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COMPOUND SYSTEMS

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Electronic transition times in supercritical compound systems*

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Abstract:

Radiative transitions of electrons to the K-shell in the supercritical atom $Z=188$ are investigated. This system may be transiently produced in $g_2^U + g_6^{Cm}$ collisions with bombarding energies close to the nuclear Coulomb barrier. For the total transition time we obtained $\tau = 8.8 \cdot 10^{-19} \text{ s}$. The dominance of transitions with magnetic multipolarity is pointed out.

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Positron production has been observed in quasi-molecular collisions of very heavy ions such as $g_2U + g_6Cm$ with a combined charge $Z=Z_1+Z_2=188$. For specific ion scattering angles the measured energy distribution of the emitted positrons exhibits distinct structure (Berdermann et al. 1981, Bokemeyer et al. 1981). According to the ideas of Reinhardt et al. (1981b) the projectile and target may come into nuclear contact even for bombarding energies slightly below the nuclear Coulomb barrier. These authors furthermore assume that for a period of $T \sim 4 \cdot 10^{-20}$ s a superheavy compound system is produced. This long sticking time causes phase shifts in the complex electron excitation amplitude leaving as observable effect oscillations in the positron spectra and δ -electron distributions (Soff et al. 1979b). In the superheavy system $Z=188$ the electron K-shell is imbedded as resonance in the negative energy continuum. A vacant K-shell thus may lead to spontaneous positron production (Reinhardt and Greiner 1977, Reinhardt, Müller and Greiner 1981a). Reinhardt et al. (1981b) predicted a pronounced peak in the positron spectra due to the spontaneous part of the positron production mechanism thereby indicating the energetical location of the $1s_{1/2}$ -resonance in the negative energy continuum.

Motivated by these theoretical investigations we considered the question whether a created K-vacancy may also decay by radiative transitions during the sticking period. This would represent a competing process to the spontaneous positron creation. On the other hand the radiative transitions could possibly manifest themselves as peaks in the quasi-molecular photon spectra. A corresponding calculation for deep inelastic collisions of lighter nuclei was presented by Anholt (1979b). For the theoretical ingredients see also Anholt (1978) and

Anholt (1979a). Quasi-molecular radiation for superheavy systems has been observed in Pb + Pb collisions with ion energies far below the nuclear Coulomb barrier (Stoiller et al. 1980, Mokler and Liesen 1981). Fair agreement with the calculations of Kirsch et al. (1979) was obtained. However, the background due to strong nuclear Coulomb excitation of the Cm-target and the U-projectile and subsequent nuclear radiative transitions is expected to dominate over the quasi-molecular photon spectrum. The influence of a delay time due to a nuclear reaction on the quasimolecular photon spectrum in a Pb+Pb collision has been discussed in a recent paper of Kirsch et al. (1982).

The initial step in the theoretical determination of transition rates is the calculation of electron binding energies and wavefunctions. For levels in the discrete spectrum this is easily achieved by solving the radial Dirac equation with standard predictor-corrector methods (Soff et al. 1979a). For the nucleus we assumed a homogeneously charged sphere with a radius $R=1.2 A^{1/3}$ and $A=A_1+A_2=486$. In the system $Z=188$ the $1s_{1/2}$ - and the $2p_{1/2}$ -states are both imbedded as resonances in the negative energy continuum. The relativistic continuum wavefunctions are computed numerically as described extensively by Soff et al. (1979a). The energy eigenvalue E_r of the resonance may be evaluated by two different methods which yield identical results. As a function of the continuum energy E a pronounced maximum of the probability density $|\psi(r_p, E)|^2 r_p^2$ occurs at the position r_p of the first peak. As second signature for the resonance the phase δ of the continuum wavefunctions takes the value $\delta = \pi/2$ at this specific energy. In fig. 1 we show the binding energies of various bound states. The arrows indicate the considered radiative transitions to the $1s_{1/2}$ -state. Most of the transitions may also take place via internal electron-positron pair conversion since the corresponding energy differences are above the pair production threshold. But we shall not

discuss this type of Auger process in more detail. Furthermore, we also neglect radiative transitions from electron states of the Dirac sea to the vacant resonance state which is equivalent to positron bremsstrahlung in the strong Coulomb field of the nucleus.

