Radiative Recombination between Free Electrons and Bare Carbon Ions

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Absolute rate coefficients for radiative recombination between fully stripped carbon ions and free electrons have been measured for relative energies between 0 and 1 eV. The experiment was performed with a merged-beam technique. A fast-pulsing technique was used to turn on and off the electron source to allow subtraction of background signals stemming from electron capture in the rest gas. The data are compared with the theory for radiative recombination, as derived by Stobbe in 1930 and by Bethe and Salpeter in 1957. The present data constitute the first direct test of the theory for radiative recombination.

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The spontaneous emission of radiation produced when an electron makes a transition from one bound state to another lower-lying state is due to the coupling between matter and the electromagnetic field. The theory was developed by Einstein in 1917.[1] The same coupling may introduce transitions from ionic continuum states to bound states of the ion under emission of electromagnetic radiation. The latter process is known as radiative recombination (RR). In the case of a bare carbon ion, this process may be written as

$$C^{6+} + e^- \rightarrow C^{5+}(n) + h\nu, \tag{1}$$
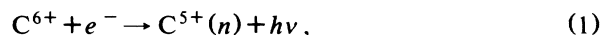
where $h\nu$ is the emitted photon, the energy of which equals the kinetic energy of the initial free electron, plus the binding energy of the hydrogenic level n. Evidently, RR is the inverse photoionization process. The theory for radiative recombination involving bare ions was treated by Stobbe[2] in 1930 and later by Bethe and Salpeter[3] who gave an analytical formula for the cross section for RR.

Early experimental attempts to measure the radiative-recombination-rate coefficient have failed because the very high electron densities used resulted in collisional recombination becoming the dominating recombination process.[4] Recently, radiative recombination between protons and electrons in large ion storage rings have been observed.[5] These measurements were performed with a merged-beam technique in the electron cooler of the storage ring. In the experiments, however, the "temperature" kT of the electron target was not known. In fact, the measured rate of neutral hydrogen was used to estimate the electron temperature, and, consequently, the theory for RR was not tested.

In the present experiment, the electron density is sufficiently low that collisional recombination can be neglected. Further, we have developed a technique which independently measures the electron temperature of our electron target.[6] Thus we are able to obtain the rate coefficient for RR on an absolute scale.

Such a measurement is not only of fundamental interest. The theory for RR has been used to normalize

experimental data for other electron-ion recombination processes.[7] As mentioned above, the process is also being used to estimate the quality of the electron beam in electron coolers. We would like to emphasize that the present technique may easily be applied to nonfully stripped ions. RR for such systems is more elaborate to calculate but perhaps of even more interest from an applications point of view. At the moment, such data are not available.

The present experimental setup has been discussed in detail elsewhere,[6,8] and only a brief description will be given here, with emphasis on the changes that have been introduced to measure the background contribution accurately. A 24-MeV C^{6+}-ion beam was delivered by the Aarhus EN tandem accelerator. The 6+-charge component was obtained by shooting 24-MeV C^{4+} through a thin carbon post-stripper foil. A switching magnet then selected the C^{6+} ions which were directed towards the target. Over a section of 1 m, the ions were merged with a beam of electrons. After the interaction, the electrons were deflected and collected in a Faraday cup. The ions were charge-state analyzed with an electric field of 10 kV/cm perpendicular to the ion-beam direction. The C^{5+} ions, which had collected one electron, were counted by a position-sensitive channel-plate detector. The main beam of C^{6+} ions was collected in a Faraday cup. The electric-analyzer field sets an upper limit, n_{max}, to the number of Rydberg states n which survives to the ion detector; n_{max} may be evaluated according to[9]

$$n_{max} = (6.2 \times 10^8 q^3/E)^{1/4}, \tag{2}$$

where q is the ion charge and E is the field in units of V/cm.

