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Recombination of Au^{20+} at low electron–ion collision energies

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Abstract
The rate coefficient for the recombination of Au^{20+} with free electrons was measured in the electron–ion collision energy range of 0–10 eV by employing the electron–ion merged-beams technique at the heavy-ion storage ring TSR of the Max-Planck-Institute for Nuclear Physics in Heidelberg, Germany. In contrast to earlier measurements with more highly charged Au^{25+} (Hoffknecht *et al* 1998 *J. Phys. B: At. Mol. Opt. Phys.* **31** 2415), sharp dielectric recombination resonance features are observed.

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1. Introduction

Dielectronic recombination (DR) of ions with only a few electrons is relatively well understood. For example, for Li-like Sc^{18+} even higher-order quantum electrodynamic effects and hyperfine effects, which show up in the measured DR spectrum, are well explained by theoretical calculations [1]. DR of heavier ions with more electrons such as Au^{20+} (59 electrons) is much less well understood. Clearly, an accurate theoretical description of such many-electron systems is extremely challenging. This is especially true if the parent ion has a complicated atomic shell structure such as, e.g., an open 4f shell. So far, the only ion with an open 4f shell for which low-energy DR has been studied both experimentally and theoretically is Au^{25+} [2–5] with a ground-state 4d^{10} 4f^{8} configuration. Exceptionally large recombination rate coefficients at near-zero electron–ion collision energies were found and qualitatively explained by the presence of a multitude of overlapping, individually unresolvable DR resonances. Here we present the experimental low-energy (0–10 eV) merged-beam DR rate coefficient of Au^{20+}, an ion where the 4f shell is almost filled in the 4d^{10} 4f^{13} ground-state configuration.

2. Experiment

The recombination measurements were carried out at the heavy-ion storage ring TSR of the Max-Planck-Institute for Nuclear Physics (MPIK) by applying procedures that have been described previously (see [6] and references therein). For the present experiment ^{197}Au^{20+} ions were produced by the MPIK linear accelerator facility and injected into TSR with an energy of 180 MeV. In two of the straight sections of the storage ring, electron beams were guided by magnetic fields such that they moved collinearly (centered on the same axis) with the ion beam [7]. One of the electron beams was used for continuous electron cooling of the ion beam and the other was used as an electron target for the recombination measurements. Recombined Au^{19+} ions were separated from the Au^{20+} beam by the first TSR dipole magnet behind the electron–ion interaction region and counted with a single-particle detector [8] with nearly 100% efficiency.

Usually, absolute merged-beams recombination rate coefficients are derived from the measured recombination count rates by an appropriate normalization on electron and ion currents. In the present experiment, the ion current was so low that it could not be measured. Therefore, the signal from the beam-profile monitors, which are based on residual

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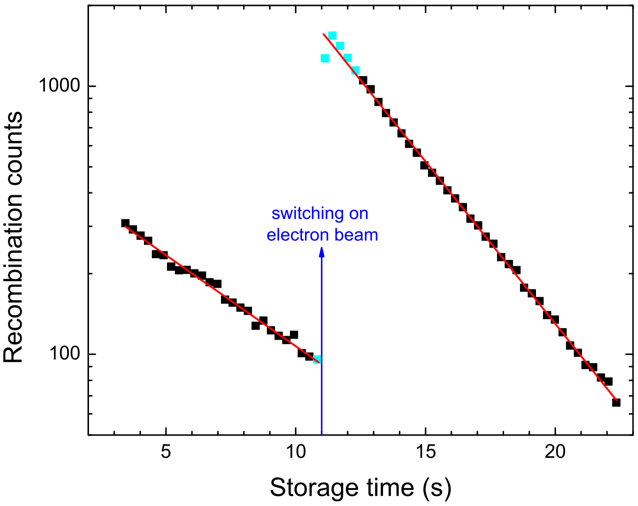

Figure 1. Recombination counts as a function of storage time. The target electron beam was switched on at $t = 11$ s (marked by the vertical arrow). The full lines are fits of exponentials to the data points. Light colored data points were excluded from the fit since they exhibit a nonexponential behavior, which is probably due to slight residual-gas pressure variations caused by the electron-beam switching.

gas ionization by the ion beam, was used as a proxy for the ion current. The relative recombination rate coefficient was put on an absolute scale by normalization to the recombination rate coefficient α_0 at zero electron–ion collision energy. The latter was determined by a separate measurement of the storage lifetime of the ion beam [9].

