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Probing superheavy quasimolecular collisions with incoming inner shell vacancies

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Abstract

With the advanced accelerator technologies used at the SIS/ESR heavy ion facility at GSI, the highest charge states (bare, H-like, etc.) even for the heaviest ions can be provided for experiments at moderate collision velocities ($v_{ion} < v_K$). Hence, inner shell vacancies can be provided prior to collisions for the innermost shells of transiently formed superheavy quasimolecules. However, projectile K-vacancies may be destroyed while penetrating solids. The goal of the present investigation is to establish how far at relatively low collision velocities, high incoming ionic charge states do survive in thin solid targets and hence, how far thin solid targets can be utilized for studying superheavy quasimolecules with well-defined, open, incoming, inner shell vacancy channels. The dependence of quasimolecular collisions on projectile charge state (q) and target thickness (t) is studied in very thin Au solid targets for 69 MeV/u U^{q+} ions ($73 \leqslant q \leqslant 91$).

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Keywords: Ion–atom collisions; K X-ray emission; High Z systems

1. Introduction

The structure of superheavy molecules formed transiently during slow collisions between very heavy collision partners has been studied at relatively low velocities both experimentally and theoretically starting from the seventies; for a survey see e.g. [1]. For very heavy collision systems, these studies of quasimolecules were partially hampered by the low incoming charge state of the projectile, i.e. no incoming inner shell vacancies could be provided prior to the collision. The inner shell vacancies in the quasimolecules had to be produced during the observed collision. Now at the SIS/ESR heavy-ion facility at GSI even the heaviest ions ($Z\alpha \rightarrow 1$, where α is the fine structure constant) can be provided for experiments with the highest charge states (bare, H-like, etc.) and at relatively moderate velocities. Moderate velocity means $v_{ion} < v_K$, where v_{ion} is

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the velocity of the ion and v_K the orbital velocity of the electrons in the atomic shell of interest, here the K-shell. Hence, superheavy quasimolecules ($Z_1 + Z_2 > 160$, Z_1 and Z_2 being the atomic number of the projectile and target, respectively) can be investigated with projectiles carrying inner shell vacancies prior to collisions. Although in principle an ideal preservation of the high incoming projectile charge state during a collision can only be guaranteed for a gas target, these studies were limited by the extremely low luminosities.

The first objective of the present investigation[1] was to determine the survival probability of the projectile inner shell vacancies while penetrating a solid. For a sufficiently long survival of the projectile inner shell vacancy, superheavy quasimolecules could be probed with very thin solid targets. Here, we investigate the vacancy transfer between the innermost quasimolecular levels of superheavy quasimolecules [1].

We studied the U–Au collision system for 69 MeV/u highly charged U^{q+} projectiles (up to H-like) with thin Au targets. For close collisions and inner shells we are in the quasiadiabatic collision regime. For the Au K-shell the adiabaticity factor yields $\eta \leqslant 0.35$ ($\eta = (v_{ion}/v_K)^2$). Hence, the inner shell vacancy transfer can be considered within the quasimolecular picture using adiabatic correlation diagrams [2]. For U^{91+} projectiles, the conditions are beyond the equilibrium charge state which is about 86+ [3]. In a similar experiment [4] with 69 MeV/u Bi^{q+} ions and thin Au targets, the long survival probability of the inner shell vacancies in solid targets was confirmed and the charge state evolution of the projectiles in the bulk was studied additionally.

2. Experimental details

A U-ion beam pre-accelerated by the UNILAC at GSI to 11.4 MeV/u and $q = 73+$ was injected into the heavy ion synchrotron SIS. After acceleration up to 73 MeV/u, the ions were extracted slowly from the SIS and an Al stripper foil (20 mg/cm^2) was used for producing the high charge states required (H-like, He-like, B-like, C-like, etc.). The emerging charge states were magnetically separated. Finally, a charge state selected, well collimated, U^{q+}-ion beam ($q = 73$, 86, 88, 90 and 91) of 69 MeV/u impinged on thin Au targets of thickness t ($t = 18$, 50 and 170 μg/cm^2, the thinnest one had a thin carbon backing of 15 μg/cm^2). Fig. 1 shows the schematic experimental set up as a top view. With the target foils positioned normally to the beam direction, the X-rays emitted from collision partners were detected by two intrinsic Ge(i) detectors (with solid angles of 0.089 sr and 0.051 sr) positioned in the same plane at an angle of 120° to the beam direction (backwards).

