Impact-parameter dependence of *K*-vacancy production in chlorine-argon collisions*

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We have measured the probability per collision for the production of Cl and Ar *K* vacancies in the bombardment of argon gas targets by 15- and 30-MeV chlorine projectiles. By detecting the Cl and Ar *K* x rays in coincidence with Cl ions scattered to a known angle we have deduced the dependence of the probability on impact parameter *b*. The sum of Ar and Cl *K*-vacancy production probabilities, presumably a measure of $2p\sigma$ vacancy production, is found to depend in magnitude on the charge state of the Cl projectile, but the shape of the summed probability curve, when plotted versus *b*, is not charge-state dependent. The measured shape is close to that expected for *K*-vacancy production via $2p\sigma$-$2p\pi$ rotational coupling. The data suggest that, for these collisions, the production of $2p\pi$ vacancies at large internuclear distances is important and that a two-step mechanism for the production of the *K* vacancies is operating.

INTRODUCTION

The production of *K* vacancies in slow ion-atom collisions between nearly symmetric collision partners of low nuclear charge (Z) is well described in terms of the electron-promotion model of Fano and Lichten.[1-3] Vacancies in the $2p\sigma$ molecular orbital (see Fig. 1) are produced via rotational coupling at small internuclear distances with the $2p\pi$ orbital, provided $2p\pi$ vacancies are brought into the collision. Further transfer of $2p\sigma$ vacancy to the $1s\sigma$ orbital, "vacancy sharing," allows both the lighter and heavier collision partners to have nonzero *K*-vacancy production probabilities.[4] The $2p\pi$-$2p\sigma$ coupling process has received considerable theoretical investigation by Briggs and Macek for symmetric[5] and by Taulbjerg, Briggs, and Vaaben for asymmetric collisions.[6,7] Experimental total cross sections for Ne-Ne collisions are in good agreement with the calculations at low energy.[8,9] Impact-parameter-dependent vacancy production probabilities give further support to the model for first-row collision partners.[6,10,11]

If the number of $2p\pi_x$ vacancies brought into the collision, N_π^0, is zero, the rotational coupling mechanism cannot operate, and this effect has been seen at very low velocities by Fastrup *et al.*[2,11,12] However, there is evidence[3] that at higher velocities even collision systems which bring no initial $2p\pi$ vacancies into the collision may produce such vacancies at large internuclear distances which then enable the $2p\pi$-$2p\sigma$ rotational coupling to operate. The number of $2p\pi$ vacancies brought into the close encounter region, $N_\pi(v)$, then becomes a function of the dynamics of the collision. Both total cross-section measurements of Fastrup *et al.*[12] and Stolterfoht *et al.*[9] and impact-parameter dependent probabilities of Lutz *et al.*[13] show that this two-step process is important in collisions between first-row partners at scaled velocities as low as 0.1. For higher-Z systems, evidence for creation of $2p\pi$ vacancies at large internuclear distances via the sharing of $2p$ vacancies between heavy and light collision partners has been given.[14] Meyerhof has attempted to treat systematically the dynamics of the production and destruction of $2p\pi$ vacancies in terms of vacancy sharing between the more tightly bound $2p$ shell and nearby atomic orbitals.[15]

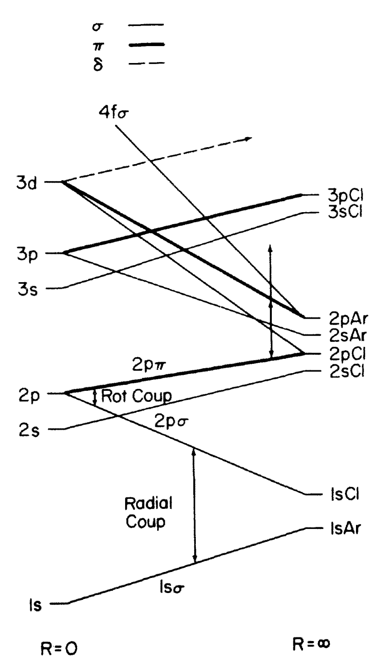

FIG. 1. Correlation diagram for the Cl-Ar system. The level order for large R is that appropriate to the ionization states of Cl used in the present experiment.

For higher Z collision systems the $2p$ binding energies become large and the production of $2p\pi$ vacancies in a single collision becomes less probable. Under such conditions the production of $2p\sigma$ and $1s\sigma$ vacancies might proceed via direct excitation to the continuum or to higher vacant orbitals.[16] It is not clear at what Z this direct process becomes competitive with the two step process.

