Negative-continuum dielectronic recombination for heavy ions

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In a collision between an electron and a bare heavy nucleus, the main reaction channel in a wide range of collision energies is the radiative recombination (RR). If the energy of the incident electron in the nuclear rest frame is larger than the ground-state energy of the corresponding He-like ion plus the positron rest energy, the incident electron can be captured into the $1s$ state with simultaneous creation of a free-positron–$1s$-electron pair:

$$X^{Z+} + e^- \to X^{(Z-2)+} + e^+ \,.$$

This process may be denoted as "negative-continuum dielectronic recombination" (NCDR), since it is similar to the usual dielectronic recombination (DR) for a few-electron atom ([1, 2, 3] and references therein), except for the fact that the second electron is not an electron already bound to the ion but an electron from the negative continuum ("Dirac sea") which is "lifted" into a bound state. This is illustrated in Fig. 1. In contrast to the DR process, NCDR is not a resonant process due to the continuum structure of the spectrum at electron energies $\varepsilon < -mc^2$.

It has to be noted, that NCDR is not a unique mechanism for electron-positron pair creation. A lot of previous calculations were devoted to electron-positron pair creation, in particular for collisions of heavy ions at the Coulomb barrier with supercritical fields involved (see, e.g., Ref. [4, 5]). However, the processes investigated in those works considerably differ from NCDR, since in ion-ion collisions one has to deal with electrons and positrons in a two-center Coulomb field. A review on some investigations on electron-positron pair creation at relativistic energies can be found in Ref. [6].

The differential cross section for the NCDR process is given by ($\hbar = m_e = c = 1$)

$$\begin{aligned}\frac{d\sigma}{d\Omega_f} &= \frac{2\pi^3|\mathbf{p}_f|}{\varepsilon_f \mathbf{p}_i^2} \sum_{m_i,m_f} \Big| \sum_{P,\kappa_i,\kappa_f,M_f} (-1)^P \, i^{l_i+l'_f} \\ &\times \exp(i\Delta_{\kappa_i} + i\Delta_{\kappa_f})\sqrt{2l_i+1} \\ &\times C^{j_i\,m_i}_{l_i\,0,\,(1/2)\,m_i} C^{j_f\,M_f}_{l'_f\,m_{l'_f},\,(1/2)\,-m_f} Y^*_{l'_f,m_{l'_f}}(-\mathbf{p_f}/|\mathbf{p_f}|) \\ &\times \langle PaPb|I(\varepsilon_i - \varepsilon_{Pa})|(\varepsilon_i,\kappa_i,m_i)(-\varepsilon_f,\kappa_f,M_f)\rangle \Big|^2 ,\end{aligned}$$

where (ε,κ,m) is the electron wave function with energy ε, angular momentum and parity determined by κ, and angular momentum projection m. P is a permutation operator, Y and C denote spherical harmonics and Clebsch-Gordan coefficients, ε_i, $\mathbf{p_i}$ and ε_f, $\mathbf{p_f}$ denote energy and momentum of the incoming electron and outgoing positron, Δ_κ is a phase shift, and I is an expression related to the photon propagator [7]. Details will be published elsewhere [8].

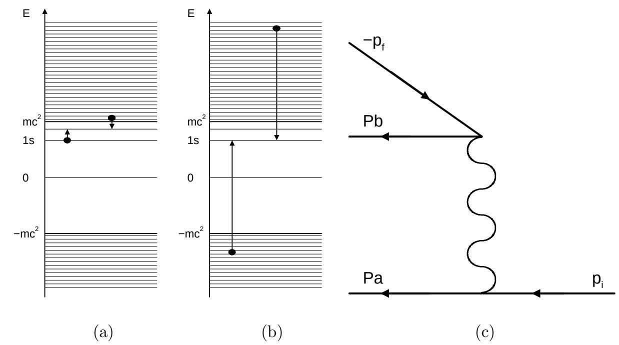

Fig. 1: Schematic representation of DR (a), NCDR into the $1s^2$ state (b), and NCDR diagram (c). a and b are $1s$ states with opposite angular momentum projections.

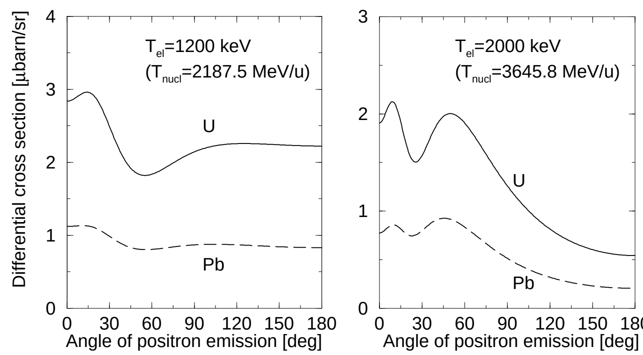

Fig. 2: Differential cross section of NCDR in the nucleus-rest frame for kinetic energies of the electrons of 1200 keV and 2000 keV.

The signature of positron emission makes our new process clearly distinct from all other types of electron capture and it will be observable at the next generation of heavy-ion storage rings at GSI.

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