Target and projectile K x-ray production by 100, 160, and 200 MeV Nb collisions with thick solid targets

E. Liarakapis, T.J.M. Zouros

► To cite this version:

E. Liarakapis, T.J.M. Zouros. Target and projectile K x-ray production by 100, 160, and 200 MeV Nb collisions with thick solid targets. Journal de Physique, 1990, 51 (8), pp.735-745. 10.1051/jphys:01990005108073500 . jpa-00212405

HAL Id: jpa-00212405

<https://hal.science/jpa-00212405>

Submitted on 1 Jan 1990

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Classification
Physics Abstracts
34.50

Target and projectile K x-ray production by 100, 160, and 200 MeV Nb collisions with thick solid targets

E. Liarokapis (*) and T. J. M. Zouros (**)

Wright Nuclear Structure Laboratory, Yale U., New Haven CT 06520 U.S.A.

(Reçu le 13 novembre 1989, accepté le 8 janvier 1990)

Résumé. — On donne les valeurs des sections efficaces de production de rayons-x K dans des collisions par des projectiles de Nb sur une série de cibles ($Z = 6$ à 68) à des énergies de 100, 160 et 200 MeV. On teste différentes théories de production de trous K dans ce large intervalle d'énergie, parmi lesquelles la promotion d'électron avec partage de trous (modèle moléculaire), l'excitation directe (théorie ECPSSR), l'approximation de chocs binaires modifiée (BEA), ainsi que certains modèles semi-empiriques. On trouve que le mécanisme dominant pour la production des trous K à la fois dans le projectile et la cible est, pour la plupart des systèmes étudiés, le modèle moléculaire. Pour des collisions très asymétriques, les calculs de la théorie ECPSSR rendent compte des données à un facteur 2 près pour les cibles légères (V, Al), mais ne conviennent pas pour les cibles les plus lourdes.

Abstract. — Target and projectile K x-ray cross-sections produced in collisions of Nb projectiles with a series of targets ($Z_t = 6 - 68$) are reported for energies of 100, 160 and 200 MeV. Various K-vacancy production theories were tested over this broad range including electron promotion with vacancy sharing (molecular model), direct excitation (ECPSSR theory), modified binary encounter approximation (BEA), as well as some semi-empirical recipes. For most of the collision systems investigated the molecular model is found to be the dominant mechanism for K-vacancy production in both projectile and target. For highly asymmetric collisions, the ECPSSR calculations are found to be within a factor of two of the data for the lightest targets (C, Al), but fail for the heaviest targets.

1. Introduction.

The study of inner shell vacancy production in ion-atom collisions has received considerable attention since the early seventies. In particular, K-shell ionization has been studied extensively for light [1] and heavy projectiles [2], at both low [3] and relativistic velocities [4]. However, even today, a complete theory that can predict K-vacancy production cross-sections for all collision systems, based on first principles, is still lacking [5]. For the case of very asymmetric collision systems ($Z_p/Z_t \leq 1/2$) and moderate projectile velocities ($v_p/v_{2K} < 1$), where v_{2K} is the velocity of the K-electron and the indices p, t refer to the projectile or target

(*) *Permanent address* : Dept. of Physics, National Technical University, Athens 157 73, Greece.

(**) *Present address* : Dept. of Physics, University of Crete and Research Center of Crete, Iraklion, Greece.

atoms respectively, both direct excitation mechanism and electron capture [6] are the dominant ways of producing a K vacancy in the lighter collision partner. At rather low projectile velocities ($v_p \ll v_{2K}$) and nearly symmetric collision systems ($Z_p \sim Z_t$), the molecular model [3, 7-9] gives a good description of K vacancy production *via* the promotion of electrons from the K-shell to higher orbitals. In the case of direct Coulomb excitation, the ECPSSR theory that includes corrections for the Coulomb trajectory, the relativistic effects, and projectile energy loss in the target [10], seems to reproduce the measured cross-sections quite well for many collision systems [1]. However, this theory is in serious disagreement with data from near-symmetric collision systems [11]. For these collisions, the relative amount of projectile and target K x-rays can be predicted by the vacancy sharing model of Meyerhof [12], while the absolute cross-sections can be calculated within the modified binary encounter approximation model (BEA, Ref. [13]), which incorporates the effect of the molecular orbitals formed in the collision by introducing, in a semiempirical way, the united atom binding energy in the BEA model.

