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Impact-parameter dependent L–K vacancy-transfer in collisions of Ni^{23+} with Ge solid targets

M. Jäger [a,*], M. Schulz [b], T. Kandler [a], A. Warczak [c], H. Bräuning [d], A. Demian [d], M. Damrau [d], A. El-Sadek [d], K. Freitag [e], J. Ullrich [a], H. Schmidt-Böcking [d]

[a] *GSI, P.O. Box 110552, 64220 Darmstadt, Germany*
[b] *University of Missouri, Rolla, USA*
[c] *University of Cracow, Cracow, Poland*
[d] *IKF, Univ. Frankfurt, Frankfurt, Germany*
[e] *Univ. Bonn, Bonn, Germany*

Abstract

Using a particle–photon coincidence technique, we have measured the influence of the solid target preparation and thickness on the target K-vacancy production probability ($P_K(b)$) in collisions of 3.6 MeV/u Ni^{23+} with Ge. The probabilities were measured as a function of the impact parameter b which is calculated from the projectile scattering angle using a screened Bohr-type potential. For target thicknesses varying by more than a factor of 100, no change in the shape of the $P_K(b)$ curve was found. Even the data obtained with implanted Ge targets ($\approx 1 \times 10^{16}$ atoms cm^{-2}), used for the first time in an L–K vacancy-transfer experiment, showed the typical solid target behaviour with the adiabatic peak being shifted towards smaller impact parameters.

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1. Introduction

It is commonly accepted [1] that the mechanism of $2p\pi$–$2p\sigma$ rotational coupling is responsible for K-vacancy production in slow, nearly symmetric ion–atom collisions, where the MO (molecular orbital) model can be applied. Initial vacancies present in the $2p\pi$ orbital can be transferred by a Coriolis coupling into the $2p\sigma$ MO. This is followed by a $2p\sigma$–$1s\sigma$ vacancy sharing process (radial coupling) that distributes the vacancies between the K-shells of both collision partners on the outgoing part of the collision. According to Meyerhof [2], the fraction of K-shell vacancies going into the heavier collision partner is given by $w = 1/(1 + \exp|2x|)$ with $x = \pi(I_1 - I_2)/(v_1\sqrt{8mI})$, where I_1 and I_2 are the K-binding energies of the colliding atoms, I is the ionization energy of the $2p\sigma$ MO, m is the electron mass, and v_1 is the projectile velocity. By the observation of projectile and/or target K X-rays, the $2p\sigma$ excitation probability can therefore be obtained.

Based on theoretical calculations of Taulbjerg et al. [3], a distinct dependence of the K-shell excitation probability (P_K) on the impact parameter b is predicted. In detail, the appearance of two peaks is expected. While the so-called kinematic peak, corresponding to a center-of-mass scattering angle of 90°, is located at very small b, the adiabatic peak is seen at large impact parameter values. This characteristic dependence enables a test of the validity of the $2p\pi$–$2p\sigma$ rotational coupling model for the collision systems described above.

In previous experiments where $P_K(b)$ was measured, its impact parameter dependence turned out to fit well with the theoretical calculations around the region of the adiabatic peak, whenever gas targets were used [4–9]. On the contrary, employing solid targets, the adiabatic peak was always found to be shifted by about a factor of 2 towards smaller b-values, with respect to theory [9–13].

This discrepancy between theory and experiment is still not completely understood.

Schuch et al. [9] found that the K-vacancy production in solids cannot be explained by a two collision process of L-shell vacancy production and subsequent rotational coupling. However, quite recently, Kambara et al. [14] investigated the target thickness dependence of K-vacancy production probabilities in the Ar → Ca collision system at 40.6 MeV. They reported a target thickness effect on the shift of the $P_K(b)$ curve and explained it by multiple collisions with multiple L-vacancy production prior to the $2p\pi$–$2p\sigma$ rotational coupling.

It was the aim of this study to investigate the influence of the target density as well as the influence of the method used for target preparation on $P_K(b)$. This was done mainly for two reasons:

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[*] Corresponding author. Tel. +49 6151 3592724, fax +49 6151 3592901, e-mail m.jaeger@gsi.de.

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First, it seemed worth proving the interesting results of Kambara et al. in a different collision system, as the target thickness effect found by them was reported for the first time in the literature.

