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K-shell ionization of low Z elements in ion–solid collisions and applicability of local plasma approximation

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Abstract

K-shell vacancy production cross sections are measured using X-ray technique, in collisions of highly charged fluorine ions with various solid targets such as, Cl, K, Fe and Cu, at energies from 50 to 110 MeV. The experimental data is compared with an ab initio model based on local plasma approximation (LPA) and the usually employed ECPSSR. A detailed comparison with the LPA model is presented as a function of generalized perturbation strength.

Keywords: Inner shell ionization; ECPSSR; LPA

1. Introduction

The study of heavy-ion induced inelastic processes involving strongly bound electrons in the inner shells provides an opportunity for stringent test of various theoretical models. Particularly so when the projectile velocity is very close to the inner shell electronic velocity. Ionization and electron transfer involving inner shells are the two dominant processes in case of heavy-ion collisions. There have been numerous studies on the total ionization cross sections of the deeply bound electrons and several empirical scaling laws have been proposed. Some of the experimental results on the inner-shell ionization can be found in various compilations as referred in detail in our previous work (Kadhane et al., 2003a, b). Most of the theories, however, have been developed for collisions in which the target is a single gas atom or molecule. Some of the commonly used models are not *ab initio* models but are semi-empirical in nature. However, they are quite successful in reproducing many experimental data for relatively complicated atoms, for which an exact and *ab initio* calculation is extremely difficult. An example of this is the well known ECPSSR approximation (Brandt and Lapicki, 1981). This model is based on the perturbed stationary state (PSS) approximation, with modifications introduced in the first order Born approximation to account for the effects due to the polarization and enhanced binding energy of the target electrons, Coulomb (C) deflection, energy loss (E) and relativistic (R) wave functions in a semi-empirical manner. The successful description of experimental data via an analytical expression makes the ECPSSR approximation very convenient in obtaining K-shell ionization cross sections, although it is not an *ab initio* calculation. Additional complications arise if the collision system involves a solid target. In such collision systems the solid-state effect, which arises from the large electron density fluctuation and plasmon excitation, is known to influence the atomic collision processes, as evident from many experimental results in the past [see

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Refs. 24 to 31 in Kadhane et al. (2003b)]. Most of the studies on atomic collisions with solids are related to the interaction of the ion with the free electron gas (FEG). However, high-velocity experiments have shown that the target inner-shell electrons also contribute to the dynamic screening and therefore these electrons should be considered in order to have a complete picture of the dynamic screening of the ion (Rozet et al., 1999, Vernhet et al., 1998, Fuhr et al., 1998). One of the models for dealing with core-electron polarization is the local plasma approximation (LPA). Details on the calculations can be found in Montanari et al. (2002), Kadhane et al. (2003a, b) and references therein. On the other hand, we present here an alternative model to describe the interaction of the swift ions with the inner shell electrons of the solids. The usual formalism to deal with collisions involving solid targets is the dielectric theory, first proposed by Bohr and extensively employed since then by Echenique et al. (1990). Within this formalism, the target electrons are considered to respond collectively to the passage of the projectile. The polarization of the medium can be described as a wake of density fluctuation trailing the ion, producing a wake-induced electric field. This response of the electrons in the solid to the ion perturbation is known as the solid-state effect.

We present a set of comparison of the two models with the K-shell ionization cross sections in the intermediate velocity range (few MeV/u). An example with fluorine projectile will be discussed in detail.

2. Experimental details

A well collimated beam of fluorine ions with energies between 50 and 110 MeV and different charge states was provided by the BARC-TIFR Pelletron facility at TIFR. Targets of K, Cl (in the form of KCl), Fe and Cu were prepared on 10 μg cm^{-2} thick C backing with thicknesses of 1.6, 1.6, 2.43, 0.58 and 1.9 μg cm^{-2}, respectively. Such thin targets were chosen to ensure single-collision condition. The targets were mounted on a rotatable multiple target holder assembly. The K X-rays, which arise due to the production of the target K-shell vacancy and its decay, were detected using a Si(Li) detector of 30 mm^2 in area and 3 mm in thickness mounted inside the vacuum at an angle of 45° with respect to the beam direction. The detector with a resolution of 165 eV at 6.9 keV, equipped with a Be window of thickness 25 μm was used. A silicon surface barrier detector was mounted at 135° to detect the elastically scattered particles. This was used to measure the target thickness *in situ* at lower energies than the Coulomb barrier for all target-projectile combinations. The target chamber was electrically isolated from the beam line and the vacuum pump in order to collect the charge on the entire chamber, which was used for normalization.

