Chaotic many-body states as a source of strong enhancement of electron recombination with multicharged ions

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In this work we consider the problem of recombination of low-energy electrons with multicharged ions. It has been known for a while that in such systems the recombination rates can be much greater than those due to simple single-particle direct radiative recombination (RR). The size of this enhancement ranges from a factor of about ten for Ar^{13+}, Au^{50+}, Pb^{53+}, and U^{28+} [1] to over a hundred for Au^{25+} [2]. For few-electron ions, e.g., C^{4+}, Ne^{7+} or Ar^{15+}, the observed rates are described well by the sum of direct and dielectronic recombination rates, the latter being seen as individual resonances on the RR background. In other systems, like U^{28+}, the resonant structure becomes complicated, and although some individual resonances are clearly seen, most of them cannot be identified [3]. Furthermore, in Au^{25+} the observed recombination rate does not reveal any resonant structure at all, at electron energy resolution of 0.1 eV. The energy dependence of the rate at low electron energies (~ 1 eV) is close to that of RR, but its magnitude is about 150 times greater!

In this work we show that a dominant mechanism of recombination in this system involves electron capture into *chaotic many-electron states* of the compound ion (e.g., Au^{24+} for $e^- + Au^{25+}$), which are then stabilized by photoemission. This mechanism is similar to the usual dielectronic recombination, whereby the incoming electron interacts with one of the target electrons and forms an autoionizing doubly-excited state. However, in Au^{24+} and other complex multicharged ions the two-electron excitations are strongly mixed with three- and more electron excitations due to strong configuration interaction. The spectrum of such multiply excited states is much denser and much more complicated than the spectrum of simple two-electron excitations. This situation is analogous to that in a compound nucleus formed by neutron capture [4], where the energy of the neutron is re-distributed among a large number of valence nucleons.

A straightforward calculation of highly-excited many-electron states of an open-shell multicharged ion, like Au^{24+}, i.e. diagonalization of the Hamiltonian matrix, is a formidable task because of a very large number of configurations involved. On the other hand, this degree of complexity leads to simplifications. Owing to a large level density and small spacings between many-body basis states, their mixing by residual electron Coulomb interaction is in some sense complete. In this situation, which may be described as *many-body quantum chaos*, the average

mean-squared characteristics of the chaotic eigenstates can be calculated using statistical theory. Such theory has been developed and tested in our recent works on many-body quantum chaos in atoms [5]. This theory starts with the construction of a mean field, which defines the spectrum of single-particle states, e.g. the Dirac-Fock approximation which we use in this work. The single-particle orbitals are then used to calculate properties of many-electron states: the level density, orbital occupation numbers, mean-squared values of transition amplitudes, etc.

When this approach is applied to Au^{24+}, we find that its excitation spectrum near the ionization threshold $I = 750$ eV is indeed dominated by multiply-excited states, with level spacings $D \approx 3 \times 10^{-5}$ au ~ 1 meV for a given angular momentum and parity J^π. Their angular momenta range between $\frac{1}{2}$ and $15\frac{1}{2}$, $J \sim 5$ being the most abundant. Each of the states is a superposition of a large number N of many-electron basis states strongly mixed together within the energy range $\Gamma_{\rm spr} \approx 0.5$ a.u. (the *spreading width*): $N \sim \Gamma_{\rm spr}/D \sim 2 \times 10^4$.

Electrons scattered by Au^{25+} ions my be captured in these chaotic many-electron resonances. The energy-averaged contribution of this process to the recombination cross section is

$$\sigma^{(\rm r)} \approx \frac{\pi^2}{\varepsilon} \frac{\Gamma_\gamma \Gamma_e}{D(\Gamma_\gamma + \Gamma_e)} \approx \frac{\pi^2}{\varepsilon} \frac{\Gamma_e}{D} \qquad (\Gamma_\gamma \gg \Gamma_e), \tag{1}$$

where Γ_γ and Γ_e are the mean radiative and autoionization widths of the resonances. The second equation follows from our numerical estimates: $\Gamma_\gamma \sim 2 \times 10^{-5}$ au, $\Gamma_e \sim 5 \times 10^{-7}$ au (preliminary data), based on the statistical-theory expressions for the mean-squared dipole and Coulomb matrix elements. (Note that these numbers are different from the crude estimates presented in [6].) The radiative width, obtained as a sum over many transitions into the lower-lying states, is comparable to the resonance spacing D, and is much greater than the autoionization width. The contribution of electron capture into chaotic many-electron resonances with given J^π (1) is about ten times greater than the RR cross section. Taking into account that resonances with about ten different J and different parities are present in the spectrum, we obtain that the contribution of the resonant capture exceeds that of RR by two orders of magnitude, in agreement with experimental data [2].

In conclusion, we believe that multicharged ions, as well as complex open-shell atoms, are natural laboratories for studying many-body quantum chaos. It gives rise to such observable phenomena as strong quasicontinuous (due to tiny resonance spacings) enhancement of the electron-ion recombination.

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