Winters *et al.*[17] have previously measured total cross sections for K-x-ray production in collisions of sulphur and chlorine ions with targets of similar nuclear charge. They found no proportionality between the cross sections and N_π^0. It was suggested that this might be interpreted as evidence for the direct process. The present work was undertaken to investigate further whether the direct or two-step process dominates the K-vacancy production. Since $N_\pi(v)$ may depend in a rather complex way on the parameters of the collision, it is difficult to determine on the basis of energy or Z dependences of total cross sections, which mechanism, if either, is operating. On the other hand, the impact parameter dependence of the probability for $2p\sigma$ vacancy production in the rotational coupling model may be predicted on a sound theoretical basis[6] and should be a distinct signature of the process. Thus, we have undertaken to measure the impact parameter dependence of the probability for producing either Cl or Ar K x rays in Cl-Ar collisions at Cl energies of 15 and 30 MeV, corresponding to scaled velocities of 0.27 and 0.38, respectively, relative to the Ar K-shell electron velocity. The sum of the two vacancy-production probabilities is presumably a measure of $2p\sigma$ vacancy production and is independent of the subsequent sharing of this vacancy between Ar and Cl K shells.

EXPERIMENT

Chlorine beams of 15 and 30 MeV from the KSU Tandem Van de Graaff were directed onto a target of argon gas. A schematic of the cell is shown in Fig. 2; further detail is given in Ref. 18. The incident Cl charge state could be chosen by post-stripping the accelerated beam with a 10-μg/cm^2 C foil and selecting the desired charge state with the beam switching magnet. Incident charge states of +5, +6, and +11 were used. Cl and Ar x rays were detected by an 80-mm^2 Si[Li] detector which viewed the cell at right angles to the beam through 25-μm Be and 6-μm Hostaphan[19] windows. The Si crystal was located 2.4 cm from the beam axis. The beam was collimated by square apertures located 5.6 m apart adjusted to half widths between 0.2 and 0.5 mm. The downstream slit was located 15 cm before entrance to the 1.5-cm-long gas cell. Scattered Cl ions were detected in a surface barrier detector located at a distance downstream ranging from 2.18 to 0.65 m. This detector was collimated by annuli of inner/outer diameters ranging from 4.09/4.60 to 17.1/19.1 mm and could be scanned laterally to the beam axis in both dimensions. Positioning of each annulus was done on the beam, by seeking symmetry in the scattering distribution, to a precision of 0.1 mm. The gas cell was differentially pumped in such a way as to maintain beam line pressure below 8×10^{-6} Torr for target pressures as high as 200 mTorr.

Standard coincidence circuitry was used to record coincidences between Ar or Cl K x rays and scattered Cl ions. Typical count rates were 10 and 4×10^3 Hz in the Si[Li] and surface barrier detectors respectively, yielding coincidence rates between 1 and 10^{-2} Hz. The time window used

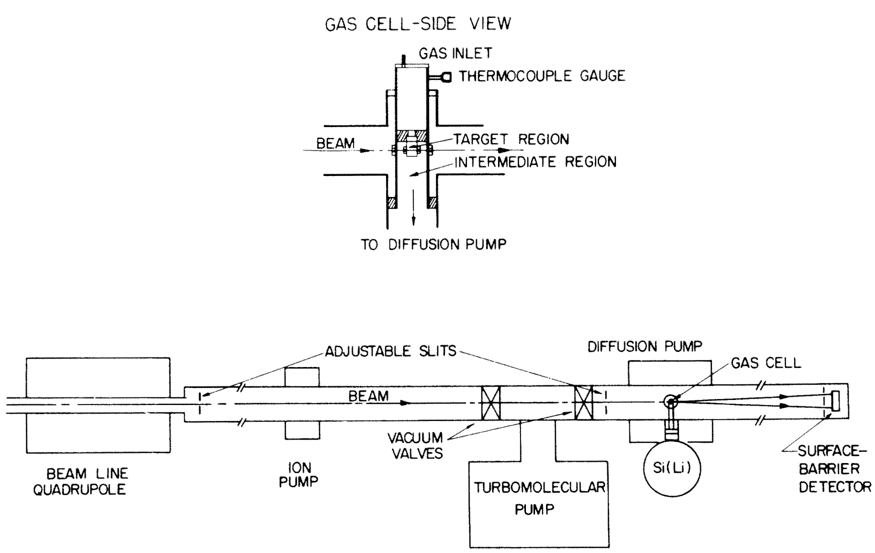

FIG. 2. Schematic of experimental arrangement.

was typically 100 nsec, with a reals to randoms ratio always above 3. With the thin gas targets, the count rate in the Si[Li] detector due to slit scattering was not negligible. The ratio of this background to scattering from the gas, measured by removing the gas from the target, was never allowed to exceed 10%.

