Multiple Electron Capture by 46 MeV/u Pb^{81+} Ions from Solid Targets

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Abstract

Significant multiple electron capture has been found in collisions of 46 MeV/u Pb^{81+} ions with thin carbon foils. An increase in the many-electron capture probability has been observed for the thinnest targets, which is contrary to the normally assumed process of subsequent single-electron capture in the bulk. This shows the significant contribution of the surface for multiple electron capture. Further evidence is found for a strongly reduced capture probability from the exit surface as compared to the entrance surface. Absolute yields for electron capture and projectile ionization are presented and discussed within a Monte-Carlo simulation.

1. Introduction

Fuelled by new developments and applications the interaction of highly charged ions with solid targets has attracted increasing interest in recent years. In contrast to pure ion – atom collisions as in gaseous targets the interaction with solid targets is strongly influenced by the presence of neighboring atoms and the collective behaviour of the target electrons. This collective response leading to a polarization of the target can be described as a wake of electronic density fluctuations trailing the ion. The resulting electric field not only induces shifts in binding energy [1–6] but is also of importance for energy loss calculations [7].

For very slow, highly charged ions the interaction with the surface plays an important role (see e.g. [8] for an overview). Even before entering the target the ion captures electrons from the surface into high Rydberg states leading to the formation of so called hollow atoms [9–12]. These surface effects have so far been investigated mostly for highly charged light ions (e.g. Ar^{17+}, Ar^{18+}) in the keV energy region available from ECR sources. In this energy region the classical overbarrier-model [13] has been successfully applied to describe the formation of hollow atoms. However, due to the low energy only the interaction with the entrance surface could be studied so far.

The SIS/ESR accelerator and storage ring facility at GSI, Darmstadt, gives a unique opportunity to extend these studies on solid-state effects towards highly charged (bare, hydrogen-like etc.) very heavy ions ($Z\alpha \rightarrow 1$). Using the Accel-Decel-Technique [14] beams of hydrogen-like ions

up to uranium with energies down to below 15 MeV/u and intensities in the order of 10^5 ions/s are available. In a first experiment towards understanding ion-solid target interaction in this regime we have studied multiple electron capture from thin carbon foils by 46 MeV/u Pb^{81+} ions [15]. In the next section we will give a short description of the experiment. In Section 3 we will focus on the interpretation of the experimental data using a simple model and a Monte-Carlo simulation followed by a discussion in Section 4.

2. Experiment

The experiment has been performed at the atomic physics beamline in Cave A at GSI, Darmstadt. The setup is shown schematically in Fig. 1. The end station can be served with beams of heavy highly charged ions either directly from the synchrotron SIS with energies in the range 100 MeV/u–1 GeV/u or with decelerated ions from the
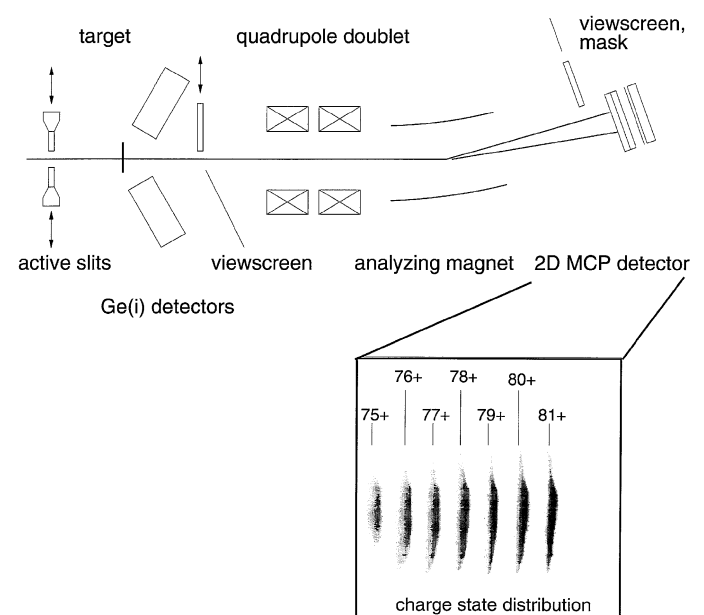

Fig. 1. Experimental setup and charge state distributions for 46-MeV/u Pb^{81+} on a 80-μg/cm^2 gold target as detected on the projectile detector.

