K-K charge transfer and electron emission for 0.13-MeV/u F^{8+} + Ne collisions

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(Received 29 January 1987)

We have measured the impact-parameter dependence $P(b)$ of Ne K-Auger- and δ-electron production for 0.23- and 0.13-MeV/u F^{8+} + Ne collisions. For the higher energy an improved agreement with multiple-state atomic expansion theory has been found compared to previous data. A strong damping in the oscillatory structure of the $P(b)$ which appears at the smaller collision energy shows a significant discrepancy of experiment and theory. For δ-electron production it is shown that dominant contributions arise from very distant collisions greater than or equal to 0.4 a.u.

I. INTRODUCTION

The qualitative understanding of the K-K charge-transfer process in heavy-collision systems has seen some impressive progress since the first data on K-electron capture[1] exhibited large discrepancies of experimental results with the only theory[2] then available on total cross sections. The *ab initio* calculations by Fritsch and Lin[3] have shown very good agreement with a large body of data on total cross sections[4] as well—a far more sensitive test—as with some impact-parameter (b) -dependent studies of the K-K charge transfer.[5–7]

For the single K-K charge transfer in F^{8+} + Ne, agreement of theory and experiment at 0.53 MeV/u is very good in both absolute probabilities and the location in b of extrema and turning points. At 0.23 MeV/u there is a discrepancy between the position of the minimum which was experimentally found at $b = 0.21$ a.u. and that found by theory at $b = 0.18$ a.u. Also, at larger impact parameters the second maximum in the experiment was found to be damped compared to the theoretical prediction. Similarly, for S^{15+} + Ar, the agreement of theory and experiment at the lowest collision energies is only marginal and no indication of a reason for this to be so is evident.[6] For this reason it was considered important to systematically extend the data set for the F^{8+} + Ne collision system to lower collision velocities where an expected richer structure in the impact-parameter dependence of the K-K charge-transfer probability $P(b)$ should allow a determination of more extrema and turning points in the $P(b)$ distribution. We thus measured the impact-parameter dependence of target K Auger and continuous energy electron probability for 0.23- and 0.13-MeV/u F^{8+} projectiles and derived from these data K-K charge-transfer probabilities.

II. EXPERIMENTAL PROCEDURE

A tandem Van de Graaff accelerator in its normal mode of operation will prouce high-quality beams for ions in charge states close to the equilibrium charge state $\bar{q}$ attained by standard foil or gas stripping of ions at the accelerator terminal.[8] However, at a given velocity the fraction of projectiles in charge states far above $\bar{q}$ falls rapidly below useful levels. For example, in our experiment investigating K-K charge transfer for bare F^{9+}

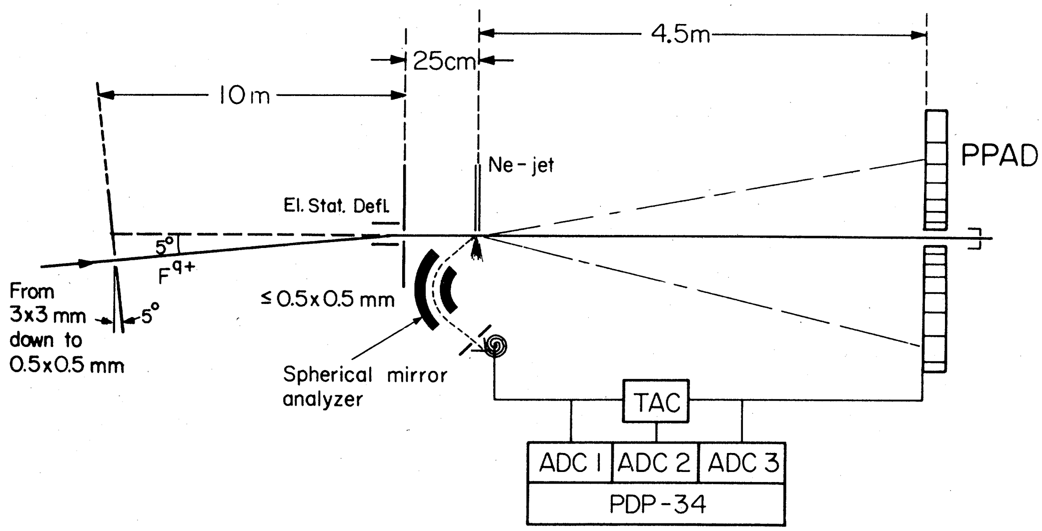

FIG. 1. Experimental setup; ADC is an analog-to-digital converter, TAC is time-to-amplitude converter.