To date a lot of data have been accumulated for light projectiles ($Z_p < 10$, Ref. [1]), while data for heavier collision systems is rather limited [2]. In this investigation we test generally accepted theories of K vacancy production for collision systems involving heavier ions. This work evolved out of our interest in molecular-orbital x-rays produced in heavy ion-atom collisions and the need to know K x-ray cross-sections for various symmetric and slightly asymmetric collision systems involving Nb projectiles [14]. The Nb + Z_t collision systems were studied using a series of solid targets ($Z_t = 6 - 68$). K x-ray production cross-sections for both projectile and target K x-rays were measured for three projectile energies so that their energy dependence could be studied. The data was compared with the predictions of the modified BEA and the ECPSSR theory. The ECPSSR theory approximates, within a factor of two the measured cross-sections for the Nb + C and Nb + Al collision systems, it underestimates the K-vacancy cross-sections for all other collision systems studied, even for the quite asymmetric system (Nb + Sm), where direct excitation should be the dominant mechanism for K x-ray production [6]. An improvement in the theoretical predictions for the Nb + C and Nb + Al collision systems is obtained using semi-empirical correction factors [15] which as in the case of the ECPSSR theory also account for Coulomb deflection, binding energy, and relativistic effects. The relative ratio of the K-vacancy cross-sections of the two collision partners is shown to follow the vacancy sharing formula [12], while the absolute cross-sections are found to agree quite well with the predictions of the modified BEA [13], even for quite asymmetric collision systems ($Z_{\text{Light}}/Z_{\text{Heavy}} \approx 0.6$).

In the following, the experimental procedure is described and the results for the three different projectile energies are presented. Theoretical calculations based on the direct excitation mechanism and the molecular model are compared with the measured K x-ray cross-sections.

2. Experiment and apparatus.

Low intensity $^{93}_{41}\text{Nb}^{+q}$ ($q = 9-16$) ion beams were obtained from a negative ion sputtering source and accelerated to projectile energies of 100, 160, and 200 MeV using the tandem Van-de-Graaff accelerator of the Wright Nuclear Structure Laboratory at Yale University. A series of targets from $Z_t = 6$ to $Z_t = 68$ were placed inside an aluminum scattering chamber on a ladder with eight target positions and inclined at 45° with respect to the beam direction (Fig. 1). Most of the targets were prepared by evaporating the monoisotopic material on $30 \mu\text{g}/\text{cm}^2$ carbon backing. The thickness of the targets, shown in table I, was determined by α -particle energy loss measurements.

Fig. 1. — Experimental setup showing scattering chamber, x-ray detectors, particle detectors and beam line.

Table I. — Table of *K* x-ray cross sections (in barns), target thickness (in $\mu\text{g}/\text{cm}^2$) and the exponent α (see Eq. (8)) for the Nb projectile and the various targets at the three collisions energies used. The relative error for the cross sections is 18 % for $Z_t > 32$ and 25 % for $Z_t > 32$.

Target Element	thickness $\mu\text{g}/\text{cm}^2$	100 Mev	Target 160 MeV	200 MeV	α_{target}	100 MeV	Projectile 160 MeV	200 MeV	α_{proj}
$^6\text{C}^{12}$	30					7.0	35	90	3.6 ± 0.3
$^{13}\text{Al}^{27}$	180					5.0	40	120	4.3 ± 0.3
$^{22}\text{Ti}^{48}$	290	25000		120000	2.1 ± 0.4	6.4		180	4.6 ± 0.3
$^{24}\text{Cr}^{52}$	200	11000	26000	58000	2.2 ± 0.4	9.2	95	260	4.7 ± 0.3
$^{26}\text{Fe}^{56}$	270	7100	19000	41000	2.3 ± 0.4	12	120	365	4.7 ± 0.3
$^{28}\text{Ni}^{58}$	220	6900	16000	29500	2.0 ± 0.4	30	220	550	4.3 ± 0.3
$^{30}\text{Zn}^{64}$	200	5900	12200	23000	1.8 ± 0.4	85	360	1000	3.4 ± 0.3
$^{34}\text{Se}^{80}$	280	2100	8100	13000	2.7 ± 0.3	90	700	1700	4.4 ± 0.3
$^{35}\text{Br}^{79}$	70	1850	7300	12000	2.7 ± 0.3	130	930	1900	3.9 ± 0.3
$^{39}\text{Y}^{89}$	130	2900 *	6200 *	12500 *	2.0 ± 0.3 *				
$^{41}\text{Nb}^{93}$	520	950	2800	5000	2.2 ± 0.2	950	2800	5000	2.2 ± 0.2
$^{42}\text{Mo}^{98}$	300	680	2700	4100	2.5 ± 0.3	1100	3600	5100	2.2 ± 0.3
$^{47}\text{Ag}^{107}$	160	70	400	700	3.4 ± 0.3	1050	3400	4700	2.1 ± 0.3
$^{50}\text{Sn}^{120}$	340	8.5	70	200	4.4 ± 0.3	590	2000	4100	2.7 ± 0.3
$^{52}\text{Te}^{130}$	135	3.0		85	4.8 ± 0.3	490		3200	2.7 ± 0.3
$^{56}\text{Ba}^{138}$	50	0.5	3.5	14.5	4.9 ± 0.3	250	870	1750	2.8 ± 0.3
$^{62}\text{Sm}^{144}$	200	0.15	0.7	2.9	4.1 ± 0.3	150	600	1200	3.0 ± 0.3
$^{68}\text{Er}^{166}$	70		4.8	9.6	3.1 ± 0.8		500	730	1.7 ± 0.8

