K-shell capture by protons from O_2, N_2, and Ne†

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We have measured the ratio of the cross section for K-electron capture to that for total K-vacancy production for 0.75–5-MeV protons on targets of O_2, N_2, and Ne. This was done by detecting Auger electrons from the target K-shell relaxation in coincidence with charge-neutralized projectiles. The fraction of K-shell vacancy production due to electron capture ranges from 0.028% to 3.3%, and the K-shell fraction of total electron capture from 2.5% to over 80%. By combining these data with previously measured (or calculated) cross sections for total K-vacancy production, we deduce cross sections for K-shell capture alone. The cross sections follow Oppenheimer-Brinkman-Kramers scaling laws for higher velocities, and are in fair absolute agreement with more complete charge-transfer calculations.

I. INTRODUCTION

The capture of electrons by fast point projectiles from atomic and molecular targets has received a great deal of attention over the years. A review of various theoretical approaches was given by Mapleton,[1] while the experimental situation was recently reviewed by Tawara and Russek.[2] Of particular interest at high velocities are treatments of the process in first-order perturbation theory. The Oppenheimer[3]-Brinkman and Kramers[4] (OBK) approximation, which employs only the projectile-electron interaction as the perturbing potential, is known to give cross sections which are too high in absolute value but which seem to scale properly with target nuclear charge (Z_2), bombarding energy, and principal quantum number of target or projectile shell. Partially due to their convenience, OBK cross sections are widely used in estimating capture cross sections. Nikolaev[5] showed that, by introducing screening corrections and by applying appropriate scaling factors, the OBK results could be used to predict, with remarkable accuracy, total cross sections for electron capture by fast protons on various gases. Mapleton[6] used a somewhat different scaling of OBK to find good agreement between theory and experiment for protons on He, N, 0, and Ar at high energies.

More complete Born calculations have met with varying degrees of success. Jackson and Schiff[7] showed that, by including the nucleus-nucleus interaction in the perturbing Hamiltonian, good agreement with experiment for protons on hydrogen could be obtained. Bates[8] showed that, when treated correctly, this term should not contribute at all, but that a term similar in importance and effect, although different in physical origin, results from a correct treatment of the nonorthogonality of initial and final states.

In recent years attention has been called in particular to the capture of inner-shell electrons. At projectile velocities comparable to those of the inner electrons, inner-shell capture may represent a significant fraction of the total capture[1,5] and will ultimately dominate at high energies. Interest in inner-shell capture is due in part to the fact that the electron-transfer process may contribute strongly to inner-shell vacancy production. This is the case particularly when the projectile nuclear charge (Z_1) approaches that of the target (Z_2). The role of charge transfer between K shells of target and projectile in K-vacancy production has been discussed by Halpern and Law[9] and by McGuire.[10] The former used an empirically scaled Oppenheimer[3]-Brinkman and Kramers[4] (OBK) calculation to indicate the importance of this channel, while the latter reached a similar conclusion based on the binary-encounter approximation.[11]

Although one might wish for a more precise high-Z_2 theory, such has not proved to be easily forthcoming. The attempt to extend the Jackson and Schiff calculation to higher Z_2 is disastrous, as was shown by Halpern and Law.[12] They found that inclusion of the full nucleus-nucleus interaction leads to unphysically high cross sections, orders of magnitude above experiment. Omidvar *et al.*[13] found that a reduction of this term by $1/Z_2$ led to more reasonable cross sections. Other attempts to improve on the OBK results for inner-shell capture at high Z_2 include use of the eikonal approximation[14] and introduction of the increased binding concept.[15]

While experimental cross sections for total capture are legion,[2] those for capture from specific target shells are few. At low energy, the total-capture cross sections will be dominated by capture from the outermost shell, but capture from an inner shell is more difficult to isolate. Experi-

mental data on K-shell to K-shell electron exchange for high Z_1 may be inferred from the projectile charge-state dependence of K-vacancy production cross sections,[16-23] but no more direct data is available. Attempts to isolate this channel experimentally by coincident detection of K-vacancy production and charge-changing events is masked by multiple processes for large Z_1. For low Z_1, however, the coincidence experiment is possible and has previously been reported by Macdonald *et al.*[24] for the case of protons on the argon K shell. In this paper we report similar results for targets of nitrogen, oxygen, and neon. The experiment yields directly the ratio between K-shell capture and K-vacancy production cross sections. By combining these results with known cross sections for the latter process, cross sections for capture from the K shell alone may be obtained.

