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First recombination experiment of fluorine-like nickel ions at the main cooler storage ring

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Abstract
Absolute non-resonant recombination (RR) rate coefficients of Ni^{19+} ions were measured by employing the electron–ion merged-beams technique at the main cooler storage ring in Lanzhou. Using the electron cooler and energy detuning system, we obtained a narrow momentum spread ($\Delta p/p \sim 2\times10^{-4}$) and tuned precisely relative energies (minimum electron energy detuning step voltage 1 V) between electrons and ions. In addition, we compared the RR rate coefficients with the theoretical ones calculated by the self-consistent-field Dirac–Slater method, and found that they are in good agreement.

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(Some figures may appear in color only in the online journal)

1. Introduction

Dielectronic recombination (DR) and non-resonant recombination (RR) are two important processes in electron–ion collisions, which play important roles in various plasmas and are also powerful tools to investigate the structure of atomic ions [1]. RR has been generally investigated [2–4] and RR rate enhancement is observed at very low relative energies (typically $\leqslant 10$ meV), where the experimental RR rate coefficients are higher than the theoretical ones, while at higher energies the experimental rate coefficients are in good agreement with the theoretical ones. Here we present the low-energy (0–16.4 eV) RR rate coefficient of fluorine-like Ni^{19+}, where an ion captures a free electron and releases a photon:

$$e^- + Ni^{19+}[2s^2(2p^5)_{3/2}] \longrightarrow Ni^{18+}[2s^2(2p^5)_{3/2}nl]^* + h\nu. \quad (1)$$

In addition, the self-consistent-field Dirac–Slater method (SCFDS) [5] is used to calculate RR rate coefficients and compare them with measured ones.

2. Experiment

Recombination measurements were carried out at the main cooler storage ring [6, 7] at the Institute of Modern Physics in Lanzhou. The present experimental setup shown in figure 1 consists of an ion storage ring, an electron cooler and a particle detector [8]. The $^{58}Ni^{19+}$ ions were produced

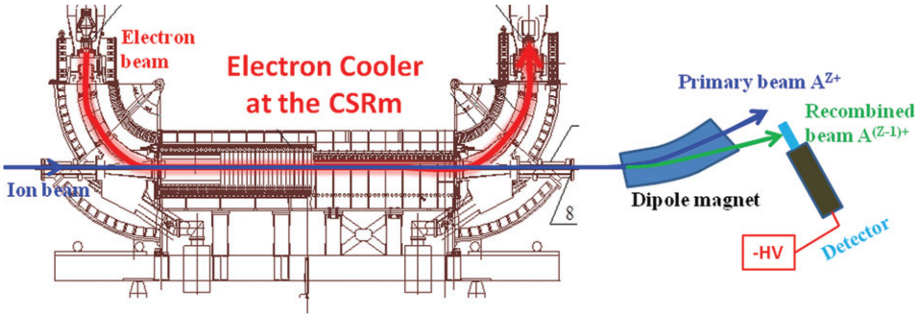

Figure 1. Sketch of the experimental setup showing the electron cooler section and the detector for recombined ions.

in a superconducting electron cyclotron resonance (ECR) ion source [9], accelerated to 6.4 MeV u^{-1}, and finally injected into the ring with a typical ion current of 20 μA and a half-lifetime of 37 s. The ion beam is merged with a magnetically guided electron beam (beam radius about 2.5 cm) with a fixed beam current of 65.6 mA in the cooling section. The cooling voltage and density of the electron beam are -3.4612 kV and 4.14×10^6 cm^{-3}, respectively. After about 5 s cooling, the momentum spread of the ion beam was about 2×10^{-4}.

The detuning voltages were applied to the cathode to change the electron energy with a minimum step of 1 V. During a measurement cycle, the electron energy was stepped by 10 ms for detuning, and 90 ms for electron cooling. Those ions that capture electrons are separated from the main beam by the first bending magnet downstream of the cooler and detected by the scintillator particle detector (CsI + PMT) [6] in a pocket (stainless steel window with a thickness of 30 μm). In addition, the space-charge potential is about 20 V at cooling energy for an electron beam current of 65.6 mA. Thus the corrected electron energy and ion energy are used to calculate the relativistic relative energy between an electron and an ion:

$$E_{\rm rel} = \sqrt{m_{\rm e}^2c^4 + m_{\rm i}^2c^4 + 2m_{\rm e}m_{\rm i}\gamma_{\rm e}\gamma_{\rm i}c^4(1-\beta_{\rm e}\beta_{\rm i}\cos\theta)} - m_{\rm e}c^2 - m_{\rm i}c^2, \tag{2}$$

where m_x, β_x and γ_x $(x = {\rm e, i})$ are the mass and Lorentz factors, respectively. e and i denote the electron and the ion, respectively. c is the speed of light, and θ is the angle between the electron and the ion beams. Generally, θ is optimized to approach 0 mrad by minimizing the width of the ion beam.