projectiles at 0.53 MeV/u, useful beams of F^{9+} in the experiment after collimation were 10^{-7} of the analyzed beam. Similarly, 0.23 MeV/u with $v/v_K=0.30$ proved to be the lower limit to get reasonable hydrogenlike F^{8+} beams. To do experiments at even lower collision velocities requires a principally different technique for the production of high-quality beams of slow highly charged projectiles. For experiments at low specific velocities where more interesting features of the *K*-*K* charge transfer are to be expected the Brookhaven Double Emperor in the four-stage mode appears to be an accelerator facility highly suited for producing high quality beams of slow bare and hydrogenlike projectiles.[9,10] In this mode a high-energy beam from the first Emperor is injected into the second Emperor, which is run at negative terminal voltage, there accelerated again, poststripped inside the terminal at high velocity, with accordingly small resultant angular spreading dominantly to the intended high charge states, and then decelerated in the second half of the second Emperor to the desired low velocity. Due to the large electron-capture cross sections for highly charged very slow projectiles, even a background gas in the beamline of better than 2×10^{-7} Torr over a collimation length of typically more than 10 m represents a significant target and will generate a non-negligible fraction of nonhydrogenlike projectiles. We thus inserted a 5° electrostatic deflector as a beam purifier directly before the last collimator before our spectrometer chamber at the end of the long collimation path to assure that only F^{8+} projectiles would enter the target region (see Fig. 1).

The only connection between target chamber and (upstream) beamline was a hole of 2 mm diameter, 5 cm before the target, i.e., the object point of the electron spectrometers. Electrons emitted at 90° with respect to the beam direction in the $F^{8+}+\mathrm{Ne}$ collisions were analyzed with two hemispherical sector analyzers situated on either side of the target area. Scattered particles were detected with a 16-ring position-sensitive parallel-plate avalanche detector (PPAD).[11] For two different distances of the PPAD to the target, projectile scattering angles between 0.7 and 20 mrad could be subtended. At each scattering angle θ the relative probability $P(\theta)$ for the respective electron-producing processess (continuum or Auger electrons) were derived from the ratio of coin-

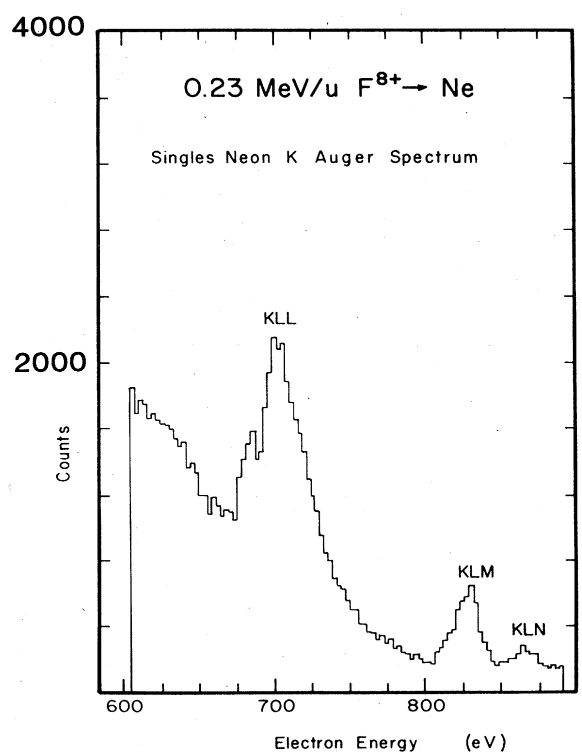

FIG. 2. Electron spectrum for 0.23-MeV/u F^{8+} impact excitation between 605 and 880 eV with the Ne *K* Auger groups at approximately 700 and 850 eV above the δ-electron background.

cidences of electrons with particles at angles $\theta_i \pm \Delta\theta_i$ (that is, ring number i) to all particles scattered into the angles $\theta_i \pm \Delta\theta_i$ (slit-scatter corrections taken into account). The conversion of scattering angles into impact parameters was done using a screened Coulomb potential with a previously[5] experimentally determined screening radius $a = 0.52$ a.u. Absolute probabilities were derived from normalizing the relative experimental $P(b)$ distribution for 0.23-MeV/u F^{8+} which was measured with the same setup as for 0.13 MeV/u to achieve an optimum overlap with previously measured data and using the normalizing factor derived from this case then for the 0.13-MeV/u data as well. Details are discussed in Sec. V.