(*) For Yttrium, the total cross section (projectile + target) was measured.

Two different hyperpure germanium detectors (HpGe) were used, one with a 10 mm diameter and an energy resolution of 177 eV at 6 keV, predominantly used for the K x-rays of the lighter atom, and the other with a 1000 mm² active detection area and an energy resolution of 560 eV at 6 keV used to detect the K x-rays of the heavier partner. The two detectors were located symmetrically at $\pm 90^\circ$ with respect to the beam line in front of the 3.8 cm diameter windows on the side of the cylindrical chamber (Fig. 1). The windows were covered by 25 μ m mylar, which was thick enough to prevent electrons from reaching the x-ray detectors. When necessary, absorbers were used to attenuate L x-rays as well as the K x-rays of the lighter atom. The total efficiencies (including absorbers) of the HpGe detectors were measured as a function of photon energy using calibrated x-ray sources placed at the position of the beam spot on the targets. The formulation outlined in Ref. [16] was used to interpolate efficiencies at other energies and to account for the large detection angle [17] within an accuracy of $\sim 10\%$.

Two surface barrier particle detectors were used to count the scattered ions (Fig. 1) anchored to the top cover of the chamber, and carefully positioned at $\pm 30^\circ$ with respect to the beam line at a distance of 5.5 cm from the target holder. On the front face of each detector, a collimator 4 mm $\times$ 6 mm wide and magnets (~ 500 G) were used, to prevent the numerous electrons produced in the collisions to reach the particle detectors. The solid angle subtended by each particle detector was measured using standard particle sources in the place of the targets. Typical counting rates for the particle detectors were ~ 300 Hz, while their energy resolution was a few MeV.

With this positioning of the two particle detectors (left-L30 and right-R30), any wandering of the beam on the target could be inferred from differences in the L30 and R30 counters (defined as L-R anisotropy). Because of the close geometry utilised, small changes in the position of the beam spot on the target (~ 1 mm), could lead to a 20 % difference in the counting rates of the two particle detectors. Since three projectile energies were used, the beam was collimated at the center of the target at the beginning of each run. Never-the-less, the L-R anisotropy was found to be in a few cases as large as 40 %, implying that the beam spot was 2 mm off-center.

The different inclination of the target relative to the particle detectors also introduced a serious effect. The target thickness that the scattered ion passed through before reaching the L30 particle detector was about four times that of the R30 detector, introducing a large spread in the energy of the scattered projectile from the recoil or the C backing (Fig. 2). Thus, only the total counts (target + projectile) in the L30 detector could be used for the correction of the small variations of the beam spot on target (from the L-R anisotropy).

Electronics and data acquisition system dead-time was measured with a live-time pulse generator and found to be negligible ($< 1\%$).

