Differential cross sections for state-selective electron capture by low-energy Ar^{q+} ions from He and Ar

S. Yaltkaya, E. Y. Kamber, and S. M. Ferguson
Department of Physics, Western Michigan University, Kalamazoo, Michigan 49008-5151
(Received 4 May 1992; revised manuscript received 28 January 1993)

Doubly differential cross sections, in angle and energy, for state-selective single-electron capture from He and Ar by Ar^{q+} ions have been studied experimentally at laboratory impact energies between $25q$ and $100q$ eV ($q=4$ and 5, where q is the ion charge state) and scattering angles between 0° and 5°, by means of translational energy-gain spectroscopy. The translational energy-gain spectra show that only a few final states were selectively populated depending on the charge state of the projectile, ionization potential of the target, and weakly on the impact energy. A resonable description of the populated final states is described qualitatively in terms of the reaction windows, which are calculated using a multichannel Landau-Zener model. The general features of the differential cross sections are discussed in terms of a semiclassical curve-crossing model.

PACS number(s): 34.70.+e, 34.50.Fa

I. INTRODUCTION

Over the past few years considerable effort has been directed towards experimental and theoretical studies of electron-capture processes in slow collisions of multiply charged ions and atomic and molecular targets. The field has developed rapidly since sources for intense beams of multiply charged ions such as recoil ion sources, electron-beam ion sources (EBIS), and electron-cyclotron-resonance (ECR) ion sources became available [1]. The interest in electron-capture processes stems not only from fundamental aspects but also from their importance in the study of the role of impurity ions in controlled thermonuclear fusion and astrophysical plasmas.

The study of the collision of multiply charged argon ions with different atomic and molecular gases has been the subject of extensive investigation experimentally, by using translational energy spectroscopy, photon emission spectroscopy, and electron spectroscopy techniques. Most of the previous experiments on these collision systems have been concerned with total cross-section measurements, translational energy-gain measurements at forward scattering angles, angular distributions without energy analysis, and very recently state-selective differential cross sections. Nielsen *et al.* [2] measured state-selective absolute single-electron capture cross sections for 1-keV Ar^{q+} ($q=6-10$) ions on Ne, Ar, and Xe by means of energy-gain spectroscopy. Giese *et al.* [3] have used translational energy-gain spectroscopy to determine the final-state populations following single-electron capture by Ar^{q+} ($q=4-8$) ions from D, D_2, and Ar at an energy of $545q$ eV. Puerta *et al.* [4] studied single-electron capture by $200q$ eV Ar^{q+} ions ($q=3$ and 4) from rare-gas targets. Afrosimov *et al.* [5] measured the kinetic-energy distribution, by using coincidence techniques, of both particles after collisions of Ar^{q+} ions ($q=3-7$) with He. McCullough, Wilson, and Gilbody [6] have used translational energy spectroscopy to study the distributions of excited product ion channels in single-electron capture by Ar^{q+} ($q=4-6$) ions in H, H_2, and He at q keV and $2q$ keV. Kamber [7] has measured single- and double-electron capture into selected states by means of translational spectroscopy for collisions of 12-keV Ar^{4+} and 15-keV Ar^{5+} with rare-gas atoms. Andersson *et al.* [8] have examined the influence of angular scattering effects on energy-gain spectra for single-electron capture in Ar^{6+}-He collisions at impact energies between 200 and 2000 eV. Very recently Biedermann *et al.* [9] have measured state-resolved angular distributions of single- and double-electron capture in 19–200-eV Ar^{4+}-Ar collisions.

II. EXPERIMENTAL APPARATUS

The present measurements have been obtained on a doubly differential energy-gain spectrometer (see Fig. 1), described previously by Kamber *et al.* [10]. Low-energy multiply charged ions were produced in a recoil ion source by using 25-MeV F^{4+} ions from the Western Michigan University (WMU) tandem Van de Graaff accelerator as a pump beam. Over the last few months we have been able to increase the intensities of the recoil ion beams by up to a factor of 3 from the recoil ion source, mainly through a complete redesign of the source. The recoil source consists of a collision chamber, pusher, and two lenses. The pump beam passes through the collision chamber which has entrance and exit apertures of 2.5 and 3 mm diameter, respectively. The pump beam was post-stripped to median charge state (7+) immediately before the ion source. Ions formed in the ion source were drawn out of the collision chamber perpendicular to the pump beam through a 2.5-mm-diam aperture in the lens L1 under the action of an electric field from the lens L2 which penetrates into the collision chamber through the aperture in L1. The pusher P was kept at the same potential as the collision chamber, while the voltages of P and L1 were set so as to optimize the resolution and transmission of the detected ions. Typical voltages of P and L1 were

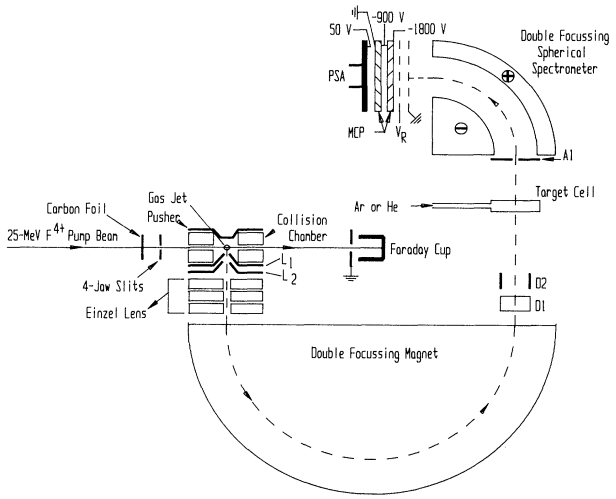

FIG. 1. Schematic of the experimental apparatus. D1 and D2 are electrostatic deflectors, A1 is the angular selection aperture, V_R is the retarding grid, MCP labels the multichannel plates, and PSA is the position-sensitive anode. L1 and L2 are lenses.

50 and 49 V, yielding accelerated energies close to q eV_1, where e is the electron charge, q the charge state, and V_1 the voltage of the pusher P. An Einzel lens was used to focus the ion beam extracted from the source into a 180° double focusing magnet. After mass selection the ion beam was again focused by two pairs of deflectors D1 and D2 and directed into a gas cell 3 mm long. The entrance and exit apertures of the cell were 1 and 2 mm, respectively. The scattered ions that had undergone charge-changing collisions were energy analyzed by means of a 90° double-focusing electrostatic analyzer (ESA), and then detected by a one-dimensional position-sensitive channel-plate detector, which is located at the focal plane of the ESA. The detector device is made of two 3.25-cm-diam microchannel plates (MCP) followed by a position-sensitive anode (PSA). The scattering angle is selected by means of an aperture A1 (1 mm diameter) in front of the ESA. The energy resolution of the 250-eV Ar^{5+}-ion beam was 1.4 eV full width at half maximum (FWHM), and the angular resolution was 1° (FWHM). A typical charge state spectrum of argon from the WMU recoil ion source pumped by a 25-MeV F^{4+} beam is shown in Fig.

