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IMPACT PARAMETER DEPENDENCE OF K-SHELL IONIZATION IN Cu-Cu COLLISIONS

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INTRODUCTION

The impact parameter dependence of K-shell vacancy production in adiabatically slow heavy ion collisions is qualitatively described by the electron promotion model of Fano and Lichten [1]. This model developed by Briggs and Macek [2] and extended to asymmetric systems by Taulbjerg et al. [3] has been discussed in many papers; see, e.g., Meyerhof et al. [4,5]. In the model, the 2p vacancies existing prior to the collision or created in the same collision at large distances are transferred through the $2p\pi - 2p\sigma$ rotational coupling to the K-shell of the lighter partner of the collision and, in the outgoing part of the trajectory, shared between the lighter and heavier partners via radial coupling of the $2p\sigma - 1s\sigma$ molecular orbitals. The number of $2p\pi$ vacancies existing in the first stage of the collision remains as a free parameter of the model.

The model of electron promotion via the $2p\pi - 2p\sigma$ rotational coupling explains quantitatively the K-shell excitation in adiabatically slow collisions for light systems [6,7]. However, the recent experiments performed on heavier systems and more energetic collisions [8-14] disagree significantly with the predictions of this model, indicating the presence of other mechanisms of K-shell excitation. The two-level rotational coupling model neglects the presence of other molecular levels into which the K-shell electrons may be transferred, especially in heavier systems with an increased density of states. This problem was studied in terms of a statistical model of ionization developed by Mittleman and Wilets [15] and Brandt and Jones [14,16]. The inner shell ionization is treated as a diffusion problem of the electron moving through a ladder of level crossings. The model has two free parameters: an effective interaction range R_0, usually assumed to be the Thomas-Fermi screening length in the combined atom, and a diffusion constant D_K (for K-shell). The diffusion model was used to explain the K- and L-shell excitation in medium-mass heavy ion collisions [13-16].

In the present work, an experiment has been performed to study the K-shell ionization differential cross section in the symmetric collision system Cu-Cu with a bombarding energy of 63 MeV. The results are compared with the predictions of the models mentioned above.

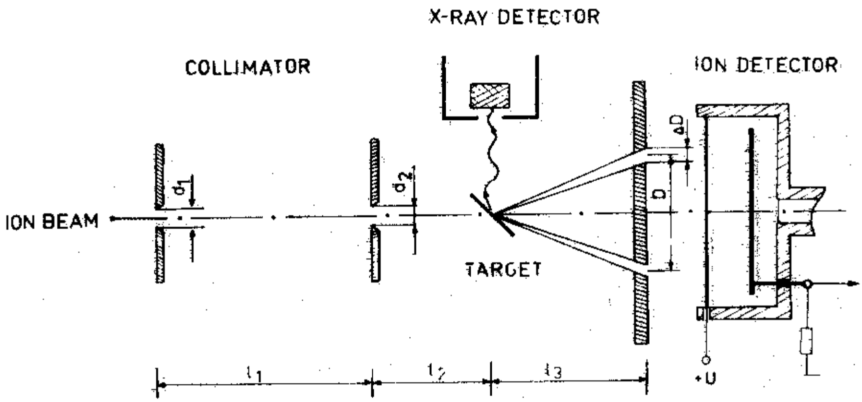

Fig. 1. Collimator set-up and geometry of the experiment. The dimensions (in mm): $d_1 = d_2 = 1$; $\Delta D = 1$; $\ell_1 = 320$; $\ell_2 = 85$; $\ell_3 = 40, 80$ or 230 and $D = 16, 20, 24, 28$ or 32 depending on the acceptance angle of scattered ions.