3. Data analysis and results.

The counts in each K x-ray peak were integrated, using a Gaussian line shape fit on a quadratic background and corrected for the total efficiency. Nucleus-nucleus bremsstrahlung [18] and MO x-rays [14] which contribute a rather structureless continuum in the region of high x-ray energies, were considered as part of the quadratic background to the K x-ray peaks. The peaks in the particle detector spectra were identified and integrated. In those cases where the recoil peak could not be resolved from the projectile peak, the total intensity of both peaks was considered. This was particularly true for the L30 particle detector (see Fig. 2), where the integration of each peak was rather uncertain and therefore the total counts in the spectrum were used. The total counts in each particle detector defined the L-R

Fig. 2. — Spectra of the two (left and right) particle detectors for collisions of 200 MeV Nb with Sn.

anisotropy to an uncertainty of $< 10\%$ depending on the collision system and the target thickness used. The L-R anisotropy was used in the correction of the solid angle subtended by the R30 particle detector. It should be noted that any absolute error in the solid angle ($\sim 20\%$) results in an overall normalization uncertainty and will not affect the relative values of the K x-rays cross-sections. The efficiency of each particle detector was considered to be independent of the particle energy.

Most of the targets were made by evaporating the target material onto a $30\text{ }\mu\text{g}/\text{cm}^2$ carbon backing and therefore contributions to the Nb K x-rays from carbon had to be subtracted. The relative thickness of the backing to the thickness of the target (known approximately) was deduced from the integrated peak areas in the particle detector spectra due to the carbon backing and the target atoms. From this ratio the Nb K x-ray contribution of the carbon backing was calculated and found to be rather small ($< 5\%$ of all Nb K x-rays), for all collision systems. Finally, the absorption of the emitted K x-rays by the target and the backing was estimated and found to be negligible in all cases.

The K x-ray cross-sections for Nb and the target atoms $\sigma(K)$ were deduced from the Rutherford cross-section of the scattered Nb ions $\sigma_{\text{Nb}}(\theta_R)$, using the formula

$$\sigma(K) = \sigma_{\text{Nb}} \frac{Y(K)}{Y(\text{Nb})} \frac{\epsilon^{\text{R30}}(\text{Nb})}{\epsilon^x(K)} \tag{1}$$

where $Y(K)$, $Y(\text{Nb})$ are the target K x-ray and Nb ion yields respectively ; ϵ^{R30} and ϵ^x are the total efficiency (detection solid angle plus absorbers, if any) for the particle and the x-ray detectors respectively. It should be noted that the Rutherford cross-sections have been calculated using the average energy of the projectile as it traversed the target and at the deflection angle $\theta_R (= 30^\circ \pm \delta\theta)$ which was consistent with the L-R anisotropy of the two particle detectors. In this way, any wandering of the beam on the target was taken fully into consideration. It bears emphasis, that by normalizing to the Rutherford cross-section, any uncertainty in the value of the target thickness could only affect the evaluation of the average projectile energy inside the target and introduces a negligible error in the K vacancy production cross-sections.

Fig. 3. — Projectile (●) and target (○) K x-ray cross section (in barns) as a function of the target atomic number Z_t for 100, 160, and 200 MeV collisions. Error bars are of the order of the size of the data points. Continuous line : ECPSSR theory [10]. Dashed line : Anholt and Meyerhof [15].

The measured cross-sections of both projectile and target K x-rays for the three energies of 100, 160, and 200 MeV are shown in table I and are also plotted in figure 3. These cross-sections include a relative error of 10 % due to the total efficiency of the x-ray detectors (in the case of targets of $Z_t < 32$ the error was ~ 20 %), a maximum error of 10 % from the integration of the peaks (both K x-rays and particle spectra) and an overall normalization error of 20 % due to the particle detector efficiency and solid angle. Cross-sections were evaluated under the assumption of isotropy, since K x-rays are known to be quite isotropic [19] in the emitter frame of reference, and the error introduced from the transformation to the laboratory frame of reference is very small (< 1 %).

Any dependence of these cross-sections on the initial charge state of the impinging ion was neglected. For the charge states used in our collision systems, the innermost shells responsible for the K-shell ionization were fully occupied. Therefore, the effect of the initial projectile charge state on the fluorescence yield (ω_q) should be < 10 % [11, 14, 20].