The data were collected on a CAMAC-based high-speed data acquisition system interfaced to the PC.

Typical X-ray spectra at a beam energy of 83 MeV for each target are presented in Fig. 1. For the case of Cu and Fe, the K_α and K_β lines are well separated; for the case of K and Cl, these lines are not well resolved. The spectra were analyzed by using a multi-parameter fitting program to obtain the peak position and intensity. The intensities were corrected for the detector efficiency and transmission through the Be window. The ionization cross sections were derived from the measured X-ray cross sections and the K-shell fluorescence yields, ω_K.

Fig. 2 shows the shift in the X-ray energy as a function of projectile energy. This shift is due to simultaneous multiple ionizations in the outer shell (mainly in the L-shell) of the target, causing the binding energies to shift on higher side. As can be seen from the trend in Fig. 2, as the projectile velocity increases the probability of multiple ionization (in L and M-shells) decreases hence causing the energy shift to decrease. The ω_K

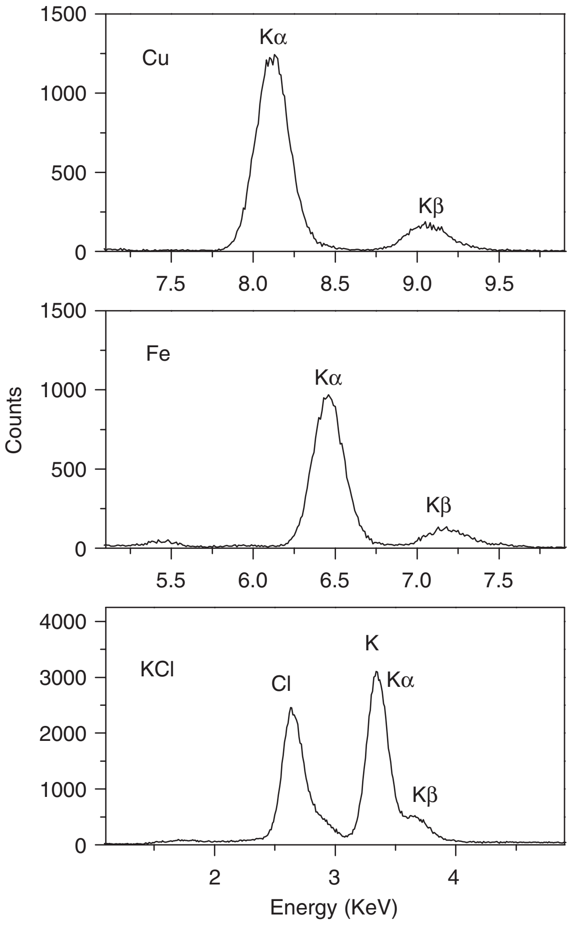

Fig. 1. X-ray spectrum from various targets due to 83 MeV F^{6+} beam.

