COLLISIONAL AND RADIATIVE PROCESSES USED FOR DIAGNOSTICS IN A HEAVY-ION STORAGE RING EMPLOYING ELECTRON COOLING

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Abstract

In a heavy-ion storage ring operated with an electron cooler and an internal gas target serious limitations in the ion-beam lifetime may arise from electron-ion-recombination and electron-capture processes. On the other hand, it is a great challenge to make use of those processes for the development of in situ diagnostic methods. Here, estimates are presented of the time constant for ion-beam loss due to total electron-ion collisional-radiative recombination in the electron cooler. The pattern of the x-ray emission following recombination is analyzed in detail with regard to its use as a diagnostic probe and it is shown how spectroscopic methods can be used to measure ion-beam properties and how to monitor the time history of the electron-cooling process.

1 INTRODUCTION

There is a wide-ranging interest in the development of heavy-ion storage rings employing electron cooling as evidenced by the large number of projects presently underway. These new devices will cover essentially all ions of the periodic table in almost all charge states and in a wide energy range. One of the primary motivations for the use of heavy-ion storage rings is the study of highly charged ions as the simplest atomic systems. By atomic spectroscopy, the more fundamental concepts will be discernible such as relativistic and QED effects which drastically increase with the nuclear charge Z.

The methods of atomic spectroscopy can also be used as diagnostics of the ion beam and of the electron-cooling process. For this purpose it is essential to know details of the ion-atom collisions in a target introduced into a storage ring and of the ion-electron collisions in an electron-cooling device which give rise to an excitation of the ion and a subsequent radiative decay. In the internal target the most important processes will be electron capture into bound and continuum states of the ion. Whereas for a rigorous calculation of capture cross sections details of the electronic structure of the collision partners are important there exist approximate semiempirical scaling laws [1,2] which are useful for accelerator design to predict loss rates for a wide range of ions and energies.

In this report we concentrate on the ion-electron recombination processes. They represent ion losses which are present, already without a target introduced into the storage ring, whenever electron cooling is employed. The main ion-electron processes in merged ion and electron beams of low relative velocities, as realized by an electron cooler, are direct radiative electron capture (REC) and three-body recombination followed by collisional and radiative stabilization. In order to use these processes as diagnostics the total rates as well as the photon spectra involved have been evaluated as a function of the electron- and ion-beam properties. For a careful design of an experiment it is also very important to analyze the kinematical situation of a fast x-ray emitting source. For simplicity we restrict ourselves to completely stripped ions with the notion that most of the results may be modified to apply also to ions bearing an electronic core.

2 TOTAL RECOMBINATION LOSSES

The situation in the electron cooler as viewed from an ion moving with the mean ion velocity $< v_{ion} >$ is illustrated in figure 1, where the distribution of the kinetic energy of the electrons is indicated by the shaded area. In a recombination process the excess energy can either be taken off by a photon or by a second electron. The first process, REC, is the time-reversed photoionization and populates predominantly the most tidely bound states, i.e. the K shell in case of bare ions. The second process, three-body recombination, is the time reversed electron-impact ionization and involves high-Rydberg states with binding energies comparable to the thermal energy kT_e of the electrons.

Such loosely bound electrons can be easily reionized in a second collision. Therefore, we count as a net recombination only those ions which stabilize through a chain of collisional and spontaneous radiative processes.

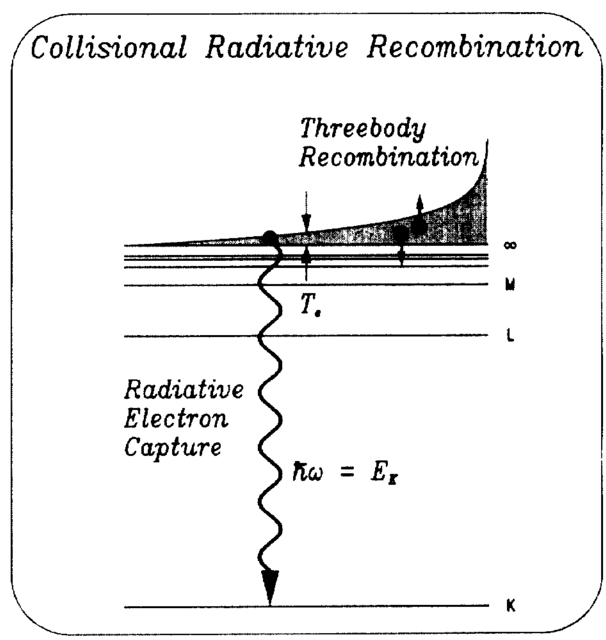

Figure 1: Radiative electron capture and three-body recombination of cooling electrons.