The thick targets used in these measurements can give rise to effects such as energy loss of the projectile, increased ionization of the projectile, and contributions from target recoils. The average energy loss of the projectile was taken into consideration by correcting the measured K x-ray cross-sections in accordance with their projectile energy dependence (Eq. (8) see below) and by evaluating the Rutherford cross-sections at this average projectile energy. Since the fluorescence yield of the projectile is fairly large ($\omega_{Nb} = 0.747$, Ref. [21]), the effect of the increased ionization should be small even for light collision systems ($Z_t < 28$). The dependence of the K x-ray cross-sections on the thickness of the target has been previously observed for many collision systems, all of them utilising relatively light projectiles [22, 23]. For Ni and Nb projectiles impinging on Ni, Nb, and Sn targets, no such target thickness dependence was observed [17, 24]. Therefore, it is expected that at least for $Z_t \geq 28$, such effects should be small for both projectile and target K x-ray cross-sections.

4. Discussion.

In figure 3 we present the measured K x-ray cross-sections both for the projectile and target as a function of Z_t . Following Meyerhof *et al.* [3, 9], this data can be tentatively divided into three regions. The bell shaped central region ($22 < Z_t < 62$) having a near exponential dependence on Z_t , and the regions with $Z_t \ll Z_p = 41$ or $Z_t \gg Z_p = 41$, for which, with the exception of Erbium ($Z_t = 68$), the measured cross-sections vary rather smoothly with Z_t (see Fig. 3).

The theoretical predictions of the ECPSSR theory [10] are also shown in figure 3 as continuous lines. It is seen that only for the Nb + C ($Z_t = 6$) and Nb + Al ($Z_t = 13$) collision systems, the measured cross-sections are reproduced within a factor of two. For the rest of the targets, the theoretical predictions deviate from the data by one to four orders of magnitude with the theory consistently underestimating the data. Within the formulation of direct Coulomb excitation, some semi-empirical corrections have been proposed that account for energy loss, relativistic effects, and the deflection of the incoming ion [15]. The predictions of this theory (shown in Fig. 3 by dashed lines) are similar to those of the ECPSSR theory, showing only slightly better agreement in absolute value with the measured cross-sections.

For symmetric or slightly asymmetric collision systems, it has been shown [9] that the main K-vacancy production mechanism in both collision partners is the creation of a $2p\sigma$ molecular orbital (MO) vacancy which is subsequently shared between the K-shells of the two atoms. According to Meyerhof *et al.* [3]:

$$\sigma_L(K) = (1 - w) \sigma_{2p\sigma} + w \sigma_{1s\sigma} + \sigma^{K-L}(K) \approx (1 - w) \sigma_{2p\sigma} + \sigma^{K-L}(K) \quad (2)$$

since always $\sigma_{1s\sigma} \ll \sigma_{2p\sigma}$ and $w \leq 1/2$, and

$$\sigma_H(K) = w \sigma_{2p\sigma} + (1 - w) \sigma_{1s\sigma} \quad (3)$$

where σ_L , σ_H are the K-vacancy cross-section for the light and heavy collision partners respectively, σ_i is the cross-section for the creation of a vacancy in the i -th molecular-orbital ($i = 1s\sigma, 2p\sigma$), $\sigma^{K-L}(K)$ is the K-vacancy cross-section of the lighter atom due to K-L matching [25] and w is the vacancy sharing factor [12].

For $\sigma^{K-L}(K) \ll \sigma_{2p\sigma}$ (i.e. only slightly asymmetric systems),

$$\sigma_L = (1 - w) \sigma_{2p\sigma} \quad (4)$$

$$\sigma_H = w \sigma_{2p\sigma} + (1 - w) \sigma_{1s\sigma} \quad (5)$$

and thus

$$\frac{\sigma_H}{\sigma_L} = \frac{w}{1 - w} + \frac{\sigma_{1s\sigma}}{\sigma_{2p\sigma}} = e^{-2x} + \frac{\sigma_{1s\sigma}}{\sigma_{2p\sigma}} \quad (6)$$

where x is defined by

$$x \equiv \pi (I_H^{1/2} - I_L^{1/2}) / (2 m_e v^2)^{1/2} \quad (7)$$

I_H and I_L being the K-shell binding energies of the heavy and light atoms and v the projectile velocity respectively.

Under the assumption that $\frac{w}{1 - w} \gg \frac{\sigma_{1s\sigma}}{\sigma_{2p\sigma}}$, we can directly compare the calculated ratio, $\left(\frac{w}{1 - w} \right)$, to the measured ratio of the cross-sections (σ_H/σ_L) as functions of the target atomic number. This is shown in figure 4. The K-vacancy cross-sections used to evaluate the ratio of (σ_H/σ_L) were deduced from the measured K x-ray cross-sections (Tab. 1), using neutral atom fluorescence yields [21]. The ionization state of the projectile is expected to influence the value of its fluorescence yield, while the degree of ionization will vary with target thickness and projectile energy. The error introduced by using neutral atom fluorescence yields is estimated to be $\sim 10\%$ [11, 14].