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ESR storage ring with energies down to below 15 MeV/u. A permanently installed charge state spectrometer behind the target region consisting of two quadrupoles and a 10 Tm dipole magnet allows the measurement of final charge state distributions at energies up to 560 MeV/u. A position sensitive micro channel plate (MCP) detector with fast delay line readout [16] located 2.5 m behind the magnet detects up to 8 charge states simultaneously. With a dispersion of 8.35 mm/% a separation of about 10 mm is achieved for Pb^{82+} and Pb^{81+}. While in principle the MCP detector can handle overall count rates in the order of MHz, the strong localization of the charge states leads to local efficiency losses if the rate per charge state exceeds about 10 kHz.

For the experiment, bare 250 MeV/u lead ions delivered by the SIS were injected into the ESR. After deceleration and cooling they were extracted via charge exchange towards Cave A. This extraction via radiative electron capture does preserve the high quality of the cooled beam. The beam size at the target was measured on a viewscreen to be about 7×4 mm and thus significantly smaller than the 20 mm free diameter of the self supporting targets. Furthermore, using an empty target frame no perceptible background contribution to the charge state distribution could be found.

3. Experimental results and simulation

3.1. *Projectile ionization*

Figure 2 shows our measured absolute cross sections for the projectile K-ionization of Pb^{81+} at 46 MeV/u and 185 MeV/u in comparison with data on Au^{78+} from Stöhlker et al. [17] and Claytor et al. [18] as well as PWBA calculations [19]. Besides the good agreement with the PWBA calculation we also find good agreement with SCA calculations using the program IONHYD by Trautmann et al. [20,21]. Furthermore for the carbon targets used with thicknesses between 11 $\mu g/cm^2$ and 46 $\mu g/cm^2$ no dependence of the cross section on the target thickness has been found. This demonstrates the quality of the targets and the single collision conditions.

3.2. *Electron capture*

Electron capture yields as a function of target thickness for 46 MeV/u Pb^{81+} on carbon are shown in Fig. 3. For single electron capture a total cross section of $\sigma_{1-cap} = 13.3 \pm 0.7$ kbarn is obtained. As with the projectile ionization no significant dependence of the cross section on the target thickness ist found, showing clearly, that we are in the single collision regime and that re-ionization of electrons captured in the bulk is neglegible. In contrast to single electron capture, where the yield increases with target thickness, multiple electron capture intially shows a strong decrease with target thickness before reaching saturation or increasing again for thick targets. As has been detailed in [15] this is contradictory to the behaviour expected on the assumption of subsequent single electron capture in the bulk, which would result in a monotonous increase with target thickness.