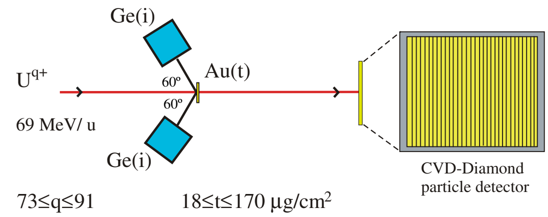

Fig. 1. The experimental set-up showing the Ge(i) X-ray detectors and the position sensitive CVD-diamond particle detector.

Behind the target the ion beam was monitored by a one-dimensional position sensitive CVD-diamond detector [5,6] for normalization of the X-ray emission. An enlarged front view of the particle detector is shown on the right hand side of Fig. 1. This newly developed radiation-hard detector (active area of 60×40 mm^2) consists of a polycrystalline diamond layer (chemical vapour deposition (CVD)) and the 32 gold stripes contacts in front make it, position sensitive in one dimension. The stripes are 1.8 mm broad with a 0.2 mm pitch and have independent read-outs [6].

3. Results and discussion

3.1. K X-ray emission

Fig. 2 depicts the K X-ray spectra measured in the laboratory by one of the Ge(i) detectors for $U^{91+,86+}$ ions

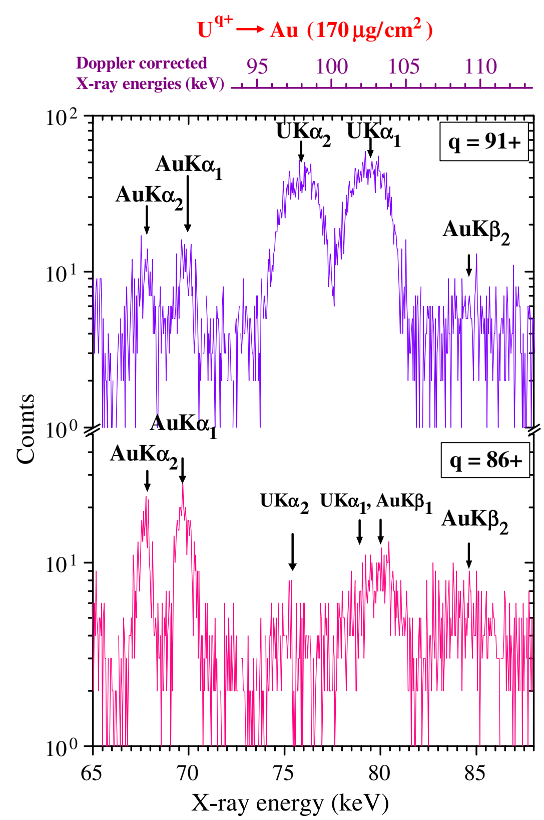

Fig. 2. K X-ray spectra measured in the laboratory frame by the Ge(i) detector for $U^{91+,86+}$ ions incident on the 170 μg/cm^2 Au target.

[1] Part of the Ph.D. Thesis work of P. Verma.