II. EXPERIMENT

Conceptually the experiment is equivalent to that of Ref. 24, except that the Si(Li) x-ray detector of that experiment is replaced by a cylindrical mirror electron analyzer. A proton beam is brought into the interaction region containing the target gas of interest. Emerging protons are magnetically swept onto a charge-collecting plate while hydrogen atoms resulting from electron capture are allowed to proceed onto the face of a surface-barrier detector. Events in which the captured electron comes from the target K shell are followed by the emission, with probability $1-\omega_k$, of a K-Auger electron from the target ion. Here ω_k, the K-shell fluorescence yield, is very small (0.01 for singly ionized neon), so that K-x-ray emission is negligible. The small size of ω_k dictated the detection of Auger electrons, rather than x-rays, for the light targets used here. The coincident detection of hydrogen atom and K-Auger electron signals capture from the target K shell.

A. Apparatus

A schematic of the apparatus is shown in Fig. 1. The proton beam was provided by the KSU Tandem Van de Graaff accelerator for energies 2 MeV and above, and by a 3-MV single-ended Van de Graaff below 2 MeV. The beam was collimated by a 1-mm-diam circular aperture located 2.5 cm before entrance into the interaction cell. Auger electrons generated by the collision were dispersed by the cylindrical mirror analyzer and detected by a channeltron electron multiplier (CEM). The analyzer was used in an off-axis geometry which allows the beam to enter the instrument through a shadow zone in its azimuthal acceptance and to exit cleanly for subsequent charge separation and detection. Electrons are accepted over the angular range of 95°–174° relative to the beam direction. In order to maximize the electron-detection efficiency, the spectrometer was operated at a low resolution (typically 5%), for which the average probability of detecting an electron emitted within the interaction region was of the order 10^{-4}. The exact value of this efficiency does not enter the data analysis. A detailed description of the electron analyzer appears elsewhere.[19,23]

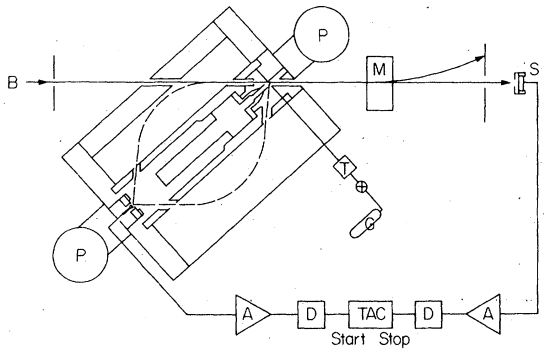

FIG. 1. Schematic of the apparatus. Letters indicate: B—beam; P—diffusion pump; T—thermocouple gauge; G—gas supply; M—magnet; S—surface barrier detector; A—amplifier; D—fast discriminator; TAC—time-to-amplitude converter.

Standard timing electronics were used to record coincidences between events registered in the surface-barrier and CEM detectors. For the latter detector, a fast amplifier followed by a fast discriminator provided the timing signal used to start a time-to-amplitude converter (TAC). In most cases, a timing single-channel analyzer, operating in the cross-over timing mode (ORTEC 420A) was used to provide a stop signal from the surface-barrier detector. For situations of low reals-to-randoms, some improvement in time resolution was effected by using an inductive pick off on this detector (ORTEC 260). With the latter system a time resolution of approximately 10 nsec full width at half maximum (FWHM) was obtained.