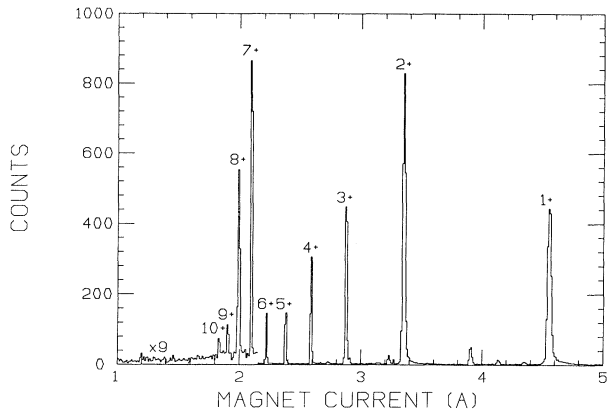

FIG. 2. Charge state spectrum of argon recoil ions from the recoil ion source pumped by a 25-MeV F^{4+} ions from the WMU Van de Graaff accelerator. The numbers indicate the argon charge state. The relative height of the peak Ar^+ is changed because of saturation of the detector.

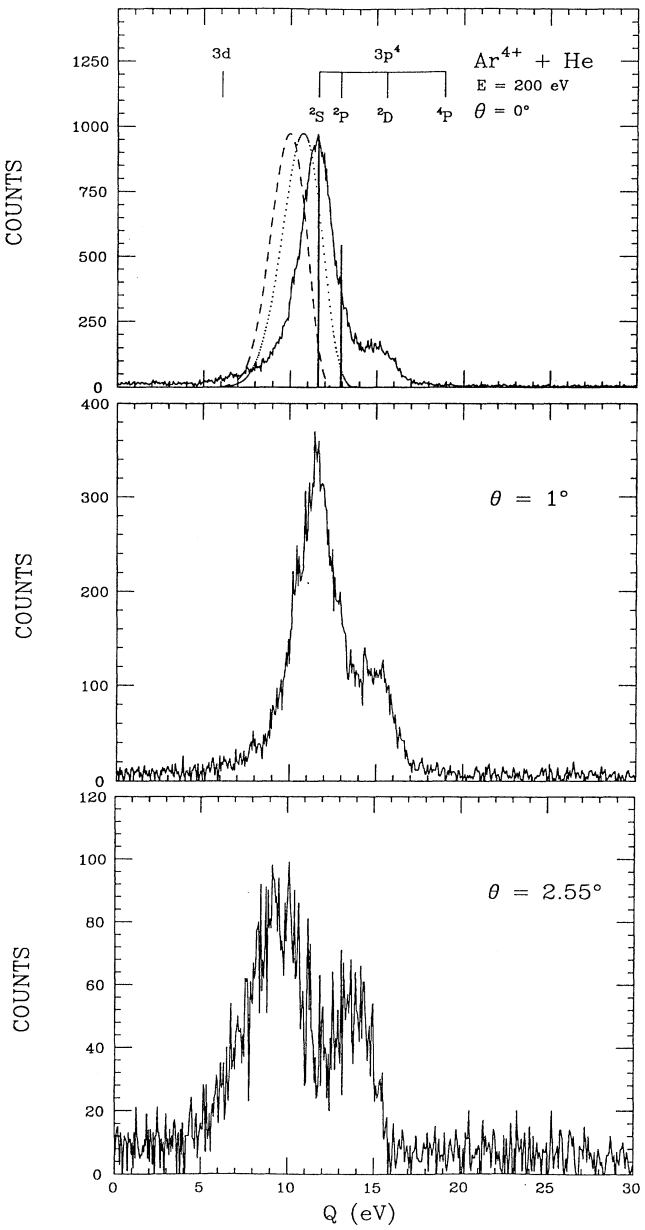

FIG. 3. Translational energy-gain spectra for single-electron capture by 200-eV Ar^{4+} ions from He at different scattering angles. Also shown are reaction windows calculated on the basis of a single-crossing Landau-Zener theory using values of H_{12} containing factors 9.13 (broken curve) and 5.48 (dotted curve). Vertical lines show results of our MCLZ calculations (see text).

2. Argon ions with charge states from 1 to 10 are obtained with intensities sufficient for translational energy-gain measurements.

III. RESULTS AND DISCUSSION

In low-velocity collisions, single-electron capture into excited states of projectile ions is one of the most prominent features of the collision process between multiply charged ions and atomic or molecular targets. Perhaps the main topic of interest in such processes is the distribution of captured electrons over the final-state quantum numbers (n,l,m). Both the absolute values of the partial cross sections as functions of the impact energy and the shapes of the n and l distributions of captured electrons at a fixed energy present a sensitive test of the theoretical calculations for the process.

Many of the observed features in collision processes between multiply charged ions and atomic targets can be explained with the assumption that quasimolecules are formed during the collision. The dominant mechanisms in the single-electron capture processes are then the diabatic transitions at pseudocrossings of the ingoing potential energy curve with the multitude of outgoing potential energy curves.

In the present work we have measured translational energy spectra of product ions resulting from electron-capture processes in collisions between low-energy Ar^{q+} ions and He and Ar at selected projectile scattering angles. These processes may be summarized by the equation

$$A^{q+}+B \rightarrow A^{m+}+B^{n+}+(m+n-q)e+\Delta E \ , \quad (1)$$

where q and m,n are the initial and final charge states of the projectile and target, respectively, and ΔE represents the energy defect of the reaction channel involved. Moreover, the collision products may be formed in excited states.

From kinematic calculations, based on classical two-body dynamics, the translational energy of an ion undergoing inelastic scattering differs from the energy of the projectile ion E_0 by

$$Q=E_{\text{inelastic}}-E_0=\Delta E-\Delta K \ , \quad (2)$$

where ΔK is the translational energy given to the target, and ΔE is the energy defect of the reaction.

