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Double Electron Capture in Relativistic U^{92+} Collisions Observed at the ESR Gas-Jet Target

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Abstract

Processes associated with double electron capture into bare U^{92+}-ions have been observed under single collision conditions. Regions of very low cross sections, close to mbarn, have been explored successfully. In particular, an attempt to register photons with twice the energy of single K-REC photons has been performed. Moreover, K-REC spectra associated with double charge exchange have been analysed in terms of their angular distribution. As a result, evidence for correlated electron capture has been found.

1. Introduction

Radiative electron capture (REC) of a single electron, observed in fast collisions of fully stripped high-Z ions with light target atoms, is a dominant charge-exchange process [1]. Here, the fundamental electron–photon interaction mechanisms can be studied complementary to photoionization experiments when considering REC as time reversal of photoeffect. Recently, considerable efforts, directed onto electron-photon interaction, went towards details of double photoionization of two-electron systems. This phenomenon, in particular, deals with very challenging problems of atomic physics where the electron-electron interaction should be taken into account thus entering the area of correlation effects [2].

In order to follow this guideline, the main intention of the present experiment was to observe processes associated with capture of two electrons into bare and fast heavy ions. Measurements of projectile X-rays associated with double charge exchange give access to the investigation of the following radiative processes:

- double radiative electron capture (DREC) a two-step process in which two uncorrelated electrons are captured in one collision and two photons are emitted, both with the energy of single REC photons. The cross section for this process (σ_{DREC}) can be calculated within the independent electron approximation and presented in the form [3]:

$$\sigma_{\mathrm{DREC}} = 0.13 \cdot \sqrt{Z_{\mathrm{t}}} \cdot a_0^{-2} \cdot \sigma^2_{\mathrm{REC}}(Z_{\mathrm{t}}) \qquad (1)$$

  where Z_t is the target atomic number, a_0 Bohr radius, and σ_{REC} stands for the cross section for single REC. So far, this process has not been observed and verified experimentally;

- radiative double electron capture (RDEC) – a one-step process, where the energy and momentum gained by capture of two correlated electrons is converted into one photon with approximately twice the energy of a single REC photon. In analogy to REC, the RDEC can be treated as time inversion of double photoionization. Using the principle of detailed balance, one obtains, in the high energy limit, an approximation for the cross section of RDEC (σ_{RDEC}) [4]:

$$\sigma_{\mathrm{RDEC}} = A \cdot (Z_{\mathrm{t}} - 1) \cdot \frac{0.0932}{Z^2} \cdot \frac{\sigma_{\mathrm{ph}}(2\hbar\omega)}{\sigma_{\mathrm{ph}}(\hbar\omega)} \cdot \sigma_{\mathrm{REC}}(Z_{\mathrm{t}}) \qquad (2)$$

  where $A \leq 1$ stands for the phase-space fraction accessible to RDEC [4], σ_{ph} is the cross section for single photoionization caused by a photon with energy of $h\omega$ ($2h\omega$). Very recent theoretical consideration of RDEC [5], within a non-relativistic approximation, gives for σ_{RDEC} a very small fraction of σ_{REC} which varies between 10^{-6} ($Z = 18$) and 10^{-9} ($Z = 92$). Here again, there is no direct experimental evidence for the process. The only experiment aiming at observing of RDEC photons [4] provided us with an upper limit estimate of σ_{RDEC} (for $Z = 18$) which was very close to the nonrelativistic predictions given in [5]. However, it was suggested in [5], that in the high-Z region, due to relativistic effects, the corresponding RDEC cross section should be strongly enhanced with respect to the nonrelativistic prediction. Therefore, at high-Z, a scattering of theoretical predictions for σ_{RDEC}, covering six orders of magnitude, requires urgently an experimental clarification.

