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Proposal for experiments at Tandem accelerator

Atomic inner-shell processes studied by integral measurements at MeV/u energies

Motivation

(1) Inner-shell ionization cross sections

The excitation of the X-rays in the light ion - atom collisions has been intensively studied in the last decades in order to develop and test theoretical approaches, as well as to build a database of X-ray production cross sections for applications, like the particle induced X-ray emission (PIXE). Therefore, a rather good understanding of X-ray production by light ion impact (protons, alpha particles etc.) has been obtained (see e. g. [1] and references therein). The situation is less satisfactory for heavier ions, with less and disparate data.

Direct ionization of the inner- (K- and L-) shells by light ions can be reasonably described by first-order treatments based on the plane wave Born (PWBA) and semi-classical (SCA) approximations. These theoretical approaches have been further extended to include higher order effects, like the energy loss (E), coulomb deflection (C) and relativistic (R) effects within the perturbed stationary state (PSS) approach, which takes into account electron binding or polarization effects, resulting in the so-called ECPSSR model. In the SCA, the electron binding effect is included in an extreme case, the united-atom (UA) limit; the separated-atom (SA) limit of the SCA calculations does not at all take into account the binding effect.

In slow collisions with heavier projectiles, molecular-orbital (MO) excitation mechanisms may come into play. As shown before for slow collisions in the asymmetric collision system ^{48}Ti + Pt [2], the inner-shell ionization could not be explained by only direct ionization from atomic states (plus possible electron capture contribution); furthermore, the MO mechanisms that are specific for the K-L level matching region should have an important contribution. Instead, in the ^{12}C, ^{16}O, ^{32}S, ^{35}Cl + Pt collisions, the ionization mechanism from atomic states has dominant contribution.

The first aim of this proposal is to obtain new experimental evidence about setting up the quasi-molecular mechanism of electron promotion. This will be done by comparison of new experimental data, for projectiles like ^{40}Ca and/or ^{51}V, with direct ionization calculations (plus possible non-radiative electron capture contribution).

Another aim of this measurements is the applicability of heavier ions to the analytical work. Using PIXE with heavier ions than protons needs to supplement the present data of inner-shell ionization cross sections with new ones, for many projectiles, target elements and impact energies. New data are necessary also to overcome the difficulties for standardization of heavy-ion PIXE, e.g. due to the presence of multiple ionization processes, which induce modifications in the X-ray energies and relative yields.

(2) Radiative electron capture

The knowledge of accurate ionization and recombination (charge changing or charge transfer) reaction rates of heavy ions is crucial in different domains, like ionization balance of highly charged ions in hot plasmas, research of X-ray lasers etc.

One of the fundamental processes in atomic collisions is the transfer of an electron from a target atom into a fast-moving projectile. For electron capture into highly charged ions, three different mechanisms should be considered:

- non-radiative electron capture (NREC);
- radiative electron capture (REC) [3]; for loosely bound target electrons, REC is almost identical to radiative recombination (RR) of free electrons which is the inverse of the photoelectric effect; therefore, measurement of REC cross sections may be a way to indirectly determine photo-ionization cross sections[+)]; and
- resonant transfer and excitation (the inverse of an Auger transition).

In the non-relativistic domain, the dominant electron transfer process is NREC where the electron is transferred without radiation from a bound target state into a bound state of the projectile. The energy and momentum gained in the capture process are shared between the projectile and the target atom. For non-relativistic collisions, the cross-section dependence on the projectile and target atomic number (Z_P and Z_T) is given by first-order perturbation theory and scales approximately like $\sim Z_T^5\, Z_P^5 / v^{12}$, where v is the projectile velocity. The NREC process is dominant for heavier target atoms.

On the other hand, for high collision velocities and low-Z targets, electron transfer is entirely determined by REC, where the coupling between the electron and the electromagnetic field of the fast-moving projectiles leads to the emission of a photon carrying away the momentum and energy difference between the initial and final electron states. The general scaling property of REC cross sections derived from the non-relativistic dipole approximation is given as $\sim Z_T\, Z_P^5 / v^5$, where Z_P and Z_T are the projectile and target atomic number, respectively, and v is the projectile velocity.

Proposals

For the present beam, we propose two integral measurements:

(1) Inner-(K- and L-) shell ionization and setting up of quasi-molecular mechanism of electron promotion: integral ionization cross sections in dependence of collision energy for different projectiles.

As said before, we intend to obtain new experimental evidence about setting up the quasi-molecular mechanism of electron promotion. This will be done by comparison of the experimental data with direct ionization calculations (plus possible electron capture contribution). The existing data of Pt L-shell ionization (by ^{12}C, ^{16}O, ^{32}S, ^{35}Cl and ^{48}Ti projectiles) in the MeV/ u energy region will be extended to other projectiles, like ^{40}Ca and ^{51}V.

The data will be compared with direct ionization models (SCA and ECPSSR). Possible set up of quasi-molecular mechanisms for ^{40}Ca projectile will be analyzed.

By using the energy and yield shifts measurements, outer-shell multiple ionization probabilities could be estimated and interpreted in terms of first order models (the geometrical model).

(2) Radiative electron capture (REC) measurements.

We propose to measure REC cross sections in dependence of bombarding energy in the MeV/u range in two collisions: ^{31}P + Cr and/or ^{35}Cl + Cr; thin Cr target will be used. The mean electron binding energy in the final state as well as the inverse photo-ionization cross sections will be estimated and compared with theoretical predictions.

Experiment

The collimated ion beams of ^{40}Ca an/or ^{51}V in the first experiment and ^{15}P and/or ^{35}Cl in the second (having charge states q=3-10), charge state and energy selected by a 90^0 analyzing magnet, will bombard thin self-supported Pt or Cr targets, tilted at 45^0 to the beam direction. The emitted X-ray spectra will be measured with a Ge HP detector, placed at 90^0 to the beam direction. The scattered projectiles are measured by using a thin plastic scintillator foil (110 μm thickness) placed at 90^0 or at a forward angle. Measuring the Coulomb scattered particles simultaneously at 90^0 and the forward angle, and using the angular dependence given by the Rutherford cross section, after correcting for detector solid angle, will allow us to determine the forward scattering angle. The efficiency and the solid angle of the X-ray and particle detectors will be measured using calibrated X-ray and alpha radioactive sources (^{241}Am).

The needed beam time

(1) Because the excitation function will be measured at 15 energies, about 2.5 hours/energy (the X-ray counting rate is limited at less than 1000 Hz), we appreciate about 2.5 days per collision system, therefore 5 days are needed for two collision systems: ^{40}Ca + Pt and ^{51}V + Pt.

(2) For the proposed measurements, excitation functions for ^{31}P, ^{35}Cl + Cr, about 3 days will be necessary.

In conclusion, the total needed beam time: 5 + 3 days (preferably at different times), any time during the present beam period.

References

[1] I. Fijal-Kirejczyk et al., Phys. Rev. A 77, 032706 (2008)
[2] M.M. Gugiu et al., Rom. J. Phys. (in press);
D.E. Dumitriu et al., ICACS 22 (Berlin, 2006)
[3] H.A. Bethe and E.E. Salpeter, "Quantum Mechanics of One- and Two-Electron Atoms" (New York: Academic Press, 1957).

+) In order to derive photoelectric cross sections from the RR cross sections (or vice-versa), we have to apply the principle of detailed balance for the inverse reaction and then perform a Lorentz transformation from the laboratory frame to the projectile frame of reference.