Be K-shell Auger-electron emission in slow-ion—surface collisions

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We have observed beryllium K-shell Auger electrons from clean Be surfaces bombarded by 2.5—10-keV Ne, Ar, and Kr ions at 45° incidence. The electron spectra show a broad structure similar, although not identical, to that observed under electron impact, which was assigned to the KVV transition from excited Be decaying in the bulk of the solid. A small sharp line is identified to result from the decay in vacuum of neutral Be($1s\,2s^2 2p$) sputtered from the solid. The Auger yields can be scaled when plotted against the maximum energy transfer in a projectile-Be collision, indicating that excitations occur mainly from symmetric collisions between target atoms. This is supported by Monte Carlo simulations of the atomic collision cascade in the solid. We have applied these simulations to evaluate the relative role of symmetric and asymmetric collisions in early measurements of Be K x-ray yields, at higher energies. By comparing experimental and simulated results, we obtained information about the variations of the fluorescence yields and outer-shell occupation numbers with projectile energy.

I. INTRODUCTION

Due to the large density of target atoms, solids can be used to observe relatively improbable atomic collision events, like the excitation of shallow inner shells at impact energies in the keV range. The interpretation of these observations is complicated, however, by multiple collisions inside the solid, which slow down and deflect the projectile and produce a cascade of moving target atoms.

We have previously shown that, for aluminium bombarded by noble-gas ions, one can explain features in the L-shell Auger spectra to result from Al atoms decaying inside and outside the solid.[1,2] The yields of these Auger electrons could be scaled with the maximum energy transfer in a projectile-Al collision, indicating that the excitations were caused mainly by collisions between target atoms (t-t) as found for other light targets.[3] These excitations are thought to result from the coupling of the promoted $4f\sigma$ molecular orbital (MO) to other empty MO's.[4] For He^+ and Ne^+ projectiles, we observed a departure from this scaling at low energies which we attributed to excitation by two-electron transitions in collisions between the projectile and a target atom (p-t).

In this work we extend the studies to the case of K-shell excitation by keV ions, using Be as a target. The mechanism of excitation in symmetric collisions in this case is different from that described for the $2p$ shell, and is thought to be the rotational coupling[5] of the $2p\sigma$ and $2p\pi$ MO's.

There exist previous studies of Be K-shell excitation but at larger energies. Terasawa *et al.*[6] measured Be K x-ray yields from thick Be targets bombarded with different 15—600-keV ions of atomic number Z_p in the range 1—18. They obtained cross sections from the yield data considering the slowing down of the ions in the solid, but neglecting excitations in t-t collisions. Piacentini and Salin[7] analyzed these experiments in the light of their theory of K-shell excitation by rotational coupling between $2p\sigma$ and $2p\pi$ MO's. They found a large difference between theory and experiment in the case of Ne on Be which they attributed to additional excitations from the coupling of the $2p\sigma$-$3d\sigma$ MO's. It can be seen that the discrepancy of their results with experiments, analyzed on the basis of p-t collisions, increases with Z_p at low energies.

A different approach was used by Benazeth *et al.*[8] who measured the production of Be K Auger electrons from thick Be targets bombarded by 10—100-keV noble-gas ions. In the analysis, they again assumed that excitations in t-t collisions were unimportant. They compared their results for Ar on Be with those of Terasawa *et al.*[6] and found large differences in the magnitude of the derived cross sections.

Recently, Scharnagl and Hink[9] measured the production of Be K x rays from Be foils, a few hundred Å thick, bombarded by 10—120-keV projectiles of Z_p in the range 1—5. These authors also neglected in their analysis excitations by energetic Be recoils. The cross sections thus extracted were discussed in terms of the $2p\sigma$-$2p\pi$ coupling, and an assumed number of $2p$ vacancies in the projectile inside the solid, in the case of the heavier projectiles.

These works left open the question on the relative role of p-t and t-t collisions in Be K-shell excitation in solid targets. It has therefore not been possible to do a meaningful comparison with current theories and answer the question on which are the main excitation mechanisms.

The purpose of our work was to find these answers. To this end we made an analysis of the spectra and projectile energy dependence of the yields of Be K-shell Auger electrons, similar to what we used previously to study the case of L-shell excitation with Al targets. We made the experiments with 2.5—10-keV Ne, Ar, and Kr ions incident on clean Be targets at 45° incidence. To these measurements we have added the study of recoil effects using a computer simulation of the penetration of the projectiles in the solid and of the motion of recoiling target atoms. We applied these results to explain our experiments and previous x-ray emission measurements.

II. EXPERIMENTS

A. Apparatus

The apparatus has been described in detail previously.[2] The target, a high-purity beryllium disk, was mounted inside an ultrahigh-vacuum chamber operating at a base pressure of $\sim 10^{-10}$ Torr. The sample was cleaned by sputtering with low-energy Ar ions. The surface concentration of the main remaining contaminants, oxygen and implanted argon, was less than 0.5% and 0.7%, respectively, as determined by electron-induced Auger-electron spectroscopy.