From the cross section σ_{REC} calculated for the REC process [3,4], the total rate coefficient may be taken as $\alpha_{REC} = v_e \cdot \sigma_{REC}(v_e)$ as long as the relative kinetic energy is larger than the width of the distribution:

$$\alpha_{REC} = 1.7\,10^{-13}\,\frac{Z^2}{\sqrt{E_e}}\left[0.577 + \ln\left(3.69\frac{Z}{\sqrt{E_e}}\right)\right] \quad \left[cm^3 s^{-1}\right], \quad (1)$$

where E_e is the relative electron energy in eV.

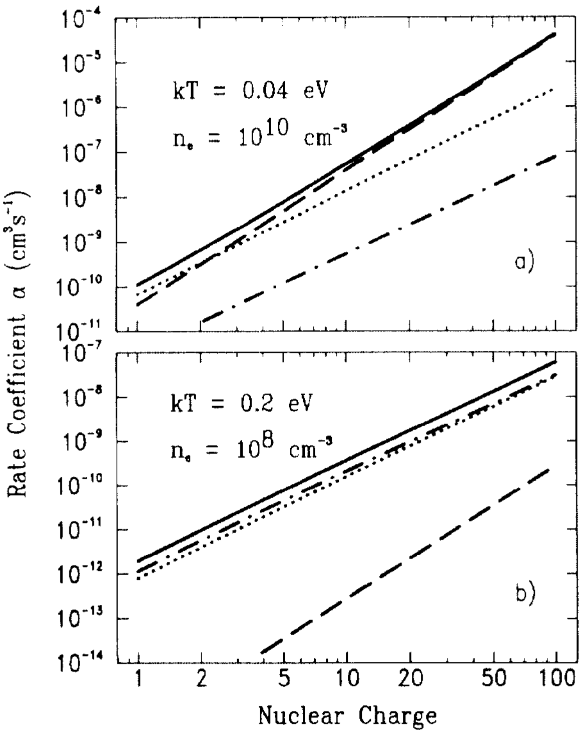

Figure 2: Rate coefficients for recombination of bare heavy ions with cooling electrons. The dashed line represents the collisional contribution α_{coll}, the dotted curve the radiative contribution α_{rad}, and the dashed-dotted line the contribution due to radiative electron capture α_{REC}, whereas the solid curve represents the sum.

Because the rate peaks at matching velocities the tuning of the electron energy can be sensed by an x-ray detector measuring the total rate. In order to calculate the rate for matching mean velocities one has to integrate over the velocity distribution $f(\vec{v}_e)$,

$$\alpha = \int f(\vec{v}_e)\, v_e \sigma(v_e)\, d^3\vec{v}_e \tag{2}$$

This can be easily done for isotropic and for flattened ($T_{\parallel} \ll T_{\perp}$) Maxwellian distributions [5]. For a flattened distribution function the total REC rate in units of cm^3s^{-1} reads

$$\alpha_{REC} = 3.02 \cdot 10^{-13} Z^2 (kT)^{-0.5} \left\{ \ell n \frac{11.32Z}{kT^{0.5}} + 0.14 \left(\frac{kT}{Z^2}\right)^{1/3} \right\}. \tag{3}$$

Detailed calculations for three-body-recombination processes were performed for hydrogenic plasmas [6]. However, it is not obvious how these results could be applied to heavy ions of both high nuclear and ionic charge. Therefore, we developed [7] a model which enables an estimate of the total recombination-rate coefficient for various values of the relevant parameters such as electron density n_e and temperature T and for all values of the nuclear charge Z.

In our calculations we follow the line of arguments given by Byron et al. [8] who realized that the net rate of the total recombination is limited to the rate of de-excitation of a level with (reduced) binding energy $\epsilon^* = -RZ^2 \;/\; \left(n^{*^2} kT\right)$ at which the total collisional plus radiative de-excitation rate as a function of binding energy has a minimum. The total rate coefficient is

$$\alpha = \alpha_{coll} + \alpha_{rad} + \alpha_{REC} \tag{4}$$

where α_{coll} is the rate coefficient for collisional recombination [9] without any radiation being included:

$$\alpha_{coll} = 2.0 \cdot 10^{-27} n_e Z^3 (kT)^{-4.5} \quad \left[cm^3 s^{-1}\right] \tag{5}$$