The translational energy ΔK given to the target is given by [11]

$$\Delta K=\frac{m_p}{m_p+M}(1-\cos\theta)\left[\frac{2ME_0}{m_p+M}-\Delta E\right] + \frac{m_p(\Delta E)^2}{4ME_0}\cos\theta \ , \quad (3)$$

where m_p and M are, respectively, the projectile and target masses, E_0 is the laboratory translational energy of the projectile, and θ is the scattering angle. For zero scattering angle, this energy reduces to

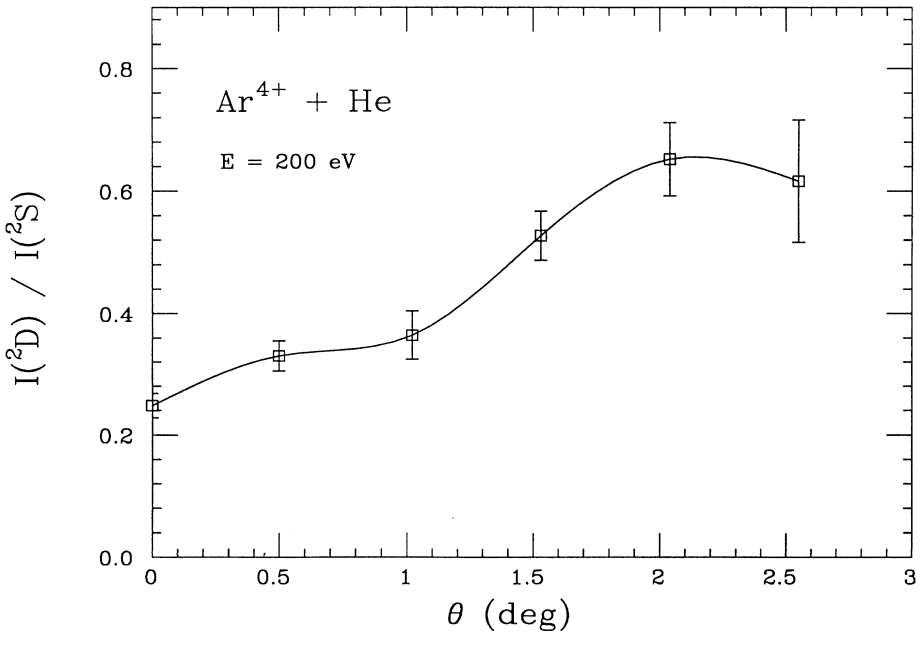

FIG. 4. The ratio $I(^2D)/I(^2S)$ as a function of the scattering angle.

$$\Delta K = \frac{m_p(\Delta E)^2}{4ME_0} \quad . \tag{4}$$

However, at low impact energies and for heavy projectile ions in collision with light targets, values of ΔK, calculated on the basis of zero and nonzero scattering angles, are found to be large and have been observed as a shift for a particular reaction channel in the translational energy spectrum [12]. This indicates that it is necessary to take account of ΔK in the analysis of translational energy gain measurements for low-energy collisions by using Eq. (2) rather than assuming that $Q = \Delta E$.

Theoretically different models have been developed in recent years for a qualitative explanation of the main features of the state-selective electron-capture process by low-energy multiply charged ions. In this work, we have calculated the reaction windows based on the Landau-Zener theory [13] and used them to interpret the final-state populations by calculating the location of the crossing radii, in terms of the energy-gain values of the final states, where the probability of single-electron capture is large. For these calculated reaction windows, the analytical formula for evaluating the reduced coupling matrix element H_{12} developed by Olson and Salop [14] is used together with the reduction of H_{12} by 40% proposed by Kimura *et al.* [15]. We have also compared the predictions of a multichannel Landau-Zener model (MCLZ) [16], which includes Taulbjerg's f_{nl} factor [17] with our experimental results. In the following sections, the experimental and theoretical results and discussion of the individual collision systems are presented.

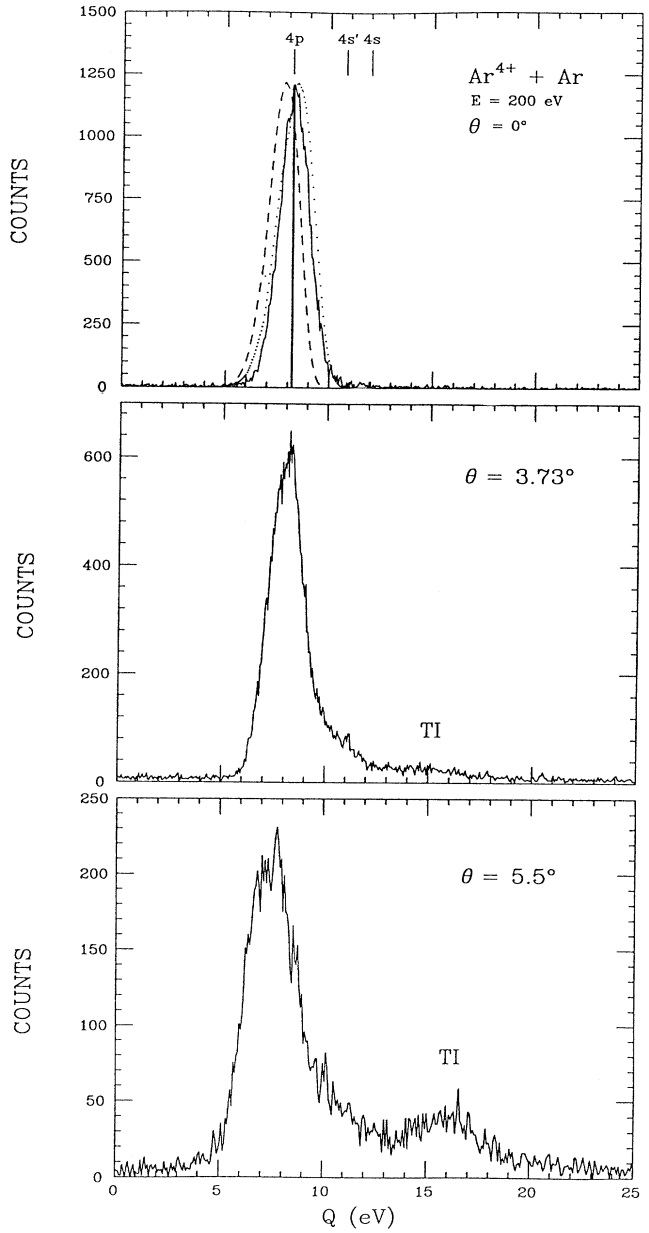

FIG. 5. Translational energy-gain spectra for single-electron capture by 200-eV Ar^{4+} ions from Ar at different scattering angles. Also shown are reaction windows calculated on the basis of a single-crossing Landau-Zener theory using values of H_{12} containing factors 9.13 (broken curve) and 5.48 (dotted curve). Vertical lines show results of our MCLZ calculations (see text).