3.3. *Monte-Carlo simulation*

The observed behaviour of the multiple electron capture yield can be readily explained if the ion can capture several electrons from the surface into high Rydberg states, despite its high velocity of about 41.5 au. These electrons are then re-ionized in the bulk with a very high probability leading to the observed decrease in yield with target thickness (see Fig. 4). As a competing process inside the bulk multiple electrons can be captured by subsequent single capture. This
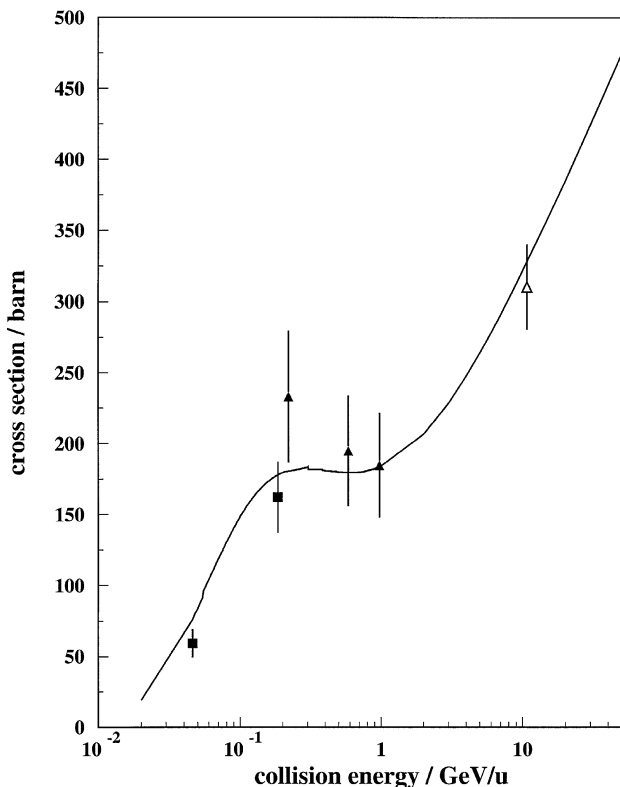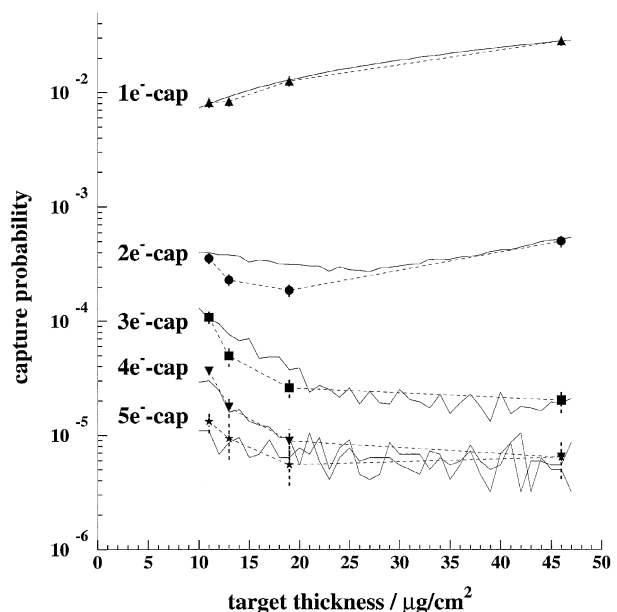

Fig. 2. Measured projectile K-ionization cross sections in comparison with PWBA calculations (solid line): Pb^{81+} our data (solid squares), Au^{78+} Stöhlker et al. [17] (solid triangles) and Au^{78+} Claytor et al. [18] (open triangles).

Fig. 3. Measured data (closed symbols with dashed lines) in comparison with a Monte-Carlo simulation (solid line). The fluctuations in the Monte-Carlo calculation indicate the statistical error of the simulation.
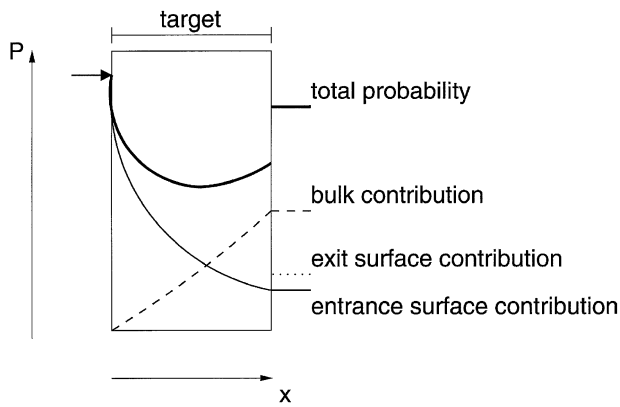
Fig. 4. Development of ion charge states inside the target for: electrons captured from the entrance surface (thin solid line), subsequent single capture in the bulk (dashed line), electrons captured from the exit surface (dotted line) and total charge state (thick solid line).
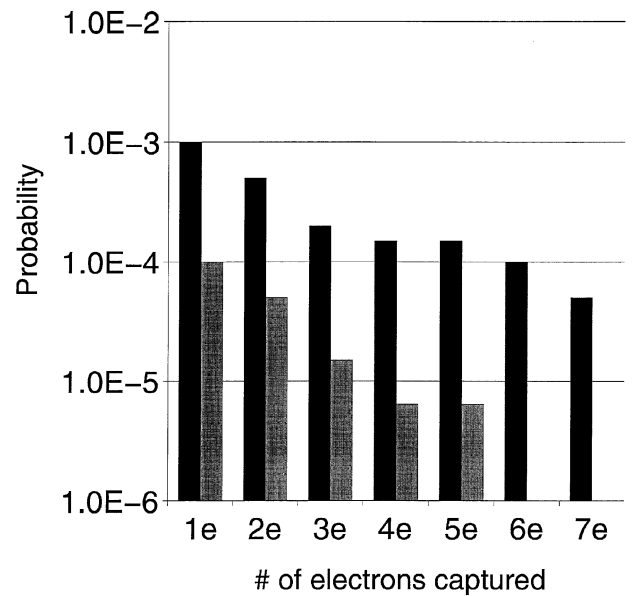