EXPERIMENTAL PROCEDURE

The experiments were performed with a 63 MeV $^{63}Cu^{4+}$ ion beam from the U-300 heavy-ion cyclotron at the JINR Laboratory of Nuclear Reactions in Dubna. The beam was directed onto the target through a two-slit collimator (see fig. 1). The collimator diminished the divergence of the beam to 0.4° and the beam diameter to 1.5 mm on the target. A 80 $\mu g/cm^2$ target of natural Cu was placed at 45° to the beam axis. The elastically scattered ions passed through an annular diaphragm into a particle detector. The measurements were performed for scattering angles ranging from 2.4° to 19.4° in the lab. system, which is equivalent to a 55 fm - 455 fm impact parameter range. The scattering angles were defined with an accuracy varying from 3% to 7%, depending on the angle value. As a particle detector, a proportional counter filled with a vapour of methyl alcohol at a pressure of 18 Torr was used. The particle detector is described elsewhere /17/. A spectrum of the scattered particles is presented in fig. 2. The X-ray spectra were measured with a 300 mm^2 × 7 mm intrinsic Ge detector with an energy resolution of 250 eV at 5.9 KeV, placed in a close geometry at 90° to the beam outside of the target chamber. The X-ray detector efficiency multiplied by its solid angle was

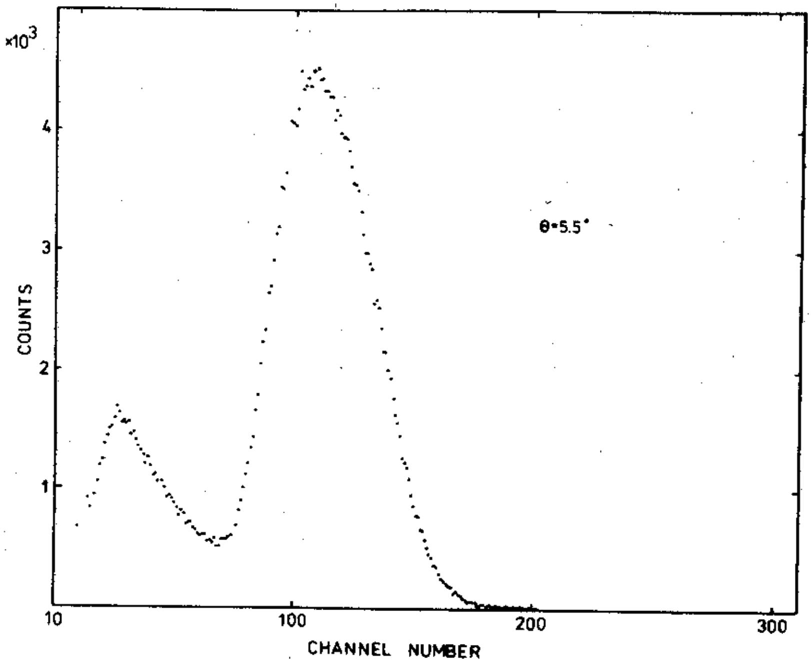

Fig. 2. A particle spectrum.

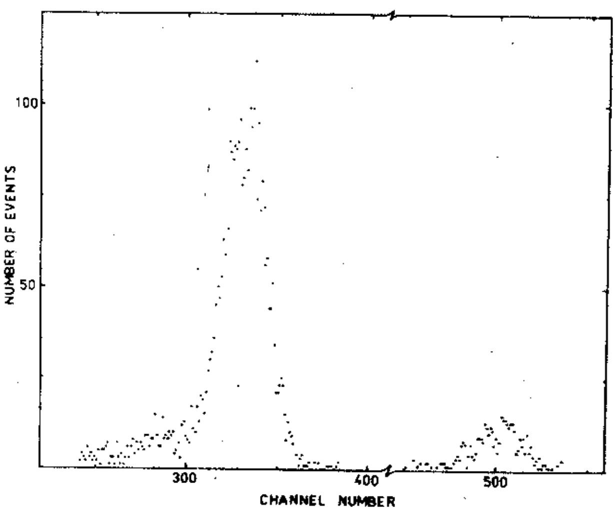

Fig. 3. A time spectrum.

calibrated with ^{57}Co and ^{241}Am standard radioactive sources placed at the position of the target. The X-ray-scattered ion coincidence measurements were performed using a standard slow-fast coincidence technique.