The surface-barrier detector had a surface area of 30 mm^2 and was located 1 m from the target region. Previous measurements of the angular distribution of protons following K-electron capture show that the solid angle subtended by this detector is easily sufficient to accept essentially all K-shell capture events. This detector was mounted on a laterally scanning track so that it could be centered positively on the neutral beam. The background pressure in the beam line was typically 2×10^{-6} torr. The region surrounding the gas cell and the analysis region of the analyzer were separately pumped by 10 and 12.5 cm diffusion pumps, respectively. For a target pressure of 30 mtorr, typical pressures at the throat

of these pumps were $\lesssim 10^{-5}$ torr.

Over the range of proton energies used, the major effect of running too-high target gas pressure is to destroy hydrogen atoms during their flight between the capture event and the magnetic-deflection region. This process results in effectively reducing the hydrogen-detection efficiency, which is taken to be unity and whose value does enter the data analysis. Using known cross sections[20] for electron loss by hydrogen in our target gases, we computed this loss probability and applied a corresponding small correction, never exceeding 4%, or our data. Experimental investigation of this problem was made by taking each coincidence measurement at target pressures of approximately 30, 20, and 10 mtorr. The dependence on target pressure was found to be less than the statistical error in the data and consistent with the dependence expected on the basis of the above analysis of the situation.

The procedure followed was to scan the electron spectrum for each target gas and to set the analyzing voltage to maximize the count rate from the K-Auger peak. Single electron rates ranged from 100 Hz(5-MeV p on O_2) to 1 Hz(0.75-MeV p on Ne). The proton current was adjusted to provide a count rate in the surface-barrier detector of typically 2–4 kHz, and a TAC spectrum was taken. Typical real coincidence rates ranged from 10 to 0.01 Hz, with a reals-to-randoms ratio never less than 2 : 1. (We remark that, at the smaller accelerator, pulsed-beam characteristics similar to those seen by Andersen *et al.*,[25] were observed with a frequency of a few hundred Hz. No structure in the randoms spectrum was observed in the 10 MHz range, however, and the reals-to-randoms ratio was kept sufficiently high to avoid serious error due to time structure in the TAC spectrum.) The analyzer voltage was then moved off the Auger peak to a nearby background region in the electron spectrum and a coincidence spectrum taken. The number of coincidences with background electrons proved negligible, but the number of single electrons was corrected by the appropriate background subtraction. The size of this correction was typically 10%.

B. Data analysis

The quantity measured, for each energy and target, was the ratio C/E where C is the number of true electron-hydrogen coincidences and E is the number of single K-Auger electrons detected during the run, corrected for background. While the acceptance of the instrument includes only some fraction of the K-Auger spectrum in each case, the analysis requires only that this fraction should be independent of whether the K electron is ejected or captured. This is quite likely to be the case for proton bombardment which incurs little outer-shell ionization. The ratio C/E was found to be insensitive to changes in analyzer slit settings and to small changes in deflection voltage near the Auger peak, giving us confidence that the above assumption is correct.

In the absence of multistep processes, C/E is equal to σ_{CK}/σ_{VK}, where σ_{CK} is the cross section for capture from the target K shell and σ_{VK} is the total K-vacancy production cross section. This result is independent of ω_k, analyzer detection efficiency, gas-target geometry, etc., since these factors enter equally into E and C. However, the ionization of the target K-shell accompanied by capture of an L electron in the same collision is in principle indistinquishable from K-shell capture. Thus, the correct expression is

$$C/E = [\sigma_{CK} + (\sigma_{VK} - \sigma_{CK})P_L]/\sigma_{VK},$$

where P_L is the average probability that, for a collision ionizing the K shell, an L electron will be captured. We have estimated P_L by dividing the cross section of L-shell capture, σ_{CL} by the geometrical area of the L shell (taken to be πr_L^2, $r_L = 4a_0/Z_2$, $a_0 = 0.53\times 10^{-8}$ cm). The L-shell cross section is given by $\sigma_{CL} = \sigma_C - \sigma_{CK}$, where σ_C is