The Ne, Ar, and Kr ions, produced in an electron-bombardment-type ion gun, were mass analyzed using a Wien filter and deflected electrostatically onto the target to avoid contamination of the beam with non-mass-analyzed neutrals. The incident angle of the ions with respect to the normal to the sample surface was 45°.

The energy of the ejected electrons was determined with a hemispherical electrostatic analyzer working at 1% energy resolution. Electrons were detected within a narrow cone 15° from the surface normal. Since we compare our electron energy spectra with those from gas-phase collisions, the electron kinetic energy must be referred to the vacuum level of the target. To calibrate the electron energy scale, we used the method described in a previous work[1] and a value of 3.9 eV for the work function of Be.[10] The electrons were detected with a channel electron multiplier; spectra were taken under computer control using signal averaging techniques.

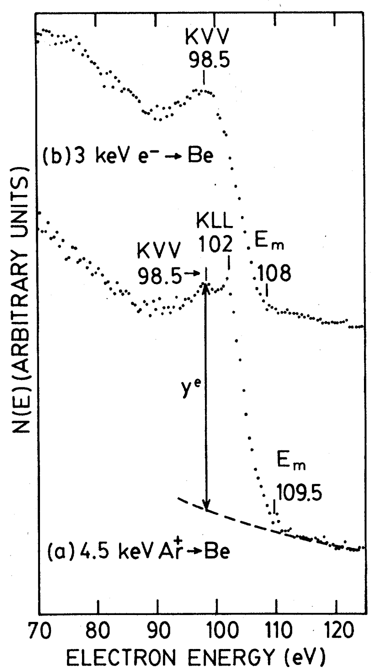

FIG. 1. Energy distribution of electrons ejected from Be by (a) 4.5-keV Ar ions and (b) 3-keV electrons. In both cases, electron energies are referred to the vacuum level of the target. The spectra were corrected for the energy-dependent transmission function of the analyzer. The channel width was 0.5 eV.

B. Auger-electron spectra

Figure 1(a) shows a typical Auger-electron energy spectrum of Be bombarded with 4.5-keV Ar^+. Though there are some differences, it is similar to that obtained under electron impact [Fig. 1(b)]. The maxima of both spectra, indicated as *KVV*, are at the same energy: 98.5 eV.

The main peculiarities of the ion-induced spectra are (1) the appearance of a sharp, atomiclike peak (*KLL*) at 102 eV (Ref. 8) which is absent in the electron-induced spectrum, and (2) a broader bandlike (*KVV*) structure[8,11] [which involves two valence-band (*V*) electrons]. The high-energy edge is found at $E_m = 109.5$ eV, in agreement with other work,[11] while E_m for the electron-induced spectrum is 108 eV.

Following previous work[1,2,12] we assume that the atomiclike peak corresponds to a *KLL* Auger transition in energetic sputtered recoils, and is broadened by the Doppler effect and the interaction with the surface. To identify this peak we used the energy-level diagram of Fig. 2, derived from Moore's tables[13] and gas-phase Auger spectra.[14] If the excited recoil has a Be^+ $1s2s^2\,{}^2S$ initial ionic state, it can neutralize by resonant capture of a valence-band electron[15] to Be^0 $1s2s^22p\,{}^1P,{}^3P$ states, when it escapes from the solid. Capture to Be^0 $1s2s^2nl$ configurations with $n \geq 3$ is not resonant since the energy required to ionize them to Be^+ $1s2s^2\,{}^2S$ is smaller than the work function of Be. Excited states $1s2s^22p\,{}^1P$, ${}^3P$ can decay to final states $1s^22s\,{}^2S$ and $1s^22p\,{}^2P$ with Auger-electron energies

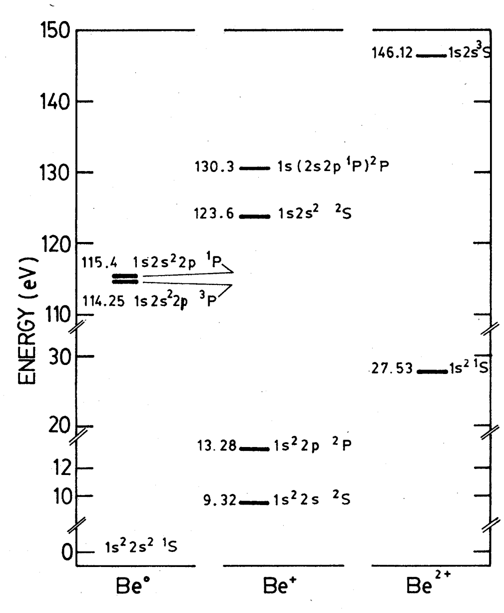

FIG. 2. Energy-level diagram for autoionizing states of Be.

$$^3P \rightarrow 1s^2 2p\, ^2P \quad 101.0 \text{ eV} , \tag{1}$$

$$^1P \rightarrow 1s^2 2p\, ^2P \quad 102.1 \text{ eV} , \tag{2}$$

$$^3P \rightarrow 1s^2 2s\, ^2S \quad 104.9 \text{ eV} , \tag{3}$$

$$^1P \rightarrow 1s^2 2s\, ^2S \quad 106.1 \text{ eV} . \tag{4}$$

We believe that the observed *KLL* line corresponds mainly to transitions (1) and (2), not resolved by our apparatus; transitions (3) and (4) fall just on the high-energy edge and therefore could account, together with (2), for the small difference found between the high-energy edges in the electron and ion-induced spectra.