For the projection of the bound state out of the continuum we applied precisely the same formalism as Reinhardt, Müller and Greiner (1981a). The original Coulomb potential $V(r)$ of a homogeneously charged sphere in the radial Dirac equation is replaced by

$$\tilde{V}(r) = \Theta(r_c - r) V(r) + \Theta(r - r_c) V(r_c) \quad (1)$$

where $\Theta(r)$ denotes the step function. The cut-off radius r_c is approximately determined by the classical turning point

$$E_r - V(r_c) = -\gamma m \quad (2)$$

The constant γ has been empirically chosen to $\gamma=0.9$. This leads to ($\hbar=c=1$)

$$r_c = \frac{-Z\alpha}{E_r + \gamma m} \quad (3)$$

The constancy of the potential (1) for $r > r_c$ guarantees the exponential fall-off of the $1s_{1/2}$ and $2p_{1/2}$ -wavefunction. The numerical solution of the radial Dirac equation with the potential (1) and the normalization of the obtained eigenfunctions for $E=E_r$ thus yield the required bound state wavefunctions.

For the evaluation of the various radiative decay widths Γ and equivalently for the transition times $\tau = \hbar/\Gamma$ we employed the formulae as published by Anholt and Rasmussen (1974) and by Soff and Müller (1977). In the cited references relativistic Hartree-Fock wavefunctions are used for the description of the electron bound states, which are replaced in

the present calculation by single electron wavefunctions. In table 1 we present the binding energies of the different initial states as well as of the final state. The associated multipolarities of the transition are indicated in the third column. The calculated decay widths Γ in eV are quoted in the last column of this table. The total decay width amounts to $\Gamma = 746$ eV which corresponds to $\tau = 8.8 \cdot 10^{-19}$ s. This radiative transition time is about a factor 20 larger than the assumed nuclear sticking time by Reinhardt et al. (1981b) and may also safely be neglected in the positron production mechanism. A striking feature is the dominance of the $2s_{1/2} - 1s_{1/2}$ transition of multipolarity M1 which yields about one half of the total decay width.

Table 1

state	binding energy [keV]	multipolarity	$\Gamma(e\gamma)$
$1s_{1/2}$	-1723.1	-	-
$2p_{1/2}$	-1241.7	E1	9.8
$2s_{1/2}$	- 440.2	M1	383.0
$3p_{1/2}$	- 204.9	E1	25.9
$3s_{1/2}$	- 149.2	M1	81.5
$2p_{3/2}$	- 139.2	E1/M2	116.1
$4p_{1/2}$	- 81.0	E1	7.2
$4s_{1/2}$	- 66.8	M1	25.2
$3p_{3/2}$	- 64.9	E1/M2	56.8
$3d_{3/2}$	- 64.9	E2/M1	11.9
$3d_{5/2}$	- 56.6	E2/M3	0.4
$4p_{3/2}$	- 36.1	E1/M2	27.1
$4d_{3/2}$	- 36.1	E2/M1	0.9
$4d_{5/2}$	- 32.4	E2/M3	0.3

Table caption:

Table 1: Radiative transitions to the $1s_{1/2}$ -state. The superheavy nucleus $Z = 188$ with $R \approx 9.4$ fm is considered. The first column denotes the initial electron state. The corresponding binding energy is given in the second column. The considered multipolarities and the radiative decay width Γ , respectively, may be taken from the last two columns.

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Z = 188

Figure Caption:

Fig. 1: Binding energies of various electron states in the superheavy atom $Z=188$. The arrows indicate the considered radiative transitions to the vacant $1s_{1/2}$ -resonance state. Additional radiative transitions from electron states of the Dirac sea to the K-shell are depicted qualitatively by the big arrow.