In order to minimize the fractional slit scattering and in some cases to achieve sufficiently high count rates, much of the data were taken at target pressures as high as 180 mTorr. Under such conditions there is appreciable alteration of the projectile charge state within the gas cell, although alteration in the beam line before the cell remains small. In order to directly assess the importance of this effect, we installed a charge-state spectrometer beyond the gas cell consisting of a small magnet and a position sensitive-surface barrier detector. Exit charge-state distributions were measured as a function of target gas pressure under the same conditions as those used for the coincidence measurements. While charge purity of the incident beam was not maintained, we were able to deduce the charge-state distribution present at the center of the gas cell. We describe the average charge state of the beam at the target center in terms of a parameter

$$\overline{N} \equiv \sum_{q=7}^{15} (q-7) f_q ,$$

where q is the chlorine charge state and f_q the measured fraction of that charge state at half the target thickness. Were the projectiles in their ground-state configuration, $\overline{N}$ would represent the average number of L-shell vacancies born by the Cl beam. Since charge-changing collisions did take place within the gas cell, there is no reason to expect the chlorine ions to be in their lowest-energy configurations throughout their passage through the cell. For example, even chlorine ions with $q \leq 7$ may possess L-shell vacancies if there are one or more M-shell electrons present. Such systems will usually relax quickly to fill the L vacancy, however. For example, the lifetime of the $(2p^5 3s)^1P^o$ state in Cl VIII is 1.0×10^{-11} sec,[20] during which a 30-MeV Cl ion will travel only 0.13 mm, a distance substantially smaller than the path through the cell. Systems which may autoionize will usually be even shorter lived. Thus the interpretation of $\overline{N}$ as the average number of L vacancies borne by the Cl is not unreasonable. We point out that metastable states with L vacancies will not relax quickly and may cause departures from this interpretation. In no case did $\overline{N}$ at the target center differ from that characterizing the incident beam by more than 1.1.

Were there no dynamic rearrangements within the L and higher shells, $N_\pi(v)$ would just equal N_π^0 which is related to N for symmetric collisions, (which we take to be appropriate to our collisions) by $N_\pi^0 = \frac{1}{6} N$. The possibility exists that, under high-pressure conditions, collisions might excite the Cl $2p$ shell without changing the projectile charge. Such an excited system would not be expected to live long, as discussed above. Nevertheless, it is important to examine directly the possibility that Cl $2p$ vacancies are created in collisions inside the gas cell and subsequently carried into a second collision in which Cl or Ar K x rays are produced. Were the two-collision mechanism important, the apparent total cross section for (Ar + Cl) K-x-ray production would initially increase linearly with target pressure. In Ref. 17 a careful study of the pressure dependence of the same cross sections as those studied here was made down to target pressures of 1 mTorr. No target-pressure dependence of the cross sections was observed for pressures to 10 mTorr and considerably higher. A pressure of 10 mTorr in the gas cell of Ref. 17 would represent roughly the same target thickness as a pressure of 37 mTorr in our target, approximately the lower end of our working range. Our total cross sections from the thicker targets, as shown in Table I, agree with the thinner target results of Ref. 17.

An independent investigation of this point was made for incident charge states +6 and +5. One would expect the observed x-ray production probabilities to be especially sensitive to multiple collisions for these incident charge states, since the projectiles bring in no $2p$ vacancies. Thus excitation of the Cl $2p$ shell in a multiple collision process might strongly affect the observed probabilities by opening the otherwise closed rotational coupling channel. To investigate this point for the lower-charge incident beams, data points were taken at gas pressures of 180 mTorr (filled circles in Figs. 3 and 4) and at 45 mTorr (open squares in Figs. 3 and 4). If the observed probabilities were

TABLE I. Summed target-projectile K-x-ray production cross sections for chlorine on argon.