III. RESULTS AND DISCUSSION

A. Noncoincident electron spectra for 0.23 MeV/u and 0.13 MeV/u

Figure 2 shows the electron-emission spectrum for 0.23-MeV/u F^{8+} + Ne between 605 and 880 eV recorded at 90° observation angle with respect to the beam axis. All electrons in the region covered are expected to be originally bound to the target. Trautmann[12] has shown that the probability for (target or projectile) K-electron ionization into the continuum is negligible. The Ne K Auger spectrum is clearly separable from the smooth exponentially shaped background of the continuum-electron spectrum resulting from target L-electron ionization into the continuum. For the Ne K Auger spectrum two groups identified[5] as KLL and KLM Auger transitions are associated with the generation of a Ne K vacancy through $2p\pi$-$2p\sigma$ rotational coupling or K-K charge transfer into the projectile K shell and subsequent Auger decay. The significant intensity of the KLM group points to strong simultaneous electron excitation processes during collisions where a Ne K electron is transferred to the projectile.[13]

At lower collision energies the situation changes dramatically. Figure 3 shows the electron-emission spectrum under the same conditions as above, but now at 0.13 MeV/u. The relative intensities of continuous and discrete parts of the spectra are more or less reversed. The Ne KLL Auger group is just visible as a shoulder in the continuous part of the spectrum and in the noncoincident spectra it is almost impossible to separate the KLM group from the background. As the analysis of the coincident spectra in the next paragraph shows, this is not so much due to the decrease of the K Auger production cross section (originating from a smaller K-K charge-transfer probability) but due to an increase in the probability for continuous electron emission perpendicular to the beam direction.

B. Coincident Ne K Auger spectra

The noncoincident spectra contain all electrons emitted into the solid angle covered by the electron spectrometer which fall into the indicated electron energy range, regardless of the scattering angle of the incident projectile which excited the electron into the continuum. Requiring a coincidence between electrons and scattered projectiles will yield for every impact-parameter interval $b \pm \Delta b$ two

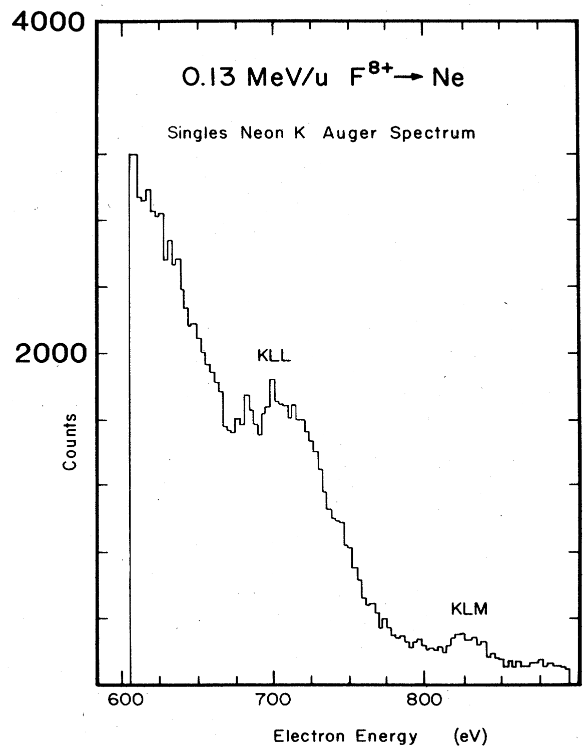

FIG. 3. Electron spectrum for 0.13-MeV/u F^{8+} impact excitation between 605 and 880 eV with the Ne K Auger groups at approximately 700 and 850 eV above the δ-electron background.

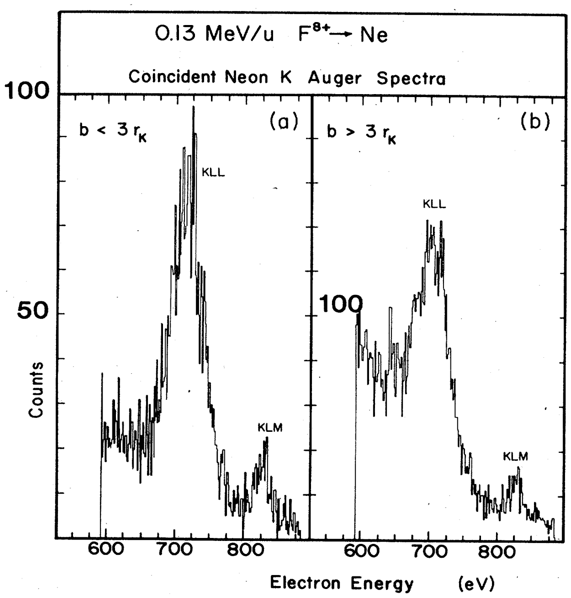

FIG. 4. (a) Electron spectrum for 0.13-MeV/u F^{8+} impact excitation between 590 and 880 eV coincident with projectiles scattered under impact parameters between 0.01 and 0.3 a.u. (b) Electron spectrum for 0.13-MeV/u F^{8+} impact excitation between 590 and 880 eV coincident with projectiles scattered under impact parameters between 0.3 and 0.6 a.u.

electron spectra coincident with projectiles scattered into $b \pm \Delta b$: one for the "real" coincidences, and one for the "random" coincidences; the true events are then derived by an appropriate subtraction of random from real coincidences.