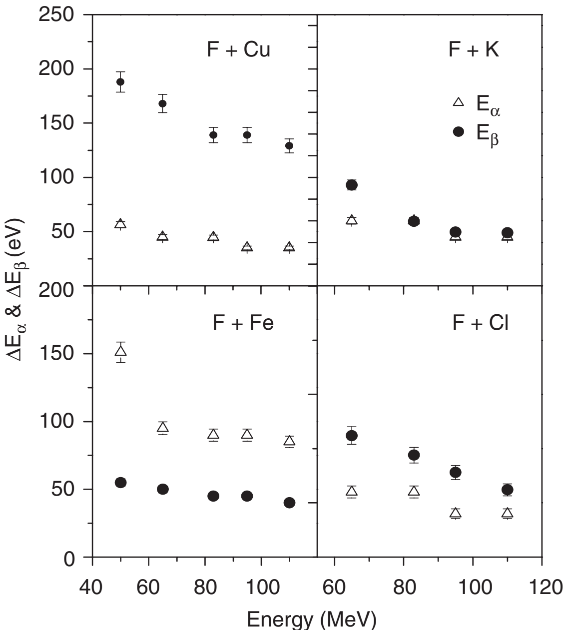

Fig. 2. X-ray peak energy shift.

Table 1
The ionization cross sections (σ_{KI}), energy shifts (ΔE_α and ΔE_β), intensity ratios, and the enhancements in fluorescence yields

T	E (MeV)	q	ΔE_α (eV)	ΔE_β (eV)	I_β/I_α	$\omega_{\mathrm{K}}/\omega_{\mathrm{o}}$	σ_{K} (kb)
Cu	50	5	56.5	188	0.176	1.22	9.8
	63	6	45	168	0.176	1.176	18.62
	83	6	44.6	139	0.163	1.176	40.9
	95	7	35	139	0.165	1.136	62.42
	110	8	35	129	0.129	1.136	103.6
Fe	50	5	55	151	0.18	—	27.84
	63	6	50	95	0.17	—	43.69
	83	6	45	90	0.173	—	83.54
	95	7	45	90	0.173	—	118.5
	110	8	40	85	0.184	—	105.1
K	63	6	60	93	0.34	1.23	568
	83	6	60	59.5	0.34	1.23	538
	95	7	45	49.6	0.37	1.23	665
	110	8	45	49	0.36	1.23	1191
Cl	63	6	55	81	0.295	1.24	923
	83	6	55	72	0.247	1.24	800
	95	7	45	64	0.268	1.24	925
	110	8	45	56	0.268	1.24	1622

values were taken from the tabulation by Krause (1979) and were further corrected for the multiple ionization of the outer shells in the target. These corrections were estimated by using the calculated data tables provided by Bhalla (1973), Bhalla (1975a), Bhalla (1975b) the measured intensity ratios of the K_α and K_β lines, and the shifts in these X-ray energies (see Table 1). The enhancements in the values of ω_{K} were found to be between 15% and 25% (Table 1). The typical errors are about 15–20% for vacancy production cross sections, which includes the uncertainties in the target thickness, detector solid angles, fluorescence yields, and counting statistics.

3. Results and discussion

The K-shell ionization cross sections are shown in Fig. 3, along with the model calculations. Charge state was chosen such that K-shell of the projectile was filled except for 110 MeV where the projectile charge state was 8+ (i.e. with one vacancy in K-shell). This caused a small amount of K–K (i.e. target K-shell to projectile K-shell) transfer cross section (about 20% of ionization) contributes in the data point. For these data points we have added the capture contribution calculated separately, to the ECPSSR calculations. The ECPSSR model shows good agreement with data except for the Cl and K targets at low energies. This indicated that at the present velocity range and target projectile combination the ion-atom description is still valid and the solid state effects are not affecting the ionization process substantially. Whereas, LPA underestimates the ionization cross sections for Cl and K by a factor of about 2. For Cu and Fe it shows relatively better agreement. This implies that LPA works better for asymmetric collision system and for near symmetric case it deviates. In order to explore this in more detail the relation between these parameters has been expressed in terms of a generalized perturbation strength $S_{\mathrm{p}} = Z_{\mathrm{p}}/(\mathrm{vp}Z_{\mathrm{t}})$ proposed by Tiwari et al. (1998). We plot the ratio, $\sigma_{\mathrm{KI}}^{\mathrm{LPA}}/\sigma_{\mathrm{KI}}^{\mathrm{EXP}}$, as a