E (MeV)	Projectile	$\overline{N}$	$\int 2\pi P_x(b) b\, db$ [a] (10^{-20} cm^2)	σ_x [b] (10^{-20} cm^2)
15	Cl^{+11}	2.92	3.05	2.88
	Cl^{+5}	0.18	1.24	1.32
30	Cl^{+11}	3.37	5.84	5.87
	Cl^{+6}	0.62	4.29	3.90

[a] Present experiment.
[b] Interpolated from Ref. 17.

due to two-collision events in which $2p\pi$ vacancies were created in the first collision, they should have appeared to decrease by a factor near 4 in going from the higher to lower gas-pressure data. This was not the case. The resulting probabilities were found to depend not at all on gas pressure at 15 MeV. The small pressure dependence seen at 30 MeV is probably due to the slightly lower charge state characterizing the lower-pressure data and may be a fluorescence-yield effect, as discussed below. Thus we are given confidence that we are not studying a multiple-collision phenomenon.

The relationship between impact parameter b and scattering angle θ was established following the procedures described by Everhart *et al.*[21] A screened Coulomb potential given by $V(R)=(Z_1 Z_2 e^2/R)e^{-R/A}$ was used, with $a=0.53\times10^{-8}$ cm$/[Z_1^{2/3}+Z_2^{2/3}]^{1/2}$. To investigate the validity of this expression we compared our measured elastic scat-

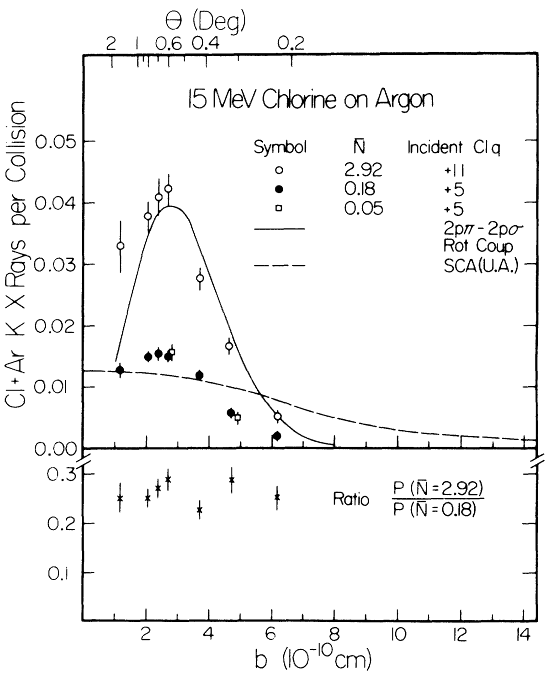

FIG. 3. The upper figure shows the probability for production of Cl or Ar K x rays, for 15 MeV Cl on Ar, plotted vs impact parameter, b. The open and filled circles show data for incident Cl charge states of +11 and +5 on 180 mTorr targets respectively. The open squares are for incident charge state +5 on a 45 mTorr target. The parameter $\bar{N}$ is defined in the text. The solid and dashed lines are theoretical curves for the $2p\pi-2p\sigma$ rotational coupling and direct ionization of the united-atom $2p$ shell, respectively. Each theoretical curve is normalized to give the total cross section represented by the higher charge incident beam. The lower figure shows the ratio between higher- and lower-incident charge data.

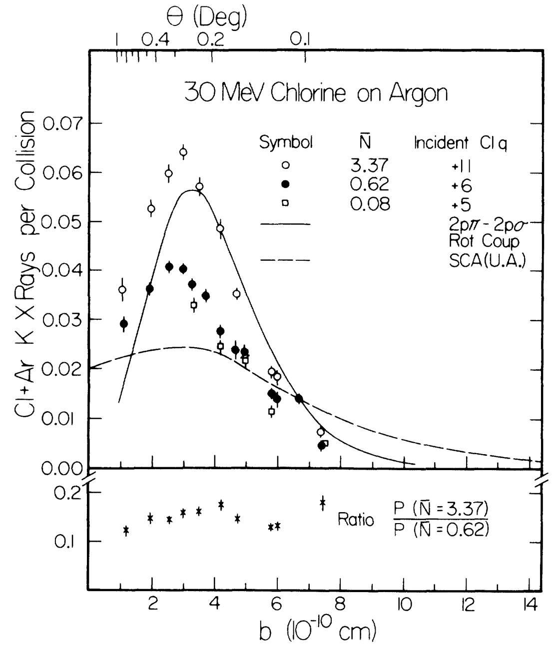

FIG. 4. Similar to Fig. 3, but at a Cl energy of 30 MeV. The open and filled circles are for incident charge states of +11 and +6 on 180 mTorr targets. The open squares are for incident charge state of +5 on a 45 mTorr target.

tering angular distribution with that predicted from the above potential. Good agreement was obtained.