Figure 4 shows two time-coincident electron spectra between 590 and 880 eV for 0.13-MeV/u F^{8+} + Ne for impact parameters 0.05–0.3 a.u. and 0.3–0.6 a.u., respectively; that is, ranges of impact parameter smaller and larger than three times the Ne *K*-shell radius. The summation of coincident spectra into two groups has been done here only to illustrate some of their interesting structures. For the calculation of Ne *K* Auger-production probabilities, the electron spectrum coincident with each ring of the 16-ring PPAD was evaluated individually.

Turning our attention now to the two electron spectra, it is directly seen that the Ne *KLL* Auger group dominates the spectra in both ranges. For impact parameters smaller than $3r_K$ the Ne *K* Auger spectrum is much more intense than the continuous electron background and even the *KLM* group can be clearly resolved from the δ-electron background. We emphasize that the intensity ratio $I(KLM)/I(KLL)$ is clearly smaller than that found for higher collision velocities indicating that the relative probability of exciting Ne *L* electrons into the *M* shell is significantly smaller at this velocity $v_{\text{proj}}/v_L = 0.12$. The centroid of the energy of the *KLL* line group is shifted 20 eV to higher energies compared to the spectra taken at 0.23 MeV/u whereas the *KLM* group shows no shift. This is consistent[13] with an average charge state of 4+ before the *K* Auger decay for a configuration $|1s^1 2l^5\rangle$ or $|1s^1 2l^4 3l^1\rangle$. This clearly indicates a degree of average outer-shell ionization simultaneous with a *K*-vacancy-creating event which is low by about $\Delta q = 3$ compared to the case of 0.53 MeV/u, where coincidences with the final charge state of the electron-emitting ion were measured and used to determine electron configurations of Ne ions after excitation during *K*-*K* charge transfer. Thus the high average Auger yield[14] for present configurations of ≈ 0.95 reduces the uncertainty of converting Ne *K* Auger production probabilities to *K*-*K* charge-transfer probabilities.

For impact parameters larger than $3r_K$ the centroid of the *KLL* group is (after the corrections for the steep slope of the underlying δe^- spectrum) the same as for the smaller impact parameters. For the *KLM* group the coincidence of both centroid energies is directly recognizable.

A remarkable feature of the two electron spectra will be noticed only if one recalls what is known so far about the dynamics of δ-electron production and *K*-*K* charge transfer. At 0.53 MeV/u a systematic investigation of the impact-parameter dependence of δ-electron production had shown that the impact-parameter dependence of δ-electron production displayed a clear maximum at 0.15 a.u., for δ-electron energies between 200 and 1600 eV and emission angles between 45° and 135°, in good agreement with the semiclassical approximation (SCA) calculations of Trautmann and co-workers.[15,16] This maximum lies well inside the range of impact parameters of dominant contribution to the *K*-*K* charge-transfer channel.[5]

Even before a quantitative statement about the *K*-*K* charge-transfer probabilities at 0.13 MeV/u, it can be concluded from a comparison of these two spectra with the singles spectrum that the dominant contribution to the δ-electron spectrum must come from impact parameters larger than those subtended in this experiment, that is, larger than 0.6 a.u. Implications will be discussed in