If the excited sputtered recoil, Be^+ $1s2s^2\,^2S$, survives neutralization, it can decay to Be^{2+} $1s^2\,^1S$ by emitting a 96.1-eV Auger electron. Since this peak was not observed, the transition rate for resonant neutralization must be much greater than for the Auger effect.[15] With this argument, we can suppose that transitions from Be^+ to Be^{2+}, such as Be^+ $1s\,(2s2p\,^1P)^2P \rightarrow Be^{2+}$ $1s^2\,^1S$, and others with Auger energies between 100 and 103 eV, must contribute very weakly to the *KLL* atomiclike peak.

Finally, we must consider transitions from initial states Be^0 $1s2s2p^2$ to Be^+ $1s^2 2s\,^2S$ or Be^+ $1s^2 2p\,^2P$, which give Auger electrons with energies greater than or equal to 108 eV, and therefore could also contribute to the shift observed in the high-energy edge.

The ratio of the yield of the atomiclike peak to that of the bandlike peak in Be is smaller than the ratios observed for other targets (Mg, Al, Si) at the same energy and incidence angle.[1] This is a consequence of the smaller lifetime of the Be *K*-shell vacancy,[16] which lowers the probability that an excited recoil escapes from the solid retaining its inner-shell hole.

C. Yields

Relevant information concerning the mechanisms for *K*-shell vacancy creation can be obtained from the variation of the Auger yield with projectile energy. To date, knowledge of the different contributions to the secondary electron background in the whole range of the spectra is poor and it is extremely difficult to provide a good estimate of the Auger peak areas, particularly at the lowest projectile energies. For this reason we took the channel intensity at 98.5 eV, measured from the extrapolated high-energy background [Fig. 1(a)], as a measure of the yields. This energy (98.5 eV) was used because it corresponds to the maximum in the electron-induced spectra. Since the shape of the *KVV* transition does not show discernible changes for different ion energies or ion species, the signal at one channel (after background substraction) should be a constant fraction of the total *KVV* signal. Use of the signal at other close energy as a measure of the Auger yield would be equivalent, since all our Auger data are in arbitrary units. The background was calculated by fitting a function of the form $N(E) = A + B/(E - E_0)^n$ to the high-energy side of the spectra, where A, B, E_0, and n are fitting constants.

Figure 3 shows Auger-electron yields from Be under Ne, Ar, and Kr bombardment as a function of impact energy, E_p. It can be seen that the shape of the curves is similar for all three projectiles and that the yields decrease with increasing atomic number. It can also be seen that, within errors, the yields are independent of the ionization state of the projectile before entering the solid.

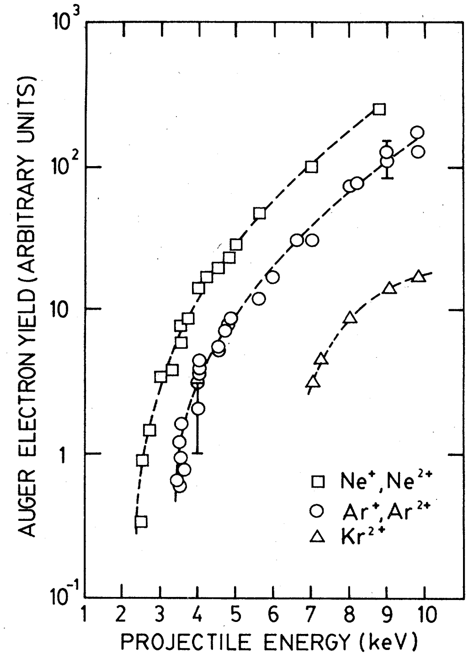

FIG. 3. Experimental Auger-electron yields of Be vs projectile energy, and typical error bars. Notice that, within errors, the yields are independent of the ionization state of the projectile before entering the solid.

III. DISCUSSION

A. Be K-shell excitation below 10 keV

The purpose of this section is to discuss whether the observed inner-shell excitations of Be at impact energies below 10 keV are predominantly produced in *p-t* or *t-t* collisions.

If vacancies are produced in *p-t* collisions, the possible excitation mechanisms for the three projectiles used are different. These mechanisms, which are indicated in Figs. 4(b)—4(d), following the rules of Barat and Lichten,[4] require at least one outer-shell vacancy in the projectile.