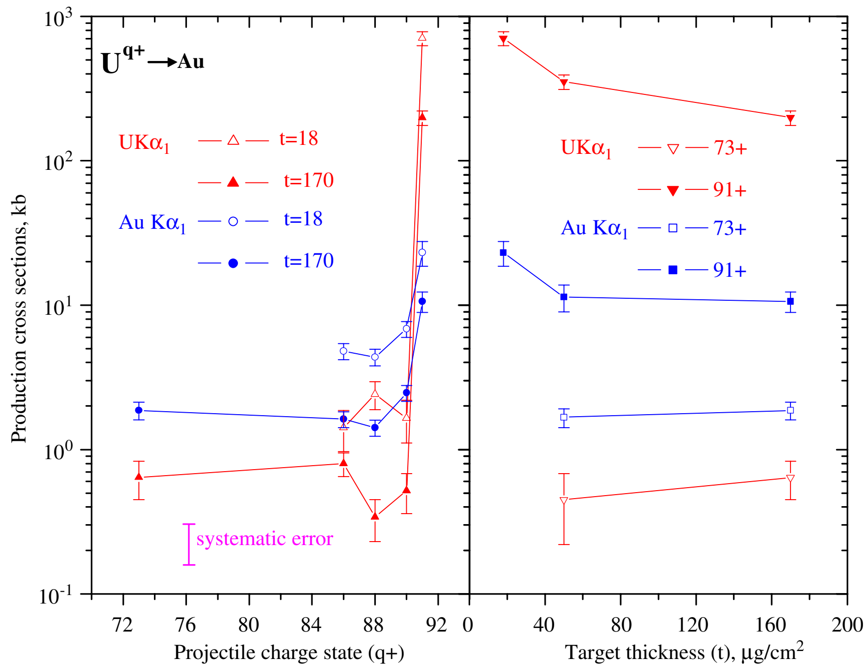

Fig. 3. Kα_1 emission cross-sections for the projectile U and target Au as a function of the incoming charge state (left part) as well as a function of target thickness (right part).

incident on the thickest (170 μg/cm^2) Au target. The Doppler corrected X-ray energies for the projectile K transitions are given at the top. A comparison of the spectra shows a strong influence of the incident charge state of the projectile-ion on the X-ray emission. At a first glance Fig. 2 reveals a reversal in the relative intensities of the U-K and Au-K X-rays for open and closed K-shells (91+ and 86+, respectively). The Au-K X-rays show a much smaller increase in yield as compared to the U-K X-rays yields for $q = 91+$.

The K X-ray emission cross-sections have been extracted by normalizing the X-ray yield to the number of projectiles monitored by the CVD-diamond detector. Due to the experimental boundary conditions (varying spill structure) of the ion beam, high systematic errors of a factor of 2 (at an average) have to be taken into account. The K X-ray emission cross-sections (corrected for the dead time) are presented in Fig. 3.

3.2. Charge state and target thickness dependence of the cross-sections

The left part of Fig. 3 shows the projectile charge state dependence of Kα_1 emission cross-sections for both the collision partners (U, Au) for 18 and 170 μg/cm^2 target thicknesses. The right part of Fig. 3 depicts the target thickness dependence of these cross-sections. It is observed in Fig. 3 that for projectiles carrying a K-vacancy (U^{91+}), the K X-ray emission increases substantially above its value for the closed K-shell (U^{90+}) not only for the projectile but to some extent also for the target. For these projectiles, the increase in the latter points to an additional vacancy production mechanism such as the coupling of the K-shells of both the collision partners (the K–K sharing process [7] is discussed below). Moreover, for projectiles with incoming L($j = 1/2$) vacancies, a slight increase in the Au-K emission might also be observed for U^{90+} in comparison to its value for U^{88+}. The cross-sections stay nearly constant for lower incident charge states (ranging from 73+ to 86+). It is emphasized that the increase in the X-ray emission with the incoming inner shell vacancies depends on the target thickness, i.e. on the survival probability of the projectile K-vacancy while penetrating the target foils.