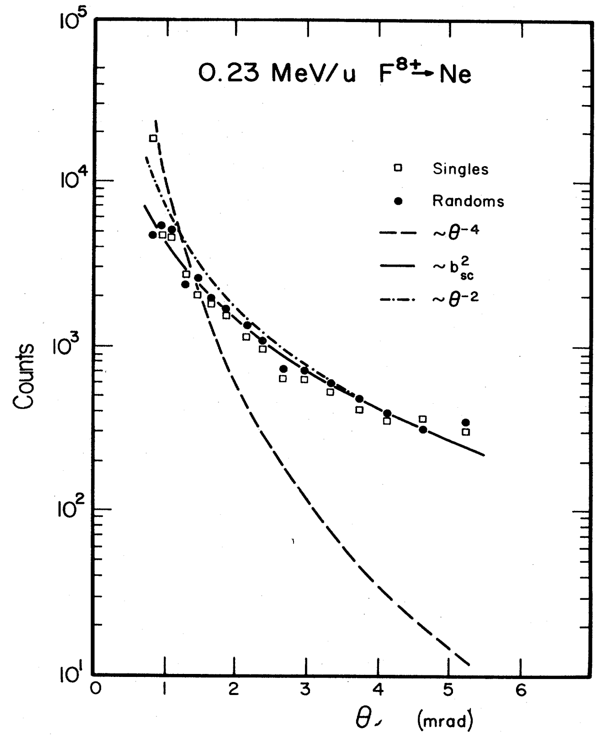

FIG. 5. Relative differential scattering cross section for 0.23-MeV/u F^{8+} projectiles from Ne for scattering angles between 0.75 and 5 mrad.

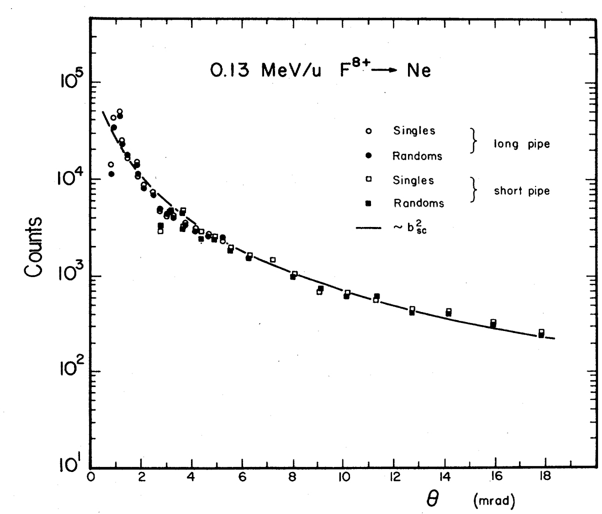

FIG. 6. Relative differential scattering cross section for 0.13-MeV/u F^{8+} projectiles from Ne for scattering angles between 0.5 and 18 mrad.

Sec. III E. The substantial corrections in the calculation of the K Auger group intensities due to the presence of the strong δ-electron intensity were taken into account by fitting an exponential background through the regions below and above the K Auger line groups and subtracting background intensities underneath the Auger groups using this exponential fit for every ring, i.e., every impact parameter.

C. Relating scattering angles to impact parameters

In a previous experiment[5] we established that an experimentally screened Coulomb potential

$$V(R,a)=V_{\mathrm{Ruth}}\exp(-R/a) \qquad (1)$$

with a screening parameter $a=0.52$ a.u. will fit the measured angular distribution of the scattered projectiles for the case of 0.23-MeV/u F^{8+} + Ne.

In Fig. 5 we compare the measured angular distribution of noncoincident scattered particles and that of random-coincident scattered particles with two calculated distribution functions, one for the unscreened Coulomb potential which follows proportional to θ^{-2} (a constant $\Delta r/r$ for all detector rings introduces a factor θ^2 into the pure Rutherford scattering rate which is proportional to θ^{-4}, therefore the particle yield should be proportional to b^2) and one for the screened potential following b_{sc}^2. The significant deviation from the Rutherford potential for scattering angles smaller than 3 mrad is clearly visible in the graph. For illustrative reasons the unweighted angular distribution for a pure Rutherford potential following θ^{-4} is included. The fluctuation of experimental data points around the b_{sc}^2 function is due to small imprecisions in the discriminator threshold settings of the PPAD.

For 0.13-MeV/u F^{8+} impact, the large range of scattering angles over which a significant coincidence rate was detected could not be covered with the PPAD at one distance from the interaction zone only (Fig. 6). Data were taken at two different distances from the target to cover small and large scattering angles, i.e., distant and close impact parameters. Again the angular distribution for noncoincident "singles" scattered particles and random scattered particles are compared with $b_{\mathrm{sc}}^2(\theta)$ and good agreement is seen for a screening radius of $a=0.52$ a.u. The experimental data points showing large deviations from the continuous b_{sc}^2 functions at 1 mrad and at ≈3 mrad are again rings where the discriminator settings were incorrect. At both detector distances (called "long pipe" and "short pipe," respectively) the same rings display this behavior.