A. Ar^{4+}-He collisions

Figure 3 shows the translational energy-gain spectra obtained for single-electron capture by 200-eV Ar^{4+} ions from He at different scattering angles. At 0° scattering angle, two peaks are clearly resolved and seen. The dominant peak correlates with capture from ground-state incident ions Ar^{4+} $(3p^2\,{}^3P)$ into the excited state $(3p^4\,{}^2S)$ of the Ar^{3+} ion, in agreement with previous measurements at higher energies and forward scattering angles [4–7]. This process is exothermic by 12.5 eV, with an avoided crossing at $R_x = 6.53$ a.u. [where R_x(a.u.) $= (q-1)27.2/\Delta E$(eV), neglecting polarization]. Significant contribution from capture into the $3p^4\,{}^2P$ state cannot be identified easily in the measured spectra. The

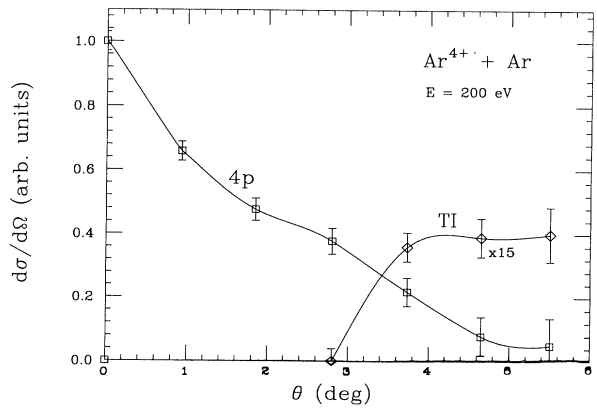

FIG. 6. Differential cross sections for single-electron capture into $4p$ state of Ar^{3+} and transfer ionization (TI) for 200-eV Ar^{4+} on Ar.

small peak arises from capture into the $3p^4\,^2D$ state of Ar^{3+} by the Ar^{4+} $(3p^2\,^3P)$ ground-state incident beam. It is expected that the incident Ar^{4+}-ion beam will contain ground-state $3p^2\,^3P$ ions as well as ions in the two metastable states ^1D and ^1S which lie, respectively, at about 2 and 4.7 eV above the ground state. These two states contribute in varying amounts to the small peak. The long tail on the lower-energy side of the dominant peak ($Q \leq 10$ eV) is due to capture by ground-state and low-lying metastable incident ions into the $3d$ state of Ar^{3+}. In their measurements at 800 eV and zero scattering angle Puerta *et al.* [4] observe, in addition to the main reaction channels due to capture into ^2S and ^2D states of Ar^{3+}, substantial peaks which they correlate with the presence of metastable states ^1D and ^1S in the incident Ar^{4+}-ion beam.

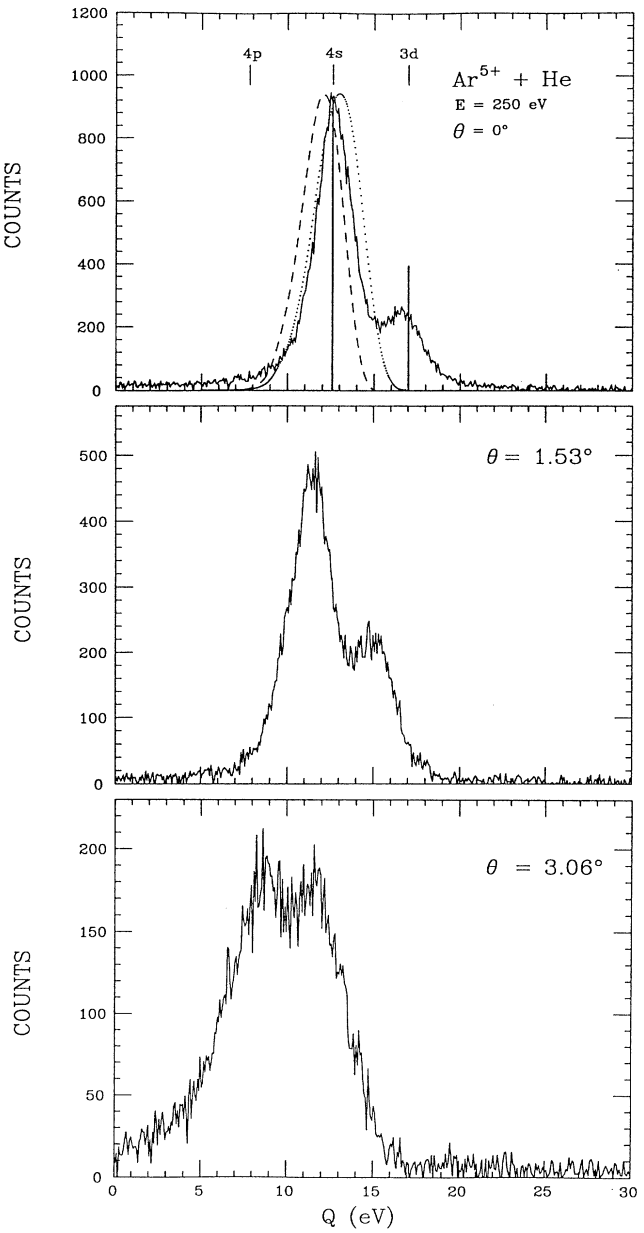

FIG. 7. Tanslational energy-gain spectra for single-electron capture by 250-eV Ar^{5+} ions from He at different scattering angles. Also shown are reaction windows calculated on the basis of a single-crossing Landau-Zener theory using values of H_{12} containing factors 9.13 (broken curve) and 5.48 (dotted curve). Vertical lines show results of our MCLZ calculations (see text).

As the scattering angle is increased, single-electron capture into the $3p^4\,^2S$ state of Ar^{3+} remains dominant, but the relative importance of capture into the $3p^4\,^2D$ of Ar^3 is strongly increased. This indicates that the angular distribution for capture into the $3p^4\,^2S$ state of Ar^{3+} is more strongly peaked in the forward direction in the Ar^{4+}-He collisions than ^2D state. In greater detail, Fig. 4 shows the intensity ratio $I(^2D)/I(^2S)$, for the reaction channels due to capture into ^2S and ^2D states taken from the observed spectra, as a function of the scattering angle. Since the ratio increases with increasing the scattering angle, we conclude that at the smallest angles only the largest impact parameter collisions play an important role. The avoided crossings at small internuclear separation cannot be reached and make small contribution. As the angle is increased, contributions from successively smaller internuclear separation regions make their appearance as would be expected. In addition, another feature of the scattering angle dependence of electron-capture spectra is that the translational energy given to the target is increasing as the angle increases [see Eq. (3)]. This feature is observed as a shift in the energy-gain of the dominant peak, which is in accordance with energy- and momentum-conservation rules.