If vacancies are produced in symmetric collisions, we must consider not only the excitation mechanism in the Be-Be system, Fig. 4(a), but also the energy transfer from a projectile to a recoiling target atom in a previous collision. As shown elsewhere,[2,3,17] if *t-t* collisions dominate, the yields should be approximately independent of the type of projectile, when plotted as a function of the maximum recoil energy γE_p, with $\gamma = 4M_p M_t / (M_p + M_t)$ (M_p, M_t are the projectile and target mass, respectively). Figure 5 shows the yields plotted as a function of γE_p. It can be seen that, within experimental errors, data for all

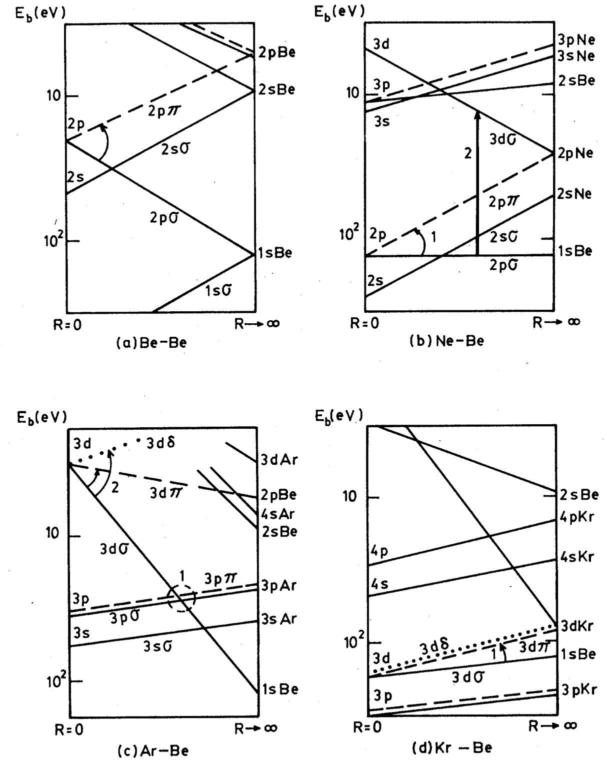

FIG. 4. Correlation diagrams for some quasimolecular collision systems. Be $1s$ holes may be produced by (a) Be-Be: $2p\sigma$-$2p\pi$ rotational coupling; (b) Ne-Be: (1) $2p\sigma$-$2p\pi$ rotational coupling and (2) K-L vacancy sharing between $2p\sigma$ and $3d\sigma$ MO's; (c) Ar-Be: $3d\sigma$ promotion and level crossings (1) or rotational coupling between the $3d\sigma$-$3d\pi$-$3d\delta$ MO's (2); (d) Kr-Be: $3d\sigma$-$3d\pi$-$3d\delta$ only, after the creation of a Kr $3d$ vacancy by promotion of the $4f\sigma$ MO. There is not much significance in outer-shell correlations due to electron-electron interactions and the splitting of the Be $2s$ level to a $2s$-$2p$ band in the solid.

three projectiles now coincide in the low-energy range and tend to a common threshold energy ~2 keV. This agrees with the threshold value of 2.2 keV predicted[18] for excitation due to the coupling of the $2p\sigma$-$2p\pi$ MO's in Be-Be collisions.

Using the Moliere interatomic potential,[19] we calculated a maximum radius for excitation of 0.28 a.u. from the measured threshold energy. As must be expected for rotational coupling, this value is lower than the sum of the mean K-shell radii of the two colliding Be atoms (<0.54 a.u.).

The preponderance of t-t collisions in the creation of Be K vacancies at keV energies is in contradistinction with previous suggestions[6,8,9,11,12] that p-t collisions dominate Be K-shell excitation in ion solid interactions above 10 keV, for all projectiles used, including Ne. It thus seems interesting to study when p-t collisions begin to be more important than t-t collisions and to see also how this effect depends on the atomic number of the projectile.

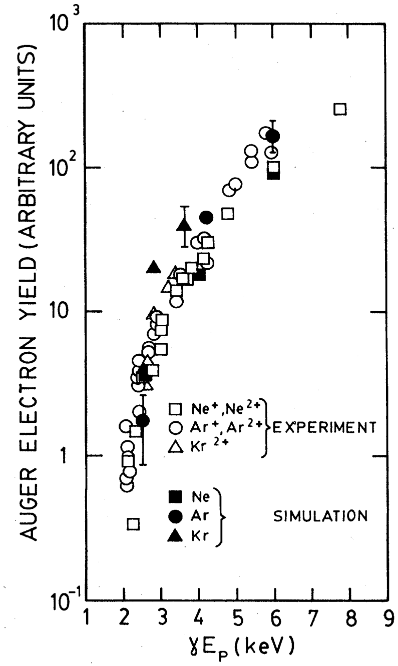

FIG. 5. Experimental Auger-electron yields of Be vs γE_p, the maximum energy transfer to a recoil. The closed symbols correspond to the Monte Carlo simulation of the excitation events in t-t collisions, normalized to the experimental value for Ar at $\gamma E_p = 6$ keV. The bars represent the typical statistical errors of the simulation.

