STATE SELECTIVE CAPTURE MEASURED FOR FAST H-LIKE Bi PROJECTILES IN COLLISIONS WITH Ni TARGET ATOMS*,**

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For 82–170 MeV/u Bi → Ni collisions the total as well as final state sensitive cross sections for non-radiative electron capture have been measured. Due to the large shell and subshell splitting in such a high-Z projectile the applied x-ray/particle coincidence method enables us to probe the theoretical predictions even with respect to the final orbital momentum dependency of this capture mechanism. For the case of the "higher potential" version of the eikonal approximation good agreement with the total cross sections data is obtained. However, the orbital momentum dependence given by the same theoretical formulation is at variance with the experimental findings.

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One of the most important reaction channels in collisions between highly charged heavy ions and neutral target atoms is the capture of target electrons into bound projectile states. The study of these processes is not only of importance from the technical point of view (*e.g.* such as the operation of heavy ion accelerators and storage rings) but provides in particular a detailed test of atomic collision theories. For electron capture into highly-charged heavy-ions one has to consider three different mechanisms: radiative electron capture (REC) [1], resonant transfer and excitation (RTE) [2], and the non-radiative electron capture process (NRC) [3]. Due to their different cross section dependencies on the atomic charge number Z_t ($\sigma_{\rm REC} \sim Z_t$, $\sigma_{\rm NRC} \sim Z_t^5$) and on the collision energy, NRC is by far the dominant capture process for heavy targets and not too high beam energies. However, in contrast to the quasifree electron capture mechanisms (REC and RTE) which have been studied shell and also subshell selectively in great detail, the experimental information about NRC in relativistic collisions between high Z projectile and low Z targets is limited up to now to total charge exchange data. More detailed experimental information is needed as a precise theoretical description of this process is difficult to perform. The main reason for this is that NRC is inherently a three-body problem where the Coulomb field of the projectile of the target nucleus leads to distortions of the atomic wave-functions even at infinite distances.

Here, we report on a dedicated study of the NRC process which was performed for heavy H-like Bi ions colliding with Ni targets at intermediate collision energies. Due to the large shell and subshell splitting in the chosen projectile system, the $K\alpha_1$ and $K\alpha_2$ transitions as well as the groundstate transitions for shells with $n > 2$ can easily be resolved experimentally. A measurement of these characteristic transitions in coincidence with the electron capture into the projectile provides n, l shell selective information for the NRC capture mechanism itself.

The experiment has been performed at the fragment separator (FRS), behind the heavy ion synchrotron (SIS), at GSI Darmstadt. The $_{83}\mathrm{Bi}^{82+}$ ions with energies between 80 and 200 MeV/u were focused on thin $_{28}\mathrm{Ni}$ target (130 μg/cm^2). After passing the target the charge states of the emerging ions were analyzed magnetically and directed onto fast scintillator counters. Here, the projectiles with the primary charge state $Q = 82+$ and the ions having captured one target electron were registered independently. The target area was viewed by a granular intrinsic germanium detector mounted perpendicular to the beam direction, which recorded the X-ray spectra in coincidence with the particle detectors. A typical coincidence X-ray spectrum is presented in Fig. 1. For more detailed description of experimental setup see Ref. [4].

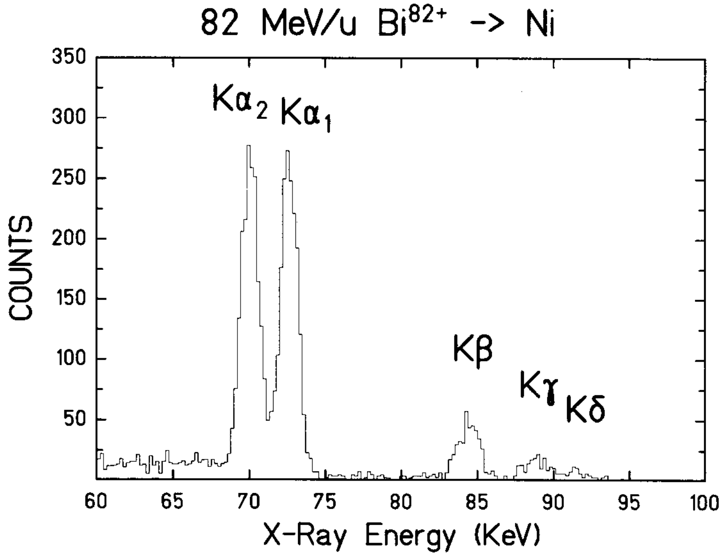

Fig. 1. Doppler corrected sum spectrum (CM-system) of the granular X-ray detector measured in coincidence with electron capture (82 MeV/u $Bi^{82+} \to Ni$).