In Fig. 3 are also shown our calculated reaction windows based on both the expression of Olson and Salop [14] and that of Kimura *et al.* [15] for H_{12} with factors of 9.13 and 5.48, respectively. Peak values have been normalized to our observed peak values in the energy-gain spectrum. It can be seen that the reaction window based on the factor 5.48 accommodates most of the observed features, while the reaction window based on the factor 9.13 favors smaller energy-gain values than observed.

We have also used the MCLZ model to calculate cross

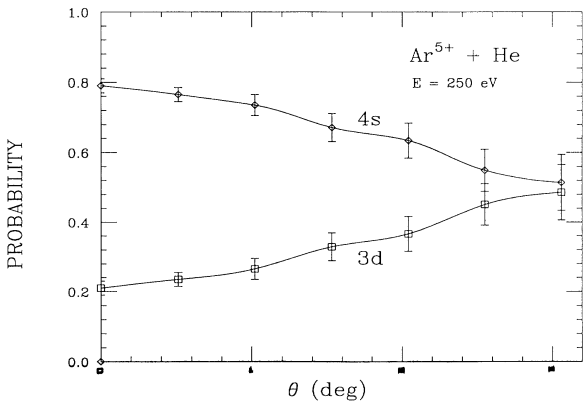

FIG. 8. Probability of single-electron capture as a function of scattering angle for 250-eV Ar^{5+}-He collisions, relative values only. ◇, $4s$; □, $3d$.

sections for single-electron capture into individual channels using the probability accumulation procedure which has been discussed in detail by several authors [3,6,7]. The results of these calculations using the Taulbjerg expression for H_{12} are shown as vertical lines in Fig. 3, the value of the largest cross section being normalized to the height of the dominant peak observed in the energy-gain spectrum. All reaction channels corresponding to ground-state Ar^{4+} ions are used in the calculations. The MCLZ calculations correctly predict the position of the dominant reaction channel and overestimate the contribution of the ^2P channel, but underestimate the importance of the ^2D and ^4P reaction channels relative to the dominant reaction channel.

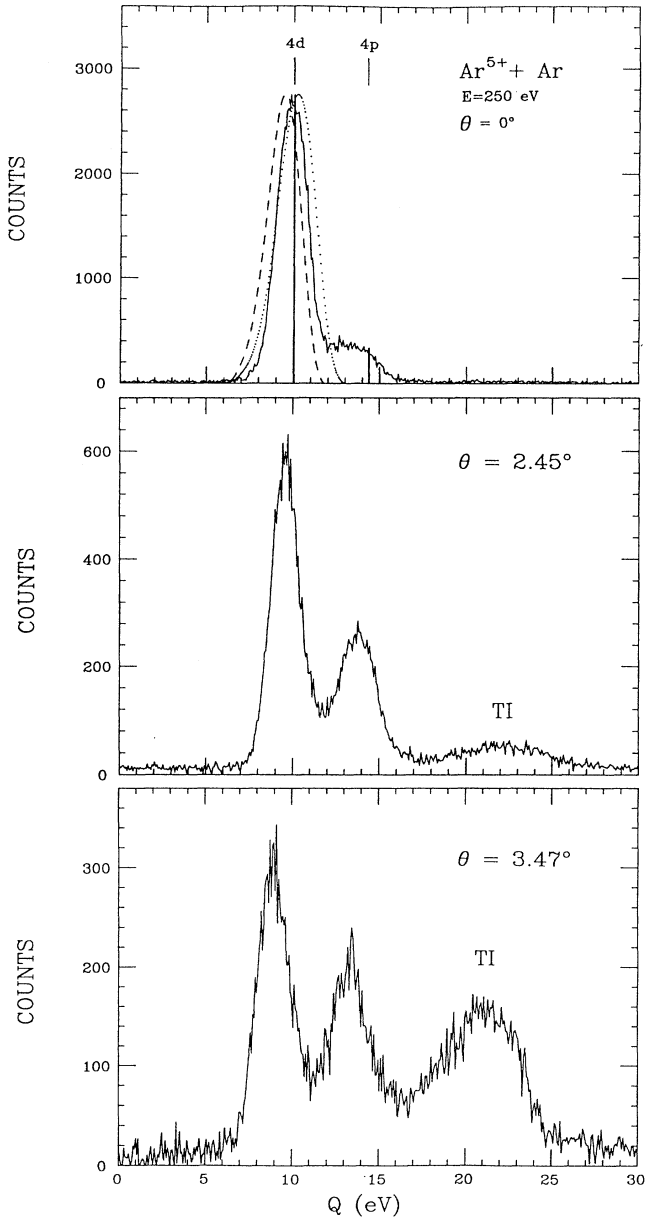

FIG. 9. Translational energy-gain spectra for single-electron capture by 250-eV Ar^{5+} ions from Ar at different scattering angles. Also shown are reaction windows calculated on the basis of a single-crossing Landau-Zener theory using values of H_{12} containing factors 9.13 (broken curve) and 5.48 (dotted curve). Vertical lines show results of our MCLZ calculations (see text).

B. Ar^{4+}-Ar collisions

Typical translational energy-gain spectra showing peaks due to single-electron capture into the excited states of the projectile product are shown in Fig. 5 for 200-eV Ar^{4+}-Ar collisions for several scattering angles. The zero-angle spectrum shows only one peak; this peak arises from single-electron capture into the $4p$ state of Ar^{3+} from ground-state Ar^{4+} ($3p^2\,^3P$). Other reaction channels having higher exoergicity due to capture into $4s'$ and $4s$ excited states open at scattering angles larger than 3°. The broad peaks, centered around 16 eV, are due to transfer ionization processes, presumably due to double-electron capture into autoionizing states which emit electrons before detection and thus appear to have captured only a single electron. Earlier measurements by Puerta *et al.* [4] for this collision system at 800 eV impact energy show that the reaction channel due to capture into the $4p$ state is predominant. Their measurements also show two small peaks at 10 and 12.4 eV, which they correlate with capture into the $4s\ ^2P$ state and the presence of metastable states in the Ar^{4+}-ion beam.

For this collision system, the reaction window based on the factor 5.48 provides the best description of the observed spectrum. Again, the MCLZ theory correctly predicts the position of the dominant reaction channel.

