сообщения
объединенного
института
ядерных
исследований
дубна

E7-80-196

W.Frank, P.Jaracz, K.-H.Kaun, J.Rüdiger, Z.Stachura

K-VACANCY PRODUCTION IN COLLISIONS OF 63 MeV Cu IONS WITH Ge AND Ag ATOMS

1980

INTRODUCTION

The differential cross section measurements of the K-shell vacancy production in asymmetric collisions of copper ions on germanium and silver targets performed in the present work are an extension of our previous work [1] on symmetric Cu-Cu collisions. Our work and other recent results for similar and heavier collision systems [2-6] show serious discrepancies between the experiment and the rotational coupling model predictions. A similar disagreement has been observed recently even for collisions of relatively low-Z and -energy Cl and Ar ions with both gaseous and solid targets [7-9]. A statistical model of inner shell vacancy production [10,11] which treats the electron promotion through many non-isolated level crossings reproduces quite well the gross structure of the experimental data especially for very asymmetric collision systems. The model, however, cannot exactly describe the shape of the K-shell vacancy production probability as a function of the impact parameter.

Both the rotational coupling model and the model of a diffusion through the level crossings explain the electron vacancy production in the K-shell of the lighter partner, exclusively. The $1s\sigma$ molecular orbital (MO), correlating in the limit of separated atoms (SA) to the 1s atomic orbital of the heavier partner over the whole range of internuclear distances, is well separated from all the other orbitals except the $2p\sigma$ MO – the 1s orbital of the lighter partner in the SA limit. Therefore, the K-shell vacancies in the heavier collision partner come from the sharing process between the $2p\sigma - 1s\sigma$ MO's in the outgoing part of the ion trajectory. The Demkov-Meyerhof model of this process [12,13] was extended by Briggs to give the impact parameter dependence of the vacancy sharing ratio. The experimental results for the Cu-Ge collision systems are compared in our work with the predictions of that model.

EXPERIMENTAL SET-UP AND DATA ANALYSIS

A beam of 63 MeV $^{63}\mathrm{Cu}^{4+}$ ions from the U-300 cyclotron of the JINR Laboratory of Nuclear Reactions in Dubna was collimated to a spot of a diameter less than 1.5 mm on the target and to a maximum beam divergence of 0.4°. Targets made of 80 $\mu g/cm^2$ natural Ge on a 20 $\mu g/cm^2$ carbon backing and of self-supporting 80 $\mu g/cm^2$ natural Ag were placed at 45° to the beam axis. The emitted X-rays were measured with an intrinsic Ge detector placed in a close geometry at 90° to the beam. The detector efficiency multiplied by its solid angle was calibrated with standard radioactive sources placed at the position of the target. The scattered ions passing through an annular diaphragm were detected with a parallel-plate avalanche detector /23/. The single spectra of X-rays and scattered particles were recorded simultaneously with the coincidence spectra, and this permitted a determination of both the differential and total cross sections. A detailed description of the experimental procedure and data analysis is given in our previous work on the symmetric Cu-Cu collision system /1/. The absolute values of the total cross section of the K-shell ionization σ_K and the vacancy production probability $P_K(b)$ were derived from the measured X-ray yields σ_X and $P_X(b)$ by using the fluorescence yield ω_K. We used the single vacancy values of ω_K taken from the work of Langenberg et al. /20/. According to calculations of Bhalla /16/ and Larkins /17/ for differently ionized Ar atoms, the fluorescence yield ω_K differs significantly from its value for a neutral atom only for an almost completely stripped L-shell.