The electron density in the target was about 4×10^7 cm^{-3}, and the background pressure in the beam line was $(1-2) \times 10^{-11}$ Torr. At maximum, the yield of C^{5+} ions produced by RR was 10% of the total production of C^{5+} ions, most of which was due to electron capture in the rest gas. To distinguish the signal from the background, we adopted a modulation technique by which the electron beam was chopped at a frequency of 250 Hz. This

was done by modulating the anode potential between 0 and -2 kV. When the anode voltage was at -2 kV, the electron beam was turned off since the cathode potential was about -1100 V. The rise time of the voltage applied to the anode was 4 μsec. In the middle of the 2-msec interval, when the electron beam was on, one analog-to-digital convertor (ADC) was opened for 1.4 msec to measure signal plus background. Likewise, when the electron beam was turned off, another ADC was opened for 1.4 msec to measure the background signal only. In this way, two position spectra with C^{5+} ions in the ion detector were obtained. Figure 1 shows such spectra at zero relative energy. At each relative energy, the true RR signal $N^{C^{5+}} - N_0^{C^{5+}}$ was obtained as the difference in yield for electrons on and electrons off, integrated between the two arrows shown in the figure. The rate coefficient for the RR process was then obtained as

$$\langle v\sigma\rangle = \frac{1}{\epsilon}\frac{N^{C^{5+}} - N_0^{C^{5+}}}{N^{C^{6+}}}\frac{v_i}{\rho_e L}, \tag{3}$$

where $N^{C^{6+}}$ is the number of incident C^{6+} ions, ρ_e is the electron density, L is the target length, v_i is the ion velocity, and ϵ is the ion-detection efficiency which was known.[8]

The relation between the rate coefficient and the cross section for RR is

$$\langle v\sigma\rangle = \int v\sigma f(\bar{v})d\bar{v}, \tag{4}$$

where $f(\bar{v})$ is the relative velocity distribution. We chose to represent this distribution by a product of two Maxwell distributions,

$$f(\bar{v}) = \frac{m}{2\pi kT_\perp}e^{-mv_\perp^2/2kT_\perp}\left[\frac{m}{2\pi kT_\parallel}\right]^{1/2}$$
$$\times e^{-m(v_\parallel - \Delta)^2/2kT_\parallel}, \tag{5}$$

where $v_\perp$ and $v_\parallel$ are the electron-velocity components perpendicular and parallel to the ion-beam directions, respectively, Δ is the detuning velocity which defines the relative energy ($\frac{1}{2}m\Delta^2 = E_r$). $T_\perp$ and $T_\parallel$ are the two temperatures which characterize the relative motion of the electrons and ions. We emphasize that the electron temperature[10] as defined in Eq. (5) is related to the ion rest frame and is not identical to the energy resolution of the merged-beam experiment.[11] The contribution to the energy spread from the transverse temperature is independent of the relative energy (E_r), whereas the contribution from the longitudinal temperature is proportional to the square root of $kT_\parallel E_r$. To be able to compare the rate coefficient obtained from Eq. (3) with theory, one must know $f(\bar{v})$, i.e., $T_\perp$ and $T_\parallel$ must be known.

To determine $T_\perp$ and $T_\parallel$, we used a 24-MeV C^{4+}-ion beam produced in the same way as the C^{6+} beam. That is, the C^{4+} ions were also created via the post-stripper foil to include possible angular effects due to scattering in the foil. C^{4+} in the metastable $1s2s$ states exhibits some very sharp dielectronic-recombination resonances,[6,8] the cross section of which may be represented by δ functions. The rate coefficient given in Eq. (4) was then calculated, and $T_\perp$ and $T_\parallel$ were determined from a fit to the obtained resonances. In Fig. 2 is shown the fit
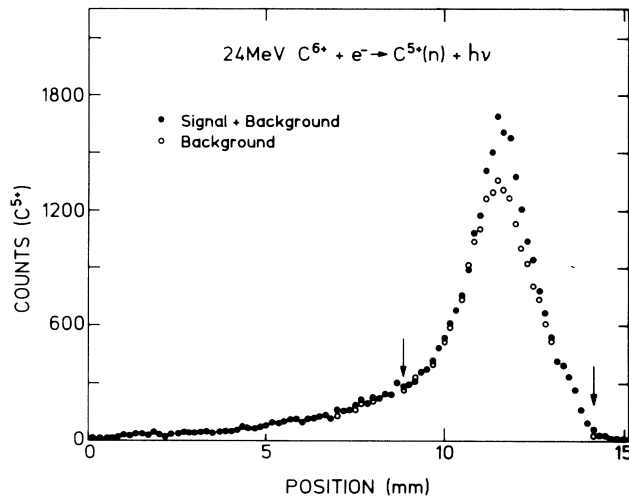