Second, the target preparation method was of special interest in view of quasimolecular radiation experiments that are planned at the storage ring (ESR) at GSI. MO radiation experiments suffer from a lack of luminosity when employing gaseous targets, especially for higher-Z projectiles. Therefore, solid targets prepared by ion implantation, thus avoiding the problem of inhomogeneous surface structures occurring by the evaporation of very thin target layers, were thought to be suitable for these MO experiments.

2. Experimental

The experiments for the determination of $P_K(b)$ were performed using a scattered-ion-X-ray coincidence setup. The projectile beam of 3.6 MeV/u Ni^{23+}-ions was delivered by the UNILAC linear accelerator of GSI, Darmstadt. It was collimated down to a spot of less than 0.5 mm^2 by means of two pairs of slits mounted 2 m apart in front of the target. The solid targets had a density of Ge-atoms varying between less than 4×10^{15} cm^{-2} and 4×10^{17} cm^{-2} (corresponding to less than 0.5 μg cm^{-2} and 50 μg cm^{-2}, respectively). Targets were mounted at 45° with respect to the beam direction, thus increasing their actual density by a factor of $\sqrt{2}$. Their normal orientation towards the beam was such, that the C-backing was located upstream. The targets were prepared using three different techniques: either as a self-supporting target, or by evaporation of target material on a carbon backing of approximately 20 μg cm^{-2}, or by implantation of 25 keV ^{74}Ge ions into a 520 Å thick carbon foil. According to calculations using the TRIM-program [15], this should result in a Ge-distribution in the carbon foil with a mean depth of 195 Å. The thickness of the conventionally prepared targets was checked by weighing (≥ 5 μg cm^{-2}) or by a photoabsorption measurement (≤ 11.5 μg cm^{-2}), whereas the number of Ge-atoms implanted was derived from an implantation current measurement.

The characteristic X-rays produced in the collisions were detected by two Si(Li)-detectors mounted at 90° relative to the beam axis, covering a solid angle of $\Omega_x/4\pi = 1.5\%$. For registration of the deflected Ni-ions, a parallel-plate avalanche counter (PPAC) with delayline-readout was used. This detector was located at a distance of 181 cm from the target, thus covering the scattering angle region between 0.13° and 1.3°. For the conversion of scattering angles into impact parameters, a Bohr screened potential was applied. The coincidence data were recorded in a list mode. The absolute probability for target K-vacancy production was determined by

$$P_{\text{Ge-K}}(b) = \frac{N_c}{N_p} \frac{1}{\epsilon_x} \frac{4\pi}{\Omega_x} \frac{1}{\omega_{\text{Ge}}},$$

where N_c and N_p are the numbers of true coincident events and total scattered projectiles, respectively, ϵ_x is the X-ray detector efficiency, and ω_{Ge} is the germanium-K fluorescence yield.