The present experiment was performed for Cu ions scattered at angles ranging from 1.9° to 19.5° in the lab. system. The transformation of scattering angles into impact parameters was done using the Rutherford formula. For the measured range of scattering angles the uncertainties introduced by neglecting the screening are several times smaller than those introduced by geometrical factors. The targets used in the experiment were thick enough to ensure an equilibrium charge state of the projectile /2/. However, multiple collisions in a target of finite thickness change the values of the ionization cross section σ_K, the probability $P_K(b)$, and the shape of the $P_K(b)$ distribution. A Monte-Carlo calculation simulating the trajectory of a projectile traversing the target indicates a dispersion and small shift into a higher value of the final angle of a scattered projectile with respect to the single collision case. As an example, for the collision system Cu-Ge the calculated shift was 0.18° with a dispersion of 0.05° for the scattering angle of 1.9° and 0.14° with a dispersion of 0.07° for an angle of 5.6° (lab.). The calculated correction values should be treated as a maximum estimate because of the use of a non-screened Coulomb potential for the small angle secondary collisions. Another effect of multiple scattering in the target is an increase of the absolute values of σ_K and $P_K(b)$. For $P_K(b)$ it is of the order of $\Delta x \cdot \sigma_K$, where Δx is the target thickness in atoms per cm^2 (see the work of Tserruya et al. /8/). The correction is 0.036 and 0.003 for the $P_K(b)$ values for the Cu-Ge and Cu-Ag collision systems, respectively. It amounts to ~10% of the measured values in each case. The sum of the $P_K(b)$ values of the lighter and heavier collision partners, corrected for the multiple collision effects, is presented in fig.1 together with the results for the Cu-Cu system obtained in the previous experiment /1/. The vertical error bars in the figure represent only statistical uncertainties.

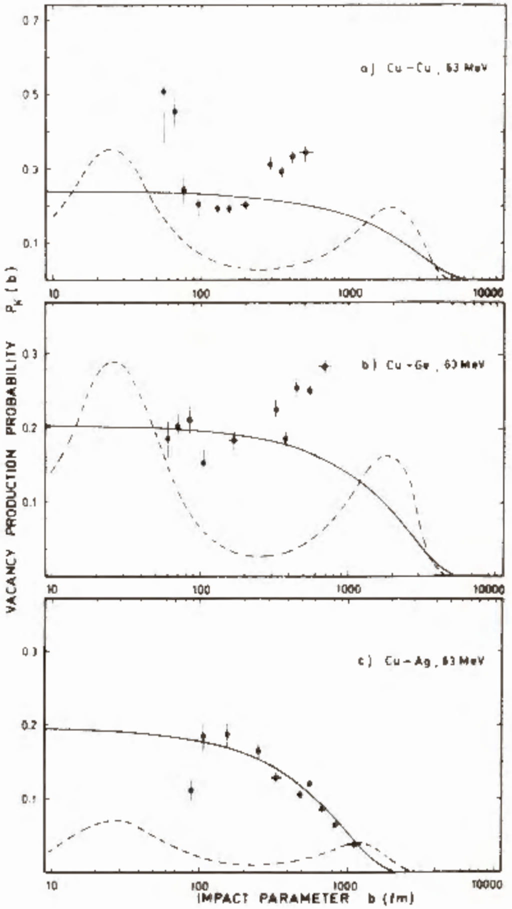

Fig.1. Experimental results and theoretical predictions for the impact parameter dependence of the K-shell vacancy production in Cu+Cu (a), Cu+Ge (b) and Cu+Ag (c) collisions. The broken lines refer to the rotational coupling and the solid lines to the statistical model predictions. The vertical errors represent statistical uncertainties only. The values of the model parameters are shown in the Table.

RESULTS AND DISCUSSION

1. $2p\sigma$ Vacancy Production

The experimental values of $P_K(b)$ were compared with the theoretical predictions of the $2p\pi - 2p\sigma$ rotational coupling model. The theoretical curve was calculated for a homonuclear collision using a computer code of Jäger /21/ and scaled using the scaling prescription of Taulbjerg et al. /22/. The theoretical values should be multiplied by a factor ν, the number of vacancies in the $2p\pi_x$ orbital, created prior to the collision or at the initial stage of the same collision. It was obtained from the value of the experimental total cross section. The normalization factors ν are similar for the Cu-Cu and Cu-Ge collisions, but considerably smaller for the Cu-Ag collision (see the Table). The broken lines in fig.1 represent theoretical predictions for $P_K(b)$. As is seen in the figure, the theory explains qualitatively the valley in the $P_K(b)$ distribution, but it fails to predict the magnitude of the effect both for symmetric and asymmetric collisions. The experiment also suggests, that the increase of the $P_K(b)$ values for large impact parameters starts at smaller values than the adiabatic peak at $b \simeq 2r_K(UA)$ in the rotational coupling theory.