B. Be K-shell excitation above 10 keV

At energies above 10 keV, other workers[6,9] found that the Be K x-ray production cross sections σ_x, for projectiles of Z_p from 4 to 10, decrease (except for Ne^+) with increasing Z_p [Fig. 6(a)]. This effect was in apparent agreement with (a) a reduced K-shell radius and higher Coulomb deflection and (b) a decrease in the number of $2p$ vacancies in the heavier projectiles, since

$$\sigma_x = \omega N_\pi \sigma_{rot} , \qquad (5)$$

where ω is the Be K-shell fluorescence yield, N_π the initial number of vacancies in the $2p\pi$ orbital, and σ_{rot} the cross section for $2p\sigma$-$2p\pi$ rotational coupling.

These workers did not consider the possibility of vacancy creation in symmetric collisions. Nevertheless, if only asymmetric collisions are important and (b) is valid even in solids, where the ionization state of the projectile before the excitation collision may change due to previous collisions, the same dependence of σ_x with Z_p must hold when plotted in the reduced coordinates (ru) proposed by Taulbjerg *et al.*[18] These are the appropriate coordinates for the treatment of the $2p\sigma$-$2p\pi$ rotational coupling, which is the main mechanism for Be K-shell excitation in the studied systems.

It can be seen in Fig. 6(b) that the order has reversed for projectile velocities below 0.1 ru: heavier projectiles have larger σ_x (0.1 ru corresponds to ~40 keV in the case of B, ~76 keV for N, and ~175 keV for Ne). As will be

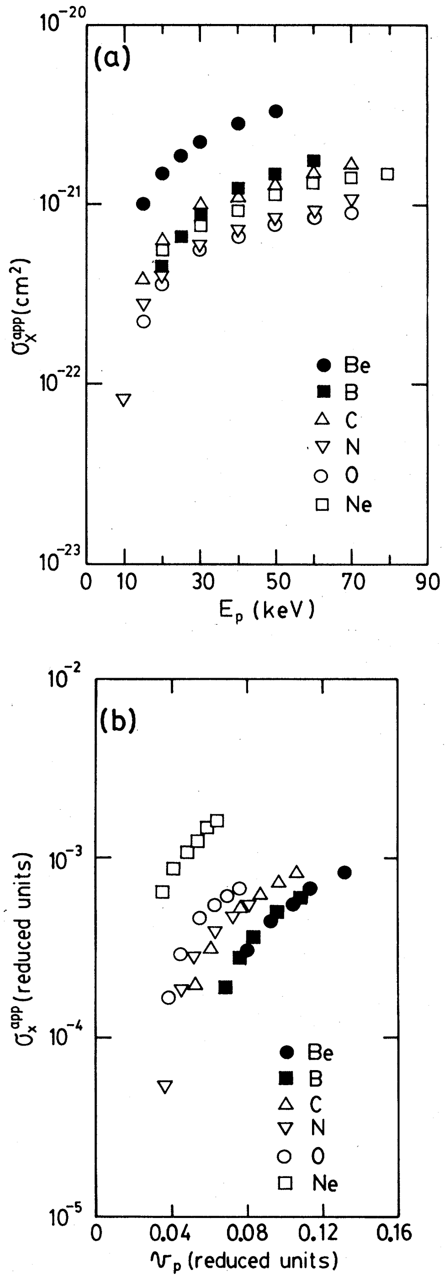

FIG. 6. Apparent Be K x-ray production cross sections σ_x^{app} obtained by Terasawa *et al.* (Ref. 6; C,N,O,Ne) and Scharnagl *et al.* (Ref. 9; Be,B) (a) vs the projectile energy E_p, and (b) vs the projectile velocity v_p in the reduced coordinates of Taulbjerg *et al.* (Ref. 18).

shown in the next section, this result agrees with the assumption that t-t collisions are important even in this energy range.

When both p-t and t-t collisions may create vacancies, a more powerful tool than the measure of threshold energies is needed to separate the p-t and t-t contributions to the total yield. For this purpose we adapted a Monte Carlo program which simulates trajectories and excitation events in the penetration of heavy ions in solids.

C. Monte Carlo simulation

This program traces the trajectories of a large number of individual particles (projectiles and all fast recoils) inside the solid. Particles move in straight-line segments changing their direction by binary nuclear encounters with randomly located target atoms. The energy of the moving atoms decreases as a consequence of nuclear and electronic energy losses. In each collision (p-t and t-t), the program calculates the probability[18] for the $2p\sigma$-$2p\pi$ rotational coupling (this number, multiplied by the unknown number of vacancies in the $2p\pi$ MO, N_π, gives the probability for 1s-vacancy production). The simulation cannot be used to estimate the number of vacancies produced in p-t collisions involving Ar and Kr ions, because in these cases there are other excitation mechanisms with uncertain values of the excitation probability (see Fig. 4).

In order to simulate our measured Auger-electron yields we used an exponential electron escape probability, $\exp(-x/L)$; x is the position measured from the surface of the solid, where excitation occurs, and $L=6.1$ Å, the attenuation length for 100 eV electrons in Be.[20] The distance traveled by the excited recoils before decaying, which is directly related to the K-hole lifetime, was assumed to be zero. This neglect, which is inadmissible when atomic KLL peaks are to be simulated, does not change appreciably our results for the yields, because of the small lifetime of the Be K vacancy ($\sim 10^{-14}$ sec).