The contribution of radiative de-excitation has been shown to be [7]

$$\begin{aligned} \alpha_{rad} &= 2.1 \cdot 10^{-13} Z^{1.5} (kT)^{-0.25} (\epsilon^*)^{1.25} exp(-\epsilon^*) \\ &+ 9.6 \cdot 10^{-14} Z^2 (kT)^{-0.5} \cdot \\ &\cdot \int_{-\epsilon^*}^{0} exp(-\epsilon) \ell n \left\{ \frac{(n^* - 1)^2 \left(n(\epsilon)^2 - 1\right)}{n(\epsilon)^2 - (n^* - 1)^2} \right\} d\epsilon \quad \left[cm^3 s^{-1}\right] \end{aligned} \tag{6}$$

Figure 2 shows the rate coefficient for collisional-radiative recombination according to equation (4) as a function of the nuclear charge for two different sets of electron temperature and density. For high density and low temperature, as in figure 2a), the threebody-collision contributions α_{coll} and α_{rad} dominate whereas for the more typical parameters of figure 2b) the radiative terms α_{REC} and α_{rad} are most important.

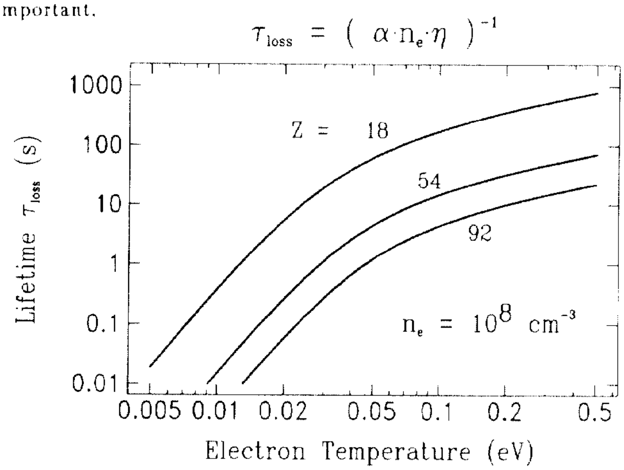

Figure 3: The time constant τ_{loss} for ion beams of Ar^{18+}, Xe^{54+} and U^{92+} as determined by recombination losses as a function of electron temperature. At high ion-beam vlocities the time constant shown has to be multiplied with the relativistic parameter γ^2. The ratio of the length of the cooling section to the circumference of the storage ring was set to $\eta = 0.02$.

From the total rates time constants τ_{loss} are deduced which are shown in figure 3 for three different ions as a function of electron temperature. The electron density has been set to 10^8 cm^{-3} and the effective cooler length to 2 % of the ring circumference. Whereas for electron temperatures of a few tenths of eV beam lifetimes of $\tau_{loss} >$ 10 s can be assured for all ions, there are obvious problems in cooling heavy ions with very cold electrons.

3 PHOTON SPECTRA

The bound-bound transitions following three-body recombination are governed by intrinsic atomic parameters such as natural level widths. To the contrary the free-bound transitions of the REC are determined by the thermodynamic state of the electron beam. In particular, there is no influence of a finite width of the final state if radiative capture to the 1s ground state is considered to which we will pay special attention. We start from the differential REC cross section and calculate the doubly differential rate coefficient $\partial^2\alpha/\partial\Omega/\partial E_x$ for a given longitudinal and transverse electron temperature $T_{\parallel}$ and $T_{\perp}$, respectively. We note that a finite ion temperature can be taken into account by adding the ion temperature multiplied with the electron-to-ion mass ratio

$$T = T_e + \frac{m_e}{m_i} T_i \tag{7}$$

With E_0 denoting the ground state binding energy the result of our calculation [10] can be written as:

$$\frac{\partial^2 \alpha_{REC}}{\partial\Omega\partial E_x} = 6.7\,10^{-16} \frac{E_0^3/E_x^2}{kT_\perp kT_{/\!/}^{1/2}}\, exp\left\{-\frac{E_x - E_0}{kT_\perp}\right\} \cdot \qquad (8)$$

$$\cdot \int_0^1 \left[1 + \cos^2\vartheta + \left(1 - 3\cos^2\vartheta\right) x^2\right] exp\left\{-r^2 x^2\right\} \; dx$$

with

$$r^2 = (E_x - E_0)\left(\frac{1}{kT_{/\!/}} - \frac{1}{kT_\perp}\right).$$

This gives the angular (ϑ) and spectral (E_x) distribution in the emitter frame of reference. It depends on both the absolute value and on the ratio of $T_\perp$ and $T_{/\!/}$ as demonstrated in figure 4.