From the recombination rate measured at relative energy $E_{\rm rel}$ of the electron and the ion, the experimental rate coefficient α can be deduced by [10]

$$\alpha = \frac{R\gamma_{\rm i}^2}{\eta N_{\rm i} n_{\rm e}}. \tag{3}$$

Here R is the background-subtracted count rate, and η is the ratio of the effective cooling section length (3.4 m) to the ring circumference (161.00 m). $N_{\rm i}$ and $n_{\rm e}$ are the number of stored ions and the density of the electron beam, respectively.

3. Results and discussion

As shown in figure 2, the RR rate coefficients were obtained by subtracting the DR rate coefficients through data processing, and compared with the calculated ones by SCFDS [5]. We fitted the experimental spectra with an empirical function equation (4) [11] to get the contribution of RR and with an analytical formula equation (5) [12] to get the contribution of DR:

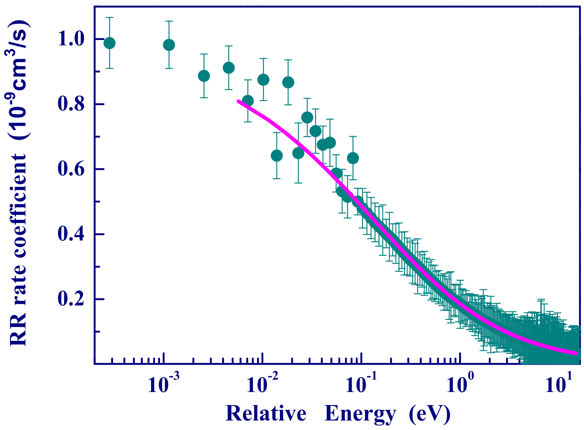

Figure 2. Experimental RR rate coefficients (solid circles) and the results of SCFDS [5] (solid line) as a function of relative energy.

$$\alpha_{\rm RR} = a_0 + a_1 E_{\rm rel} + a_2 / \left(1 + a_3 E_{\rm rel} + a_4 E_{\rm rel}^2\right), \tag{4}$$

$$\alpha_{\rm DR} = \frac{\sigma_{\rm DR}\upsilon_{\rm DR}}{m_{\rm e}\sigma_\perp^2\zeta}\exp\left(-\frac{\upsilon_{\rm DR}^2 - \upsilon_{\rm rel}^2\zeta^{-2}}{\sigma_\perp^2}\right) \times \left[{\rm erf}\left(\frac{\upsilon_{\rm rel} + \upsilon_{\rm DR}\zeta^2}{\sigma_\parallel\zeta}\right) - {\rm erf}\left(\frac{\upsilon_{\rm rel} - \upsilon_{\rm DR}\zeta^2}{\sigma_\parallel\zeta}\right)\right], \tag{5}$$

where the coefficients a_i $(i = 0$–$4)$ are determined by the fitting results. $\sigma_{\rm DR}$ and $\upsilon_{\rm DR}$ label the cross section and the relative velocity corresponding to the DR resonance. The relative velocity is denoted by $\upsilon_{\rm rel}$ corresponding to the relative energy $E_{\rm rel}$, and $\sigma_{\parallel,\perp}$ and ζ are given by $\sigma_{\parallel,\perp} = (2kT_{\parallel,\perp}/m_{\rm e})^{1/2}$ and $\zeta = (1 - T_\parallel/T_\perp)^{1/2}$. Here $T_\perp$ and $T_\parallel$ are the transversal and longitudinal electron temperatures, respectively. $m_{\rm e}$ is the electron rest mass.

The theoretical RR results are convoluted with the transversal electron temperature 0.2 eV and the longitudinal electron temperature 0.33 meV, and the cut-off quantum number limited by field ionization is 95 [13]. The experimental RR rate coefficients are in good agreement with the theoretical ones in the whole energy range within the error bars as shown in figure 2.

In summary, the first radiative recombination experiment was successfully performed at the CSRm using Ni^{19+}

ions, and the absolute rate coefficients were extracted. The experimental results are in good agreement with theoretical SCFDS calculations. More experiments are in preparation to investigate the dielectronic recombination with highly charged ions.

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