Figure 6 displays the measured differential cross section ($d\sigma/d\Omega$) for single-electron capture by Ar^{4+} ions from Ar into the $4p$ state of Ar^{3+} at a collision energy of 200 eV. The data show that the distribution for capture into the $4p$ state is strongly peaked in the forward direction and is a relatively smooth function. In transfer ionization processes, however, projectile ions are scattered into larger angles compared with single-electron capture, because of strong Coulomb repulsion between collision

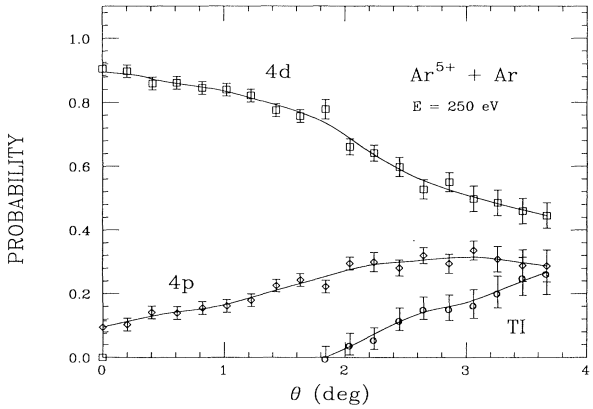

FIG. 10. Probability of single-electron capture as a function of scattering angle for 250-eV Ar^{5+}-Ar collisions, relative values only. □, $4d$; ◇, $4p$; ○, transfer ionization (TI).

partners after the collision. Roncin, Barat, and Laurent [18] measured the differential cross sections for single- and double-electron capture by highly charged ions by using a coincident energy-gain spectroscopy technique. They found that for electrons captured simultaneously the scattering occurs in the forward direction, whereas for electrons captured successively the scattering occurs at finite angles. Comparison with the recent measurements of Biedermann *et al.* [9] at 200 eV incident beam energy shows good agreement with our measurements.

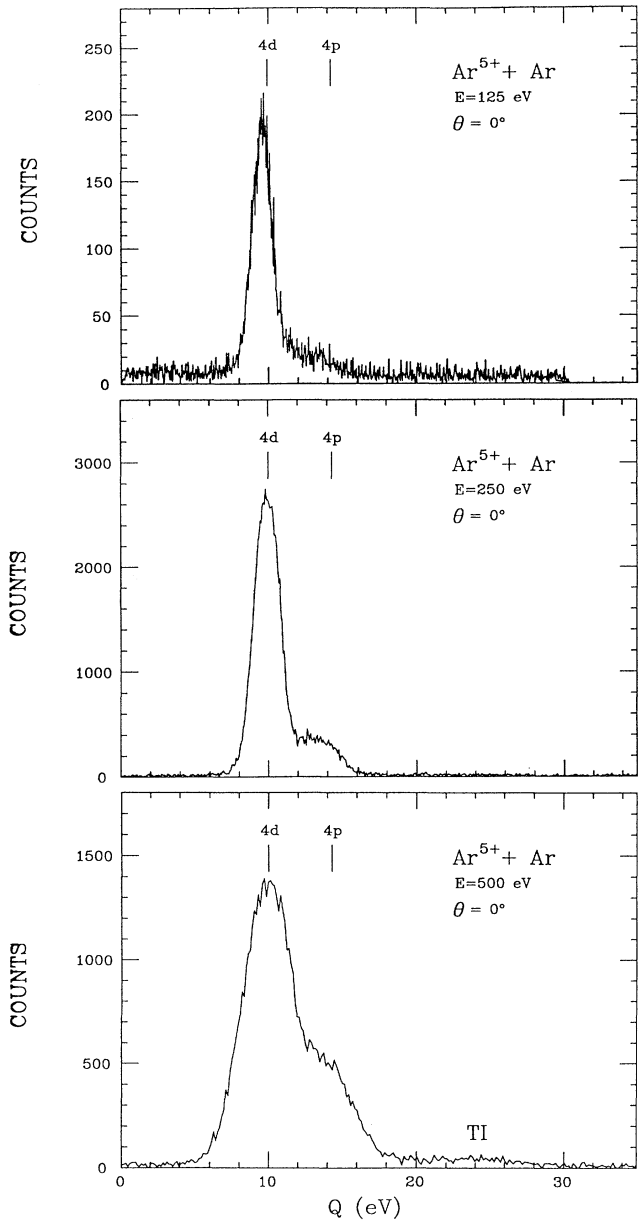

FIG. 11. Translational energy-gain spectra for single-electron capture by Ar^{5+} ions from Ar at various collision energies.

C. Ar^{5+}-He collisions

Figure 7 shows the translational energy spectra for single-electron capture by 250-eV Ar^{5+} ions from He at scattering angles of 0°, 1.53°, and 3.06°. At 0° scattering angle, the dominant peak is due to capture into the $3s^2\,3p(^2P)\;4s$ state of Ar^{4+}. There is also a significant contribution from the reaction involving capture into the $3d$ state. Again, a relative shift of about 4 eV in the energy gain of the $4s$ capture channel is observed going from scattering angle of 0° to 3.06°, which is attributed to the translational energy given to the target.

At each scattering angle the observed spectrum was used to determine the electron-capture probabilities (i.e., relative values only) for the processes corresponding to capture into the $4s$ and $3d$ states. The electron-capture probability is found from the ratio of the intensity of each reaction channel to the total signal. Figure 8 shows the probability of electron capture as a function of scattering angle. In Fig. 8, it is again demonstrated that with increasing scattering angles contributions from avoided crossings at smaller internuclear separations (large Q value) become gradually more important as one would expect.

Our calculated reaction window based on the factor 5.48 accommodates most of the observed features in the spectrum, while the MCLZ theory overestimates the contribution of the $3d$ capture channel.

D. Ar^{5+}-Ar collisions

In this collision system, the observed zero-angle spectrum at an impact energy of 250 eV shows that capture into the $(3s^2 3p4d)$ state dominates, while capture into the $(3s^2 3p4p)$ state shows less contribution (see Fig. 9). The electron-capture probabilities (i.e., relative values only) for the reaction channels corresponding to capture into $4p$ and $4d$ states of the Ar^{4+} ions and transfer ionization processes produced in Ar^{5+}-Ar collisions are displayed in Fig. 10. Two features can be emphasized: (i) the $4d$ state of Ar^{4+} produced in the electron-capture process is

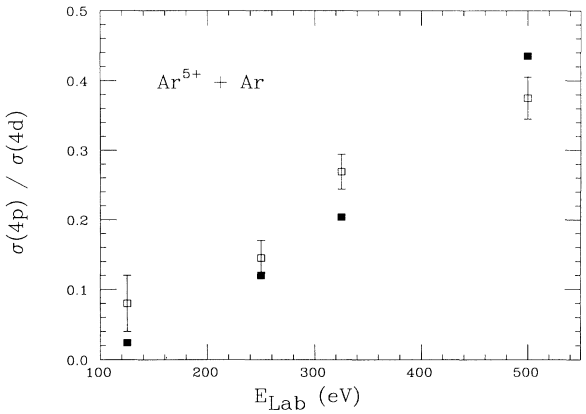

FIG. 12. Collision energy dependence for the ratio of single-electron capture cross sections $\sigma(4p)/\sigma(4d)$ in the Ar^{5+}-Ar collision system. □, our results; ■, MCLZ predictions.

strongly forward scattered. This behavior corresponds to a large impact parameter mechanism. (ii) The reaction channel due to capture into the $4p$ state of Ar^{4+} is significantly populated in the collision process and becomes comparable to capture into the $4d$ state for scattering angles approaching 3°. (iii) The contribution of transfer ionization strongly increases with increasing scattering angle.