Figures 3 and 4 show our results for 15- and 30-MeV Cl projectiles, respectively. The (Ar+Cl) K-x-ray production probability, $P_x(b)$, is defined as the ratio of the number of (Ar+Cl) K x rays to the number of scattered Cl ions, divided by the absolute efficiency of the x-ray detector. This efficiency was calculated to be 5.5×10^{-3} from the known geometry of the system and known absorption in the detector and gas cell windows, assuming isotropic x-ray emission. The absolute scales in Figs. 3 and 4 are based on the efficiency thus obtained. We place an error bar of 50% on our absolute scale, although our relative errors are much smaller and are shown on the figures. Total x-ray production cross sections obtained by integrating these curves are shown in Table I. These are in good agreement with those of Ref. 17.

FLUORESCENCE YIELDS

The Cl charge-state dependence of Cl and Ar x-ray production seen in Figs. 3 and 4 and in Ref. 17 could be due to a charge-state dependence of either the primary K-vacancy production probability or of the fluorescence yields of the departing ions. In order to isolate the charge-state dependence of the K-vacancy production alone, we measured the cross sections for production of Ar K-Auger electrons for 30-MeV Cl^{+6}, Cl^{+10}, and Cl^{+11} on Ar. The cylindrical mirror analyzer described in Ref. 18 was used to disperse electrons from the collisions. Target gas pressures below 25 mTorr were used. Data handling and reduction procedures are described in Ref. 18. Absolute cross sections given in the table were obtained by assuming the atomic Ar fluorescence yield of 0.12[22] for collisions with the Cl^{+6} beam and taking σ_x for this collision from Ref. 17. This procedure was deemed preferable to relying on the ratios of absolute x-ray and Auger cross sections from independent experiments, especially since the absolute precision available in either experiment was not high. The results are shown in Table II. While the Ar K-x-ray production cross section increases by a factor of 2 in going from Cl^{+6} to Cl^{+11} the Ar K-Auger production cross section rises by only a factor of 1.13. Although the cross sections presented in Table II are for the target only, the ratio between intensities of target and projectile x rays was found by Winters *et al.* to be independent of charge state.[17] Thus it appears probable to us that the outer-shell electrons of two so nearly symmetric systems are shared in such a way during the collision that the fluorescence yields of the departing ions, while different from their atomic values, are in a *ratio* which is not dependent on the projectile charge state. Thus much of the charge-state dependence seen in Figs. 3 and 4 and in Ref. 17 must be attributed to a dependence of the final fluorescence yields on the initial projectile charge states.

TABLE II. Auger-electron and x-ray production cross sections and fluorescence yields for the K-shell of argon in collision with 30-MeV chlorine ions.

Projectile	σ_a [a] (10^{-20} cm^2)	σ_x [b] (10^{-20} cm^2)	ω_k [c]
Cl^{+6}	≡8.8	1.20 ± 0.12	≡0.12
Cl^{+10}	10.6 ± 2.1	2.26 ± 0.23	0.18 ± 0.04
Cl^{+11}	9.9 ± 1.0	2.53 ± 0.25	0.20 ± 0.03

[a] Present experiment.
[b] From Ref. 17.
[c] From $\omega_k = \sigma_x/(\sigma_x + \sigma_a)$; ω_k (Cl^{+6}) taken from Ref. 22.

DISCUSSION

If the two-step mechanism dominates, then the *shape* of the plot of $P_x(b)$ vs b should be that predicted for the $2p\pi$-$2p\sigma$ rotational coupling mechanism. We presume that the production of $2p\pi$ vacancies in the first step is not b dependent over the range in b covered by the data. This appears likely, since the first step must occur at much larger internuclear distances than those necessary for effective $2p\pi$-$2p\sigma$ coupling.

We have evaluated the theoretical probability, $P_r(b)$, for $2p\sigma$ vacancy production assuming a single initial vacancy in the $2p\pi_x$ orbital, from the universal tables and scaling laws of Taulbjerg, *et al.*[6] The solid curves shown in Figs. 3 and 4 are normalized curves for the rotational coupling process, $AP_r(b)$, where A has been chosen such that $A\int 2\pi P_r(b) b\, db$ is equal to $\int 2\pi P_x(b) b\, db$ for the higher-charge beam in each figure. The similarity between experimental and theoretical shapes is remarkable. Of particular interest is the decrease of the experimental $P_x(b)$ at small b, which is predicted by the theory. We consider the near agreement between theoretical and experimental shapes to be strong evidence that the primary mechanism responsible for $2p\sigma$ vacancy production here is the $2p\sigma$-$2p\pi$ rotational coupling.