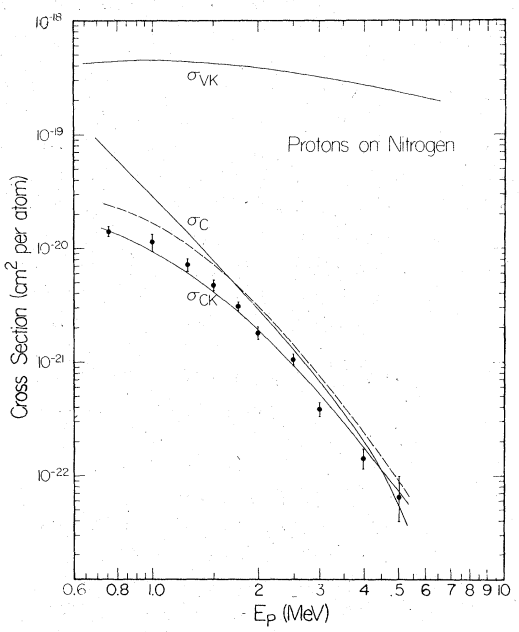

FIG. 2. Cross sections for total K-vacancy production (σ_{VK}); total electron capture (σ_C) and K-electron capture from nitrogen by protons. Values of σ_{VK} are PWBA, from Ref. 26. σ_C is taken from Ref. 2; values of σ_{CK} are the present results. Solid curve through σ_{CK}, Nikolaev OBK, normalized to give the experimental σ_C at $V = 1$. Dashed curve through σ_{CK}, binding-energy corrected OBK of Ref. 15.

TABLE I. Cross sections per target atom and cross-section ratios for protons on various gases.

E (MeV)	σ_{CK}/σ_{VK} [a] (%)	σ_{CK}/σ_C (%)	σ_{VK} [b] (10^{-20} cm^2)	σ_{CK} (10^{-22} cm^2)
		Neon		
1.0	1.94 ±0.24	2.5	8.2	15.9 ±2.0
1.25	1.91 ±0.14	7.8	9.0	17.2 ±1.2
1.48	1.63 ±0.20	13	9.3	15.2 ±1.9
1.77	1.44 ±0.20	21	9.4	13.5 ±1.8
2.0	1.11 ±0.09	26	9.6	10.7 ±0.9
2.5	0.68 ±0.06	34	9.5	6.5 ±0.6
3.0	0.53 ±0.03	45	9.3	4.5 ±0.3
4.0	0.22 ±0.02	55	8.4	1.82±0.18
5.0	0.11 ±0.01	79	7.6	0.87±0.08
		Oxygen		
0.75	2.98 ±0.20	7.0	23.5	70 ±5
1.0	2.48 ±0.30	16	25.0	62 ±7
1.25	1.81 ±0.15	26	25.5	46 ±4
1.48	1.48 ±0.10	40	25.5	38 ±3
1.77	0.99 ±0.07	47	24.6	24.4 ±1.7
2.0	0.66 ±0.06	43	24.0	15.8 ±1.6
2.5	0.35 ±0.03	44	22.5	7.8 ±0.8
3.0	0.22 ±0.02	51	20.8	4.7 ±0.5
4.0	0.095±0.007	55	18.0	1.71±0.12
5.0	0.045±0.005	85	16.1	0.72±0.07
		Nitrogen		
0.75	3.25 ±0.20	20	44.0	143 ± 9
1.0	2.53 ±0.30	39	45.0	114 ±13
1.25	1.63 ±0.20	52	43.9	72 ± 9
1.48	1.13 ±0.08	60	42.0	48 ± 4
1.77	0.76 ±0.05	69	40.3	30.3 ± 2
2.0	0.46 ±0.04	61	38.5	17.6 ± 1.5
2.5	0.300±0.03	79	35.6	10.3 ± 1.0
3.0	0.119±0.01	57	31.9	3.82± 0.32
4.0	0.052±0.007	71	27.2	1.41± 0.19
5.0	0.028±0.008	118	23.2	0.65± 0.19

[a] Present results.