2. Experiment

The experiment was performed at the heavy ion storage ring, ESR, at GSI in Darmstadt. Bare U^{92+} ions at an energy of 286 MeV/u have been used in collisions with gaseous N_2- and Ar-targets, with densities ranging from $4.7 \cdot 10^{11}/\mathrm{cm}^3$ up to $5.9 \cdot 10^{12}/\mathrm{cm}^3$ [6]. After passing through the target, the ions were charge state analysed in the next ESR bending magnet and collected in a movable position-sensitive multiwire proportional counter (MWPC). In Fig. 1, the charge-state distribution for $U^{92+} \rightarrow$ Ar collisions is shown. The separation between the two neighbouring charge states (91^+ and

90$^+$) amounts to about 80 mm. Due to this large separation (the diameter of the ESR beam tube amounts to 250 mm) it was necessary to tune the trajectory of the primary beam out of the centre in order to detect both charge states of interest simultaneously on the detector. As observed in Fig. 1, the rate of single down-charged U^{91+} is over four orders of magnitude larger than for double down-charged U^{90+} ions. In order to observe efficiently processes related to double capture, the particle detector was placed at a position where no single down-charged ions could hit the detector. Further on, single collision conditions for double electron capture were tested by measuring the yield U^{90+} ions as function of the target density (see Fig. 2). The linear dependence observed in the figure points clearly to single collision conditions, a crucial requirement of the measurement. In this context, Fig. 1 presents first experimental evidence for double electron capture occurring in single collisions of bare uranium ions with Ar atoms.

To register X-ray emission related to double capture events, the atomic physics photon detection chamber at the internal jet target of ring has been used [7,8]. This environment allows us to view the beam/jet target interaction zone at a multitude of different observation angles with respect to the beam axis. For our current investigation an array of germanium detectors, covering observation angles in the range from almost 0° up to 150° has been installed. The X-ray detectors were triggered by signals from the particle detector.

3. Data analysis

In the case of $U^{92+} \rightarrow N_2$ collisions, single electron capture is predominantly determined by REC, with a measured cross section of 880 ± 100 b which is in accordance with our previous experimental and theoretical results [1]. In this collision system double capture should be mediated mainly by two uncorrelated REC processes. The cross section value for the process of (8 ± 3 mb), measured for the first time in this experiment, is in good agreement with Eq. (1) (10.4 mb). Fig. 3 clearly shows that in this collision system the cross section associated with double charge exchange is about five orders of magnitude smaller than that for single capture channel.

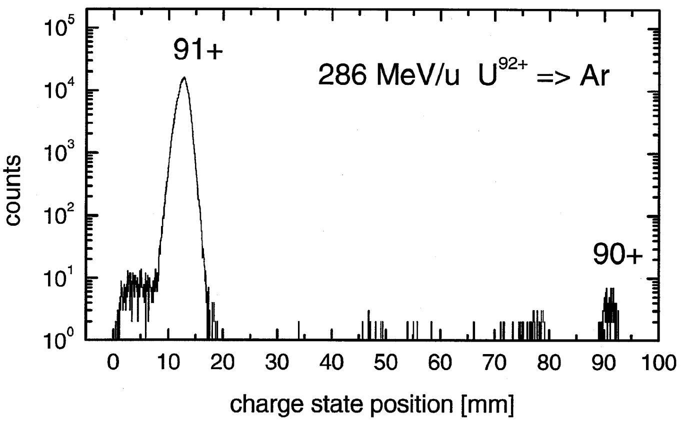

Fig. 1. Charge state spectrum of U-ions after passage of U^{92+}-ions through a thin Ar-target. The primary ion beam could not be registered simultaneously.

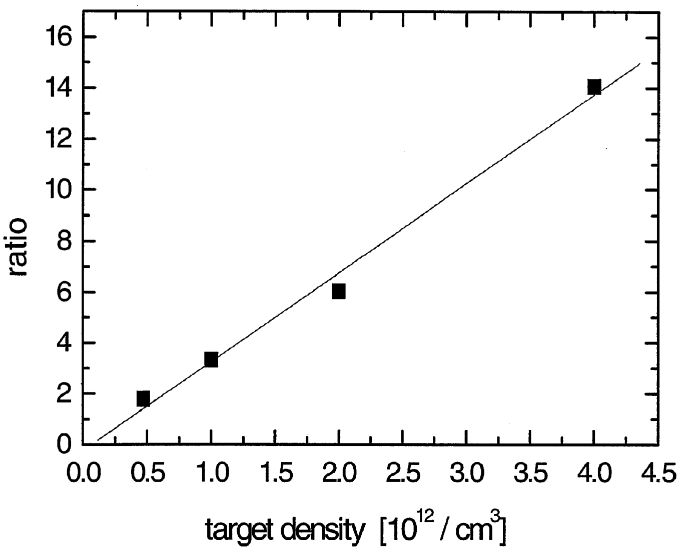

Fig. 2. Ratio of double charge-exchange yield over the number of ions passing through the N_2-target (in arbitrary units).