This conclusion relies on the supposition that other possible mechanisms, such as direct $2p\sigma$ ionization, will not have the same impact-parameter dependence. The total cross sections for this process have been calculated by Thorson.[23] Unfortunately, the calculated $P(b)$ for direct $2p\sigma$ ionization is not immediately available. We think it unlikely that the $P(b)$ for such a process will have the same shape as that for the rotational coupling, especially for small b. Indeed, one might expect[24] the direct process to behave in a manner similar to direct Coulomb ionization[25] of the $2p$ shell of the united atom ($Z = 35$). The impact-parameter-dependent probabilities for this process, $P_{SCA}(b)$, have been calculated from the tables of Hansteen *et al.*[26] The resulting curves are shown as dashed lines in Figs. 3 and 4. Each curve has been normalized such that $\int 2\pi P_{SCA}(b) b\, db$ is equal to $\int 2\pi P_x(b) b\, db$ for the higher-charge incident beam. At 15 MeV the $P_{SCA}(b)$ curve decreases monotonically as b increases from zero, in qualitative disagreement with the data. At both energies the direct ionization curve places far too much cross section at large b. Thus while a more definitive exclusion of the direct process in this case cannot be made without a theoretical study more appropriate to these nearly symmetric collisions, we feel that the data strongly suggest the dominance of the rotational coupling mechanism.

In order that the rotational coupling mechanism operate, $2p\pi$ vacancies must be present when the nuclei are at small internuclear separations. The data shown in Figs. 3 and 4 suggest that $N_\pi(v)$ is not simply related to the number of chlorine L-shell vacancies brought into the collision, as would be the case if no rearrangement of L-shell electrons took place during the collision. In particular, no proportionality between $P_x(b)$ and $\bar{N}$ is seen. The ratio between $P_x(b)$ curves for high and low values of $\bar{N}$, given in the lower curves in Figs. 3 and 4, is nearly constant with b, suggesting that the vacancy production mechanism is not particularly sensitive to N_π^0. Indeed, if the curves were divided by the fluorescence yields interpolated from Table II, they would very nearly lie on top of one another at 30 MeV. Our interpretation of these observations is that $N_\pi(v)$ at the higher energy is almost entirely determined by transitions within the manifold of L and higher orbitals which take place at large internuclear separation. In particular, it is not possible to write $N_\pi(v) = N_\pi^0 + N_\pi(v)$, where $N_\pi(v)$ is the dynamic component of $N_\pi(v)$. Such a separation of dynamic and static contributions to $N_\pi(v)$ is apparently appropriate at sufficiently low velocities[3,12,15] since $N_\pi(0) = N_\pi^0$. We see no reason for expecting it to be valid in general, however.

Experimental data on the fluorescence yields at 15 MeV are not available, but it is expected that their dependence on projectile charge state is at least no greater than that at 30 MeV. Thus, the increase in $P_x(b)$ in going from $\bar{N} = 0.18$ to 2.92 must be due at least in part to a dependence of $N_\pi(v)$ on the incident Cl charge state at the lower velocity.

If the two-step process is assumed to dominate, absolute values for $N_\pi(v)$ may be extracted from the data using $P(b) = N_\pi(v)P_r(b)$. Here $P(b) = P_x(b)/\omega_k$, where ω_k is a weighted average of the Cl and Ar fluorescence yields. If one takes the atomic fluorescence yields[21] for Ar and Cl (0.12 and 0.095 respectively) to be valid for the lower $\bar{N}$ data in Figs. 3 and 4, evaluation of the above expression at the maximum of the $P_x(b)$ curves gives $N_\pi(v) = 0.25$ and 0.59 for 15- and 30-MeV projectiles, respectively. Similarly one may extract $N_\pi(v)$ from the total cross sections of Ref. 17 using $\sigma_v = N_\pi(v)\sigma_r$, where σ_v is the sum of K-vacancy production cross sections for Cl and Ar and $\sigma_r = \int 2\pi P_r b\, db$. Only the lowest charge-state data were used, for which the fluorescence yields were interpolated from Table II.