The counting rate of the X-ray detector was kept below 600 counts/sec and that of the particle detector at 50-500 counts/sec,giving a ratio of true to random coincidences better than 2 for large scattering angles and better than 5 for the smallest angles. A typical time spectrum is shown in fig. 3. The two-dimensional energy-time spectra of coincident events (fig. 4) were recorded and processed at a TPAi minicomputer. The single spectra of X-rays and scattered particles were recorded simultaneously with coincidence spectra, what permitted a determination of both the total and differential cross sections. In the single particle spectra, ions scattered on the collimator slits were observed. However, a coincidence measurement proved that these low energy particles do not contribute significantly to the X-ray yield.

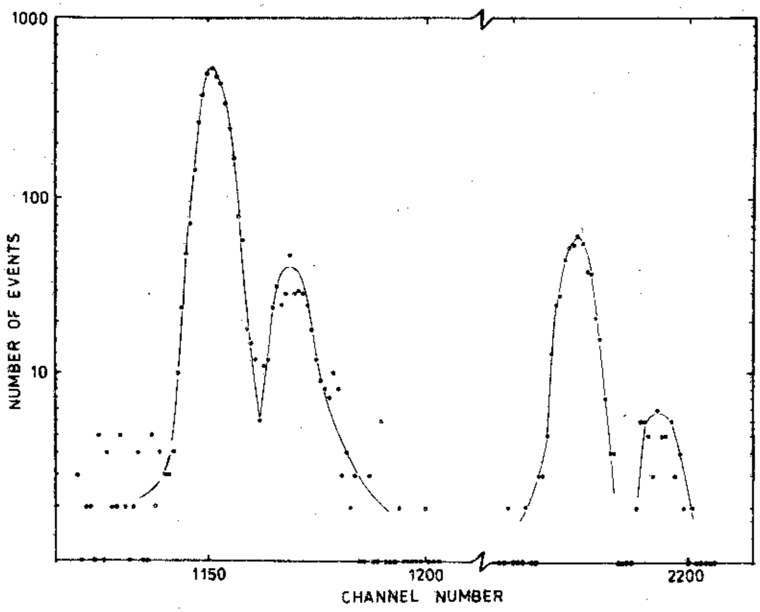

Fig. 4. An X-ray-time coincidence spectrum.

DATA ANALYSIS

The KX-ray emission probability can be obtained from measurements according to the formula

$$P_X(b) = \frac{N_X^c(\theta)}{\epsilon \cdot N_I(\theta)}, \qquad (1)$$

where $N_I(\theta)$ is the number of ions scattered into the angle θ in the lab. system, $N_X^c(\theta)$ is the number of coincident KX-rays, ϵ is the X-ray detector efficiency multiplied by its solid angle in the geometry of the experiment, and b is the impact parameter corresponding to the scattering angle θ. The K-vacancy production probability is given by

$$P_K(b) = \frac{P_X(b)}{\omega_K}, \qquad (2)$$

where ω_K is the KX-ray fluorescence yield. The total cross section, $\sigma_K = 2\pi \int_0^\infty P_K(b) b\, db$, was evaluated from the formula

$$\sigma_K = \frac{N_X^s}{\epsilon \cdot \omega_K N_I(\theta)} \cdot \int \frac{d\sigma_R}{d\Omega} d\Omega, \qquad (3)$$

where N_X^s is the number of X-rays registered in a single spectrum, and the integration is made over the angle of acceptance of the particle detector and over the area of the target exposed to the beam.

