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Lamb Shift in Li-Like Ions of Gold, Lead and Uranium

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Energies of the dielectronic recombination (DR) resonances are measured with extremely large accuracy in electron coolers of storage rings where a very good energy definition of the merged ion and electron beams can be achieved. This enables a precise evaluation of the Lamb shift for heavy ions and hence provides a test of the QED theory in strong fields. The radiative (QED) corrections scale approximately with Z^4 and therefore become increasingly important for the heaviest ions. The same is true for corrections caused by relativistic effects and by the finite size of the nucleus.

At the electron cooler of the Experimental Storage Ring (ESR) of the GSI in Darmstadt the $2s_{1/2} - 2p_{1/2}$ energy splitting was measured for Li-like ions of gold, lead and uranium. The principle of measurement is shown in Fig. 1. Free electron from the cooler beam can be captured into bound state of the ion. The sum of binding and kinetic energy of the electron is released by photon emission or is used to excite one of the bound electrons of the ion whenever the resonance condition is fulfilled. In the Li-like ions the $2s_{1/2} \rightarrow 2p_{1/2}$ excitations are possible from the ground-state, thus providing $1s^2 2p_{1/2} n l_j$ DR resonances in the low energy domain ($n l_j$ denotes quantum numbers of the captured electron). The recombined ions with one additional electron leave the beam trajectory and are detected in the particle detector positioned downstream the beam line. When changing the relative kinetic energy of the merged beams we scan over an infinite series of DR resonances where the free electrons are captured into high Rydberg states until the series limit is reached. The limit can be evaluated from energy extrapolation of the individual DR resonance peaks. The Lamb shift defined as the $2s_{1/2} \rightarrow 2p_{1/2}$ excitation energy is equal to the kinematic energy of electron moving relative to the ion, measured at the DR series limit ($E_B = 0$).

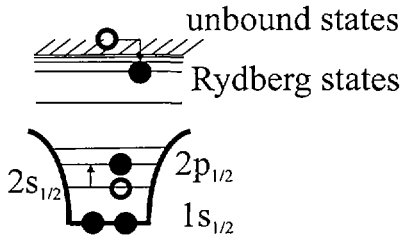

Fig. 1: DR process in the Li-like ion.

In the present work the following method of evaluating the Lamb shift has been used. For high values of the quantum number n the mutual influence of core and Rydberg electrons can be neglected and the excitation energy E_∞ (Lamb shift) is equal to: $E_\infty(Z) = E_{Res}(Z,n,j) + E_B(Z,n,j)$, where E_{Res} is the DR resonance energy and E_B the binding energy of the Rydberg electron. Energy differences between Rydberg states can be computed accurately e.g. in an H-like approximation. Simultaneous fit of this equation to a multitude of DR resonances permits us to evaluate the series limit energy with a large accuracy. The accuracy of the fit was improved by using the theory based knowledge about the shape of resonances with large fine-structure ($n < 25$). As seen in Fig. 3, the component intensities and energy splitting are well reproduced by the MCDF calculation if only large enough j-components are included.

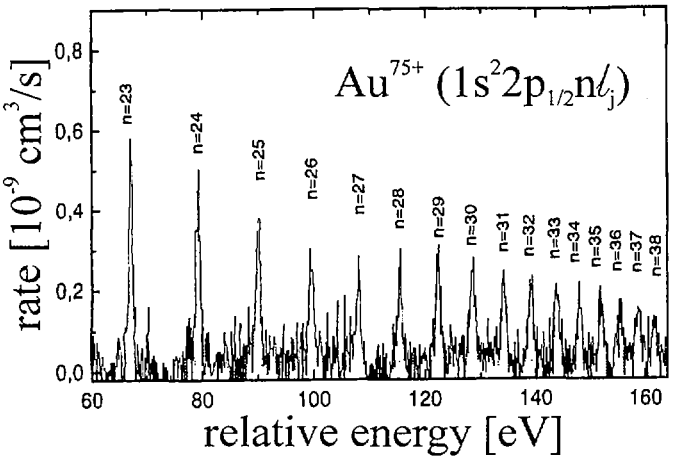

Fig. 2: DR resonances observed in the Li-like gold. Radiative recombination (RR) and background contributions are subtracted.