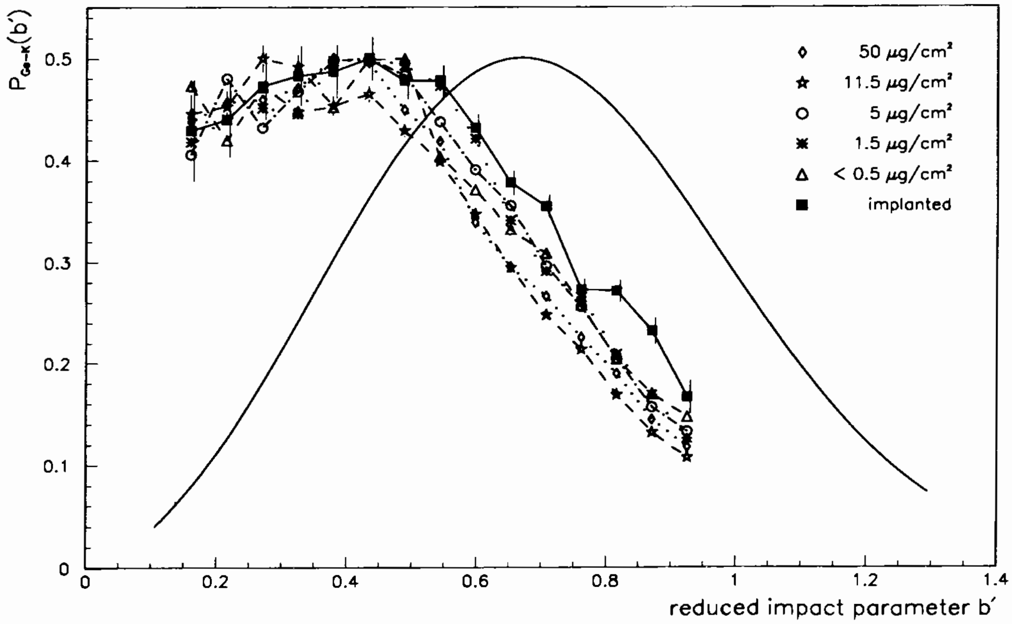

Fig. 1. Normalized target K-shell vacancy-production probabilities as functions of the reduced impact parameter b'. The full line represents the theoretical prediction of Taulbjerg et al. [3] under the assumption of a straight-line trajectory.

We discuss only the target X-ray emission here, because in contrast to the characteristic Ni-K radiation, Ge-K X-rays cannot be produced by interaction of the projectiles with the backing material.

Additionally, the scattering of Ni-ions has been corrected for collisions with carbon atoms. This correction is independent of the scattering angle and does therefore only affect the absolute magnitude of the $P_K(b)$ curve, but not its shape.

The influence of the backing material was also investigated by comparing the results of measurements with a target being mounted backing upstream in the first case and, then, with the reversed order of the layers for the second experiment. Background coming from slit scattering was always below 20 s^{-1}, which is negligibly small compared to a projectile rate of at least 5000 s^{-1} for the thinnest targets. The accelerator duty cycle of 20% is not included into these numbers.

The error bars shown in the figures are only statistical errors.

3. Results and discussion

In Fig. 1, the measured data are shown in comparison with the theory of Taulbjerg et al. [3] (full line) under the assumption of a straight-line trajectory. It is obvious that the shape of the curve is reproduced quite well for the higher impact parameters, but the maximum is shifted by about a factor of 2, and the minimum on the left-hand side of the theoretical curve is filled up. This is a result expected for a solid target. The position of the "shifted" adiabatic peak is in reasonable agreement with the results of Schuch et al. [16], who found this maximum at a reduced impact parameter value of $b' \approx 0.33$ for the collision system Ni → Ge at 90 MeV.

In accordance with the results of Annett et al. [10] and Schuch et al. [9], this behaviour of $P(b)$ is demonstrated here for target thicknesses ranging over a factor of more than 100. There is no significant change of the position of the maximum with the target thickness. Thus, the results of Kambara et al. [14], that stand in contrast to those obtained by Schuch et al. [16], could not be confirmed.

The effect of multiple collisions in the solid target, resulting in an enhanced probability for projectile L-vacancy production, should also be of minor importance in this experiment, at least as long as the shape of $P_K(b)$ is concerned.

On the one hand, the incident charge state of 23 + is the mean (equilibrium) charge state of 3.6 MeV/u Ni ions after passing through a sufficiently thick (carbon) stripper foil [17]. So the charge exchange processes, the projectile ion can undergo on its path through the target, cannot change the mean charge state and will therefore not have an important influence on the average L–K vacancy transfer probability.

On the other hand, the target thickness range of interest in this investigation extends down to very thin targets where the probability for multiple collisions is low compared to the previous experiments by Kambara et al. [14]. The thinnest target they used had a density of 3×10^{16} Ca-atoms cm^{-2}, which is one order of magnitude larger than the thinnest one used here. Nevertheless, no thickness effect is observed in our measurement, neither in thin solid targets, nor in thick targets, where multiple scattering with additional L-vacancy production is expected to occur markedly.

In spite of the fact that germanium, the target material, is the heavier collision partner, the L-shells of nickel and germanium are energetically swapped, due to the high charge state of the projectile ion. Therefore, the vacancies present in the nickel L-shell should be directly transferred into the 2pπ orbital during the collision. Thus, in the MO picture, rotational coupling could take place without previ-