In the lab. system

$$\frac{d\sigma_R}{d\Omega} = \frac{d\sigma_R}{d\Omega'} \cdot \frac{d\Omega'}{d\Omega} = \frac{a^2}{(1-\cos\theta')^2} \times \frac{\sqrt{[(p+\cos\theta')^2 + \sin^2\theta']^3}}{1+p\cos\theta'}, \qquad (4)$$

$$\cos\theta' = -p\sin^2\theta + \cos\theta\sqrt{1-p^2\sin^2\theta}, \qquad (5)$$

where θ and θ' are the scattering angles in the lab. and c.m. systems, respectively, $p = \frac{A_1}{A_2}$, and $a = \frac{1}{2} \cdot \frac{Z_1 Z_2 e^2}{E} \cdot \frac{A_1 + A_2}{A_2}$ is the one-half internuclear distance of closest approach in a head-on collision, E is the energy of the incoming particle in the lab. system. Numbers 1 and 2 refer to the projectile and target, respectively. The assumption $p \lesssim 1$ is made. The X-ray detector efficiency ϵ was evaluated with an accuracy of ~ 20%. The value of the fluorescence yield ω_K for the "neutral atom" of Cu was taken from the work of Langenberg et al.[18]. According to Forther et al.[19], the ω_K value for a highly ionized atom differs significantly from that for the "neutral atom" only for an almost empty L-shell, which is not the case in our experiment.

RESULTS AND DISCUSSION

In the experiment both the impact parameter dependent differential cross section $P_K(b)$ and total cross section σ_K were evaluated, according to formulae (1,2) and (3-5), respectively. In both evaluations, the number of scattered ions registered in the ion detector was used as a normalization factor. The value of the total cross section σ_K obtained independently for every scattering angle served as an additional test of the correctness of a given differential cross section measurement. The

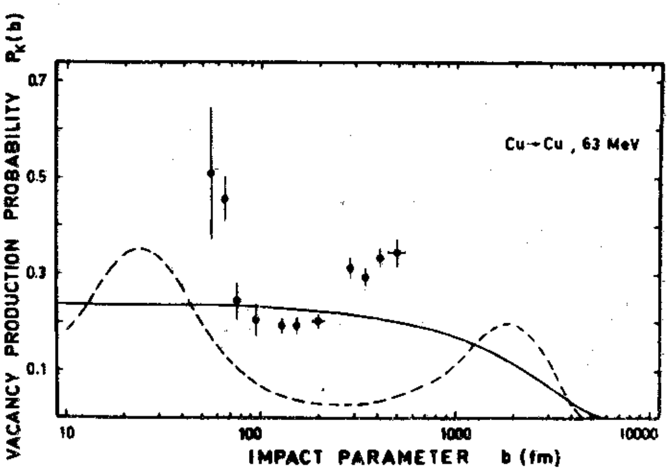

Fig.5. Experimental values of $P_K(b)$ compared with two models: ———— statistical model; $R_0 = 1.15\times10^{-9}$ cm, $D_K = 21.3$ cm²/sec, - - - - - $2p\pi - 2p\sigma$ rotational coupling; $\nu = 0.35$. The error bars represent only statistical uncertainties.

mean value of the total cross section obtained in the present work is $\sigma_K = (53.3 \pm 10.7)$ kbarns. The accuracy of σ_K amounts to 20%, which comes from the uncertainty of the X-ray detector efficiency. Only statistical errors were presented for the $P_K(b)$ values. The overall uncertainty in $P_K(b)$ contains also the uncertainty in the evaluations of the X-ray detector efficiency and the number of scattered ions. The data obtained in the present work are shown in fig.5. They are compared with theoretical predictions.

a) Comparison with a $2p\pi-2p\sigma$ Rotational Coupling Model

The theoretical values of $P_K(b)$ in the two-level rotational coupling model were calculated using a computer code described in ref.[20]. The program calculates the probability $P_K(b)$ per 1 vacancy present in the $2p\pi_x$ state. The number of $2p\pi_x$ vacancies, ν, was evaluated from a comparison of the experimental and theoretical total cross sections