Fig. 5. Probabilites for multiple electron capture from the entrance (black) and the exit (gray) surface as used in the Monte-Carlo simulation.

yield increases with target thickness and will dominate the observed final ion charge state for thick targets, where all electrons captured from the surface into high Rydberg states are already completely re-ionized. This is indicated by the observed increase in yield for double capture at the thickest target (see Fig. 3). The very small re-ionization probability for single electron capture shows, that these electrons are captured into tighter bound states than the ones captured from the surface.

Electrons captured from the exit surface finally result in a thickness independent addition to the total capture yield, thus giving a minimum yield. If the capture probabilities from entrance and exit surfaces are equal, this minimal yield is exactly half of the total yield for zero target thickness. As the observed minimum in the target thickness dependence also includes contributions from capture in the bulk and surviving electrons from capture at the surface, the observed minimal yield should be more than half of the yield at zero target thickness assuming an overall small autoionization probability after the target. As is obvious from Fig. 3 our data is in clear and unexpected contradiction to this assumption, indicating a significantly higher yield for zero target thickness. This means, that the capture probability from the entrance surface is much larger than from the exit surface.

Based on this description we have performed Monte-Carlo simulations, which reproduce the experimental data quite well, as is also shown in Fig. 3. In the simulation the ion captures one or more electrons from the entrance surface according to the probabilies given in Fig. 5. It is then traced on a straight line through the target in steps of $0.1 \, \mu g/cm^2$. For each step the following processes are considered: single capture in the bulk ($\sigma_{1-cap} = 13.3 \, kbarn$), ionization of the initial electron in the ground state ($\sigma_I = 54 \, barn$), re-ionization of electrons captured in the bulk ($\sigma_{Ibulk} = 10 \, kbarn$ per electron), re-ionization of electrons captured from the surface ($\sigma_{Isurf} = 2400 \, kbarn$ per electron) and radiative decay to the K-shell. Radiative decay to higher shells and Auger decay have lower transition rates and thus have a neglegible probability to occur while the ion is traversing the target. We currently ignore them in the simulation. The cross sections σ_{1-cap} and σ_I are directly taken from the measured data. The re-ionization cross section σ_{Ibulk} is taken as the upper limit allowed by our data on single electron capture. The value for σ_{Isurf} is obtained by fitting an exponential decay to the data for double and triple capture. It should be noted, that these fits yield the same value, when one active electron in an excited state for double and two active electrons for triple capture are assumed. This is reasonable as radiative decay to the K-shell as a competing process is on the same time scale and allows the decay of one excited electron without changing the final charge state. In addition the value of σ_{Isurf} actually used is higher than the result of the fit ($\sigma_{Isurf} = 1800 \, kbarn$), but still in agreement with the data available up to now. The radiative decay rates to the K-shell for neutral Pb with a single vacancy are in the order of $10^{17} \, s^{-1}$ [22]. For our simulation with highly charged ions we take a reduced transition rate of $10^{16} \, s^{-1}$. Finally upon leaving the target, the ion again captures one or more electrons from the exit surface. The respective probabilities are shown in Fig. 5. Of all input parameters to the simulation these probabilities are the least well defined ones. The probabilities for capture from the exit surface are taken as the difference between the measured yield at $46 \, \mu g/cm^2$ and the expected yield based on subsequent single capture in the bulk (see also [15]). For capture from the entrance surface, the fit mentioned above does not yield reasonable values. Thus these probabilities have been adjusted freely for best agreement with the data. However, this agreement can only be reached when the capture probability from the exit surface is an order of magnitude smaller than from the entrance surface. This strongly supports the description of the collision process given above.