[b] For Ne, smooth curve through data of Ref. 25; for oxygen and nitrogen, plane-wave Born approximation (PWBA), Ref. 26.

the known[2] total electron-capture cross section. Thus, since $\sigma_{VK} \gg \sigma_{CK}$

$$\frac{\sigma_{CK}}{\sigma_{VK}} = \frac{C/E - \sigma_C/\pi r_L^2}{1 - \sigma_{VK}/\pi r_L^2} . \quad (1)$$

The inclusion of the additional terms resulting from the two-step process changes our extracted values for σ_{CK}/σ_{VK} by only 15% for the worst case of 1-MeV p on Ne and by less than 0.5% above 2 MeV. However, the importance of this process would increase rapidly at lower bombarding energy, where σ_{CL} becomes very large. Since an accurate correction for its contribution is not really possible, at lower energies a reliable extraction of σ_{CK}/σ_{VK} will become impossible. This is essentially the reason why similar data for high Z_1/Z_2 would be difficult to interpret.

Values of σ_{VK} have been measured for p on Ne by Woods *et al.*,[23] and were used to extract σ_{CK} from Eq. (1). Similar data are not available for O_2 and N_2 targets. We have thus been forced to employ theoretical plane-wave Born approximation (PWBA) cross sections for σ_{VK} for these targets.[26] This calculation should be rather good for this range of energy and Z_1/Z_2 ratio, however. A similar calculation for p on Ne is in excellent agreement with the data (See Fig. 4). In any event, should better values for σ_{VK} become available at a later date, the values of σ_{CK}/σ_{VK} given in Table I, which are nearly independent of the value of σ_{VK} used in the right hand side of Eq. (1), may readily be used to calculate better values of σ_{CK}. Our results given in Table I, and Figs. 2–4 show values of σ_{CK} deduced from the data. The curve labeled

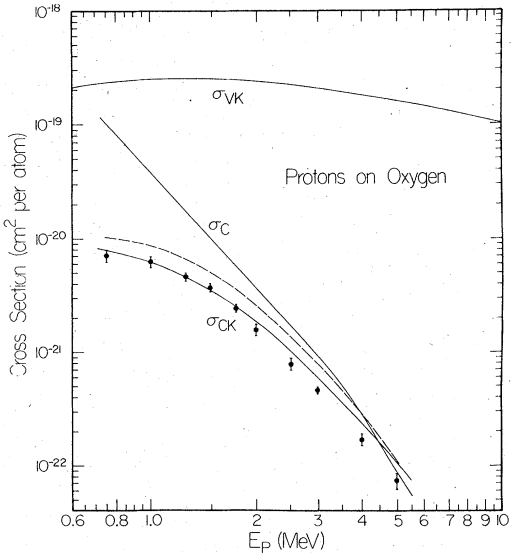

FIG. 3. Same as in Fig. 2, but for an oxygen target.

σ_C in these figures is a smooth curve drawn through the data reviewed in Ref. 2.

III. DISCUSSION

A. Target nuclear charge scaling

In the OBK formulation the cross section per target electron for electron exchange between K shells of hydrogenic systems may be written as[27]

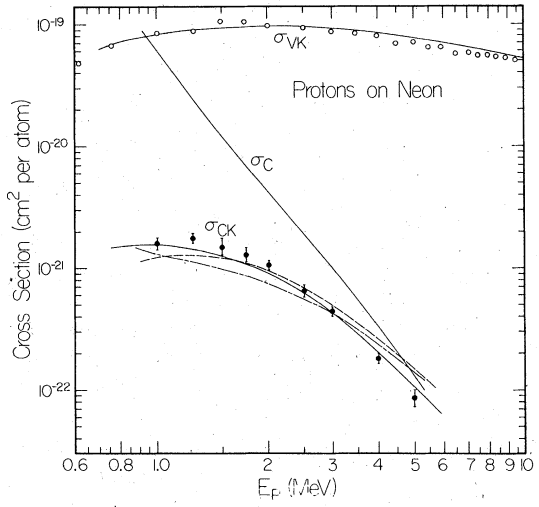

FIG. 4. Same as in Fig. 2, but for a neon target. Data points for σ_{VK} are from Ref. 23. The dash-dot and dashed curves through σ_{CK} are the Born C (BC) and atomic-expansion calculations of McGuire (Ref. 31) and Lin (Ref. 33), respectively. For clarity, the binding-energy corrected OBK has been omitted.

