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Proposal for experiment at Tandem accelerator

Coincidence measurements for double inner-shell vacancy production and sharing in dependence of projectile velocity

Motivation

Double electron transitions in atomic collisions have received much attention for a long time both theoretically and experimentally (see e.g. ref. [1-5]), and many of these studies have been done on the simplest two-electron atom – He (see e.g. ref. [6]). The double ionization of inner-shell electrons is a special case of double electron transition.

At very fast atomic collisions, such double transitions involve the electron-electron interaction, because two interactions of the projectile with the target electrons is less probable. This is the so-called two-step 1 (TS1) mechanism: the double ionization occurs predominantly via electron-electron interactions following a single interaction with the projectile.

At moderately fast collisions for high projectile-Z (charge state q), double electron transition could proceed with higher probability via two interactions of the projectile with the active electrons (the two-step 2 mechanism – TS2). Then, TS2 is a second-order process which does not involve the electron-electron interaction (electron correlations). Generally, the term electron correlation is used any time the data cannot be explained by the independent electron model (IEM). For ex., IEM cannot explain the observed dependence on the projectile charge sign (positive or negative ions) of the double ionization/excitation of He by proton and electron (antiproton), or the observed dependence on the projectile charge q for heavier projectiles.

Total ionization cross sections for single ionization by fast projectiles with small charge q are well described by first order perturbation theory, which gives a projectile-Z^2 dependence of the cross sections. Double ionization is a four-body problem with strong interactions, which may be described in terms of the coherent sum of the first- and second-order terms in the Born expansion in the interaction strength, given by the projectile-Z. This gives a Z^3 contribution in the cross sections.

In slow collisions of heavy ions in the K-L level matching region, two main mecanisms are contributing to K (projectile) and L (target) vacancy production [7]: (i) the formation of vacancies in the highly promoted molecular orbital (MO) 3dσ at small internuclear separations, and (ii) the sharing of these vacancies on the outgoing part of the collision, between the two collision partners. The sum of the production cross sections in the K and L levels can be interpreted as the vacancy formation cross section in the 3dσ highly promoted MO.

An enhancement of 3dσ MO ionization at small impact parameters in the 1.5 MeV/u Ni + Pb collision has been observed [8]. Integral measurements on MeV/u Mn, Fe, Co, Ni, Cu +Au, Bi collisions [9] have evidenced an anomalous, non-exponential, behavior of the vacancy sharing probability.

Therefore, we expect that the study of two vacancy production and sharing in such heavy collision systems could give new insight into the underlying mechanisms. The same time, as mentioned before, the ratio of double to single ionization cross sections could probe either electron correlation or higher order terms in the perturbation expansion.

Some of previous measurements on light collision systems (e.g., in studies involving double ionization-excitation, or double excitation) have used high resolution X-ray or Auger electron spectroscopy, where the hyper-satellite lines corresponding to different transitions could be well distinguished in the spectra.

We propose here to use another technique, the X-X coincidences, by which the integral double ionization cross sections could be measured. The proposed collision system is ^{56}Fe + Pt (but other targets, like Au and Bi, could be also taken into account).

Experiment

X-ray-X-ray coincidences, with two detectors placed at 90 degrees to the beam direction, as well as single X-ray spectra normalized to the scattered projectiles at a small angle to the beam direction will be measured. A standard slow-fast coincidence circuit and the multiparameter acquisition system of the department will be used.

The double vacancy production will be signaled by the hyper-satellite X-ray (the first X-ray deexciting a double K vacancy), which could be distinguished from the satellite one (the second X-ray) in the X-ray spectra. The X-ray spectra will be analyzed off-line by using a least-squares fit program.