Our calculated reaction window using the factor 5.48 accommodates most of the observed spectrum. For this collision system, the MCLZ theory predicts relative cross sections which are in good agreement with our measurements.

Giese *et al.* [3] have studied the Ar^{5+}-Ar system at a collision energy of 2725 eV. They found that the reaction channel correlating with capture into the $4p$ state produced almost the same contribution as did the reaction channel due to capture into the $4d$ state. This is attributed to the high impact energy they used since the position of the reaction window, which indicates the favored final states, depends mainly on the collision energy of the projectile. When the collision energy is reduced the adiabaticity of inner crossings will become increasingly pronounced, while the transition probability at distant crossings becomes larger. Therefore the reaction window shifts towards larger internuclear separations if the collision energy is reduced and vice versa. The variation of the translational energy spectra for single-electron processes as a function of collision energy for the Ar^{5+}-Ar collision system is illustrated in Fig. 11. The relative cross sections for capture into the $4d$ and $4p$ states of Ar^{4+} become of comparable importance at 500 eV and the cross-section ratio $\sigma(4p)/\sigma(4d)$ increases with increasing collision energy from 0.08 at 125 eV to 0.375 at 500 eV, which are in good agreement with the MCLZ predictions as shown in Fig. 12.

IV. TWO-STATE MODEL

The semiclassical two-state scattering model has been used to estimate the critical angle θ_c, which corresponds to capture at an impact parameter equal to the crossing radius, by assuming that capture occurs at a localized curve crossing between the potential energy curves for entrance and exit channels [19,20]. For small angles, $\theta_c = Q/2E$, where Q is the exoergicity of the collision and E is the laboratory impact energy. Assuming that the entrance channel is independent of internuclear distance (i.e., zero interaction energy) and the exit channel is given by Coulomb energy only, there are two branches to the deflection function $\theta(b)$ which meet at a critical angle θ_c. The upper branch corresponds to capture at the crossing on the way in, and the lower one to capture on the way out. However, the entrance potential is not flat but is strongly promoted somewhat inside the crossing because there are usually reaction channels with higher Q value than the active one, whose behavior at the crossing with the entrance channel is adiabatic. This promotion causes the lower branch of the deflection function to rise at small angles, producing a rainbow angle θ_r.

The differential cross sections for these collision sys-

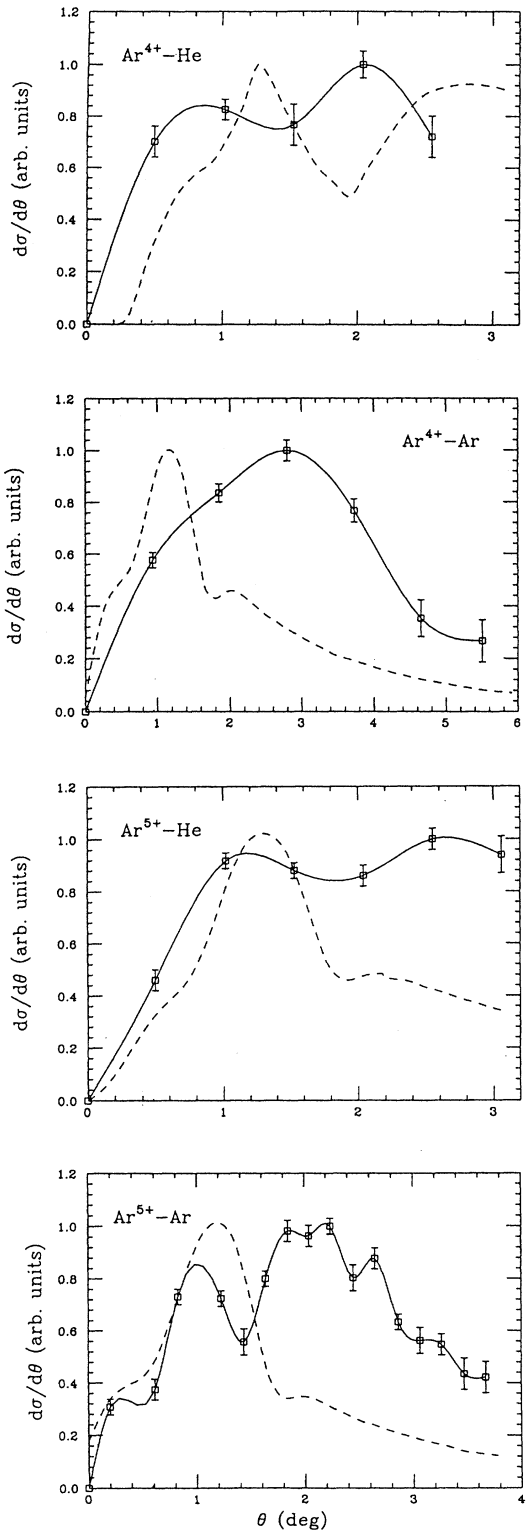

FIG. 13. Experimental and calculated differential cross sections ($d\sigma/d\theta$) for single-electron capture processes at collision energies of $50q$ eV (where q is the projectile charge state). □, the present results; the broken curves are the theoretical calculations folded with experimental resolutions. Spline lines are drawn to guide the eye.

tems are interpreted using a simple two-state diabatic curve-crossing model employing Coulomb potential energy curves [21,22]. The experimental differential cross sections and the theoretical calculations folded with the experimental resolution are shown in Fig. 13. For the Ar^{4+}-He collision system, the calculation is performed assuming that capture into the ^2S state is the only dominant reaction channel with the ^2D channel strongly promoting the entrance channel. The experimental data show a broad distribution for angles less than $\theta_c = 1.63°$ and a maximum near a scattering angle of 2°. This distribution represents contributions from capture on the way-out branch of the deflection function. The calculation contains a peak slightly less than $\theta_c = 1.63°$ with a shoulder located near $\theta = 0.8°$, which is a rainbow effect caused by ^2D promotion of the entrance channel. The calculation contains also a broad distribution for angles greater than 2°, which is the contribution from capture in the way-in branch of the deflection function. The overall shape of the theoretical calculation is not in good agreement with the data. The capture process is certainly at least a four-channel one, including the entrance channel and the capture channels ^2S, ^2P, and ^2D. In addition to these reaction channels one must take into account the presence of metastable states in the Ar^{4+}-ion beam and the contributions due to capture into $3d$ states.