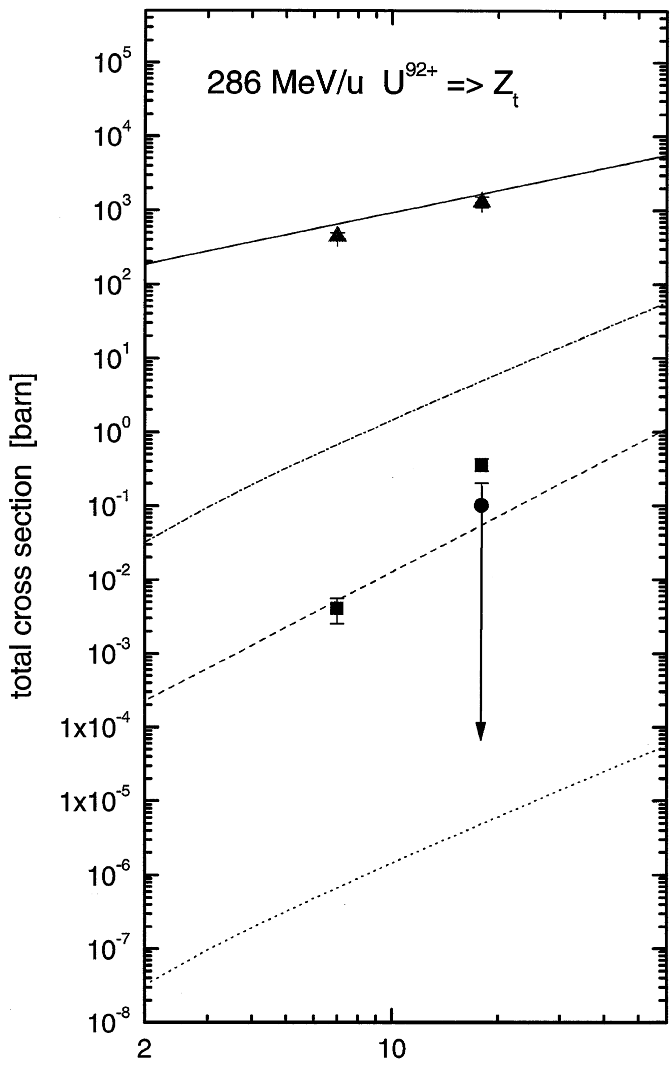

Fig. 3. Cross sections measured in the experiment: triangles – single capture; squares – double capture; circle – RDEC estimate. Lines show theoretical predictions: solid line – REC; dashed line – DREC (formula (1)); dotted line – RDEC (nonrelativistic approximation [5]); dash-dotted line – RDEC (relativistic corrections included [5]).

For $U^{92+} \rightarrow$ Ar collisions about 75% of the cross section for single electron capture is due to REC [1]. The other part of the cross section is due to non-radiative electron capture (NRC). Therefore, the measured cross section value for double charge exchange (360 ± 70 mb) is most probably composed of the cross sections for all the possible combinations of the uncorrelated REC and NRC transitions. According to Eq. (1) the contribution consisting of two uncorrelated radiative transitions (DREC) amounts to 54.9 mb. Significant deviation of the measured cross section from this value (comp. Fig. 3) is probably related to a strong contribution of NRC to double capture.

In addition, the angular distribution of K-REC photons associated with double electron capture was registered. However, only in the case of $U^{92+} \rightarrow$ Ar collisions the statistical significance was sufficient for an analysis (Fig. 4). The corresponding differential cross sections were determined by normalising the photon yields to the number of K-REC photons measured in coincidence with single capture where the angular distribution is experimentally known [7]. It turns out from the data plotted in Fig. 4 that the differential cross sections at 60° and 120° deviate from the emission pattern known for K-REC associated with single electron capture (dashed line). The observed angular distribution (see solid guide line in Fig. 4) can be a signature of quadrupole emission which suggests an influence of the second electron involved into the capture process. However, due to the relatively large experimental uncertainties, this suggestion has to be verified in future experiments.