In Fig. 5 we show a plot of $\bar{N}_\pi(v)$ vs $1/v$. Meyerhof[15] has suggested that $N_\pi(v)$ is due to radial coupling at large R between the $2p\pi$ and higher vacant π orbitals, and has applied Demkov's model for vacancy transfer between parallel orbitals. Although the high velocities of the present collision call into question the quantitative applicability of this model, we find it informative to pursue it nevertheless. The probability w for vacancy transfer from the $2p\pi$ orbital with asymptotic ion-

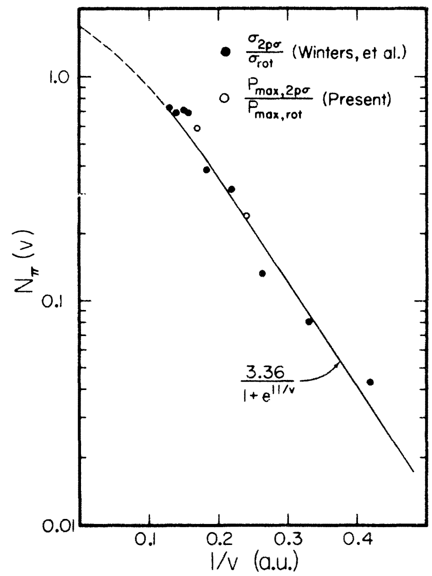

FIG. 5. Experimental values for $N_\pi(v)$ in Cl-Ar collisions, plotted vs $1/v$, where v is the Cl velocity in a.u. The open circles are derived from the low-charge state cross sections of Winters *et al.* (Ref. 17). The filled circles are from the present data.

ization energy I_1 to a vacant orbital with energy I_2 is given by[4]

$$w = 1/(1 + e^{2|x|}),$$

where

$$x = \frac{13.5}{v}\,\frac{I_1 - I_2}{\sqrt{I_1} + \sqrt{I_2}}.$$

Here I_1 and I_2 are in keV, v in a.u. The solid line in Fig. 5 is of the form $N_\pi(v) = C/(1 + e^{\alpha/v})$. From the data points at low v we find $\alpha = 11$, $C = 3.36$. If one takes $I_1 = 348$ eV, the $2p$ binding energy for Cl^{+7} (empty M shell),[27] this value of α gives $I_2 = 33$ eV. The exact value of I_2 is rather sensitive to the value of I_1 used. In the vacancy-sharing model C should equal 2.0 and $N_\pi(v)$ should not exceed unity. [For total emptying of the $2p\pi$ orbitals before the close encounter, $N_\pi(v)$ may be as large as 2, since there are two $2p\pi_x$ orbitals.] The higher value of C obtained here may reflect deficiencies in the model, although the discrepancy is almost within the 50% absolute error bar quoted on the data.

The true mechanism for production of $2p\pi$ vacancies is certainly more complex than that supposed by the vacancy-sharing model. It is difficult to identify a single orbital to which the transfer might go. Initially the nearest vacant π orbital is the $3p\pi$ which correlates to the Cl $3p$ shell and whose asymptotic binding energy is near 90 eV for Cl^{+7}. There are numerous vacant π orbitals with which sharing might occur, many of which lie at least as close to the $2p\pi$ orbital as does the fictitious level whose binding energy is 33 eV. Thus, we conclude that the production of $2p\pi$ vacancies with probabilities as high as are needed to explain the present data seems quite possible, and indeed the operation of the two-step mechanism is in no way surprising.

CONCLUSION

We have presented experimental evidence that the impact-parameter dependence of the $2p\sigma$ vacancy production probability in Cl-Ar collisions is very close to that expected if the vacancy production is produced by the strong $2p\pi$-$2p\sigma$ coupling. This is true independent of whether $2p\pi$ vacancies are present initially in the incoming projectile. We interpret this as evidence that $2p\pi$ vacancies are produced at large internuclear distances in single collisions. A vacancy-sharing model for the production of $2p\pi$ vacancies suggests that the $2p\pi$ vacancy production probabilities needed to explain those data are not unreasonable. While we do not pretend to exclude the operation of direct $2p\sigma$ ionization processes in collisions where the $2p\pi$-$2p\sigma$ channel seems to be more than marginally closed, we point out that, as supported by the experimental evidence of this paper, it is not surprising that the two-step process is important. Presumably at sufficiently high Z the $2p\pi$ vacancy production probability will become low enough that the multistep process may be ignored, but this may not occur until one goes to considerably larger Z than is often assumed, certainly above $Z = 18$. So long as the multistep process is important, total K-vacancy production cross sections may be dominated by higher-shell processes, and studies of the cross sections' dependence on Z and collision velocity may be a study of $N_\pi(v)$ rather than of the inner-shell process itself. Thus, one must use caution in the interpretation of K-vacancy production cross sections for nearly symmetric collision partners in terms of inner-shell interactions alone.