$$\sigma_{OBK} = \frac{2^8}{5}\left(\frac{Z_1}{Z_2}\right)^5 \pi \left(\frac{a_0}{Z_2}\right)^2 \frac{F(s)}{V^2}, \tag{2}$$

where

$$F(s) = (1 + s^2/4)^{-5},$$

$$s = V\{1 - [1 - (Z_1/Z_2)^2]/V^2\},$$

$$V = v/Z_2 v_0.$$

Here v/v_0 is the projectile velocity in atomic units, thus V is the velocity of the projectile scaled to that of the electron to be captured. For $Z_1 \ll Z_2$ the dependence of s on Z_1 and Z_2 is slight and $F(s)/V^2$ becomes a universal function of scaled velocity. For the cases of concern here, capture to the $1s$ state of hydrogen is expected, on the basis of the OBK calculation, to comprise roughly 86% of the target K-shell-capture cross section and we thus concentrate our attention on this process. For capture from a screened K shell with binding energy U_K, we take some account of screening by substituting into Eq. (2) an effective target charge given by by $(Z_2^2)_{\text{eff}} = U_K/13.6$ eV, giving a cross section per atom of

$$\sigma_{OBK} = \frac{2^9}{5} Z_1^5 \pi a_0^2 \left(\frac{U_K}{13.6\ \text{eV}}\right)^{-7/2} \frac{F(s)}{V^2} \tag{3}$$

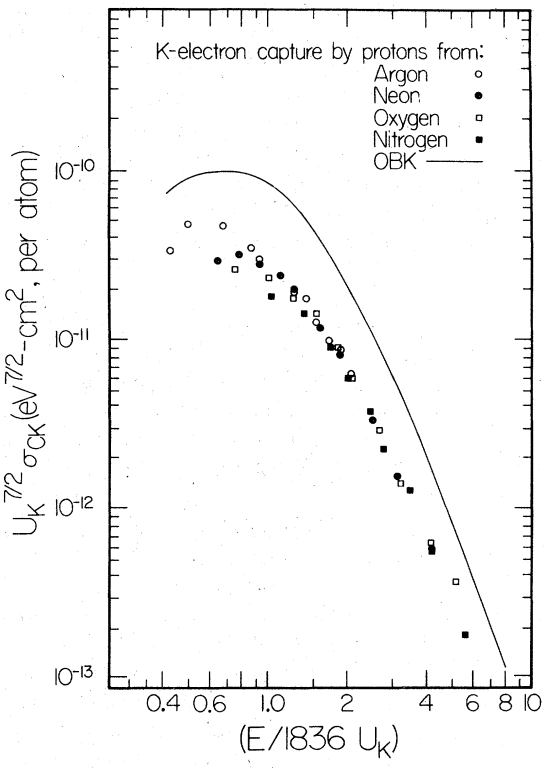

FIG. 5. Plot of $U_K^{7/2}\sigma_{CK}$ vs $E/1836\,U_K$. The argon data are from Ref. 24. The solid line is from Eq. (2), multiplied by 2.

and $V=(E/1836U_K)^{1/2}$, where E is the proton energy. Since for $Z_2 \gg Z_1$, $s=V-1/V$, the right-hand side of Eq. (3) is given entirely in terms of the target K-shell binding energy.

In Fig. 5 we show a plot of $U_K^{7/2}\sigma_{CK}$ versus $E/1836U_K$. We include the p+Ar data of Ref. 22 in this and further discussions. We plot, throughout, cross sections per target atom, implicitly assuming that a diatomic target may be treated as two separate atoms. This is a poor assumption for L-shell processes, but probably a good one for the K-shell processes of interest here. If the OBK scaling of Eq. (3) is correct, the data should fall on a universal curve, and this is seen to be the case for scaled velocities above 1, breaking down somewhat for lower velocities. It is perhaps remarkable that such a simple scaling procedure works as well as it does, since $U_K^{7/2}$ varies by a factor of more than 10^3 in going from nitrogen to argon. The solid curve in Fig. 5 is the OBK universal curve of Eq. (3) for $Z_2 \gg Z_1$ and is seen to ride a consistent factor of about 3 above the data. This again illustrates the well-known fact that OBK consistently over estimates capture cross sections.