In the following we restrict the comparison of our experimental findings to the eikonal approximation [5] which is known to provide reliable cross section predictions within a factor of three and to the OBK approximation [6]. The latter approach overestimates in general the experimental cross section data by up to an order of magnitude. However, the OBK approximation is most widely used in order to estimate the final orbital momentum dependency of the NRC process [6]. The eikonal approximation includes higher order Born terms in an approximate way. In the "prior" version it treats the electron-projectile interaction in first order while the electron-target interaction is treated nonperturbatively and in the "post" version vice versa. In the "higher potential" prescription [7] (also called "strong potential" approximation), the stronger of the two Coulomb potentials is treated nonperturbatively and the weaker one in first order. Therefore, we use the "prior" version for $Z_p/n_p < Z_t/n_t$ (Z_p and Z_t the projectile and target atomic number, respectively n_p and n_t is the principal number of the projectile and target atomic shell, respectively) and the "post" version for $Z_p/n_p > Z_t/n_t$, respectively. In Fig. 2 we present the measured total cross section for ${}_{83}Bi^{82+} \to {}_{28}Ni$ versus projectile energy in comparison with the OBK and eikonal results. For completeness we have to add that all the competing capture processes are found to be negligible. In the calculation the capture cross sections from the initial K- and L-shell into all final projectile states up to $n = 10$ were computed and summed up. The closest agreement with the experimental data is found for the "higher potential" description of the eikonal approximation. All other approaches disagree with the experimental findings and in particular the OBK approximation overestimates the data by a factor of about 10.

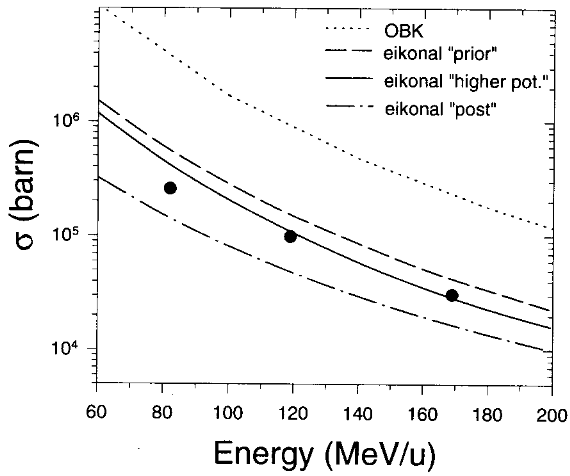

Fig. 2. The measured total cross sections for electron capture from Ni target to $_{83}Bi^{82+}$ projectile compared with predictions of OBK and various version of eikonal approximation.

Compared to the total cross section measurement the analysis of the characteristic K X-rays — especially of the $K\alpha_2/K\alpha_1$ line intensity ratio — allows a more detailed insight into the capture mechanism. The $K\alpha_2$ line of heavy He-like ions is composed of transitions from 2s and 2p states (1s2s $^3S_1$, 1s2p $^3P_1 \to$ 1s^2 $^1S_0$), but the $K\alpha_1$ line contains only transitions from 2p states (1s2p $^1P_1$, 1s2p $^3P_2 \to$ 1s^2 $^1S_0$). Therefore, the $K\alpha_2/K\alpha_1$ intensity ratio reflects the population of 2s and 2p states at the moment of the K X-ray emission. In Fig. 3 the $K\alpha_2$ to $K\alpha_1$ intensity ratios extracted from the measured coincidence X-ray spectra taken at 90° observation angle are plotted as a function of the beam energy. In addition, the predictions of the various versions of the eikonal theory as well as of the OBK approach are depicted in the figure. The theoretical intensity ratios were computed by considering the individual cross sections $\sigma(n,l)$ for capture into all excited projectiles states up to $n = 10$ and by additional extended cascade calculations. For the latter the required transition rates were derived by using the GRASP code [8]. In contrast to the total cross sections the "post" version fits the measured data very well, whereas the results of the "higher potential" description fails now completely in predicting the observed line intensities. In order to elucidate in more detail this obvious inconsistency, we have plotted in Fig. 4 the orbital momentum dependency of the "higher potential" and "post" versions (Fig. 4 bottom and top , respectively). The "post" version calculations show a smooth n, l cross section dependency and that the non-radiative electron capture populates preferentially $l = 1 - 2$ states. In contrast, the "higher potential" version predicts wider l distributions with the maximum around $l = 3$, which cause that the cascade transitions in this case feed mainly 2p state and increase the intensity of $K\alpha_1$ line. It also shows an artificial jump in both the n and the l cross section dependency when going from the "post" to the "prior" version. Following the definition given above this change in the "higher potential" prescription takes place for $n = 4$. We have to point out that this inconsistency is required in order to bring the eikonal approach in agreement with the total cross section data.

