+,51+}$ which are isoelectronic with $Pb^{52+,53+,54+}$, respectively. In this paper we present preliminary results of the measurements. The analysis of the data material available from the beam time is still in progress, however, the results presented here will not change much any more.

2. Experiments and results

For the measurement of recombination spectra at low relative energies $E_{\rm rel}$ between electrons and ions in storage ring coolers, the effects of the cooling forces [8] have to be considered. When the energy of the electron beam is switched away from cooling conditions the friction between the electron and the ion beams causes the ion velocity to shift towards the new electron velocity. The cooling forces strongly depend on the charge and the mass of the ions and hence the drag effect is the most disturbing with highly charged heavy ions. However, it can be circumvented by fast switching of the electron beam energy between cooling and data-taking energies. For relative energies $E_{\rm rel} \gg kT_{\perp}$, where $T_{\perp}$ is the transverse electron beam temperature and k is Boltzmann's constant, the cooling forces rapidly decrease. Thus, for relative energies beyond about 0.5 eV a switching scheme with dwell times on data-taking energy of the order of tens of milliseconds is sufficiently fast to avoid problems with the drag forces and hence with the definition of $E_{\rm rel}$. Efficient schemes of that type are applied to recombination and ionization studies using fast high-voltage amplifiers. However, at lower relative energies defeating the drag effect requires additional effort. For this reason, a new data taking scheme has been developed [9] for the TSR in which the switching between cooling and data-taking is carried out with a low-voltage high-power amplifier that allows switching times much smaller than 1 ms. Thus, the dwell time on data-taking can be reduced to about 1.5 ms without too much reduction of the duty cycle. The counting rates of recombined ions together with all other relevant parameters are recorded as a function of time with bins of 100 μs duration. With the resulting time resolution it is possible to monitor the development of the electron energy and the drag effect of the electron beam on the circulating ion beam. If necessary, only small time spans after each switching of the electron energy can be used to build the recombination spectrum. The duty cycle of this scheme may go down when only a small time span can be used; on the other hand, the data taken in this way will yield more accurate results.

The analysis of the detailed time spectra has revealed a time dependence in resonance peak energies. This observation can be used to recover data with improved energy resolution. In particular, widths of resonance peaks occurring at energies greater than 0.2 eV will become smaller. The analysis of the time spectra with this aspect is still in progress. We anticipate that the absolute rate data presented in this paper (which were taken with the 1.5 ms dwell time mode) will need little correction after finalizing the evaluation. Figure 1 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 $E_{\rm rel} = 0$ (which looks rather massive on the double-log scale). Within approximately $4 \cdot 10^{-4}$ eV the recombination rate drops from its maximum, which is as high as $1.8 \cdot 10^{-6}$ $\rm cm^3\,s^{-1}$, to half this value. This is the highest recombination rate coefficient observed so far in merged beams experiments with atomic ions. The solid line in fig. 1 represents a calculation of the rate for radiative recombination (RR) based on the Bethe–Salpeter formula [10] which was modified by the corrections previously described by Andersen et al. [11]. The enhancement factor beyond the expectation of RR theory is about 60. At the electron density $n_{\rm e} = 10^7$ $\rm cm^{-3}$ 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.

Apart from the recombination maximum at $E_{\rm rel} = 0$ there are huge dielectronic recombination peaks. The one with the lowest energy is already at $E_{\rm rel} = 30$ meV. Detailed analysis of the shape of this resonance yields electron beam temperatures corresponding to the thermal energies $kT_\perp = 16$ meV and $kT_\| = 1 \cdot 10^{-4}$ eV. 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

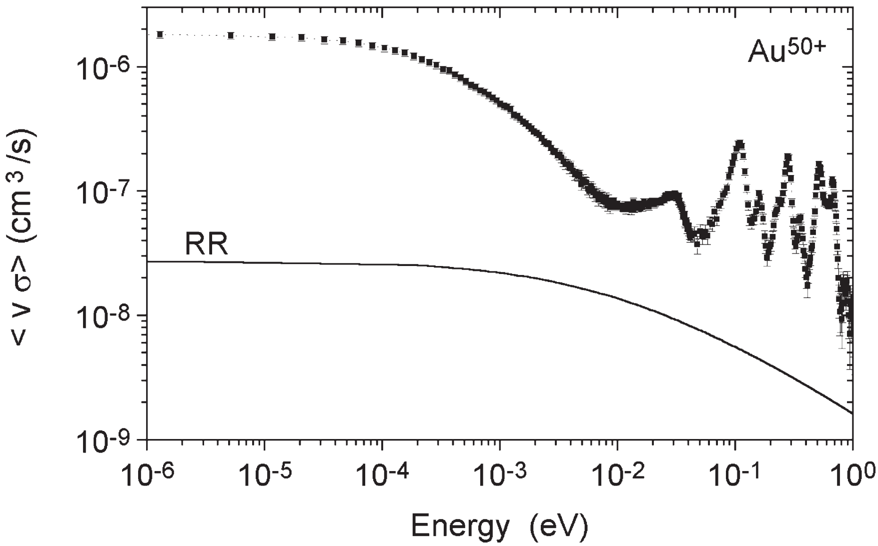

Fig. 1. Recombination rates of electrons with 3.6 MeV/u Au^{50+} ions measured at the TSR as a function of the relative energy in the electron–ion center-of-mass frame. The curve denoted by RR is a calculation of the rate for radiative recombination. It agrees with the experimental rate observed at energies between 4 and 5 eV where no resonances appear to be present. For further details see the text.