$$\sigma_K = \nu \cdot 2\pi \int_0^\infty P_K(b)\, b\, db,$$

and is equal $\nu \simeq 0.35$. Calculations predict a characteristic two-humped curve composed of an adiabatic peak positioned around the distance equal to twice the K-shell radius in the combined atom and of a kinematic peak at small values of b, corresponding to a 90° deflection of a scattered ion in the c.m. system. The theoretical curve of $P_K(b)$ multiplied by the factor ν is shown by a broken line in fig.5. As is seen in the figure, the shapes of experimental and theoretical curves $P_K(b)$ are similar, but the experimental values are higher by nearly one order of magnitude. In the rotational coupling model this fact could be understood if the position of the adiabatic peak was shifted towards smaller values of b. Experimentally, such a shift was observed by Bethge et al.[12] for Ni-Ni collisions. The observed shift is too large to be explained only by a different screening effect of electrons from outer shells.

b) Comparison with a Statistical Model

In the statistical model described in refs.[15,16] the impact parameter dependent probability of K-shell ionization is described by the equations

$$P_K(b) \simeq 1 - \frac{2}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{n+\frac{1}{2}} \exp\{-(n+\frac{1}{2})^2 \pi^2 s_K(b)\}, \tag{6}$$

where

$$s_K(b) = \frac{2R_0 v}{D_K}[\sqrt{1-(\frac{b}{R_0})^2} - \frac{b}{R_0} \arccos(\frac{b}{R_0})] = w_K \cdot F(\frac{b}{R_0}), \tag{7}$$

with a notation $w_K = \frac{2R_0 v}{D_K}$, where v is the relative velocity of the colliding ions, R_0 is an effective interaction range, usually taken as the Thomas-Fermi screening length in the combined atom, $R_0 = 0.885 \cdot a_0 \cdot (Z_1^{2/3} + Z_2^{2/3})^{-1/2}$, D_K is a factor describing the diffusion of electrons through the crossings of the energy levels. The function $F(b/R_0)$ is defined for $b \leq R_0$ and is equal to zero outside. The total cross section of ionization is equal to

$$\sigma_K = 2\pi \int_0^{\infty} P_K(b)\, b\, db = S(w_K) \cdot \pi R_0^2 \quad , \tag{8}$$

where, after the coordinate transformation: $\cos\Theta = \frac{b}{R_0}$,

$$S(w_K) \simeq 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{n+\frac{1}{2}} \int_0^{\pi/2} \sin\Theta \cos\Theta \exp\{-w_K \pi^2 (n+\frac{1}{2})^2 (\sin\Theta - \Theta\cos\Theta)\} d\Theta \, . \tag{9}$$

The theoretical values of $P_K(b)$ and σ_K are calculated per 1 electron in the K-shell of combined atom, and therefore should be multiplied by a factor of two before comparing with the experimental values.

In the present work both R_0 and D_K were treated as free parameters in order to reproduce both the total cross section σ_K and the values of $P_K(b)$ in the measured range of impact parameters, b .

The theoretical curve $P_K(b)$ is shown by a solid line in fig.5. The fitted values of the parameters are $R_0 \simeq 1.15 \times 10^{-9}$ cm and $D_K \simeq 21.3$ cm^2/sec., which are comparable with the expected values of the Thomas-Fermi screening length $R_0 = 1.08 \times 10^{-9}$ cm and the diffusion constant D_K from a semiempirical formula, ref.[14]

$$D_K \approx [\frac{1}{12}(Z_1 + Z_2)]^2 \cdot \frac{\hbar}{m_e} \approx 27.0 \frac{cm^2}{sec}$$

CONCLUSION

The obtained values of total cross section σ_K and the mean value of the impact parameter dependent probability of the ionization $P_K(b)$ are well reproduced by the statistical model indicating the presence of coupling to higher states. However, there is a steep rise of the $P_K(b)$ curve both for small and large values of impact parameter b , which cannot be explained in the framework of this model. On the other hand, the two-level rotational coupling model explains the shape of the experimental curve $P_K(b)$ but fails to predict the magnitude of the effect. It is evident that the problem needs additional theoretical investigations.

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