Good agreement between theory and data is observed (Fig. 4) in the region $28 \leq Z_t \leq 56$ for all projectile energies. For 100 MeV, the agreement is very good even for $Z_t = 24$ for

Fig. 4. — Experimental ratio of σ_H/σ_L (data points) with theoretical values of the sharing ratio $\frac{w}{1-w}$ versus target atomic number Z_t for the three different projectile energies. Continuous line : Calculations based on the vacancy sharing probability w formula (Eqs. (6) and (7)) without the inclusion of the term $\sigma_{1s\sigma}/\sigma_{2p\sigma}$. Dashed line : includes the term $\sigma_{1s\sigma}/\sigma_{2p\sigma}$.

which the sharing ratio ($w \sim 0.0003$) is very small. At higher projectile energies, small deviations are observed increasing in size with increasing projectile energy (Fig. 4). A difference of a factor of four between data and theory for 200 MeV Nb + Ti ($Z_t = 22$) is too large to be accounted for by variations in the fluorescence yield of the Nb projectile alone. Furthermore, contributions from direct excitation and radiative electron capture (Fig. 3, continuous lines) are $\sim 30\%$ of the total cross-section for Ti and therefore are also not large enough to account for this discrepancy. We expect the K-L matching mechanism [25] to become increasingly important in these collision systems, since the $3d\sigma$ MO, correlated to the $3p$ -level of the projectile, will be progressively excited with increasing projectile energies. Therefore the previous assumption of $\sigma^{K-L}(K) \ll \sigma_{2p\sigma}$ will not be valid any longer and contributions from the increased ionization of the K-shell due to K-L matching must be considered. Since the L-shell ionization cross-section of the heavier atom was not measured, the evaluation of these contributions cannot be carried out.

In the region of $Z_t > Z_p$, ignoring $\sigma_{1s\sigma}/\sigma_{2p\sigma}$ in equation (6), leads to rather good agreement (see Fig. 4) between the theoretical (e^{-2x} , Eq. (6)) and experimental (σ_H/σ_L) sharing ratio for all targets used up to Barium. However, for $Z_t > 56$, a consistent deviation occurs, increasing with decreasing projectile energy. Such a projectile energy dependence is not consistent with the direct Coulomb excitation mechanism [6]. So, by correcting the sharing ratio $\frac{w}{1-w}$ for the contribution from the ratio $\sigma_{1s\sigma}/\sigma_{2p\sigma}$ [26], using the measured ratio of $\sigma_{2p\sigma} = \sigma_H + \sigma_L$, (Eqs. (4), (5)) and the estimated value of $\sigma_{1s\sigma}$ [15], the agreement between theory (Eq. (6)) and data (σ_H/σ_L , Fig. 4) is improved to 40 % at 200 MeV. However, it is still off by a factor of 4 at 100 MeV (dashed line in Fig. 4). A similar disagreement increasing with decreasing projectile energy is obtained using the values from the ECRSSR theory for the $\sigma_{1s\sigma}$ value (Fig. 3 continuous line). On the other hand, any contribution from K-L level matching should further reduce the sharing ratios (Eqs. (2-3, 6)). Increasing the projectile velocity, should also increase the relative contribution of K-L matching [25], in disagreement with our data (Fig. 4). Strong relativistic corrections applied to heavier collision systems [27], might also be important in this case, though $Z = Z_t + Z_p \ll 137$. An extrapolation of the theory specifically developed for very heavy collision

systems ($Z \geq 137$, Ref. [28]), underestimates the measured cross-sections by many orders of magnitude. Since the sharing ratio formula [12] has been verified for many collision systems, the origin of this discrepancy is still not clear.

In the case of Erbium (Er), the K vacancy cross-section is larger than the cross-section of Samarium (Sm) though $Z_{\text{Sm}} = 62 < Z_{\text{Er}} = 68$ (Fig. 3). This is due to background contributions to Er from K-shell internal conversion decay. Since Er has a strongly deformed nucleus, this effect will make a large contribution to K x-ray production, while for the other targets such an effect will not be appreciable. The contribution from the direct nuclear Coulomb excitation followed by internal conversion decay has been estimated using the internal conversion factors from reference [29] and theoretical values for the direct nuclear Coulomb excitation [30] and found to account for most of the Er K x-rays. In the case of the Sm target, the relative contribution was found to be less than 10 %. Due to this contribution from internal conversion, the value of the Er K x-ray cross-section due to atomic effects alone is quite uncertain.

