KK-vacancy sharing and TET energy shift in near-symmetric heavy-ion atom collision*

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Abstract The two-electron-one-photon transitions (TET) are measured in 75 MeV Ni^{+q} + Cu collisions. The KK-vacancy sharing ratio R_{kk} is deduced, which is in agreement with the theoretical prediction of Lennard. The emission energy of TET is slightly larger than twice the corresponding K transition energy.

Keywords KK-vacancy sharing, TET, Ni^{+q} + Cu collisions

1 Introduction

X-ray spectra measured in heavy-ion collisions at medium energies (~1 MeV/u) are quite different from proton induced spectra, both in their continuous and characteristic parts. The characteristic lines (observed with a solid state detector) are broadened and shifted towards higher energies[1]. The broadening and the shift of the characteristic lines are caused by highly ionized states which are produced in heavy ion collisions. The outer shells are almost completely ionized and multiple vacancies are created in the inner shells. There even exists a certain probability for a double ionization of the K-shell. The double K shell vacancies are decayed not only by the independent transition of two electrons observable through the emission of hyper-satellites K_α^h X-rays[2], but also by a correlated two electrons transition accompanied by a single photon emission with an energy slightly larger than twice the K transition energy.

The two-electron-one-photon transition (TET) is a much less favorable radioactive decay mode. The investigation of TET X-rays from an asymmetric collision system can provide information on KK-vacancy sharing between the collision partners. Lennard *et al.*[3] developed a simple model of KK-vacancy sharing, which resulted from a modification of single K-vacancy sharing theory and consisted with independent sharing of each vacancy in the $[2p\sigma]^{-2}$ configuration between the collision partners, through $2p\sigma$-$1s\sigma$ radial coupling. The theoretical prediction by the model is in very good agreement with the experimental results.

In this paper we present experimental results which extend the Ni^{+q} + Cu system to a higher effective projectile velocity and so to a lower system parameter X_k. The measured KK-vacancy sharing ratio can still be accounted for by this model.

2 Experimental

The experiments were performed at the China Institute of Atomic Energy (CIAE) HI-13 tandem accelerator. In the measurements a self-supporting Cu target with a thickness of 1.09mg/cm^2 was bombarded by Ni^{+q} beams from the accelerator at an energy 75 MeV. The experimental set-up is shown in Fig.1. The target was oriented at 45° to the beam. The X-rays were measured at 90° with respect to the beam axis by a Si(Li) detector (28 mm^2 × 5.27 mm) having 175 eV resolution at 5.9 keV. A 13 μm thick Mylar window is used to isolate the Si(Li) detector from the vacuum chamber. An absorber made of 720 μm thick high-purity aluminum (99.99%) was mounted between the target and the Si(Li) detector to attenuate the intense K_α and K_β lines from projectile and target atoms by a factor of 10^4, while the TET X-rays were attenuated only by a factor of ~3. To reduce electronic pileup effects to a negligible amount, the total count rate was kept at a level of ~30 counts per second. The spectra were recorded on a magnetic tape and later analyzed

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with VAX 11/780 computer. The energy and efficiency of the Si(Li) detector were calibrated using an ^{241}Am standard X-ray source. The X-ray spectrum of ^{241}Am standard X-ray source was taken before and after each Ni^{+q} ion bombarding Cu target to check any amplifier drift.

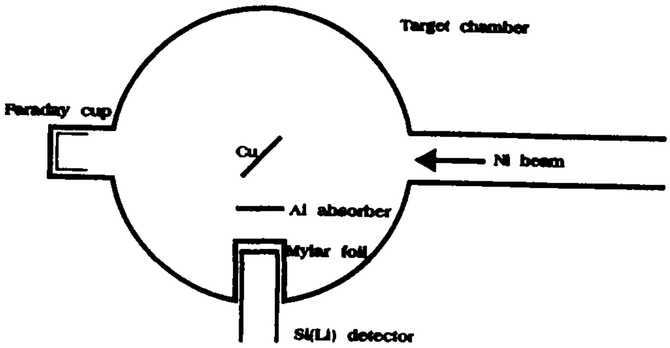

Fig.1 Experimental set-up

3 Results

Typical X-ray spectrum obtained at a Ni beam energy of 75 MeV is displayed in Fig.2. The two-electron-one-photon transitions were observed, either from a $K^2 - L^2$ ($K_{\alpha\alpha}$) or from a $K^2 - LM(K_{\alpha\beta})$ transition. Two peaks are clearly present in the TET X-ray energy region. The first peak is the Ni $K_{\alpha\alpha}$ line. The second peak is a result of overlap of Ni $K_{\alpha\beta}$ and Cu $K_{\alpha\alpha}$ lines. The Cu $K_{\alpha\beta}$ line is too weak due to the poor statistics.