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[1]U. Fano and W. Lichten, Phys. Rev. Lett. 14, 627 (1965); W. Lichten, Phys. Rev. 164, 131 (1967); M. Barat and W. Lichten, Phys. Rev. A 6, 211 (1972).

[2]Q. C. Kessel and B. Fastrup, in *Case Studies in Atomic Physics*, edited by E. W. McDaniel and M. R. C. McDowell (North-Holland, Amsterdam, 1973), Vol. III.

[3]B. Fastrup, in *Electronic and Atomic Collisions, Abstracts on the Papers on the International Conference on the Physics of Electronic and Atomic Collisions*, edited by J. S. Risley and R. Geballe (University of Washington Press, Seattle, 1975), p. 361.

[4]W. E. Meyerhof, Phys. Rev. Lett. 31, 1341 (1973).

[5]J. S. Briggs and J. Macek, J. Phys. B 5, 579 (1972); 6, 982 (1973).

[6]K. Taulbjerg, J. S. Briggs, and J. Vaaben, J. Phys. B 9, 1351 (1976).

[7]K. Taulbjerg and J. S. Briggs, J. Phys. B 8, 1895 (1975); J. S. Briggs and K. Taulbjerg, J. Phys. B 8, 1909 (1975).

[8]R. K. Cacak, Q. C. Kessel, and M. E. Rudd, Phys. Rev. A 2, 1327 (1970).

[9]N. Stolterfoht, D. Schnieder, D. Burch, B. Agaard, E. Bøving, and B. Fastrup, Phys. Rev. A 12, 1313 (1975).

[10]S. Sackmann, H. O. Lutz, and J. Briggs, Phys. Rev. Lett. 32, 805 (1974).

[11]B. Fastrup, G. Hermann, Q. Kessel, and A. Crone, Phys. Rev. A 9, 2518 (1974).

[12]B. Fastrup, E. Bøving, G. A. Larsen, and P. Dahl, J. Phys. B 7, L206 (1974).

[13]H. O. Lutz, N. Luz, and S. Sackmann, in *Proceedings of Fourth International Conference on Atomic Physics, Abstracts of Contributed Papers, Heidelberg, 1974* (Heidelberg U. P., Heidelberg, 1974), p. 657; N. Luz, S. Sackmann, and H. O. Lutz, J. Phys. B 9, 1 (1976).

[14]W. N. Lennard and I. V. Mitchell, J. Phys. B 9, L317 (1976).

[15]W. E. Meyerhof, in Second International Conference on Inner Shell Ionization Phenomena, Freiburg, 1976 (unpublished); and private communication.

[16]W. E. Meyerhof, Phys. Rev. A 10, 1005 (1974).

[17]L. Winters, M. D. Brown, L. D. Ellsworth, T. Chiao, E. W. Pettus, and J. R. Macdonald, Phys. Rev. A 11, 174 (1975).

[18]R. R. Randall, J. A. Bednar, B. Curnutte, and C. L. Cocke, Phys. Rev. A 13, 204 (1976).

[19]Supplied by Siemens Corporation, Iselin, N. J.

[20]W. L. Wiese, M. W. Smith, and B. M. Miles, *Atomic Transition Probabilities*, NSRDS-NBS No. 22 (U.S. GPO, Washington, D. C., 1969), Vol. II.

[21]E. Everhart, G. Stone, and R. J. Carbone, Phys. Rev. 99, 1218 (1955).

[22]W. Bambynek, B. Craseman, R. W. Fink, H. U. Freund, H. Mark, C. D. Swift, R. E. Price, and P. V. Rao, Rev. Mod. Phys. 44, 716 (1972).

[23]W. R. Thorson, Phys. Rev. A 12, 1365 (1975).

[24]C. Foster, T. P. Hoogkamer, P. Woerlee, and

F. W. Saris, J. Phys. B 9, 1943 (1976).

[25]J. Bang and J. M. Hansteen, K. Dan. Vidensk. Selsk. Mat.-Fys. Medd. 31, No. 13 (1959); J. M. Hansteen and O. P. Mosebekk, Nucl. Phys. A 201, 541 (1973).

[26]J. M. Hansteen, O. M. Johnsen, and L. Kocbach, At. Data 15, 305 (1975).

[27]C. E. Moore, *Atomic Energy Levels*, NSRDS-NBS No. 34, (U.S. GPO, Washington, D. C., 1970).