In the Ar^{4+}-Ar collisions, we assumed that electron capture occurs into the $4p$ state because the inner curve crossing of the entrance channel with the $4s$ state is supposed to be totally adiabatic. The differential cross section $d\sigma/d\theta$, does not peak at 0° but rises to maximum at an angle of 2.8°, i.e., outside $\theta_c = 1.2°$. Most of the distribution is due to capture on the way-in branch of the deflection function. The calculated distribution again shows a peak lying near θ_c with a shoulder at the rainbow angle. Biedermann *et al.* [9] have studied the Ar^{4+}-Ar collision system in more detail. In their semiclassical trajectory calculations, using a seven-channel model, they have assumed all six $4p$ LS terms to be open and the innermost of the two $4s$ states to be completely adiabatic. They concluded that the forward peak in their theoretical results $d\sigma/d\Omega$ is dominated by multiple rainbow scattering due to the adiabaticity of the $4s$ channel.

For Ar^{5+}-He collisions, the theoretical prediction clearly contradicts the experimental data. The calculation, which was performed assuming that the capture channel is the $4s$ state and the reaction channel due to capture into the $3d$ state is the promoting channel, clearly underestimates the contributions for capture on the way-in branch for angles greater than $\theta_c = 1.47°$. In the Ar^{5+}-Ar case, the calculation, which is constructed assuming that the $4d$ channel is open and $4p$ is the promoting channel, again underestimates the contribution from capture on the way-in branch, since the model did not take into consideration the contributions for capture into the ten unresolved $4d$ LS levels.

V. CONCLUSION

State-selective differential cross sections for single-electron capture by low-energy Ar^{4+} and Ar^{5+} ions from He and Ar have been studied by means of translational energy-gain spectroscopy. These measurements show the importance of dynamic effects in the simple electron-capture process. In particular, they reveal an interesting impact parameter (scattering angle) dependence of the electron-capture spectra; as the angle is increased, contributions from successively smaller internuclear separations (large Q values) make their appearance. The reaction window based on the factor 5.48 provides the best general description of the observed features. The MCLZ calculations correctly predict the positions of the dominant reaction channels that are observed and the relative cross sections are in reasonable general accord with our measurements. Differential cross sections ($d\sigma/d\theta$) for single-electron capture processes are characterized by broad peaks at angles greater than the critical scattering angles. This general feature is qualitatively interpreted in terms of a simple two-state model and is attributed to the capture process on the way-in branch of the deflection function. A quantitative comparison between experiment and theory must be made with a model constructed by means of an extended version of the multistate semiclassical model explained by Andersson *et al.* [8].

ACKNOWLEDGMENTS

This research was supported in part by a grant from Research Corporation. We are grateful to Dr. Roger R. Haar and Rebecca R. Hozak for their contributions to these measurements.

[1] R. K. Janev and H. Winter, Phys. Rep. **117**, 265 (1985).
[2] E. H. Nielsen, L. H. Andersen, A. Barany, H. Cederquist, J. Heinemeier, P. Hvelplund, H. Knudsen, K. B. MacAdam, and J. Sorensen, J. Phys. B **18**, 1789 (1985).
[3] J. P. Giese, C. L. Cocke, W. Waggoner, L. N. Tunnel, and S. L. Varghese, Phys. Rev. A **34**, 3770 (1986).
[4] J. Puerta, H. J. Kahlert, H. R. Koslowski, and B. A. Huber, Nucl. Instrum. Methods **B9**, 415 (1985).
[5] V. V. Afrosimov, A. A. Basalaev, M. N. Panov, and A. V. Samoilov, Zh. Eksp. Teor. Fiz. **91**, 465 (1986) [Sov. Phys. JETP **64**, 273 (1986)].
[6] R. W. McCullough, S. M. Wilson, and H. B. Gilbody, J. Phys. B **20**, 2031 (1987).
[7] E. Y. Kamber, J. Phys. B **21**, 4185 (1988).
[8] L. R. Andersson, J. O. P. Pedersen, A. Barany, J. P. Bangsgaard, and P. Hvelplund, J. Phys. B **22**, 1603 (1989).
[9] C. Biedermann, H. Cederquist, L. R. Andersson, J. C. Levin, R. T. Short, S. B. Elston, J. P. Gobbons, H. Andersson, L. Liljeby, and I. A. Sellin, Phys. Rev. A **41**, 5889 (1990).
[10] E. Y. Kamber, C. L. Cocke, J. P. Giese, J. O. K. Pedersen, W. Waggoner, and S. L. Varghese, Nucl. Instrum. Methods **B24/25**, 288 (1987).
[11] *Collision Spectroscopy,* edited by R. G. Cooks (Plenum,

New York, 1978), pp. 252.
[12] E. Y. Kamber, C. L. Cocke, J. P. Giese, J. O. K. Pedersen, and W. Wagoner, Phys. Rev. A **36**, 5575 (1987).
[13] P. K. Janev and L. P. Presnyakov, Phys. Rep. **70**, 1 (1981).
[14] R. E. Olson and A. Salop, Phys. Rev. A **14**, 579 (1976).
[15] M. Kimura, T. Iwai, Y. Kaneko, N. Kobayashi, A. Matsumoto, S. Ohtani, H. Tawara, and S. Tsurubuchi, J. Phys. Soc. Jpn. **53**, 2224 (1984).
[16] A. Salop and R. E. Olson, Phys. Rev. A **13**, 1312 (1976).
[17] K. Taulbjerg, J. Phys. B **19**, L367 (1986).
[18] P. Roncin, M. Barat, and M. Laurent, Europhys. Lett. **2**, 371 (1986).
[19] R. E. Olson and F. T. Smith, Phys. Rev. A **3**, 1607 (1971).
[20] C. L. Cocke, L. N. Tunnell, W. Waggoner, J. P. Giese, S. L. Varghese, E. Y. Kamber, and J. O. K. Pedersen, Nucl. Instrum. Methods **B24/25**, 97 (1987).
[21] H. Danared and A. Barany, J. Phys. B **19**, 3109 (1986).
[22] W. Waggoner, Ph.D. dissertation, Kansas State University, 1990 (unpublished).