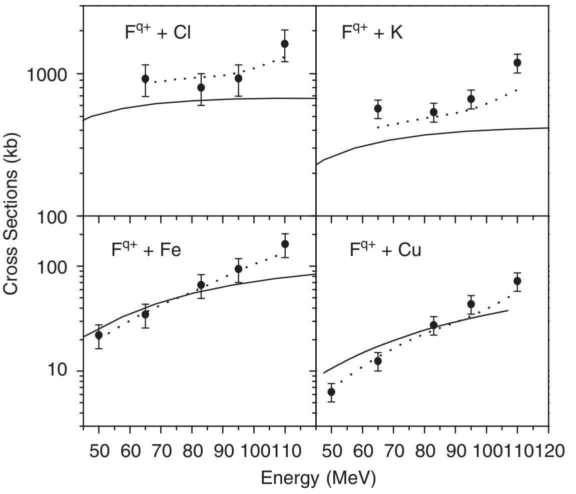

Fig. 3. K-shell ionization cross sections for various targets. Continuous lines show LPA calculations and dotted lines show ECPSSR.

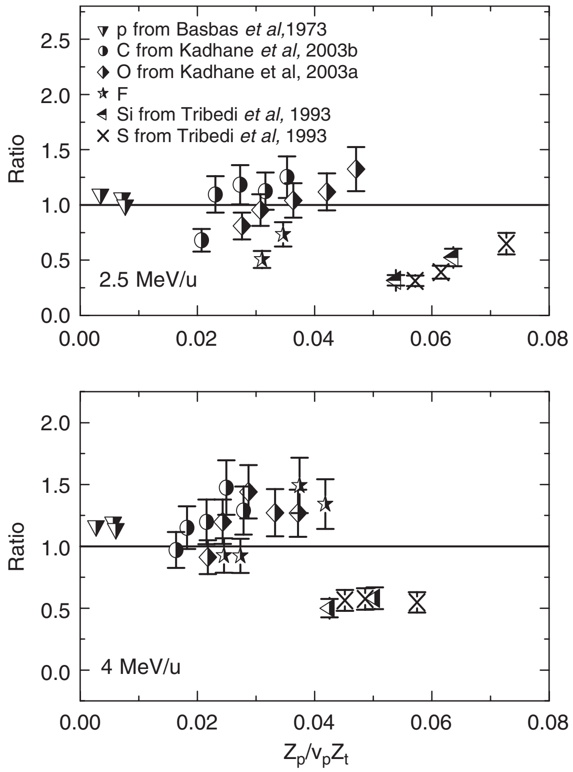

Fig. 4. Ratio of LPA and experimental data vs generalized perturbation strength (see text).

function of S_p at 2.5 and 4 MeV/u in Fig 4a and b. Data for other target projectile combinations from previous studies (Tribedi et al., 1993, 1994) and from Basbas et al. (1973, 1978) is also plotted along with the present data. It can be seen from the Fig. 4 that the ratio is close to one for the lowest value of S_p and then increases gradually with S_p, indicating increasing deviation from the LPA model. It may be concluded from both sets of data that the LPA model shows better agreement for $S_p < 0.05$.

The deviation of the LPA model from the data can be understood in terms of the failure of the basic assumption of the LPA. As the collision process becomes more symmetric, free electron gas approximation may not remain valid.

4. Conclusion

K-shell vacancy production cross sections arising from Coulomb ionization and state selective *K–K* electron transfer processes are measured in collisions of fluorine ions with solid targets of low atomic numbers ($17 \leqslant Z_t \leqslant 29$) in the intermediate velocity range. The measured ionization cross sections were used to provide a test to the LPA, which has been developed from the dielectric formalism to include the solid-state effect on atomic collisions. The *ab initio* LPA model, although, is found to give an overall acceptable agreement but tends to underestimate the data for relatively symmetric collisions and low velocities. On the other hand, the ECPSSR model, which is thoroughly developed but more semi empirical in nature, shows an excellent agreement with the measurements even for the low Z_t targets in the whole energy range considered here. A comparison with models is presented in terms of the generalized perturbation strength.

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