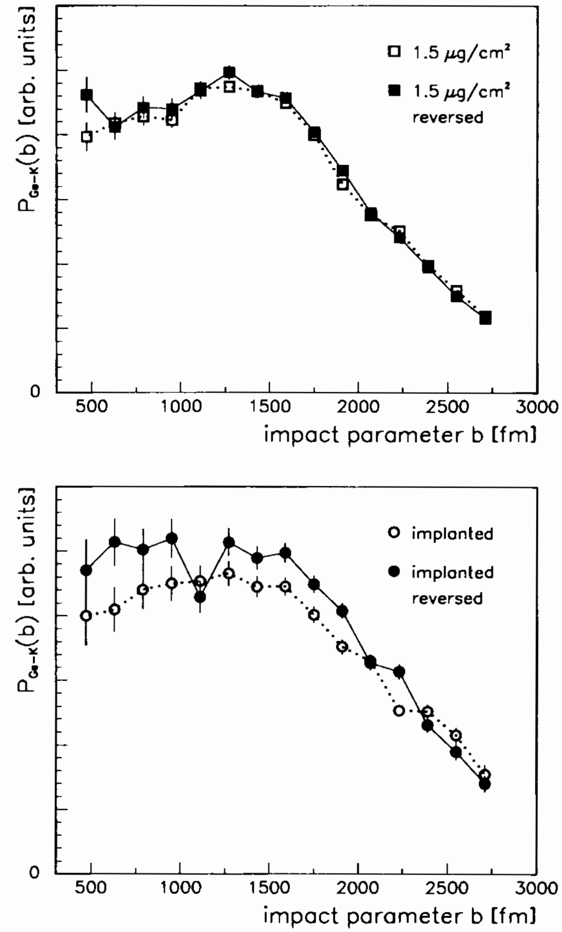

Fig. 2. $P_{Ge-K}(b)$ in comparison between targets being mounted with the backing upstream or downstream, respectively.

ous outer-shell charge transfer processes between the projectile and the target or the backing material. But this description has to be questioned for two reasons. First, dynamical outer shell charge transfer processes will of course occur during the collision, thus changing the atomic energy levels of target and projectile. Second, even if the adiabaticity parameter is small enough for the innermost shell, the MO description may not be valid for the L-shell of the united system. Nevertheless, a Ni ion of charge state 23 + will bring many inner-shell vacancies into the collision.

Moreover, other measurements showed that the shape of $P_K(b)$ is independent of the projectile charge state as long as projectile L-vacancies are brought into the collision. This condition is fulfilled either by using highly charged ions (in experiments with gaseous targets) [5–7,9] or due to collisions prior to the L–K vacancy transfer process in sufficiently thick solid targets [9,10].

If the backing material had an important effect on the impact parameter (scattering angle) dependence of the projectile vacancy production, one would expect differences between measurements with the target being mounted with the backing upstream or downstream relative to the ion beam. Such differences are not observed in the experiment, as shown in Fig. 2. Here, the implanted target and the evaporated one with a density of 1.5 μg cm^{-2} are chosen. A possible backing influence should be more pronounced in thin targets, as the ratio of backing atoms to Ge (target) atoms is higher and therefore more disadvantageous in this case. However, the two curves for the evaporated targets are identical within the error bars, and the deviations in the results obtained with the implanted targets can, to a large extent but not completely, be explained by statistical errors. Differences between these curves may result from the fact that the $P(b)$ data shown were not obtained with the same target being mounted subsequently in both directions relative to the beam. Instead, two different but identically prepared targets were employed. Probably, the implantation conditions were slightly modified, leading to a change in the density of implanted ions. This could explain the difference in magnitude, but not the phenomenon of "crossed" $P(b)$ curves, as seen at larger impact parameters. Such a behaviour was already found by Mokler et al. [18] at smaller b-values in the collision system Pb → Pb at 1.4 MeV/u. In the present state of the evaluation of the data, it is not clear whether these effects are due to systematical errors, or if they are of physical evidence. These special features of the $P(b)$ data will be discussed in more detail elsewhere.

4. Conclusion

The target K-vacancy production probability in the Ni → Ge collision system using solid targets shows deviations from the 2pπ–2pσ rotational coupling model. The deviations agree with the results of previous experiments and are well known as the so-called "solid target effect". No influence of the target thickness or the target preparation method on the position of the maximum of $P_K(b)$ could be observed. Even specially prepared (implanted) targets behave essentially identical to evaporated or self-supporting ones. As the range of investigated target thicknesses extended down to quite small values, the results indicate a severe difficulty in the application of solid targets in MO experiments. Therefore, further studies are needed to clarify this solid target effect, not only in view of applications, but also for a better understanding of the fundamental differences between ion–atom couplings in gases and solids.

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