If we do not discriminate between the satellite and hyper-satellite lines in the X-X coincidence spectra, the number of true X Kα – X Kα coincidences will be given by:

$$C_{K\alpha(2)[K\alpha(1)]} = C_{K\alpha(1)[K\alpha(2)]} \equiv C_{K\alpha K\alpha} = \Phi_p\, N_t\, \sigma_{KK}\, (\omega_K \cdot \Gamma_{K\alpha}/\Gamma_{KX})^2 \cdot 2 \cdot \varepsilon_{1K\alpha}\, \varepsilon_{2K\alpha}\, \varepsilon_c\ , \quad (1)$$

where we neglected the possible differences between the atomic deexcitation parameters ($\omega_K \cdot \Gamma_{K\alpha}/\Gamma_{KX}$, the fluorescence yield times the partial radiative width of the X Kα transitions) of the hyper-satellite and satellite lines. Here, we used [ ] to indicate the coincidence window, Φ_p is the number of incident particles, N_t – the number of target atoms per cm^2, σ_{KK} – the double K-vacancy production cross section in cm^2, and different ε give the (absolute) efficiencies of the X-ray detectors ($\varepsilon_{1K\alpha}, \varepsilon_{2K\alpha}$) or the coincidence efficiency (ε_c). Analogous expresions could be writen for X L – X L or X L – X K coincidences (in the latter case, the factor 2 is missing).

If we put the coincidence window e.g. on Kα X-rays registered by detector No. 1, their number will be given by:

$$N_{K\alpha}^{(1)} = \Phi_p\, N_t\, \sigma_K\, (\omega_K\, \Gamma_{K\alpha}/\Gamma_{KX})\, \varepsilon_{1K\alpha}\ ,$$

where we noted by σ_K the single K-vacancy production cross section; then we can write:

$$C_{K\alpha(2)[K\alpha(1)]} = N_{K\alpha}^{(1)}\, (\sigma_{KK} / \sigma_K\,) \cdot \omega_K \cdot (\Gamma_{K\alpha}/\Gamma_{KX}) \cdot 2 \cdot \varepsilon_{2K\alpha}\, \varepsilon_c\ .$$

The unknown product $N_{K\alpha}^{(1)}\cdot\varepsilon_c$ could be determined if we include in the coincidence circuit, in parallel with the signals of the detector No. 2, a generator of random pulses. Then the number of random coincidences between the Kα X-rays in the coincidence window and the generator pulses will be given by:

$$C_{g[K\alpha(1)]} = R_g\, N_{K\alpha}^{(1)}\, T\, \varepsilon_c\ ,$$

where R_g is the generator rate and T – the time window of the coincidence circuit. If we substitute the product $N_{K\alpha}^{(1)}\cdot\varepsilon_c$ from this equation into the previous one, the following relation is obtained for the ratio of double to single K-vacancy production:

$$\frac{\sigma_{KK}}{\sigma_K} = \frac{C_{K\alpha(2)[K\alpha(1)]}}{C_{g[K\alpha(1)]}} \frac{R_g T}{\omega_K(\Gamma_{K\alpha}/\Gamma_{KX})\cdot 2\varepsilon_{2K\alpha}}\ . \qquad (2)$$

The cross section σ_K for single vacancy production could be determined separately by measuring the Coulomb scattered projectiles and normalizing to the Rutherford cross section. For particle detection, a plastic scintillator mounted at small angles to the beam will be used.

Counting rate estimate, using the relation (1) :

- the beam intensity of 1 pnA, i.e. around 10^{10} particles/s,
- a target of 100 μg/cm^2, i.e. around 10^{18} atoms/cm^2
- $\sigma_{KK}/\sigma_K \approx 1\%$ and $\sigma_K \approx 10$ kb, gives $\sigma_{KK} \approx 100\ \mathrm{b} = 10^{-22}\ \mathrm{cm}^2$,
- $(\omega_K\cdot\Gamma_{K\alpha}/\Gamma_{KX})^2 \approx 10^{-2}$,
- $\cdot\varepsilon_{1K\alpha}\ \varepsilon_{2K\alpha}\ \varepsilon_c \approx 10^{-5}$,

we estimate an X-X coincidence counting rate of ≈ 0.2 s^{-1}, that means around 7200 events in 10 hours.

Our beam request is for 4 days, 2 days for beam adjustments and experiment tuning and 2 days to measure at least four energies in the range of 0.5-1.5 MeV/u. The proposed period: after 15 November, preferably in the first part of December 2010.

References

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