FIG. 1. Position spectrum of C^{5+} ions measured in the channel-plate detector. ●: signal plus background; ○: background. The spectrum was taken at zero relative energy. Arrows indicate the region of integration.
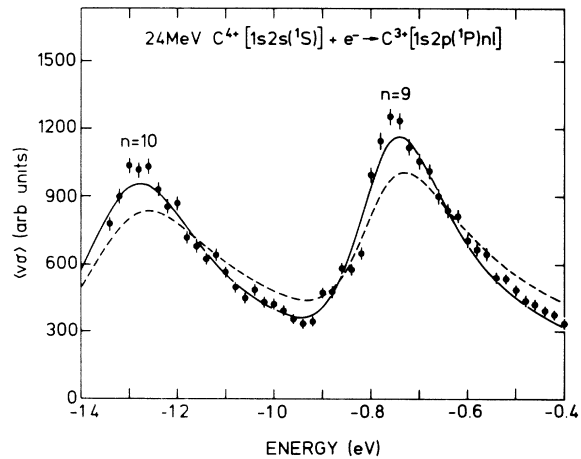

FIG. 2. The $n=9$ and 10 resonances associated with the $^1S \rightarrow {}^1P$ excitation of the dielectronic-recombination process obtained with 24-MeV C^{4+} ($1s2s$). ——: best obtainable fit which yields $kT_\perp = 0.15$ eV and $kT_\parallel = 2.2\times10^{-3}$ eV; ---: fit with $kT_\perp = 0.25$ eV fixed. Negative energies correspond to the situation where the electrons are slower than the ions in the laboratory frame.

which yields $kT_\perp = 0.15$ eV and $kT_\parallel = 2.20 \times 10^{-3}$ eV. The longitudinal temperature is about a factor of 2 higher than that obtained with a dc electron beam,[6,8] the reason being that the modulation of the anode introduced some extra ripple on the cathode voltage.

In the case where the wavelength of the photon is much larger than the extension of the bound state (dipole approximation), Bethe and Salpeter[3] have obtained the following simple analytical expression for the cross section for radiative capture to a hydrogenic level with main quantum number n:

$$\sigma_n = 2.10 \times 10^{-22} \, \text{cm}^2 \frac{q^4 E_0^2}{n E_e (q^2 E_0 + n^2 E_e)} , \qquad (6)$$

where E_e is the kinetic energy of the free electron, E_0 is the Rydberg energy, and q is the charge of the fully stripped ion. The theory of Bethe and Salpeter was based on the assumption that the oscillator strength is continuous across the continuum limit. Formula (6) is expected to be most accurate for high values of n. Indeed, corrections must be applied for the lower states.[12] For $n = 1$, 2, and 3, where the largest cross sections are found, a more accurate calculation was given by Stobbe in 1930.[2] At low energies, these corrections are 20% for $n = 1$, 12% for $n = 2$, and 9% for $n = 3$, the cross sections of Stobbe being smaller than those of Bethe and Salpeter.