To this end, the decay of the recombination count rate was monitored as a function of storage time (figure 1). The lifetime of the stored ion beam in the storage ring is limited by collisions with residual gas particles. When the electron-target beam is switched on, the lifetime is reduced even further by electron–ion recombination. The electron–ion recombination rate coefficient can thus be determined from the beam decay rate constants $\lambda^{(\mathrm{off})}$ and $\lambda^{(\mathrm{on})}$ measured with the electron target switched off and on, respectively, i.e. $\alpha_0 = [\lambda^{(\mathrm{on})} - \lambda^{(\mathrm{off})}]C/n_\mathrm{e}L$, where $n_\mathrm{e} = 9.9 \times 10^6\,\mathrm{cm}^{-3}$ is the electron density, $L = 1.5$ m is the length of the electron–ion interaction region and $C = 55.4$ m is the ring circumference. From the decay curves shown in figure 1, $\alpha_0 = 4.5 \times 10^{-7}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ was obtained. Repeated measurements yielded different values for α_0, which scatter by ±32%. We thus assume an uncertainty of ±32% for the present rate coefficient scale.

3. Results and discussion

Figure 2 displays the measured Au^{20+} merged-beams recombination rate coefficient in the electron–ion collision energy range of 0–10 eV. This exhibits much more structure than the previously measured Au^{25+} recombination rate coefficient [2] where only rather broad features were observed with widths much larger than the experimental energy resolution. In contrast, the present Au^{20+} recombination spectrum consists of many sharp DR peaks.

The qualitative difference between the Au^{20+} and Au^{25+} spectra stems from the differences in atomic structure. The approximately half-filled 4f shell in Au^{25+} supports thousands of states in the parent and the recombined ion leading to an unusually high density of DR resonance states that strongly overlap [5]. In Au^{20+}, however, the 4f shell is almost filled and the number of DR resonance states is greatly reduced although the number of electrons in the parent ion is larger than for Au^{25+}. Thus, narrow DR resonance features become observable in the Au^{20+} recombination spectrum. Only for very low electron–ion collision energies below 5 meV the experiment cannot resolve individual DR resonances. Nevertheless, their presence can be inferred from the fact that the measured recombination rate coefficient exceeds the theoretical expectation for nonresonant radiative recombination (RR) by more than a factor of 40. This factor is smaller than the respective value of 150 for Au^{25+} [2].

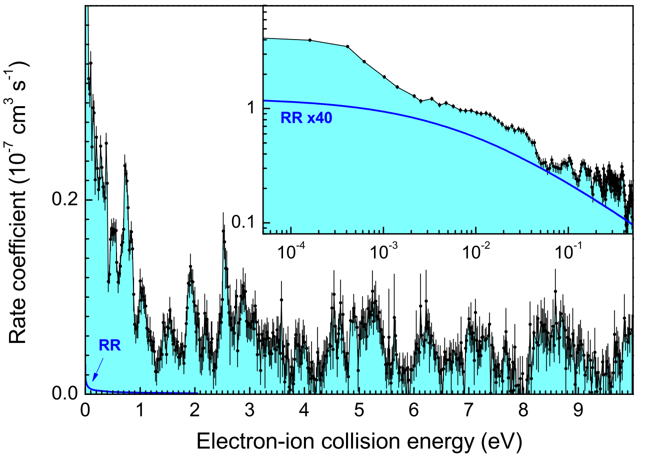

Figure 2. Experimental merged-beams rate coefficient for the recombination of Au^{20+} ions with free, low-density electrons. The inset shows the same spectrum on a double logarithmic scale in order to visualize the low-energy region of the measured DR spectrum where the recombination rate coefficient rises very sharply towards zero electron–ion collision energy. Also shown is the rate coefficient for radiative recombination (RR), which was calculated using a hydrogenic approximation with field ionization cutoff at $n = 74$ and electron beam temperatures of $k_\mathrm{B}T_\parallel = 0.1$ meV and $k_\mathrm{B}T_\perp = 10$ meV [2, 6]. For display in the inset, this RR rate coefficient has been multiplied by a factor of 40.

Atomic structure calculations with the Cowan code [10] suggest that the experimentally observed Au^{20+} DR resonances may be associated with excitations of a 4f electron to the $n = 5$ shell. Further identification of the measured resonances certainly requires considerable theoretical effort, which we hope to stimulate with the present study. The comparison with the previously measured results for Au^{25+} [2] shows that the complexity of DR spectra of ions with an open 4f shell strongly depends on the number of 4f electrons or 4f vacancies on the parent ion.

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