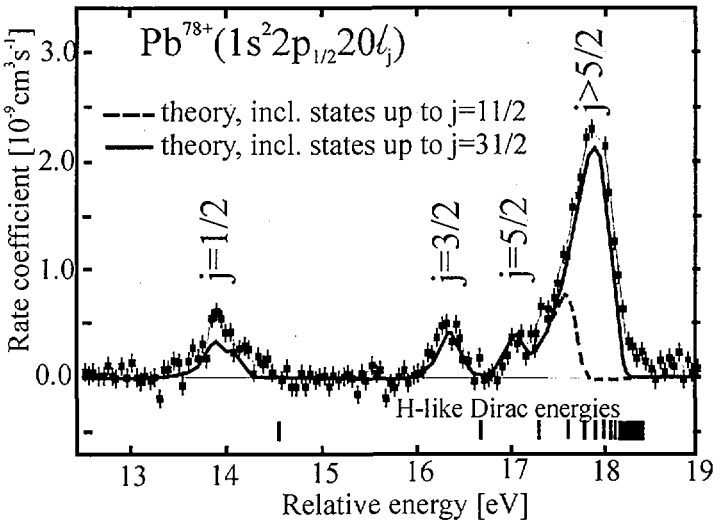

Fig. 3: Recombination rate coefficient measured for the $Pb^{78+}(1s^2 2p_{1/2} 20l_j)$ multiplet and compared to the fully relativistic calculations (GRASP code). The theory has been shifted by –0.65 eV.

From the fit the following values for the $2s_{1/2} - 2p_{1/2}$ splitting have been obtained: $E_\infty(Au^{76+})$ = 216.11(20) eV, $E_\infty(Pb^{79+})$ = 230.62(20) eV, and $E_\infty(U^{89+})$ = 280.56(20) eV. The main source of error is the available knowledge of the velocity distribution of the cooler electrons. The accuracy is comparable and the values agree with the recent calculations of the Lamb shift [1].

Reference:

1. Yerokhin et al., Phys. Rev. Lett. **85** (2000) 4699.

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Polarization of the $K_\alpha L^1$ X-Ray Satellite in Copper after 2 MeV Proton Impact

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One of the simplest systems where we can check our understanding of alignment development due to couplings to additional vacancies is a double vacancy state created by simultaneous ionization of *1s* and *2p* electrons. In the region of intermediate coupling (appropriate for copper atoms) the vacancies are coupled to a singlet $^1P_1$ or a triplet $^3P_{0,1,2}$ state and decay to a manifold of the $2p^{-2}$ ($^1S_0$, $^1D_2$, $^3P_{0,1,2}$) states. Twelve stronger and several weaker transitions are forming the $K_\alpha L^1$ satellite peak at the high energy tail of the $K_{\alpha 1}$ peak diagram. Alignment of the $1s^{-1}2p^{-1}$ double vacancy state of copper created in a collision with 2 MeV protons was studied by polarization measurement of the $K_\alpha L^1$ peak components using the bent crystal polarimeter. A resolution of 1.58 eV (FWHM) was achieved (i.e. gaussian contribution to the Voigt profile). Experimental details are described elsewhere [1]. Experimental spectra of the $1s^{-1}2p^{-1} \rightarrow 2p^{-2}$ transitions were compared with those calculated using a MCDF code GRASP92 [2].

Polarization value is defined as a ratio $P = (J_2 - J_1)/(J_2 + J_1)$, where J_1 is the intensity of X-ray radiation measured perpendicular and J_2 parallel to the beam axis. (*Please note that the difference spectrum $(J_2 - J_1)$ is approximately proportional to polarization multiplied by intensity of the transition*). Polarization is related to the anisotropy known from the angular distribution measurements by a formula $A = 2*P/(P-3)$. Anisotropy depends on the spatial orientation of spin of the initial level of transition and usually it can be decomposed into the spin dependent factor α_2 and the alignment of level: $A = \alpha_2 * \mathcal{A}_{20}$. Within the "sudden approximation" the alignment is created during collision due to the Coulomb interaction with proton what influences the electron orbital momentum, *L*. The alignment is reduced by Coster-Kronig (C-K) transitions from the non-aligned state $1s^{-1}2s^{-1}$. Further reduction of alignment comes from the spin-orbit interaction. There is no spin-orbit interaction for the ^1P state (S = 0). The formulae for reduction of alignment for the $^3P_{0,1,2}$ states can be easily derived from [3] and the factor α_2 is calculated in [4]. The aim of the present work was to evaluate the initial alignment of the $1s^{-1}2p^{-1}$ double vacancy state by fitting the calculations to experimental spectra.