In another approach the experimental results were compared with the ionization probabilities calculated from the statistical model of the electron diffusion. The relevant parameters of the model, an interaction radius R_0, and a diffusion constant D_K were fitted in such a way that both the experimental total cross section σ_K and the value of $P_K(b)$ for $b = 200$ fm were reproduced. The obtained values of R_0 and D_K are compared with the expected ones given in the Table. The statistical model predictions are presented by solid lines in fig.1. From the comparison with the experimental points for Cu-Cu and Cu-Ge collisions one can see that the diffusion model with the reasonable values of the two parameters predicts quite well the magnitude of the $P_K(b)$ distribution and the total cross section simultaneously. However, the model cannot describe the increase of the $P_K(b)$ curve for both the small and large values of the impact parameter for these collisions. In the case of Cu-Ag collisions the experimentally obtained values of the parameters R_0 and D_K differ from those expected from the semiempirical formula /4/, but the experimental points follow the statistical model curve very well.

In a quest for physical processes other than multiple scattering which could affect the experimental values of σ_K and $P_K(b)$, we calculated recoil effects and electron capture to

Table

collision system	Cu-Cu*	Cu-Ge	Cu-Ag
total cross section, σ_K, 10^3 barns	53.3±10.7	36.9±7.4	4.9±1.0
number of $2p\pi_x$ vacancies, ν	0.35	0.29	0.07
Thomas-Fermi screening length, R_0, 10^{-9} cm	1.08	1.06	0.99
fitted radius of strong interaction, R_0, 10^{-9} cm	1.15	1.06	0.40
expected values of the diffusion constant, D_K, cm^2/sec **	27.0	29.9	46.5
fitted values of the diffusion constant, D_K, cm^2/sec	21.3	22.4	8.6

---

* Ref. /1/.

**According to the semiempirical formula

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

from Ref. /4/.

the K-shell of the projectile from the target atoms. The correction for the recoil effects [18,19] was about 0.3 barns for the Cu on Ge and 0.04 barns for the Cu on Ag collision systems. The upper limit corrections for electron capture effects according to Ref.[24] give about 7 barns and 50 barns for these systems, respectively. The contribution from both processes is evidently negligible. We are not able to evaluate correctly the contribution to the K-shell vacancy production from the direct Coulomb excitation to continuum or unoccupied bound states. The direct Coulomb excitation of the $1s\sigma$ or $2p\sigma$ states to the continuum should be small because of the high binding energy of these states. The direct excitation of the $2p\pi$ orbital, if it occurs at large distances during the collision, increases the number of $2p\pi_x$ vacancies, ν, a parameter to be obtained from the experimental σ_K value. It order to check if the L-vacancies are created in the measured range of impact parameters not only at large distance, we investigated the ratio of K_β/K_α X-rays. This ratio depends on the relative abundance of the L- and M-shells. No impact parameter dependence of the ratio has been observed in the experiment (see fig.2), and this suggests that most of the L-vacancies are created at large distances. The result is merely a suggestion, because of the large statistical uncertainties and a weak dependence of the radiative transition widths on the number of L- and M-vacancies [16,17].