Results of the simulation (normalized to experiment for

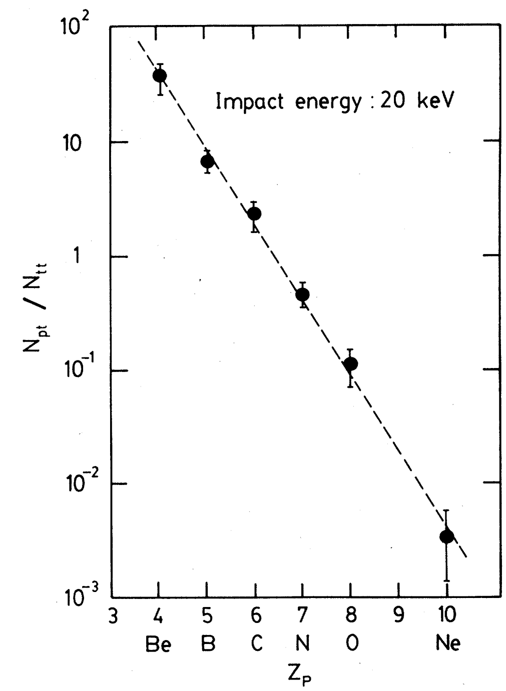

FIG. 7. Calculated ratios of the number of Be K vacancies produced in p-t collisions to those produced in t-t collisions, normalized to one vacancy in the $2p\pi$ MO, as a function of the atomic number of the projectile, Z_p. The bars represent the statistical errors of the simulation and the line was drawn merely to guide the eye.

Ar at $\gamma E_p = 6$ keV) are shown in Fig. 5, together with experimental values. Data are well fitted in the whole experimental energy range, considering only t-t collisions. No vacancy production is expected from p-t collisions in the Ne-Be system at these energies. This is because rotational coupling between the $2p\sigma$ and $2p\pi$ MO's has a threshold energy of ~ 15 keV (Ref. 18) and K-L vacancy sharing[21] is extremely improbable at the energies of our measurements, beginning to be competitive with rotational coupling near 100 keV.[7] Rotational coupling between the $3d\sigma$-$3d\pi$-$3d\delta$ MO's in Ar-Be collisions requires energies considerably greater than 10 keV.[8]

To simulate measurements[6,9] of x-ray yields, the treatment was similar but the escape probability of x rays was taken to be unity. We calculated $N_{pt}(N_{tt})$, the number of vacancies produced in p-t (t-t) collisions per initial $2p\pi$ vacancy.

Ratios N_{pt}/N_{tt} are presented in Fig. 7 for $E_p = 20$ keV and different Z_p. The strong dependence with Z_p may be qualitatively understood to result from two effects: (1) heavier projectiles are more effective in producing many energetic recoils although with a lower maximum energy, and (2) at low energies, the cross section for the $2p\sigma$-$2p\pi$ coupling decreases rapidly with increasing Z_p.

The ratio N_{pt}/N_{tt} increases with increasing energy, as shown in Fig. 8. This is caused by competing factors: (1) the energy dependence of the excitation cross sections, (2) the production of faster recoils as energy increases, and (3) the energy dependence of the total number of fast recoils. We found that the average depth where t-t excitations occur is larger than that for p-t excitations, and that both depths increase with energy. This, together with the small electron escape depth, causes the ratio N_{pt}/N_{tt} to increase faster with energy when Auger electrons, rather than x rays, are observed.[8]

The total Be K x-ray yield, Y^x, can be written as the sum of the contributions of p-t and t-t collisions: $Y^x = Y^x_{pt} + Y^x_{tt} = \omega N_\pi(p) N_{pt} + \omega N_\pi(t) N_{tt}$, where ω is the Be K-shell fluorescence yield, and $N_\pi(p)$ $[N_\pi(t)]$ the initial number of $2p_\pi$ vacancies in the asymmetric (symmetric) excitation collision.

To compare simulations with experimental results, we need the values of ω, N_π, and their variation with projectile energy, which are not known at present. The dependence of ω on projectile energy has been studied for various collision systems.[22-24] In the case of K-shell excitation in Ne^+-Ne collisions, ω increases with ion energy, and very rapidly near the excitation threshold.

If projectiles are essentially neutral inside the solid, theory[25] predicts $N_\pi(\text{Be}) = 2$ and $N_\pi(p) = \frac{5}{3}, \frac{4}{3}, 1, \frac{2}{3}$, and 0 for B, C, N, O, and Ne, respectively, in the limit of zero velocities. Experiments[26] of K-vacancy productions for other light systems, and in our energy range, have produced values of N_π much smaller than those predicted theoretically, and which increase slightly with velocity due to the dynamical creation of $2p\pi$ vacancies at large internuclear separations.