Fig. 5. — Total $2p\sigma$ MO vacancy production cross sections for $Z_t > 22$, scaled as discussed in text. Continuous line : modified BEA [13]. Dashed line : Lennard *et al.* [31].

In figure 5 the $2p\sigma$ vacancy production cross-sections are scaled by the factor $I_{2p}^2(U)/Z^2$ and plotted *versus* the scaling parameter $v_1^2/v_{2p}^2(U) = (E_1/M_1)/[I_{2p}(U)/m_e]$ for $Z_t > 22$. The cross-sections shown were calculated from the sum of the target and projectile K x-ray cross-sections corrected for the neutral atom fluorescence yield [21]. Z is the effective charge ($2Z^2 = Z_1^2 + Z_2^2$), while $I_{2p}(U)$ is the united atom binding energy. The predictions of the modified BEA [13] are shown in figure 5 as a continuous line. Within the limitations of this model ($Z_{\text{Light}}/Z_{\text{Heavy}} < 0.6$) agreement between data and theory is quite good for all targets in the region $24 \leq Z_t \leq 62$. It should be noted that, based on lighter collision systems, a modified function for the scaled cross-sections had been proposed [31]. These results are also shown in figure 5 (dashed line). Serious disagreement with our data is observed.

The K x-ray cross-sections (projectile and target) dependence on the projectile energy can be fitted to an exponential of the form :

$$\sigma(Kx) \sim E_{\text{proj}}^{\alpha} \quad (8)$$

as already shown [3]. The dependence of the exponent α on Z_t is shown in table I for both projectile and target K x-rays. With a few exceptions, α is a slowly varying function of the target atomic number, going through a minimum value for symmetric collisions. Its value increases for more asymmetric systems, in close agreement with previously reported results [3]. This dependence of the cross-sections on projectile energy was used to interpolate our reported K x-ray cross-sections (see Fig. 3) at the average projectile energy inside the target. This resulted in small corrections ($< 10\%$) to the measured K x-ray cross-sections.

5. Conclusion.

Target and projectile K ionization cross-sections were determined in 100, 160 and 200 MeV collisions of $_{41}\text{Nb}$ with various targets ($Z_t = 6 - 68$). In the region of $24 \leq Z_t < 62$, the ratio of projectile to target cross-sections agree quite well with the predictions of the molecular model and the K-vacancy sharing model [12]. Predictions of the direct excitation model (ECPSSR theory) valid for asymmetric collisions, agree within a factor of two for the lightest targets used (C and Al), but disagree by a factor of four or more with the measured cross-sections for Ti and the heaviest target Sm. A slightly better agreement is obtained if one uses a semi-empirical model of direct excitation [15].

The sum of both target and projectile K vacancy cross-sections was found to be in fair agreement with the modified binary encounter approximation [13]. However, some semi-empirical corrections to this theory proposed, based on lighter collision systems [31], were found to be in serious disagreement with our data.

The ratio of the K vacancy cross-sections for the heavy and light collision partners (σ_H/σ_L) was found to be in excellent agreement with the results of the vacancy sharing formula [12]. However, increasing disagreement was found between the measured and theoretical values of the sharing ratio as the projectile energy was increased. This signals the breakdown of the molecular model at the higher projectile energies utilised.

In conclusion, we have compared the results of various existing models for K x-ray production in heavy ion collisions. For the fairly heavy systems studied here semi-empirical or semi-classical approaches yielded the best agreement. However, even these theories could not predict the cross-sections for all collision systems studied and further corrections were usually required. More data and a more complete theory of K vacancy production in ion-atom collisions is required to clarify the situation.

Acknowledgments.

We would like to thank prof. J. S. Greenberg and Dr. J. J. O'Brien for their contributions to this work. We would also like to thank the WNSL staff at Yale University for their support. This work was partially supported by the U. S. Department of Energy, Contract No. DE-ACO2-76ER03074.

