Competition between radiative recombination and nuclear excitation by electron capture

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Abstract.

The process of electron recombination is investigated considering the possible resonant channel of nuclear excitation by electron capture (NEEC), in which a continuum electron is captured into a bound state of an ion with the simultaneous excitation of the nucleus. Transition rates and total cross sections for NEEC followed by the radiative decay of the nucleus are presented for various heavy-ion collision systems. The role played by radiative recombination (RR) in the NEEC recombination mechanism is investigated and theoretical estimates of the magnitude of the interference between the two processes are presented. We discuss the experimental possibility of discerning NEEC from the RR background, studying the angular distribution of the radiation emitted in the two processes.

1. Introduction

The process of photorecombination in highly charged heavy ions has been the subject of many theoretical and experimental studies up to today, concerning both radiative recombination (RR) and dielectronic recombination (DR) (see [1] and references therein) and their interference [2]. Nuclear excitation by electron capture (NEEC) is the nuclear physics analogue of DR, in which the role of the bound electron is taken by the nucleus. If the electronic and nuclear energy levels match, the resonant recombination process can take place with the simultaneous excitation of the nucleus. When followed by the radiative decay of the nucleus, NEEC can be considered, next to DR, as one of the resonant channels of photorecombination.

The NEEC recombination mechanism was proposed for the first time in Ref. [3]. Partly due to the RR background, NEEC has not yet been observed experimentally, although experimental observation of other atomic physics processes with regard to the internal structure of the nucleus have been reported, such as the bound internal conversion [4] and the nuclear excitation by electron transition [5]. Theoretical studies of NEEC occurring in scattering measurements are therefore particularly useful in finding candidate isotopes and transitions suitable for experiments. In Ref. [6] we derived NEEC rates and cross sections for the case of both electric and magnetic multipole transitions, paying particular interest to collision systems where experimental requirements for the observation of NEEC are likely to be fulfilled. If observed experimentally, NEEC would offer the possibility to explore spectral properties of heavy nuclei through atomic physics experiments.
As the photons emitted in different channels of the electron recombination process are indistinguishable in the total cross section, RR is expected to act as a strong background in any possible NEEC experiment. We investigate the role of RR in the NEEC recombination mechanism and present theoretical estimations of the magnitude of the interference between the two processes. The possibility to experimentally discern NEEC from the RR background is discussed. The different angular distributions of the photons emitted in the two channels of the photorecombination process can be used as means of suppressing the RR contribution in an NEEC experiment.

2. Theoretical predictions

By using the Feshbach projector formalism described in Ref. [6] and the perturbation expansion of the transition operator, we separate the direct and resonant contributions of the photorecombination process. The total cross section can be written as

$$\sigma(E) = \sigma_{RR}(E) + \sigma_{NEEC}(E) + \sigma_{int}(E),$$

with the dependence of the interference cross section on the electron energy $E$ in the general form

$$\sigma_{int}(E) = \sigma_{NEEC}(E) \frac{2(E - E_d) Y_n}{2I_i + 1} \cdot$$

Here we have introduced the dimensionless Fano profile parameter $Q_f$. Furthermore, $E_d$ is the resonance energy, $\Gamma_d$ is the total width of the excited nuclear state, $Y_n$ denotes the NEEC transition rate and $I_i$ and $I_d$ represent the total angular momentum of the nucleus in the ground and excited state, respectively.

In Ref. [6] we have presented total cross sections for NEEC followed by the radiative decay of the nuclear excited state in collision systems corresponding to $E2$ or $M1$ transitions. The energy dependence of the total cross section has the shape of a Lorentzian function, with the width given by the natural width of the nuclear excited states in the order of $10^{-5} - 10^{-8}$ eV and a resonance strength of about 1 beV or less. In Table 1 we present NEEC rates and resonance strengths for electron recombination into the $1s$ orbital of the initially bare Yb and Re ions. These are the collision systems studied for which the resonance strengths have the largest values.

| Isotope | $E_{exc}$(keV) | $E_c$(keV) | Type | $Y_n$(1/s) | $\Gamma_d$(eV) | $S_d$(b eV) |
|---------|----------------|-----------|------|------------|---------------|-------------|
| $^{174}$Yb | 76.471 | 4.897 | $E2$ | $1.79 \times 10^8$ | $4.85 \times 10^{-8}$ | $9.27 \times 10^{-2}$ |
| $^{185}$Re | 125.358 | 42.198 | $M1$ | $2.62 \times 10^{10}$ | $2.36 \times 10^{-5}$ | 1.34 |
| $^{187}$Re | 134.243 | 51.083 | $M1$ | $2.50 \times 10^{10}$ | $2.47 \times 10^{-5}$ | 1.16 |

In Figure 1 we present plots of the interference and scaled NEEC cross section terms as a function of the continuum electron energy for the $M1$ transition of $^{185}$Re and $E2$ transition of $^{174}$Yb, respectively. These are the isotopes with the largest NEEC resonance strengths for the magnetic and electric multipole transitions, respectively. The interference term $\sigma_{int}$ for both electric and magnetic cases is more than two orders of magnitude smaller that the NEEC terms $\sigma_{NEEC}$. The magnitude of the interference term can be explained by investigating the
contributions of the multipolarities that enter in the RR cross section $\sigma_{RR}$. While $\sigma_{RR}$ contains many multipolarities, the interference process involves only the RR photon with the well-defined multipolarity of the nuclear transition. Furthermore, the main contribution to the RR cross section comes from the $E1$ photon and the cross sections corresponding to the $M1$ and $E2$ photons are more than one order of magnitude smaller.