Although N_π and ω are not known, we can obtain information from limiting cases. Figure 7 shows that for Be projectiles, recoils create at most a few percent of the K vacancies and therefore, $Y^x \sim Y^x_{pt}$. On the contrary, for Ne projectiles, the main contribution to the yields arises from recoils, $Y^x \sim Y^x_{tt}$, since $N_{tt} \gg N_{pt}$ and since, as men-

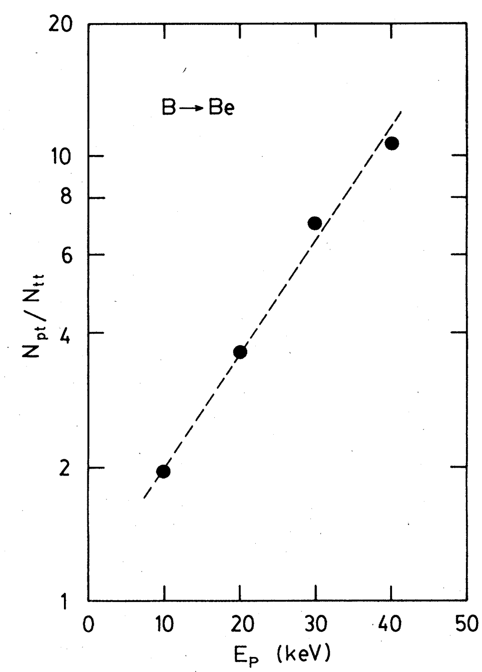

FIG. 8. Calculated ratios of the number of Be K vacancies produced in p-t collisions to those produced in t-t collisions, normalized to one vacancy in the $2p\pi$ MO, as a function of the energy of B projectiles. The line was drawn to guide the eye.

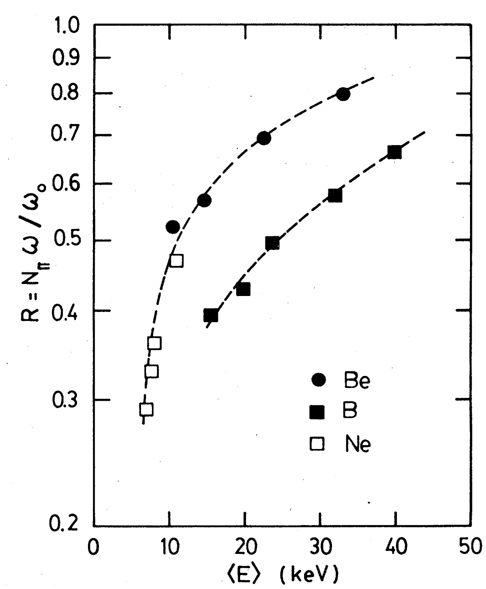

FIG. 9. The ratio $R = N_\pi \omega / \omega_0$ between measured and calculated x-ray yields as a function of the mean projectile energy (mean Be recoil energy in the case of Ne projectiles) in the excitation collision. The experimental x-ray yields were taken from previous works (Refs. 6 and 9). N_π is the number of vacancies in the $2p\pi$ MO, $\omega_0 = 3 \times 10^{-4}$ the Be K fluorescence yield measured by electron impact, and ω that corresponding to ion bombardment.

tioned above, one can expect that $N_\pi(t)$ is greater than $N_\pi(p)$.

We can thus obtain, for these two projectiles, information about the variation of the product ωN_π of Be with energy from the ratios between experiment and calculations, $R = Y^x_{exp}/\omega_0 N_{pt}(N_{tt}) = N_\pi(\mathrm{Be})\omega/\omega_0$, for the Be-Be (Ne-Be) system. Here Y^x_{exp} is the total experimental x-ray yield taken from Refs. 6 and 9 and $\omega_0 = 3\times 10^{-4}$ the fluorescence yield of Be measured under electron impact.[27]

We show in Fig. 9 the dependence of R with the average impact energy $\langle E\rangle$ in an excitation collision. $\langle E\rangle$ was derived from the Monte Carlo simulations. We can notice an excellent agreement between the data for Be and for Ne projectiles, which supports the idea that in both cases excitations are produced in symmetric collisions.

Also shown in Fig. 9 are results for B on Be, obtained by assuming that p-t collisions dominate the excitation process (see Fig. 7). Although this assumption is not as good as for the case of Be on Be, the ratio $N_\pi(\mathrm{Be})/N_\pi(\mathrm{B}) \sim 1.4$ obtained is close to the theoretical value of 1.2 expected from the model of statistical distribution of $2p\pi$ vacancies.[25]

Since N_π must remain almost constant at low energies, the drop of R near the excitation threshold is expected to be a consequence of a decrease of ω similar to that previously found[22] for the Ne K fluorescence yield in Ne-Ne collisions.

IV. CONCLUSIONS

Summarizing, our study of Be K-shell excitation produced by the bombardment of solid Be with slow heavy ions has led to the following main conclusions.

(1) The Be Auger spectra is composed of two main structures. One structure is a broad one from KVV transitions involving two valence electrons of the solid, and due to atoms that decay inside the solid. The other structure is a sharper line which originates from sputtered excited atoms which survive the transit to the surface and decay outside the solid after being neutralized by resonant electron transfer from the valence band of the metal.