D. Impact-parameter dependence of K-K charge transfer

1. 0.23-MeV/u collision energy

In Fig. 7 we compare the present data on Ne K Auger productions probabilities for the 0.23-MeV/u projectile with our previous data and two-state atomic expansion theory (TSAE) and multistate theories by Lin and coworkers.[17,18] Our present results are in general in good agreement with our previous measurement. However, after normalizing the present relative $P(b)$ distribution to

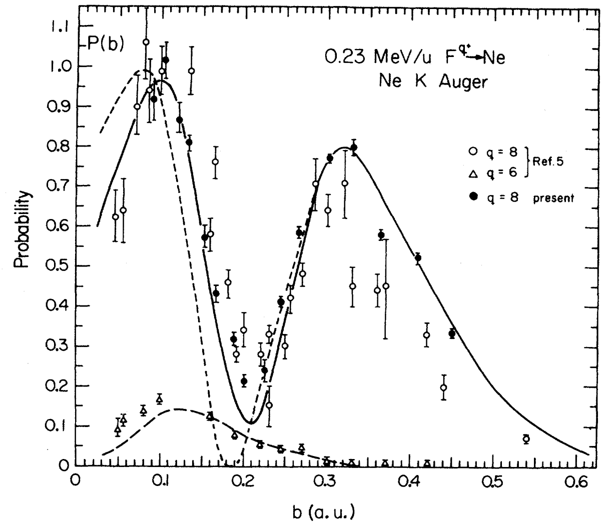

FIG. 7. Impact-parameter dependence for K-K charge transfer for 0.23-MeV/u F^{8+} incident on Ne. The dashed line represents the TSAE calculation and the solid line the AO + 6 calculations of Lin (see text).

yield a maximum overlap with previous absolute probabilities, we find some significant systematic differences between the two sets of data: slightly larger probabilities for very large impact parameters and smaller probabilities for small impact parameters. We believe that the larger probabilities found in the present experiment for large impact parameters are due to an improved experimental method. In the previous run the pass energy which was selected for the electron spectrometer was the peak of the KLL Auger group and due to a low beam intensity we did not scan the whole spectrum. Another reason for doing this had been that at 0.53 MeV/u the scanned coincident Ne K Auger spectra did not show any impact-parameter dependence.

In the present experiment the decelerated H-like beam of 0.23-MeV/u F^{8+} from the Brookhaven Double Emperor delivered enough intensity to the target to permit a scan of the electron-energy spectrum between 590 and 880 eV thus covering the Ne K Auger spectrum and the adjacent parts of the δ-electron continuum. It appears now that the intensity ratio $I(KLM)/I(KLL)$ strongly varies with the impact parameter and takes values between 0.40, at large impact parameters, and 0.15, at small impact parameters. The M shell of Ne being initially unoccupied the intensity ratio $I(KLM)/I(KLL)$ reflects the decrease of $L\rightarrow M$ electron-excitation probability with smaller impact parameters. If the number of electrons in the L shell were known at all impact parameters, the impact-parameter dependence for the absolute $L\rightarrow M$ excitation probability $P_{L\rightarrow M}(b)$ could be derived from the measured intensity ratios. A consequence of the larger $I(KLM)/I(KLL)$ ratio at very large impact parameters is that we underestimate the total Ne K Auger production probability in this collision range when the electron spectrometer is set at 700 eV as it was in the previous experiment. The same argument leads to the slightly smaller probabilities for impact parameters below 0.2 a.u. due to the very much smaller $I(KLM)/I(KLL)$ ratio. The present data show now very good agreement with the recent modified atomic orbital (AO +) approach by Fritsch and Lin[18] for impact parameters larger than 0.25 a.u. and confirm the appearance of the minimum of $P(b)$ at larger impact parameters than predicted by the TSAE theory.[17] A small discrepancy between experiment and theory at impact parameters at about 0.2 a.u. persists. One may speculate that this is due to the non-negligible channels of rotational coupling to higher states; however, it appears not to be permitted[5] just to subtract the measured rotational coupling contribution and thus a multichannel treatment appears to be necessary for $b \leq 0.2$ a.u.

2. 0.13-MeV/u collision energy

Figure 8 shows the impact-parameter dependence of Ne K Auger production for 0.13-MeV/u hydrogenlike F^{8+} impact excitation. A comparison with K Auger production for incident projectiles without a K vacancy in the entrance channel of the collision was not considered to be essential since total cross-section measurements[19] indicated a further drop in cross section at this energy compared to the data at 0.23 MeV/u. The data exhibit two clear maxima at 0.4 and 0.2 a.u. and two minima at 0.28 and 0.13 a.u. It is to be emphasized that at this very low collision velocity a significant K Auger production probability on the order of 10% is measured at impact parameters six times the Ne K-shell radius which is many orders of magnitude larger than those expected for $2p\pi$-$2p\sigma$ rotational coupling excitation or direct ionization to the continuum. A comparison of the integrated total cross sections is given in Fig. 9.