3.2.1. Target thickness dependence

From the target thickness (t) dependence of the K X-ray cross-sections we can extrapolate to the cross-sections for zero target thickness which means towards cross-sections under almost single collision conditions. This has been done by assuming an exponential decrease of the K X-ray cross-sections ($\sigma = \sigma_0 \exp(-t/\lambda)$) towards the values corresponding approximately to those for the equilibrium charge state of the projectile (e.g. to a few kbarns for U-Kα_1, see Fig. 3). Table 1 lists the cross-section values for U-Kα_1 and Au-Kα_1 transitions per incident K and L($j = 1/2$) vacancy obtained by this procedure. For an

Table 1
Increase in U-Kα_1 and Au-Kα_1 X-ray emission cross-sections (in kbarns) per incoming projectile (K, $L_{j=1/2}$)-vacancy obtained for zero target thickness i.e. approximate single collision conditions

	per K-vacancy (kb)	per L($j = 1/2$)-vacancy (kb)
U-Kα_1	700 ± 50	–
Au-Kα_1	20 ± 5	1.3 ± 0.7

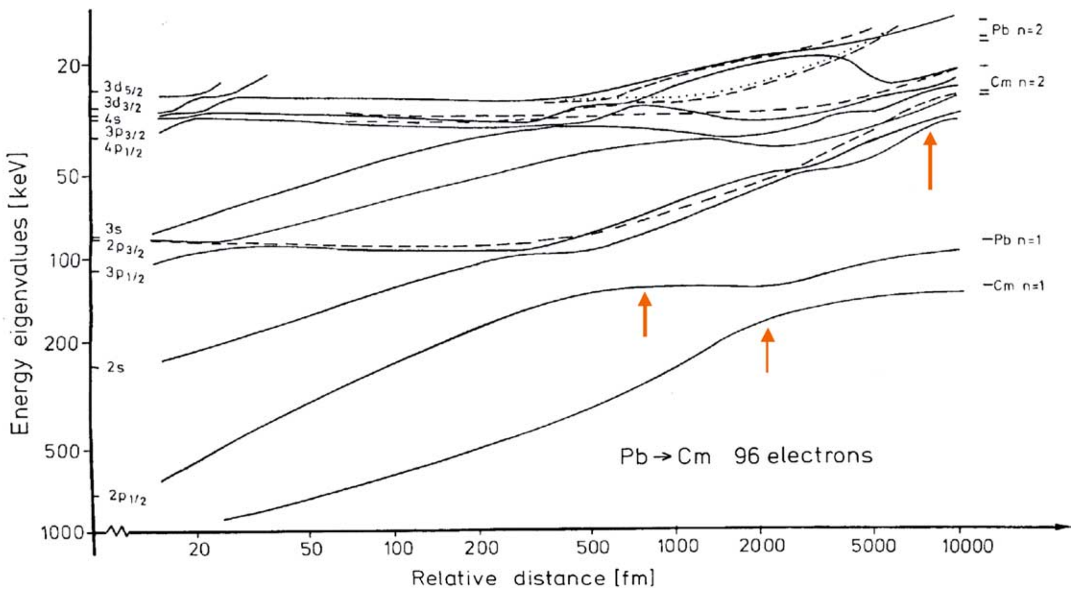

Fig. 4. Adiabatic correlation diagram for an equivalent Pb–Cm system according to [2].

incoming K-vacancy of the projectile (U^{91+}), the constant (λ) for the exponential fit leads to a half thickness ($t_{1/2}$) of 110 μg/cm^2 up to which half of the projectiles are expected to lose their K-vacancy. This corresponds to a survival (half) time ($\Gamma_{1/2}$) of $\sim 5 \times 10^{-16}$ s for the projectile K-vacancy in the bulk at our ion velocity (0.38 c). For comparison we refer to the lifetime of a K-vacancy in a "normal" uranium atom ($\sim 10^{-18}$ s) [8]. The high projectile ionization together with the size of the electron capture cross-section leads to this long survival time of the projectile K-vacancy in the bulk.