![Graph showing the interference and NEEC terms of the cross section for capture into bare Re$^{75+}$ ions (left) and Yb$^{70+}$ ions (right) as a function of the continuum electron energy. The NEEC term is scaled in both cases by a factor of $10^{-2}$.](image)

**Figure 1.** Interference and NEEC terms of the cross section for capture into bare Re$^{75+}$ ions (left) and Yb$^{70+}$ ions (right) as a function of the continuum electron energy. The NEEC term is scaled in both cases by a factor of $10^{-2}$.

The nuclear excitation is supposed to occur only for the capture of free electrons with energies in the narrow interval of the width. The largest nuclear width $\Gamma_d = 2.47 \times 10^{-5}$ eV characterizes the $^{187}_{75}$Re isotope. As an electron energy resolution in the order of $10^{-5}$ eV or less cannot be presently achieved in an NEEC experiment, the theoretical total cross section should be convoluted with the energy distribution of the electrons to give an orientation for possible measurements. The energy distribution of the incoming electrons is assumed to be a Gaussian one with the width parameter $s$. In order to show the magnitude of the NEEC cross section $\sigma_{NEEC}$ compared to that of RR, Figure 2 presents the ratio of the convoluted cross sections,

$$R(E, s) = \frac{\sigma_{NEEC}(E, s)}{\sigma_{RR}(E, s)}$$

for the case of $^{187}_{75}$Re as a function of the energy of the continuum electron for three different experimental width parameters, $s = 10$ eV, 1 eV and 0.5 eV. The RR total cross section values were taken from Ref. [7]. While for a width parameter $s = 0.5$ eV and $s=1$ eV the contribution of the NEEC term can be discerned from the RR background, for more realistic widths in the order of tens of eVs, the values of the ratio $\sigma_{NEEC}/\sigma_{RR}$ become too small to be observed experimentally.

Rather than considering the total cross sections of NEEC and RR, the ratio of the angular differential cross sections of the photons emitted in the photorecombination process provides a possibility to suppress the RR contribution. While in the case of RR the dominating $E1$ transitions determine a $\sin^2 \theta$ distribution of the photons as a function of the emission angle $\theta$, the $E2$ radiative nuclear decay has a quadrupole pattern with maxima at $45^\circ$ and $135^\circ$. We calculate the ratio of the NEEC and RR angular differential cross sections

$$R(E, \theta) = \left( \frac{d\sigma_{NEEC}}{d\Omega}(E, \theta)/d\Omega_{RR}(E, \theta) \right)_{\theta=\theta_{max}}$$

for the ionic frame emission angles $\theta_{max} = 45^\circ, 90^\circ, 135^\circ$ considering electron capture into bare Yb. The NEEC total cross section is convoluted with the energy distribution of the continuum...
electrons by assuming a Gaussian width parameter of $s=0.1$ eV. The NEEC and RR angular differential cross sections are calculated with the help of the density matrix formalism following the outline in Ref. [8]. In Figure 3 we present the ratio in Eq. (4) as a function of the continuum electron energy, envisaging the scenario of a possible NEEC experiment in a storage ring. For the capture into the Yb$^{70+}$ ion moving with the reduced velocity $\beta = 0.138$ the maximum emission angles for NEEC and RR with respect to the laboratory frame become $\theta_{\text{max}} = 39^\circ, 82^\circ, 128^\circ$. The ratio in Eq. (4) is more than one order of magnitude larger for $\theta = 39^\circ$ and $128^\circ$ than in the case of $\theta = 82^\circ$. For the emission angles $\theta = 39^\circ$ and $\theta = 128^\circ$ the RR contribution is lowered with more than 50% in comparison with the ratio of the total cross sections $\tilde{\sigma}_{\text{NEEC}}(E)/\tilde{\sigma}_{\text{RR}}(E)$.

3. Conclusions
We have investigated several aspects of electron recombination processes involving NEEC as the resonant channel. As the amplitude of the NEEC process is small, the presence of the strong RR background makes the experimental observation challenging. The competition between the NEEC and RR recombination mechanisms has been investigated, in particular the interference between the two channels and the angular distribution of the emitted photons. We have focused on finding means of experimentally distinguishing the two processes and on selecting suitable candidate isotopes for possible future measurements.

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