During the whole experiment only a few photons with twice the energy of single K-REC photons associated with double electron capture have been observed. These events we attribute to the expected RDEC process. Using the same normalisation procedure as above and taking into account the corresponding X-ray efficiencies of the detectors, differential cross sections of 1.25 mbarn/sr (at 90°) and 17.5 mbarn/sr (at 120°) with uncertainties close to 100% were determined. Averaging these two values and assuming an isotropic distribution for RDEC, an estimate for σ_{RDEC} was possible ($\sigma_{RDEC} \approx 100$ mb). This data point is presented in Fig. 3, as well. It is situated about four orders of magnitude above the prediction of an non-relativistic approach [5] and about two orders of magnitude below the predictions involving relativistic corrections [5]. Our experimental finding for σ_{RDEC} suggests that for the case of high-Z ions this process contributes to a considerable amount to the integral double electron capture probability and points to an increasing role of electron–electron correlation. Significant uncertainties due to poor statistics of the present experiment require, however, continuation of these dedicated measurements which should reveal the role of this very rare atomic process in heavy ion-atom collisions.

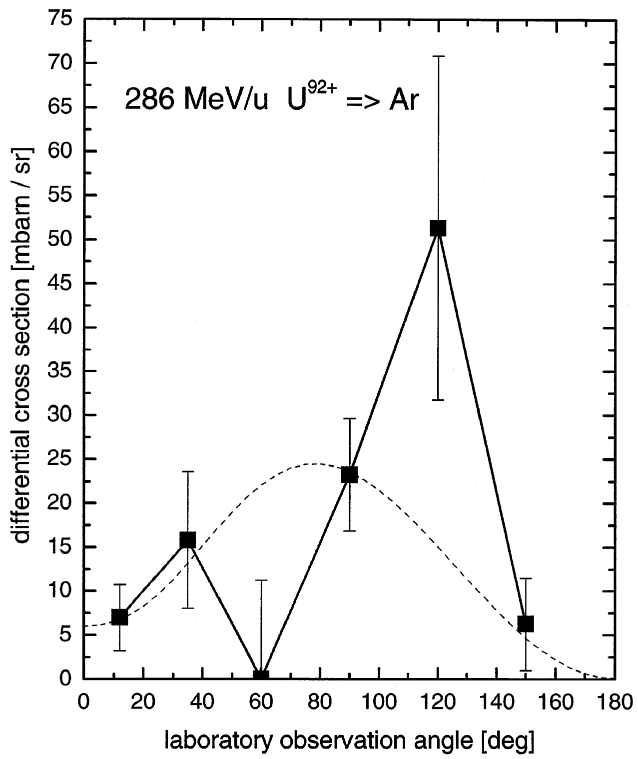

Fig. 4. Angular distribution of single K-REC photons associated with double electron capture. Dashed line describes the shape of the distribution of K-REC photons associated with single electron capture [7]. Solid line serves only to guide the eye.

4. Conclusions

For the first time X-ray processes associated with double charge exchange under single collisions conditions have been observed in heavy U^{92+}-ions at relativistic energies. In particular, cross sections for radiative electron capture have been studied for both, correlated and uncorrelated two-electron transitions. In the case of the uncorrelated process (DREC) the experimental cross-section value is described rather well by theory.

For the correlated RDEC transition the measured cross-section value seems to be very close to that for uncorrelated two electron capture, which points to an increasing role of electron-electron correlation in the studied collision system. A very similar conclusion can be drawn based on the angular distribution of K-REC photons associated with double charge exchange. In this case theory is not able to give a reasonable estimation of the observed effects. However, all these results should be considered with caution because of relatively poor statistics, a price one has to pay when entering the area of rare processes.

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References

1. Stöhlker, Th. *et al.*, Phys. Rev. A **51**, 2098 (1995).
2. McGuire, J. H., "Electron Correlation Dynamics in Atomic Collisions", (Cambridge University Press, 1997).
3. Meyerhof, W. E. *et al.*, Phys. Rev. A **23**, 3291 (1985).
4. Warczak, A. *et al.*, Nucl. Instr. Meth, B **98**, 303 (1995).
5. Yakhontov, V. L. and Amusia, M.Ya, Phys. Rev. A **55**, 1952 (1997).
6. Reich, H. *et al.*, Nucl. Phys. A **626**, 417c (1997).
7. Stöhlker, Th. *et al.*, Phys. Rev. Lett. **82**, 3232 (1999).
8. Stöhlker, Th. *et al.*, in: "X-Ray and Inner Shell Processes", AIP Conference Proc. 506 (Eds. D. S. Gemmel, E. P. Kanter and L. Young), (Chicago, Illinois, 1999) p. 389.