(2) In the low-keV energy range, Be K-shell excitations by heavy projectiles are produced mainly by symmetric collisions involving energetic Be recoils set in motion by the projectiles. The dependence of the yields of Be K Auger electrons with energy and type of projectile can be reproduced well by a Monte Carlo simulation of the motion of projectiles and recoils inside the solid, assuming that excitations occur by the $2p\sigma$-$2p\pi$ rotational coupling. A threshold center-of-mass energy of 1 keV is required to reach the internuclear distances where the coupling is effective.

(3) Previous results on x-ray emission by heavy projectiles in the energy range of tens of keV which were analyzed assuming excitations to occur only in projectile-target collisions are found to be strongly affected by recoil effects.

(4) The results extend to solid targets the observation of the strong energy dependence of the fluorescence yields near the excitation threshold.

ACKNOWLEDGMENTS

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[1]R. A. Baragiola, in *Inelastic Particle-Surface Collisions*, Vol. 17 of *Springer Series in Chemical Physics*, edited by E. Taglayer and W. Heiland (Springer, Berlin, 1981), p. 38.
[2]R. A. Baragiola, E. V. Alonso, and H. J. L. Raiti, Phys. Rev. **25**, 1969 (1982).
[3]K. Taulbjerg and P. Sigmund, Phys. Rev. A **5**, 1285 (1972); K. Taulbjerg, B. Fastrup, and E. Laegsgaard, *ibid.* **8**, 1814 (1973); K. Wittmaack, Surf. Sci. **85**, 69 (1979).
[4]M. Barat and W. Lichten, Phys. Rev. A **6**, 212 (1972).
[5]J. S. Briggs, Rep. Prog. Phys. **39**, 217 (1976).
[6]M. Terasawa, T. Tamura, and H. Kamada, J. Phys. Soc. Jpn. **33**, 1420 (1972).
[7]R. D. Piacentini and A. Salin, J. Phys. B **9**, 959 (1976).
[8]N. Benazeth, J. Agusti, C. Benazeth, J. Mischler, and L. Viel, Nucl. Instrum. Methods **132**, 477 (1976).
[9]T. Scharnagl and W. Hink, J. Phys. B **13**, 4021 (1980).
[10]V. S. Fomenko, *Handbook of Thermoionic Properties*, edited by G. V. Sansonov (Plenum, New York, 1966).
[11]F. Louchet, L. Viel, C. Benazeth, B. Fagot, and N. Colombie, Radiat. Eff. **14**, 123 (1972).
[12]W. A. Metz, K. O. Legg, and E. W. Thomas, J. Appl. Phys. **51**, 2888 (1980).
[13]C. E. Moore, *Atomic Energy Levels*, Natl. Bur. Stand., Ref. Data Ser., Natl. Bur. Stand. (U.S.) Circ. No. 35 (U.S. GPO, Washington, D.C., 1971).
[14]M. Rødbro, R. Bruch, and P. Bisgaard, J. Phys. B **12**, 2431 (1979).
[15]H. D. Hagstrum, in *Inelastic Ion-Surface Collisions*, edited by N. H. Tolk, J. C. Tully, W. Heiland, and C. W. White (Academic, New York, 1977), p. 1; R. A. Baragiola, Radiat. Eff. **61**, 47 (1982).
[16]D. L. Walters and C. P. Bhalla, Phys. Rev. A **3**, 1919 (1971); **4**, 2164 (1971).
[17]M. M. Jakas and R. A. Baragiola (unpublished).
[18]K. Taulbjerg and J. S. Briggs, J. Phys. B **8**, 1895 (1975); J. S. Briggs and K. Taulbjerg, *ibid.* **8**, 1909 (1975); K. Taulbjerg, J. S. Briggs, and J. Vaaben, *ibid.* **9**, 1351 (1976).
[19]W. D. Wilson, L. G. Haggmark, and J. P. Biersack, Phys. Rev. B **15**, 2458 (1977).
[20]C. J. Powell, R. J. Stein, P. B. Needham, Jr., and T. J. Driscoll, Phys. Rev. B **16**, 1370 (1977).
[21]N. Stolterfoht, in *Structure and Collisions of Ions and Atoms*, edited by I. A. Sellin (Springer, Berlin, 1978), p. 155.
[22]N. Stolterfoht, D. Schneider, D. Burch, B. Aagaard, E. Bøving, and B. Fastrup, Phys. Rev. A **12**, 1313 (1975).
[23]N. Luz, S. Sackmann, and H. O. Lutz, J. Phys. B **12**, 1973 (1979).
[24]Th. P. Hoogkamer, P. H. Woerlee, R. J. Fortner, and F. W. Saris, J. Phys. B **10**, 3245 (1977).
[25]J. H. Macek and J. S. Briggs, J. Phys. B **6**, 841 (1973).
[26]D. Schneider and N. Stolterfoht, Phys. Rev. A **19**, 55 (1979).
[27]C. E. Dick and A. C. Lucas, Phys. Rev. A **2**, 580 (1970).