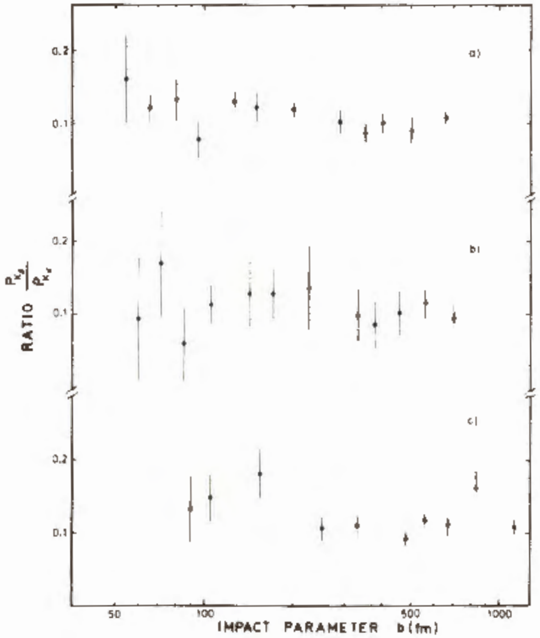

Fig.2. The impact parameter dependence of the K_β/K_α X-rays in the collisions: a) Cu+Cu, Cu KX-rays; b) Cu+Ge, Ge KX-rays; c) Cu+Ag, Cu KX-rays. The error bars represent only statistical uncertainties.

The success of the statistical model in describing the magnitude of the K-shell vacancy production shows that the rotational coupling of the isolated orbitals $2p\pi-2p\sigma$ is not the only mechanism responsible for the effect. The coupling to other orbitals clearly has to be taken into account. On the other hand, the characteristic for the $2p\pi-2p\sigma$ rotational coupling $P_K(b)$ distribution shape suggests that it still plays an important role here.

2. Vacancy Sharing

In the outgoing part of the collision trajectory the $2p\sigma$ vacancies are shared between the $2p\sigma$- and $1s\sigma$-MO's by the radial coupling. According to the Demkov-Meyerhof model of this process [12,13] the vacancy sharing ratio is

$$r = \frac{P_K^H(b=0)}{P_K^L(b=0)} = \exp(-2x) \simeq \frac{\sigma_K^H}{\sigma_K^L},$$

with

$$2x = \frac{2\pi(\sqrt{I_H}-\sqrt{I_L})}{\sqrt{2m_e v_1^2}},$$

where I is the neutral atom binding energy of the K-shell, v_1 is the velocity of the projectile, and m_e is the rest mass of the electron. The letters H and L refer to the heavier and lighter collision partners, respectively. In an extension of this model Briggs [14] gives an impact parameter dependence of the vacancy sharing ratio $r(b) = P_K^H(b)/P_K^L(b)$ for two possible cases. In the "one passage" process it is supposed that the $2p\sigma$ vacancies are created at small distances in the same collision and shared in the outgoing part of the ion trajectory. The "two passage" process takes place if the K-shell vacancies brought into the collision are shared in the ingoing and outgoing parts of the ion trajectory. The model calculations of Briggs for the O-Ne collision system [14] give essentially the same result as the more accurate one-electron two-state MO calculations [15], but the latter show a bit more complex behaviour of the vacancy sharing ratio versus the impact parameter.

In the present work we investigated the vacancy sharing ratio for the Cu on Ge and Cu on Ag collision systems. The values obtained from the total cross section measurements, 0.263±0.0002 and $(2.6\pm0.6)\times10^{-4}$, respectively, are in good agreement with the values of 0.241 and 1.64×10^{-4} obtained according to Meyerhof's formula. (The indicated errors are only statistical uncertainties). The vacancy sharing ratio versus the impact parameter b for the Cu-Ge collision system from our measurements is shown in fig.3 together with a "one passage" calculation following Briggs. The overall agreement with the predictions of Briggs is fairly good. Despite the large uncertainties there seems to be, however, an indication for some structure in the experimental curve. A similar but more pronounced behaviour has been found recently by Bethge et al./25/.

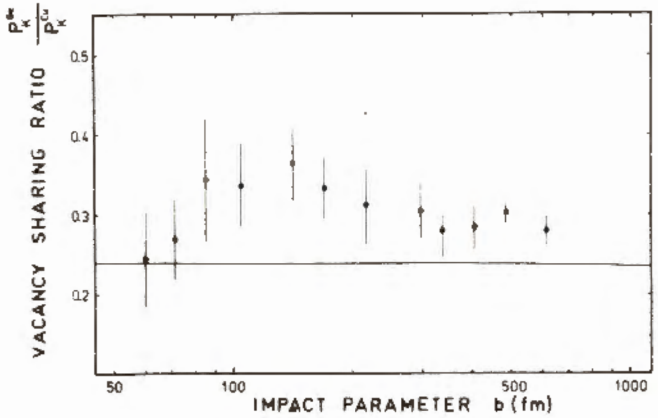

Fig.3. The vacancy sharing ratio for the Cu on Ge collision system versus the impact parameter . The solid line represents a "one passage" calculation following Briggs /14/. The error bars represent only statistical uncertainties.