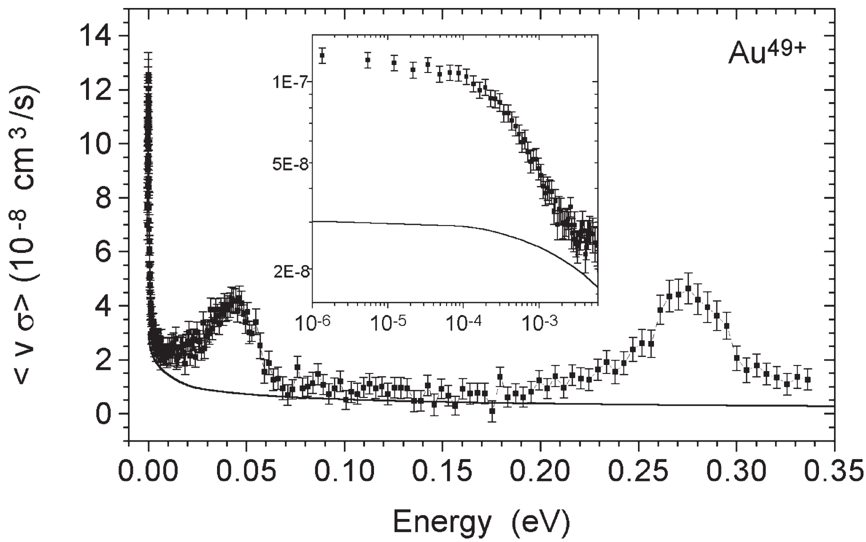

Fig. 2. Recombination rates of electrons with 3.6 MeV/u Au^{49+} ions measured at the TSR as a function of the relative energy in the electron–ion center-of-mass frame. The solid line is the rate calculated for radiative recombination. It agrees with the experimental rate observed at energies around 1.2 eV where no resonances appear to be present. For further details see the text. The inset shows the data in the lowest energy range on a double logarithmic scale.

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 Au^{51+} ions. The result of the Au^{49+} experiment is shown in fig. 2. 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. The solid line in fig. 2 represents a calculation of the RR rate with the same approach as that used for Au^{50+}.

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.

3. Summary and outlook

Recombination of ions in charge states near 50 has been investigated at the TSR. The recombination rates at zero relative energy in the electron–ion collision system measured with Au^{49+}, Au^{50+} and Au^{51+} are very similar to those inferred from storage lifetimes of isoelectronic lead ions studied at the LEAR. Apparently, the huge recombination rates observed for Au^{50+} and for Pb^{53+} ions are caused by the individual electronic structure of these ions which happens to support dielectronic recombination resonances at very low energies. The ions Au^{49+} and Au^{51+} as well as Pb^{52+} and Pb^{54+} have a different electronic structure and do not provide as many DR resonances at low energies. We hypothesize that this is the reason why the recombination rates at $E_{rel} = 0$ are much smaller than those observed with Au^{50+} and Pb^{53+} ions.

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References

[1] H.F. Beyer, D. Liesen and O. Guzman, Part. Accel. 24 (1989) 163.
[2] C. Carlsund, N. Elander, R. Mowat, D.C. Griffin and M.S. Pindzola, Physica Scripta T 22 (1987) 243.

[3] A. Müller, S. Schennach, M. Wagner, J. Haselbauer, O. Uwira, W. Spies, E. Jennewein, R. Becker, M. Kleinod, U. Pröbstel, N. Angert, J. Klabunde, P.H. Mokler, P. Spädtke and B. Wolf, Physica Scripta, T 37 (1991) 62.
[4] S. Schennach, A. Müller, M. Wagner, J. Haselbauer, O. Uwira, W. Spies, E. Jennewein, R. Becker, M. Kleinod, U. Pröbstel, N. Angert, J. Klabunde, P.H. Mokler, P. Spädtke and B. Wolf, in: *Physics of Highly-Charged Ions*, eds E. Salzborn, P.H. Mokler and A. Müller, Supplement to Z. Phys. D: Atoms, Molecules and Clusters 21 (1991) 205.
[5] S. Baird, J. Bosser, M. Chanel, J. Duran, R. Giannini, P. Lefèvre, R. Ley, R. Maccaferri, S. Maury, I. Meshkov, D. Möhl, G. Molinari, F. Motsch, H. Mulder, U. Oeftiger, J.C. Perrier, E. Roux, G. Tranquille and F. Varenne, CERN, Geneva, Internal Report PS/AR/Note 95-06 (MD), March 1995.
[6] S. Baird, J. Bosser, C. Carli, M. Chanel, P. Lefèvre, R. Ley, R. Maccaferri, S. Maury, I. Meshkov, D. Möhl, G. Molinari, F. Motsch, H. Mulder, G. Tranquille and F. Varenne, Phys. Lett. B 361 (1995) 184.
[7] S. Baird, J. Bosser, C. Carli, M. Chanel, R. Ley, R. Maccaferri, S. Maury, I. Meshkov, D. Möhl, G. Molinari, E. Syresin, G. Tranquille and F. Varenne, CERN, Geneva, Internal Report PS/AR/Note 96-08 (MD), May 1996.
[8] A. Wolf, this volume.
[9] O. Uwira, PhD Thesis, Giessen 1997, in preparation.
[10] H. Bethe and E. Salpeter, *Quantum Mechanics of One- and Two-Electron Systems* (Springer, Berlin, 1957).
[11] L.H. Andersen and J. Bolko, Phys. Rev. A 42 (1990) 1184.