As the TET X-ray line is very weak compared with the characteristic radiation, several other effects might lead to similar peaks. So that, the following tests were made to ensure that these lines are not produced by any background effect. Since the pileup peaks of the K_α lines lie very close to the expected $K_{\alpha\alpha}$ lines, this effect must be reduced to a negligible amount. This is achieved when the characteristic lines are attenuated by several orders of magnitude using appropriate Al absorber; and total count rate is kept below 30 counts per second during all runs. The impurities of targets were checked by using the X-ray fluorescence analysis method. No trace elements giving characteristic X rays at or in the neighborhood of the peaks under discussion were observed. Coulomb excitation cannot cause the observed lines as there are no known γ lines in the energy range of interest.

Considering all results presented so far, it became clear that only the following two effects remained which can explain all properties of these peaks, namely a two-electron-two-photon or a two-electron-one-photon transition in the highly excited target and/or projectile atoms. Although the first effect is orders of magnitude more probable than the second one, it cannot explain the intensity of these peaks. The two photons emitted in this transition would have to be registered simultaneously by the detector. The probability for this is negligibly small in the present experiment because of the strong attenuation of the characteristic K lines (10^{-4} in the Ni-Cu case), and the small solid angle of the detector (2.78×10^{-4}sr).

Therefore we must conclude that the observed peaks indicate the existence of a simultaneous two-electron jump accompanied by the emission of only one photon with an energy slightly larger than twice the corresponding K transition energies. This slight shift can be explained very easily by the reduced screening in the doubly ionized K shell. If the vacancies are filled by two L electrons then the transition energy is given by

$$E_x = 2E_{k\alpha} + \Delta E_s$$

if one L and one M electron are involved, then

$$E_x = E_{k\alpha} + E_{k\beta} + \Delta E_s$$

The measured energies of $K_{\alpha\alpha}$ X-ray are: E_x=15.346 keV and E_x=16.443 keV, which correspond to an energy shift ΔE_s=206 eV and ΔE_s=223 eV for Ni and Cu, respectively.

For the K_α transition the semiempirical formula[7]

$$\Delta E_s = \frac{3}{4} \times 13.6[Z^2 - (Z-s)^2] \quad (1)$$

can be used, where the shielding factor s=0.39.

Using Eq.(1), we calculate ΔE_s = 221 eV for Ni and ΔE_s=229 eV for Cu. Both values are in good agreement with the measurements, as can be seen from Table 1.

Table 1 X-ray energies observed in Ni^{+q} + Cu collision

	$E(K_\alpha)$/keV theor	$E(K_\alpha)$/keV exp	$E(K_{\alpha\alpha})$/keV exp	ΔE_s/eV exp	ΔE_s/eV cal
Projectile Ni	7.477	7.570	15.346	206	221
Target Cu	8.037	8.110	16.443	223	229