In Fig. 3, we present the experimental results. The rate coefficient as defined in Eq. (3) is shown as a function of kinetic energy of the initially free electron. The theoretical curve shown in Fig. 3 was obtained from Eq. (4), with the velocity distribution given in Eq. (5). The temperatures used were $kT_\perp = 0.15$ eV and $kT_\parallel = 2.2 \times 10^{-3}$ eV, as derived from the fit shown in Fig. 2. The theoretical cross section is given by Bethe and Salpeter, formula (6), corrected according to Stobbe for $n = 1$, 2, and 3. In the theoretical curve, values of n up to 60 were included, corresponding to the analyzer field of 10 kV/cm. The uncorrected Bethe and Salpeter theory would result in a rate coefficient which is 8% higher than the curve shown.

The uncertainty of the experimental rate coefficient is estimated to be $\pm 20\%$. This is mainly due to the uncertainty in the determination of the effective target thickness and the ion-detection efficiency. Apparently, experiment and theory are in reasonably good agreement.

Our calculation shows that the influence on the rate coefficient of the longitudinal temperature is rather weak. Changing the longitudinal temperature between 10^{-2} and 10^{-4} eV only changes the rate coefficient by a few percent for relative energies larger than 0.02 eV. At zero relative energy, the change was about 10%. Note that in the present comparison, we do take into account the finite longitudinal temperature $kT_\parallel$, which, although being much smaller than $kT_\perp$, cannot be neglected, especially not at zero relative energy.
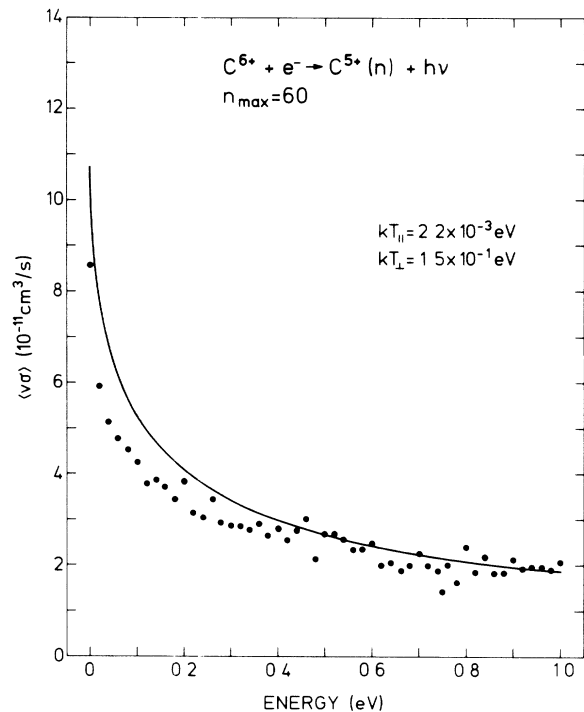

FIG. 3. The rate coefficient $\langle v\sigma \rangle$ as a function of relative energy. The solid curve is the theory by Bethe and Salpeter (Ref. 3) corrected for $n = 1$, 2, and 3 according to the calculation by Stobbe (Ref. 2).

If the transverse temperature $kT_\perp$ were about 0.25 eV, the theory and the experimental data would be in better agreement; yet such a high temperature results in a poor fit to the measured dielectronic-recombination resonances, as seen from Fig. 2.

The disagreement at low energy may be due to a poor representation of the distribution function $f(v)$. The distribution may not be perfectly described by the Maxwell distribution given in Eq. (5). The success in describing the obtained dielectronic-recombination resonances does, however, support the validity of the use of the present distribution.[6,8] The disagreement at zero relative energy could also be explained by the two beams being nonparallel. However, that is not the case at any other relative energy. Finally, experience with other similar merged-beam configurations (electron coolers)[13] indicate that the effective target length L may be smaller than the nominal length because the ion and electron beam may be slightly misaligned at the ends of the confining solenoid. This effect may decrease the effective target length by 10%-20% at low relative energies, and have essentially no effect at higher energies.

In summary, we have for the first time directly measured the rate coefficient for radiative recombination. The data agree well with calculations based on the theory of Bethe and Salpeter[3] and of Stobbe.[2] The technique applied in the present experiment provides a

powerful method for further studies of radiative recombination, also with nonfully stripped ions when no dielectronic-recombination resonances are present at around 0 eV.

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