The statistical significance of the two innermost data points does not permit the interpretation of the data structure as the third maximum in the $P(b)$ distribution. On first principles, however, an extension of data to much smaller impact parameters $b \ll r_K$ appears desirable.

The most advanced theoretical approach, a six-state atomic orbital expansion by Lin and co-workers,[18,20] shows an almost perfect agreement in the position of the extrema in the $P(b)$ distribution and in fact predicts a third maximum somewhat inside of the smallest b data of the present experiment. A significant discrepancy between experiment and theory appears in the absolute magnitude of the probability. Whereas for both minima theoretical charge-transfer probabilities drop to zero, experimental-transfer probabilities remain quite strong, a clear damping of the oscillatory structure with a much smaller experimental than theoretical P_{max}/P_{min} which cannot be due to the experimental resolution of impact parameters $\Delta b/b = \pm 5\%$. This damping may be understood qualitatively in the framework of the perturbed-stationary-state method as applied to slow nonsymmetric charge transfer[21,22] which leads to a factorization of the charge-transfer probability into an oscillating term $P'(b)$ and a damping term $D(b)$ with

$$D(b) \sim \left\{ \cosh^2 \left[\frac{\Delta E}{\hbar v} \left[\frac{b}{2\pi E_1/E_2} \right]^{1/2} \right] \right\}^{-1} . \qquad (2)$$

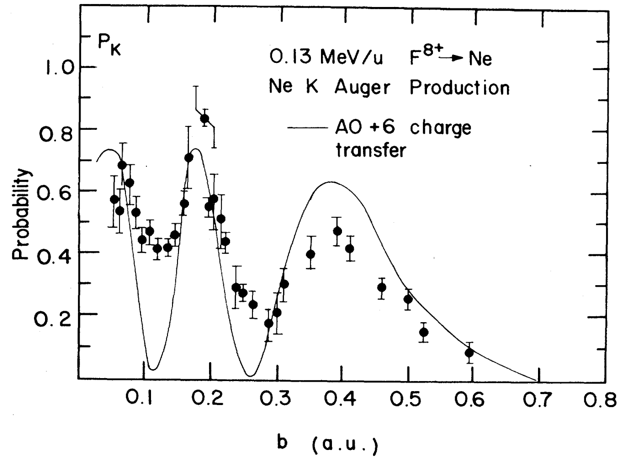

FIG. 8. Impact-parameter dependence for K-K charge transfer for 0.13-MeV/u F^{8+} incident on Ne.

It can directly be seen that this term will most significantly contribute at small collision velocities v.

Another contribution to damping which leads to nonzero probabilities in the minima $P=0$ of the two-state model may be due to strong mixing of other channels with the two active channels. This is quite plausible in view of the high intensity of δ-electron emission at electron energies comparable to the Ne K Auger energies. In the reactions

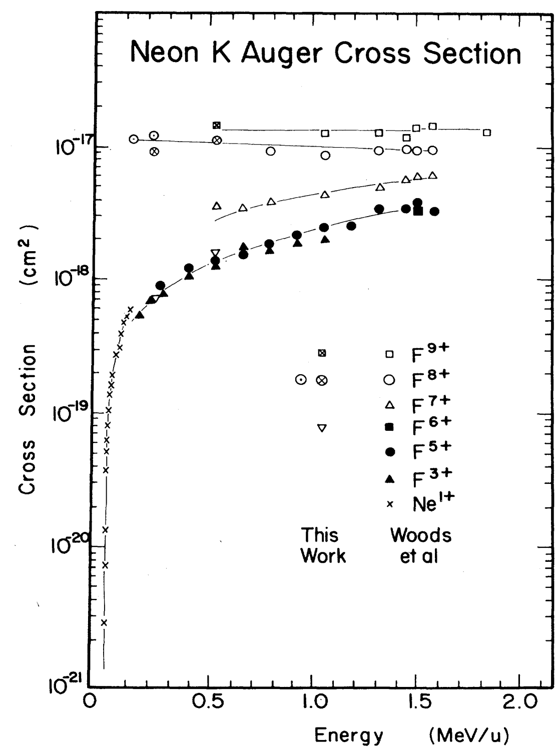

FIG. 9. Total Ne K Auger production cross section for F^{q+} + Ne between 0.13 and 1.84 MeV/u impact energy.