References

- [1] PAUL H. and MUHR J., *Phys. Rep.* **135** (1985) 47.
- [2] MONTENEGRO E. C. and SIGAUD G. M., *J. Phys.* **B 20** (1985) 299.
- [3] MEYERHOF W. E., ANHOLT R., SAYLOR T. K., LAZARUS S. M., LITTLE A. and CHASE L. F. Jr., *Phys. Rev. A* **14** (1976) 1653.
- [4] ANHOLT R., MEYERHOF W. E., STOLLER Ch., MORENZONI E., ANDRIAMONJE S. A., MOLITORIS J. D. and BAKER O. K., *Phys. Rev. A* **30** (1984) 2234.
- [5] READING J. F., *Nucl. Instrum. Methods A* **262** (1987) 160.
- [6] MADISON D. H. and MERZBACHER E., *Atomic Inner-Shell Processes*, Ed. B. Craseman (Academic, New York) 1975, p. 1.
- [7] FANO U. and LICHTEN W., *Phys. Rev. Lett.* **14** (1965) 627.
- [8] LICHTEN W., *Phys. Rev.* **164** (1967) 131.
- [9] MEYERHOF W. E., ANHOLT R. and SAYLOR T. K., *Phys. Rev. A* **16** (1977) 169.
- [10] BRANDT W. and LAPICKI G., *Phys. Rev. A* **23** (1981) 1717.
- [11] TANIS J. A., SHAFROTH S. M., JACOBS W. W., MCABEE T. and LAPICKI G., *Phys. Rev. A* **31** (1985) 750.
- [12] MEYERHOF W. E., *Phys. Rev. Lett.* **31** (1973) 1341.
- [13] FOSTER C., HOOGKAMER T. P., WOERLEE P. and SARIS F. W., *J. Phys.* **B 9** (1976) 1943.
- [14] LIAROKAPIS E., ZOUROS T. J. M. and GREENBERG J. S., *Phys. Rev. A* **36** (1987) 1669.
- [15] ANHOLT R. and MEYERHOF W. E., *Phys. Rev. A* **16** (1977) 190 ;
ANHOLT R., *Phys. Rev. A* **17** (1978) 976.
- [16] HANSEN J. S., MCGEORGE J. C., NIX D., SCHMIDT-OTT W. D., UNUS I. and FINK R. W., *Nucl. Instrum. Methods* **106** (1973) 365.
- [17] LIAROKAPIS E., Ph. D. thesis (Yale University) 1979, unpublished.
- [18] TRAUTVETTER H. P., GREENBERG J. S. and VINCENT P., *Phys. Rev. Lett.* **37** (1976) 202.
- [19] LENNARD W. N. and MITCHELL I. V., *Nucl. Instrum. Methods* **132** (1976) 39.
- [20] HALL J., RICHARD P., GRAY T. J., NEWCOMB J., PEP MILLER P., LIN C. D., JONES K., JOHNSON B. and GREGORY D., *Phys. Rev. A* **28** (1983) 99.
- [21] KRAUSE M. O., *J. Phys. Ref. Data* **8** (1979) 307.
- [22] TANIS J. A., JACOBS W. W. and SHAFROTH S. M., *Phys. Rev. A* **22** (1980) 483.
- [23] TAWARA H., RICHARD P., GRAY T. J., NEWCOMB J., JAMISON K. A., SCMIEDEKAMP C. and HALL J. M., *Phys. Rev. A* **18** (1978) 1373.
- [24] ZOUROS T. J. M., Ph. D. thesis (Yale University, 1983) unpublished.
- [25] MEYERHOF W. E., ANHOLT R., EICHLER J. and SALOP A., *Phys. Rev. A* **17** (1978) 108.
- [26] BEHNCKE H. H., ARMBRUSTER P., FOLKMAN F., MACDONALD J. R. and MOKLER P. H., *Z. Phys.* **A289** (1979) 333.
- [27] SOFF G., BETZ W., MÜLLER B., GREINER W. and MERZBACHER E., *Phys. Lett.* **65A** (1978) 19.
- [28] MÜLLER B., SOFF G., GREINER W. and CEAUSESCU V., *Z. Phys.* **A285** (1978) 27.
- [29] HAGER R. and SELTZER E. C., *Nucl. Data A* **4** (1968) 1.
- [30] ADLER K. and WINTHER A., *Coulomb excitation* (Academic Press) 1968.
- [31] LENNARD W. N., MITCHELL I. V. and FOSTER J. S., *Phys. Rev. A* **18** (1978) 1949.