An alternative screening correction could be made by substituting $Z_{2\text{eff}}=Z_2-0.3$ into Eq. (2). A plot of $(Z_{2\text{eff}})^7\sigma_{CK}$ versus $V=v/Z_{2\text{eff}}v_0$ should yield the corresponding universal curve. Such a plot is shown in Fig. 6, where again the data tend to form a common curve. The corresponding OBK curve does not peak at the same position as the data, however, and the use of a velocity-independent correction factor to predict experimental cross sections is not possible. Indeed, the OBK cross sections even fall below the experiment at low velocity. Figs. 5 and 6 illustrate the sensitivity of any comparison between experiment and OBK to the choice of screening parameters. Empirically the bonding-energy plot promises to be the more useful one, although there does not appear to be any *a priori* reason for its choice. Certainly the separation of screening factors in the wave functions from those characterizing momentum-energy conservation is to be preferred.

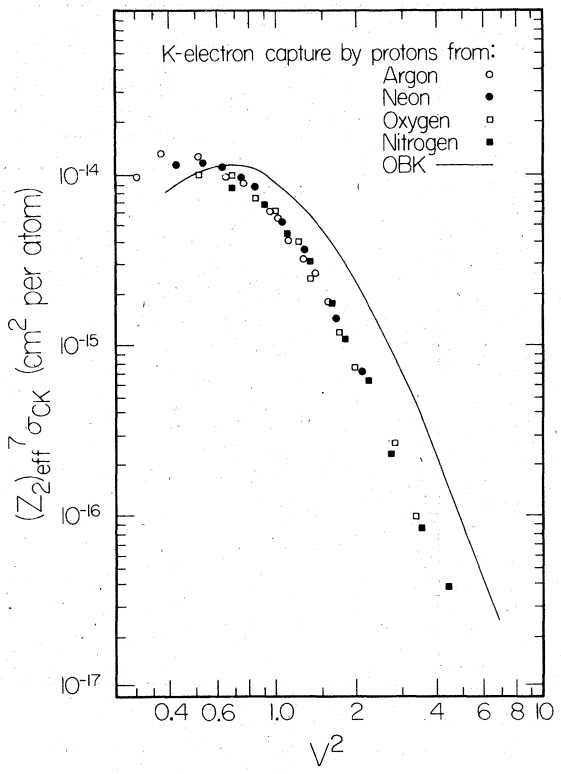

FIG. 6. Plot of $Z_{2\text{eff}}^7\ \sigma_{CK}$ vs $V^2=(v/Z_{2\text{eff}}v_0)^2$ for $Z_{2\text{eff}}=Z_2-0.3$. The argon data are from Ref. 24. The solid line is from Eq. (2), multiplied by 2.

B. Comparison to Nikolaev OBK and target shell scaling

Nikolaev's version of the OBK formulation[5] allows the separation of internal and external screening factors, a degree of sophistication higher than that of Eq. (3). In obtaining cross sections consistent with experiment, he introduces empirical scaling factors which depend only weakly on target shell and projectile energy for the cases of interest here. Such a procedure, which amounts roughly to normalizing the OBK calculation to low-energy capture from outer shells, is known to give remarkably good agreement with total cross sections at higher energies and, for the p+Ar case, to give σ_{CK} to within a factor of 2 well above the region of normalization.

We have normalized Nikolaev's OBK cross sections to reproduce the experimental total capture cross sections dominated by L capture, near $V=1$. The corresponding factors are 3.9, 3.2, and 3.2 for nitrogen, oxygen, and neon, respectively. The Nikolaev cross sections for capture from the target K shell into all projectile shells, divided by the appropriate factor, are shown as solid lines in Figs. 2–4. The agreement with experiment at low energy is remarkably good and indicate that the relative contributions from different target shells are rather well given by an OBK calculation if shell-dependent screening is properly handled. The energy dependence of σ_{CK} is also rather closely reproduced by the calculation, tending to lie only slightly above experiment at higher energies.