3.2.2. Electron capture

For projectiles carrying a K-vacancy (U^{91+}), the K X-ray emission seems to be primarily caused by electron capture to higher shells in distant collisions. This leads to a copious emission of the projectile K X-rays due to cascading and hence the observed increase in the U K X-ray (Fig. 3). The X-ray emission cross-sections given in Table 1 refer to only one decay channel of the K-vacancy. In order to account for the total K-vacancy production cross-section, a sum over all channels (Kα_1, Kα_2, Kβ_1 and Kβ_2) is required. This adds up to a factor of about 3. Thus σ_{cap} of about 2100 kb is determined by the total increase in the K X-ray emission. Using a geometrical picture i.e. ($\sigma_{\text{cap}} = P_{\text{cap}} \cdot \pi r_{\text{cap}}^2$) and assuming the probability for capture P_{cap} to be nearly 1 inside and 0 outside r_{cap}, the interaction distance for electron capture, r_{cap} can be estimated to be about 8000 fm. The corresponding arrow is marked in an equivalent correlation diagram [2] shown in Fig. 4. The total $\sigma_{\text{cap}} = \sim 2100$ kb is comparable, within our experimental uncertainties, to the semi-empirical non-relativistic scaling formula for NRC ($\sim$3000 kb) [9] and is smaller than the theoretical calculations by Eikonal approach ($\sim$14 600 kb) [10] which is not surprising as the latter is known to be more suitable at higher projectile energies.

3.2.3. K–K sharing

For inner shells we have a moderately slow collision and we are in the quasiadiabatic collision regime as mentioned earlier ($\eta \leqslant 0.35$). From the Au-Kα_1 increase for an open K-shell we can deduce an interaction distance for K–K sharing [7]. For our relativistic collision system and $q \leqslant 90+$ we observed an intensity ratio of U-Kα_1/Au-K$\alpha_1$of $\approx$0.3. This corresponds to the sharing probability of $p = 0.3$ for a single way passage (outgoing) which can be compared to $p = 0.46$ calculated for the nonrelativistic case with the Meyerhof formula [7,11]. For an incoming projectile K-vacancy, a two way passage for the vacancy transfer (in and out) has to be considered. This leads to a total probability of vacancy transfer, $P_{\text{vac.trans}} = 2p(1-p) = 0.4$. The increase in Au-K$\alpha_1$ per incident K-vacancy is $\sim 20 \pm 5$ kb (Table 1). Taking into account the total number of Au-K-vacancies (which adds up to a factor of 3 approximately) the total $\sigma_{\text{vac.trans}} \approx 60$ kb. In the geometrical picture ($\sigma_{\text{vac.trans}} = P_{\text{vac.trans}} \cdot \pi r_{\text{K-K}}^2$), we deduce a value of $\sim$2100 fm for the K–K sharing coupling distance ($r_{\text{K-K}}$) marked by the corresponding arrow in Fig. 4.

4. Conclusion

The target thickness dependence of the cross-sections showed clearly that using highly charged heavy ions at relatively low moderate velocities the projectile K-vacancy can survive while penetrating solid targets. The K-vacancy survival time in the bulk has been estimated to be $\sim 5 \times 10^{-16}$ s which is appreciably larger than the lifetime of a K-vacancy in a "normal" uranium atom. It was thus shown that for very thin solid targets ($t_{1/2} = 110$ μg/cm^2) the inner shells in superheavy quasimolecules can be probed. For the interpretation of our data in the framework of a transient U–Au molecule we use the correlation diagram for the neighbouring Pb–Cm system [2] in Fig. 4. From the variations of the X-ray emission with charge state, especially for open K-shell, we deduce interaction distances. Using simple geometrical considerations we deduced the interaction distance for electron capture, $r_{\mathrm{cap}} \sim 8000$ fm and the coupling distance for K–K sharing $r_{K\text{–}K} \sim 2100$ fm. The 1 sσ–2pσ sharing probability was found to be around 0.3. The extracted interaction distances have been found to concur nicely with the correlation diagram. For projectiles with incoming L($j = 1/2$)-vacancies, the vacancy will be transferred towards the united L-shell and will couple at intermediate distances to the target K-shell. The L–K-shell coupling and its interaction distance, (see arrow in Fig. 4 at $\geqslant$800 fm) will be discussed in a forthcoming publication.

With the results of the present investigation, the basis for a detailed probe into the inner shells of superheavy quasimolecules is laid. In the future, lower projectile energies will have to be investigated to probe these systems at better adiabatic conditions.

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