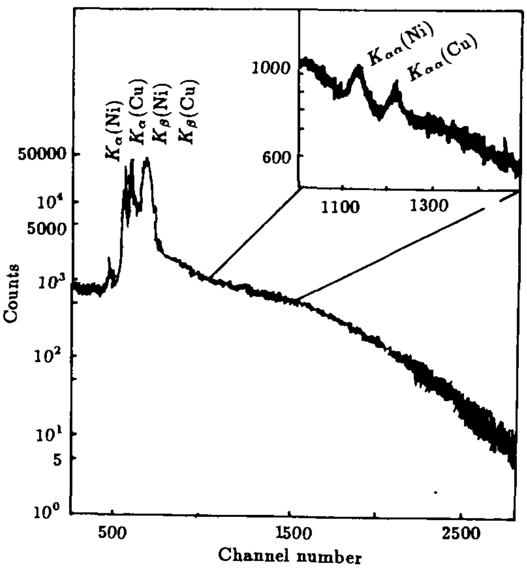

Fig.2 X-ray spectrum in Ni^{+q} + Cu collision at 75 MeV

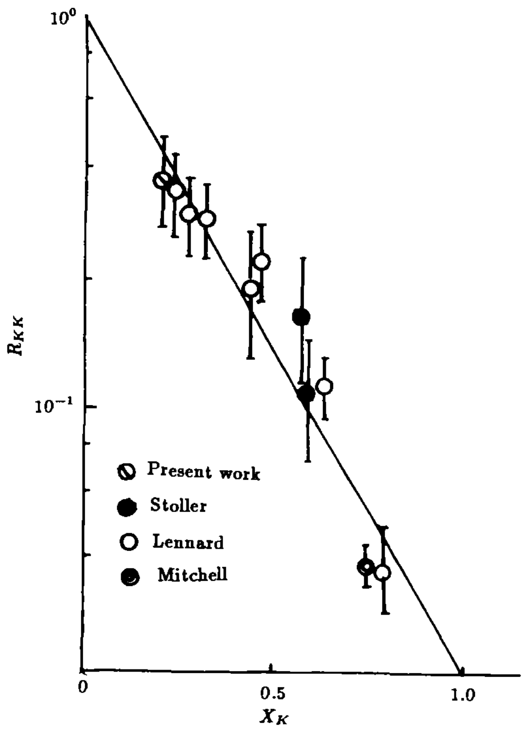

Fig.3 R_{kk} vs $X_k = \frac{\pi\left[\sqrt{I_{1s}(H)} - \sqrt{I_{1s}(L)}\right]}{v\sqrt{2m}}$

The full line is the result predicted by $R_{kk} = \exp(-4X_k)$

Because the energy of the $K_{\alpha\alpha}$ X-ray depends on the electronic configuration of the emitting atom, all characteristic lines are shifted with respect to the theoretical values due to multiple vacancies in the outer shell of target and projectile.

From the measured net areas of the first and the second peaks we can calculate the ratio of the KK X-ray yields of the heavier partner $Y(H)$ to that of the lighter partner $Y(L)$ as following

$$\frac{Y(H)}{Y(L)}=\frac{Y(\mathrm{Cu}K_{\alpha\alpha})+Y(\mathrm{Cu}K_{\alpha\beta})}{Y(\mathrm{Ni}K_{\alpha\alpha})+Y(\mathrm{Ni}K_{\alpha\beta})}=\frac{(1+P_2)(A_2\varepsilon_1/A_1\varepsilon_2-P_1)}{1+P_1} \tag{2}$$

where ε_1, ε_2 are the detector efficiencies (including the absorption and geometry corrections) at the energies of the first peak and second peak, respectively. P_1=0.25, P_2=0.195 are the ratio $K_{\alpha\beta}/K_{\alpha\alpha}$ for Ni and Cu, respectively. We obtain the KK X-ray yield ratio:

$$\frac{Y(H)}{Y(L)}=0.36\pm0.10$$

The KK-vacancy sharing ratio R_{kk} is related to the measured KK X-ray yield by the fluorescence yields

$$R_{kk}=\frac{Y(H)}{Y(L)}\frac{\omega_k^0(L)}{\omega_k^0(H)}(\frac{Z_\mathrm{H}}{Z_\mathrm{L}})^2 \tag{3}$$

where $\omega_k^0(H)$ and $\omega^0(L)$ are the neutral-atom K X-ray fluorescence yields for the heavier and lighter partners[4], Z_H and Z_L are the atomic numbers of the heavier and lighter partners, respectively. Substituting the measured $Y(H)/Y(L)$ value into Eq.(3) , we obtain R_{kk}=0.36±0.10

In Fig.3 we compare our measured value of R_{kk} with the predicted result by Lennard's model[3], R_{kk}=exp(-4X_k), where the system parameter

$$X_k=\frac{\pi\left[\sqrt{I_{1\mathrm{s}}(H)}-\sqrt{I_{1\mathrm{s}}(L)}\right]}{\nu\sqrt{2m}} \tag{4}$$

where $I_{1\mathrm{s}}(H)$ and $I_{1\mathrm{s}}(L)$ are the neutral-atom K-binding energies for the heavier and lighter collision partners, m is the electron mass and v the effective projectile velocity. Fig.3 also displays the experimental results of Lennard *et al*[3] (Cu-Co,Cu-Ni,Cu-Zn, Cu-Fe), Stoller *et al*[5] (Fe-Ni) and Mitchell *et al*[6] (Na-Ne). It can be seen that our result agrees with the predicted value of R_{kk} within the error.

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