CONCLUSION

The results obtained in the present work, together with those from our previous paper /1/, do not show any fundamental difference in the $P_K(b)$ behaviour between symmetric and asymmetric collision systems. The success of the statistical model and the failure of the $2p\pi-2p\sigma$ rotational coupling model in prediction of the magnitude of the vacancy production probability $P_K(b)$ shows the necessity of including coupling to higher molecular orbitals in the description of the effect. On the other hand, the shape of the $P_K(b)$ distribution suggests that the $2p\pi-2p\sigma$ coupling is still an important mechanism of the K-shell vacancy production.

The vacancy sharing between the collision partners is well described by the Briggs-Meyerhof-Demkov model even for such asymmetric systems as Cu on Ag. However, for the Cu on Ge collision system a slight difference is observed between the experimental values of the impact parameter dependence of this ratio and the "one passage" calculation according to Briggs, which predicts the ratio to be nearly constant in the measured range of impact parameters.

The authors would like to thank Academician G.N.Flerov for his interest in the work and the cyclotron staff for providing a high-quality beam of Cu ions.

The stimulating discussions with A.Warczak and the use of the computer code from H.-U.Jäger are gratefully acknowledged. Thanks are also due to M.Lenk and Yu.N.Grafov for their help in carrying out the experiment.

REFERENCES

1. Frank W. et al., JINR, E7-80-70, Dubna.
2. Annett C.H. et al., Phys.Rev., 1979, A19, p.1038.
3. Hagmann S. et al., J.Phys., 1979, B12, p. L395.
4. Johnson B.M. et al., Phys.Rev., 1979, A19, p.81.
5. Liesen D. et al., Phys.Rev., 1978, A17, p.897.
6. Guillaume G. et al., Phys.Lett., 1978, 68A, p.39.
7. Lutz H.O. et al., Phys.Rev.Lett., 1978, 40, p.1133.
8. Tserruya I. et al., Phys.Rev., 1978, A18, p.2482.
9. Fintz P. et al., Phys.Lett., 1979, 71A, p.423.
10. Mittleman M.H., Wilets L., Phys.Rev., 1967, 154, p.12.
11. Brandt W., Jones K.W., Phys.Lett., 1976, 57A, p.35.
12. Demkov Yu.N., Sov.Phys., JETP, 1964, 18, p.138.
13. Meyerhof W.E., Phys.Rev.Lett., 1973, 31, p.1341.
14. Briggs J.S., Harwell Report T.P., 1974, p.594.
15. Briggs J.S., Taulbjerg K., J.Phys., 1975, B8, p.1895; ibid. 1975, B8, p.1909; corrigendum ibid. 1975, B9, p.1641.
16. Bhalla C.P., Phys.Rev., 1973, A8, p.2877.
17. Larkins F.P., J.Phys., 1971, B4, p.L29.
18. Meyerhof W.E., Taulbjerg K., Ann.Rev.Nucl.Sci., 1977, 27, p.279.
19. Meyerhof W.E., et al., Phys.Rev., 1976, A14, p.1653.
20. Langenberg A., van Eck J., J.Phys., 1979, B12, p.1331.
21. Heinig K.-H. et al., JINR, E7-9862, Dubna, 1976; J.Phys., 1977, B10, p.1321.
22. Taulbjerg K. et al., J.Phys., 1976, B9, p.1351.
23. Brunner G. et al., JINR, 7-12202, Dubna, 1979 (in Russian).

24. Mokler P.H., Folkmann F., GSI-Pa-4-77, Darmstadt June 1977.
25. Bethge K. et al., MPI Annual Report 1978, p.130, Heidelberg 1979.

Received by Publishing Department
on March 6 1980.