C. Binding-energy corrected OBK

Lapicki and Losonsky[15] have recently introduced the concept of a binding-energy correction, well

known in the case of ionization, into the OBK calculation. They replace the atomic binding energy of the target shell by one which includes binding to the projectile. Such a procedure makes physical sense in the low-energy limit, and is forced to join, at high energy, the asymptotic result of Drisko.[28] The latter result is taken to be $\frac{1}{3}$ the OBK cross section, and the former will certainly lie below OBK for low Z_1 because the calculation prescribes a more tightly bound target K shell. Thus, their results, shown as dashed lines in Figs. 2 and 3 achieve the desired reduction of the OBK cross section and do give improved agreement with experiment without scaling factors. Good agreement between this calculation and the p+Ar results were reported earlier.[15] It is not clear what errors may be incurred by the use of the OBK amplitude alone and by the neglect of any corresponding binding effect in the exit channel. Thus, while the calculation promises to be useful, its range of validity is difficult to establish.

D. Improved calculations

The major shortcoming of any OBK-type formulation is likely to be its neglect of the average potential term given by Bates which results from the nonorthogonality of initial and final electronic states. For protons on hydrogen, the use of the core-core term in a full Born calculation appears to roughly correct for this neglect of the average-potential term, and reduces the theoretical cross sections into agreement with experiment.

For higher Z_2, the use of the full core term leads to unphysically large cross sections.[12,13,29] However, Omidvar *et al.*,[13] have used a reduced core-core term in their Born C (BC) calculation and find fair agreement with experiment. While the physical justification for their procedure is ultimately somewhat different from that given in their paper, it is likely that the BC calculation is a reasonable approximation to the evaluation in first-order perturbation theory of the full interaction given by Bates and thus may represent a distinct improvement over the OBK in the calculation of the total cross sections. In Fig. 4 we show the results of such a calculation for $1s$-$1s$ electron capture by p from Ne,[31] where rather good agreement with the data on an absolute scale is found. Similar success was reported earlier for the p+Ar system. One major shortcoming of the BC calculation appears to be its tendency to over-estimate the cross section at low energy.

Using the atomic-expansion method discussed by McCarroll,[30] Lin *et al.*[32,33] have recently carried out coupled-channel calculations of $1s$-$1s$ electron transfer for protons on argon, helium and neon. The impact-parameter formulation given by Bates was used, and the equation of motion solved numerically in a basis set limited to $1s$ atomic states on the two charge centers. The results for neon are shown in Fig. 4. Both the absolute values of σ_{CK} and the energy dependence seen in the experiment are rather well reproduced by the calculation. Similar success for p on argon using the same method of calculation is reported elsewhere.[32]

It is probably the case that, because of their ready availability and simplicity, OBK calculations will continue to be used to estimate inner-shell electron-capture cross sections. The results presented here appear to confirm that the scaling of OBK from one energy to another, from one target to another, or from one target shell to another is remarkably reliable, but that the absolute OBK cross sections are too high. Thus the widespread use of normalization factors applied to OBK is not unreasonable. However, it is clear that theoretical calculations exist which represent distinct improvements on the OBK, and it is to be hoped that their use may gradually supplant that of the more skeletal theory.

The results presented here do not directly bear on the question of inner-shell electron exchange for $Z_1 \sim Z_2$, for which capture becomes competitive with ionization. For the cases studied here the capture contribution to K-vacancy production never exceeds 3.3% (protons on nitrogen). Nevertheless, the success of the OBK scaling from one Z_1/Z_2 pair to another, strengthens the general arguments made for the more symmetric case by Halpern and Law and by McGuire. While one should be reluctant to extrapolate the perturbation theory results to clearly nonperturbative conditions, the general trends of the simple calculation may certainly be used as guides in charting the more difficult ground of higher Z_1/Z_2. Indeed, preliminary atomic-expansion calculations by Lin[33] for $F(+9)$ and $C(+6)$ on the argon K shell suggest that this approach may prove useful in the symmetric, as well as asymmetric, Z region.

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