4. Discussion

The presented experiment shows clearly, that multiple electron capture in thin targets is dominated by capture from the surface even at projectile velocities far above the regime where the classical overbarrier model is valid. More strikingly however is the finding, that capture from the exit
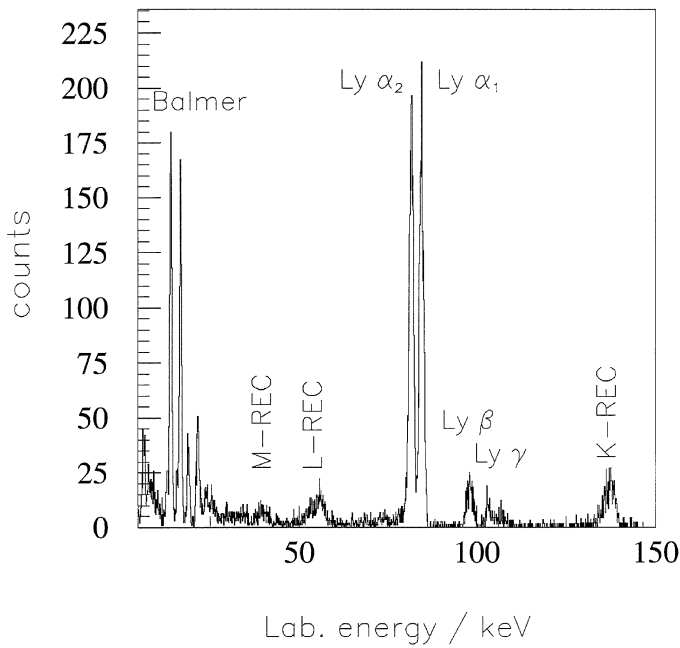
Fig. 6. X-ray spectrum in coincidence with the Pb^{80+} final charge state for 46 MeV/u Pb^{8}1+ on 46 μg/cm^2 C. The energy scale is for the laboratory frame. The emission angle is 60° with respect to the beam direction.

surface is strongly suppressed in comparison with the entrance surface, indicating either a depletion of electrons at the exit or an enhancement in electron density at the entrance surface. This is unexpected, since the internal polarization effect is weak at the ion velocity in the experiment. The plasmon response time is about 10^{-14} s in which the ion travels approximately 1 μm and will have left the target. However, already on its approach the ion due to its high field strength may polarize the target electron distribution. In this case given the slow plasmon response time the electrons would not be able to follow the ion immediately as it traverses the thin targets. While this is only a very qualitative picture it might explain the difference in capture probability at the surfaces.

The study of electron capture from surfaces into very heavy, highly charged ions might thus open another possibility to study the collective behaviour of electrons in the solid, e.g. the wake-effect. Further experiments planned at GSI will extend these studies towards thinner targets, lower energies and fullerenes. In addition differences between conductors and insulators may be expected due to different mobilities of the electrons.

Further information about the capture processes can be gained from X-ray spectroscopy in coincidence with the final charge state. Here the very heavy ions like Pb^{81+} have a very distinctive advantage over the light ions. Due to the high sub-shell splitting it is possible to extract detailed information about the state and its angular momentum in which the electrons are captured. For gas targets such experiments have already been performed [23]. We have in this experiment measured such spectra also for solid targets as shown in Fig. 6 in coincidence with the Pb^{80+} final charge state (single electron capture). The two Ly-α lines are clearly resolved. The measured cross section for radiative electron capture into the K-shell (K-REC) of $\sigma_{K\text{-REC}} = 1670 \pm$ 110 barn is in good agreement with the formula by Stobbe [24,25]. For multiple electron capture not enough statistics could be obtained so far. Together with a more refined theoretical treatment this will lead to a better understanding of the solid-state effects mentioned in the introduction.

Acknowledgements

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