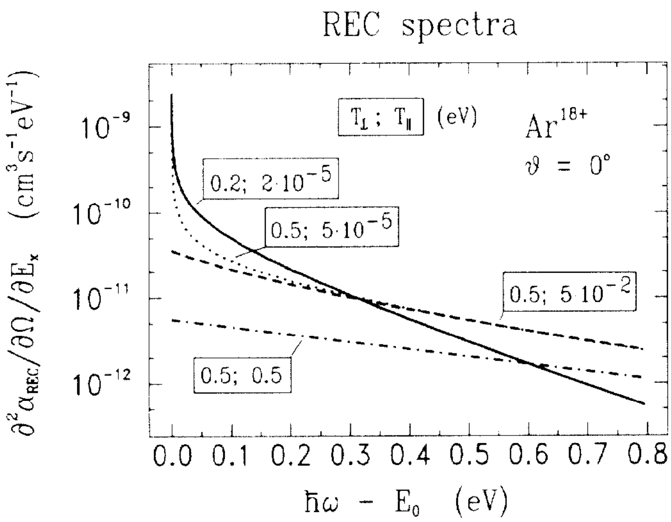

Figure 4: Photon energy- and angle-differential recombination coefficients for Ar^{18+} and for various $T_\perp$ and $T_{/\!/}$. E_0 denotes the 1s binding energy of Ar^{+18}.

The photon spectra reveal a nearly exponential decay given by $T_\perp$ and a sharp spike at $E_x = E_0$ which is due to the flattening of the velocity distribution. With a high-resolution crystal spectrometer at least the exponential decay should be observable giving a measure of the transverse temperature.

4 'DOPPLER GONIOMETRY'

In order to obtain the photon distribution in the laboratory frame we have to perform a Lorentz transformation from which we also can estimate the sensitivity of a wavelength measurement to angular and velocity widths and uncertainties. The Lorentz transformation may be written differentially as

$$\begin{aligned} \frac{\Delta\lambda}{\lambda} &= A(\alpha,\beta)\Delta\alpha + B(\alpha,\beta)\Delta\beta \\ \text{with } A(\alpha,\beta) &= \frac{\beta\sin\alpha}{1-\beta\cos\alpha} \qquad (9) \\ \text{and } B(\alpha,\beta) &= \beta\gamma^2 - \frac{\cos\alpha}{1-\beta\cos\alpha} \end{aligned}$$

where $\Delta\lambda/\lambda$ is a relative wavelength shift or precision and α is the laboratory observation angle relative to the ion-beam direction. β and γ denote the usual relativistic factors. The coefficients $A(\alpha,\beta)$ and $B(\alpha,\beta)$ are not independent from each other. There exists a velocity-sensitive geometry, namely at $\alpha = 0°, 180°$, where $A = 0$ and B takes its maximum and an angular-sensitive geometry at $\cos\alpha = \beta$ where $B = 0$ and A takes its maximum. For a measurement of ion beam velocities through Doppler shifts the zero-degree observation is the best choice whereas at $\cos\alpha = \beta$ beam divergence could be detected at a minimum sensitivity to beam velocity.

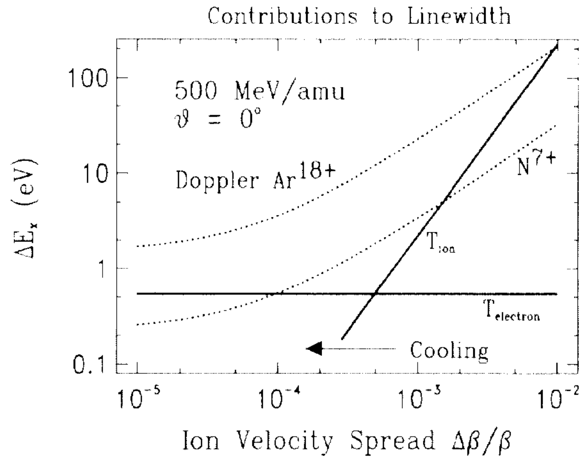

Figure 5: Contributions to the line width of REC x rays observed under zero degree from ions of 500 MeV/amu.

In figure 5 an example is given where we summarize the effects which contribute to an x-ray line width when the REC is observed under zero degree. On the abscissa electron cooling proceeds from right to left starting with a hot ion beam. The electron temperature leads to a constant contribution whereas the ion temperature decreases with cooling and falls below the electron temperature effect. In addition, there is the Doppler width of equation (9) which increases with the nuclear charge of the ion, and the corresponding x-ray energy. At high Z the latter will be the dominant effect. Consequently, lower-Z ions could be favourably used for a diagnostic of the electron beam and of the cooling and high-Z ions to measure the ion velocity and its spread.

Finally, we remark that three-dimensional computer simulations [11] of curved crystal x-ray optics have shown that for particular geometries wavelength resolution can be retained at rather large solid angles of observation giving simultaneously the x-ray profile, merely determined by the REC process, and the laboratory ion-beam velocity.

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