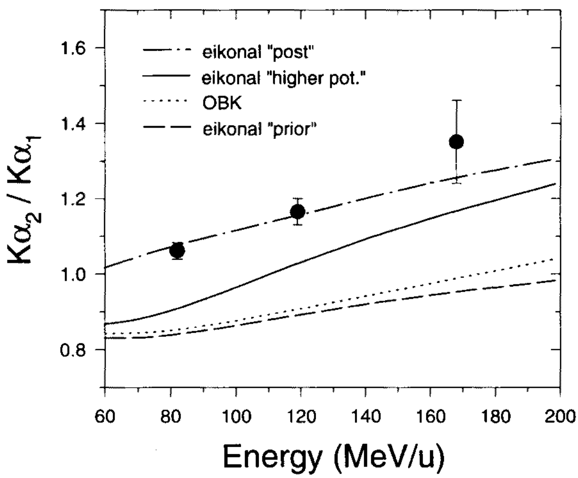

Fig. 3. The $K\alpha_2$ to $K\alpha_1$ intensity ratio determined from the X-ray spectra measured in coincidence with the electron capture compared with predictions of OBK [5] and various versions of eikonal approximation [5].

In Table I the relative yields of all groundstate transitions observed in the experiment (*i.e.* $K\alpha_1$, $K\alpha_2$, $K\beta$, $K\gamma$, $K\delta$ at 82 MeV/u) are given in comparison with the corresponding predictions calculated by using the "post" as well as the "higher potential" version. Again, it can be stated that an excellent agreement between the "post" version and the experimental findings is obtained. We would like to emphasize, that this $K\alpha$, $K\beta$, $K\gamma$, $K\delta$ series is in particular sensitive to the n-shell distribution.

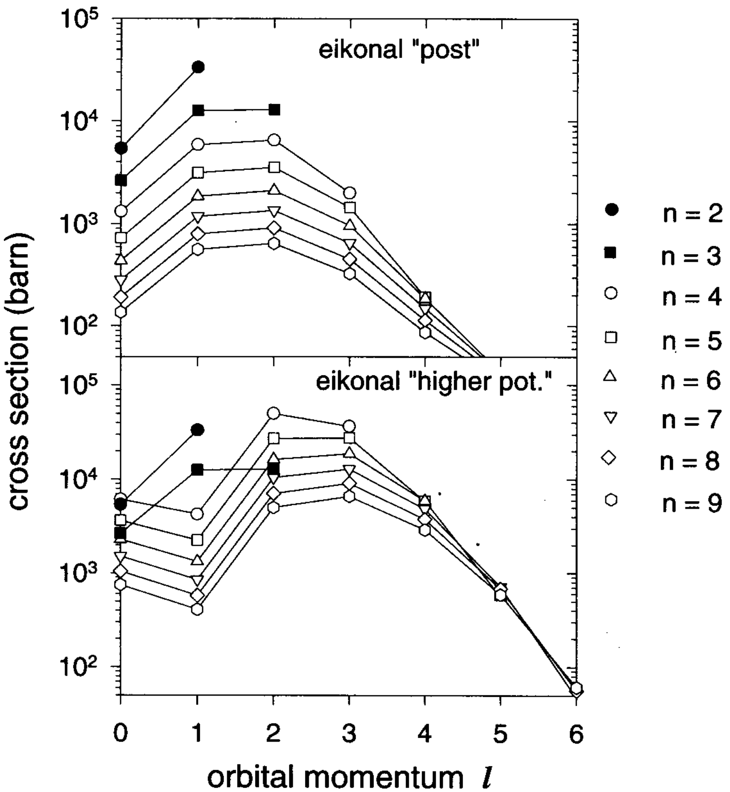

Fig. 4. The theoretical capture cross sections from Ni target atoms to individual n, l states in $_{83}Bi^{82+}$ projectiles calculated for the collision energy of 82 MeV/u. Top: "post", bottom: "higher potential" version of eikonal approximation, respectively.

TABLE I

Relative intensities of K X-rays emitted at 90° from 82 MeV/u He-like Bi ion after electron capture from the Ni target. The intensities are normalized to 100.

	Eikonal Approximations "post" ver.	Eikonal Approximations "higher pot." ver.	Experimental Results
$K\alpha_2$	44.40	42.40	43.8 ± 0.40
$K\alpha_1$	41.80	46.70	41.3 ± 0.40
$K\beta$	8.71	7.97	9.84 ± 0.30
$K\gamma$	3.34	2.15	3.45 ± 0.15
$K\delta$	1.67	0.79	1.67 ± 0.14

In conclusion, a final state selective investigation of the NRC process has been performed for H-like Bi ions colliding with Ni targets at intermediate energies. The n, l distribution of this capture mechanism, deduced from the characteristic projectile groundstate transitions measured in coincidence with electron capture, shows a good agreement with the "post" version of the eikonal approach, although the absolute cross-section strengths are in disagreement with the experimental data. The latter are well-reproduced by the "higher potential" prescription. However, it fails completely to describe our final state sensitive data. We conclude that this prescription might be an important tool for reliable total NRC cross section estimations, but for the description of the subtleties of the NRC process the post version seems to be the most appropriate approach. We have to add that predictions for the n, l distribution of the NRC process given by the OBK approximation should also be treated with care as it failed completely in reproducing our state selective data. Moreover, our data are restricted to 90° X-ray emission in the laboratory system. Angular dependent state selective capture measurements are needed to clarify the found discrepancy.

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