$$F^{8+}(1s)+\mathrm{Ne}\rightarrow F^{q+}(1s^2,\{n'l'\})+\mathrm{Ne}(1s,\{nl\})+\varepsilon' e^- \\ \downarrow \\ \mathrm{Ne}(1s^2,\{nl\})+e^-(K\ \mathrm{Auger}) \tag{3}$$

and

$$F^{8+}(1s)+\mathrm{Ne}\rightarrow F^{q+}(1s,\{n'l'\})+\mathrm{Ne}(1s^2,\{nl\})+\varepsilon'' e^- , \tag{4}$$

where $\varepsilon'' \approx E$(Ne K Auger), the channels leading to electron emission are indistinguishable and thus a direct electron-production amplitude with an only slowly b-dependent phase must be added to the two charge-transfer amplitudes thus giving rise to nonvanishing probabilities for impact parameters where the two charge-transfer amplitudes will destructively or constructively interfere. The strength of the possible interference from mixing with channels leading to K ionization can be estimated from ionization probabilities for incident F^{6+} projectiles (see Fig. 7): in the minimum for K-K charge transfer around $b\approx 0.20$ a.u. the disagreement between theory and experiment may be due to the non-negligible ionization probability here.

3. *The 1sσ-2pσ energy difference*

For a general discussion of theoretical approaches to the problem of quasiresonant K-K charge transfer, the reader is referred to the literature.[23–28] In a model of two active potential curves with a long-range coupling, two amplitudes from different paths contribute to the transfer probability; because they are indistinguishable they have to be added coherently. However, these two amplitudes accumulate different phases resulting in constructive and destructive interferences in the impact-parameter dependence of the charge-transfer probability

$$P=4p(1-p)\sin^2\phi ,$$

where p is a single passage probability through the coupling region and

$$\phi=\frac{2\pi}{vh}\int_{R_0(b)}^{\infty}\Delta E(R)\frac{R}{(R^2-R_0^2)^{1/2}}dR-\pi\beta(v,R_0) \tag{5}$$

with R the internuclear distance, $R_0=R_0(b)$ distance of closest approach, and the phase factor β is small compared to the first term.[17,21] $\Delta E(R)$ is the energy difference of the two potential curves. If ϕ takes values of integral multiples of π one gets minima for P; for half-integral multiples of π maxima will occur. In the literature[28,6] it has been established to write $\phi=(n-\frac{1}{2})\pi$ and then label maxima in the $P(b)$ distribution starting from large impact parameters with increasing integers and the minima between them with half integers. Following the procedure by Schuch,[6] one can take the dynamics out of expression (5) and $\hbar v\phi$ plotted versus the b position of the extrema should form a common curve since the integral in Eq. (5) depends only on the quasimolecular potential curves. Plotting $\phi v\hbar$ against the impact parameter b for the three collision energies for constructive and destructive interferences, one obtains indeed one common curve (Fig. 10). From this curve quantitative information on $\Delta E=\Delta E(R)$ can now be derived. Instead of following now the common procedure of integrating the phase integral numerically with $\Delta E(R)$ derived from Hartree-Fock (HF) calculations, Schuch *et al.*[6] used a parametrization of $\Delta E(R)$ first given by Müller,[29]

$$\Delta E=\frac{E_u-E_s}{\rho^2+R^2}\rho^2+E_s,\quad \rho=\frac{62\,100\ \mathrm{fm}}{\dfrac{Z_A+Z_B}{2}-1} \tag{6}$$

which allows for an exact integration yielding an analytical expression resulting in

$$\hbar v\phi=\rho^2\frac{E_u-E_s}{(\rho^2+b^2)^{1/2}}\tan^{-1}\left[\frac{(R_c^2-b^2)^{1/2}}{(\rho^2+b^2)^{1/2}}\right] +E_s(R_c^2-b^2)^{1/2} . \tag{7}$$

A best fit to our data is achieved with $R_c=0.5$ a.u. and $E_u=3.5$ keV, $\rho=8000$ fm and $E_s=0.08$ keV (dash-dotted line in Fig. 10). The continuous line results from an integration of Eq. (5) with $\beta=0$ using a Hartree-Fock program by Piacentini and Salin[30] for the H-like F + Ne collision system. The resultant energy difference from this procedure is clearly smaller than ΔE_{HF} (see Fig. 11). It would be very desirable to compare the fit to experimental data with improved HF energies based on measured charge distributions on projectile and target.

E. The continuous electron spectrum

The Ne K-Auger-electron spectra which signify a K-K charge-changing event are superimposed on a δ-electron continuum. This continuum principally carries the immediate information about the collision system because the electrons in it are emitted promptly during the collision and not many hundreds to thousands of collision times later as products of nonradiative rearrangement of the collision partner.

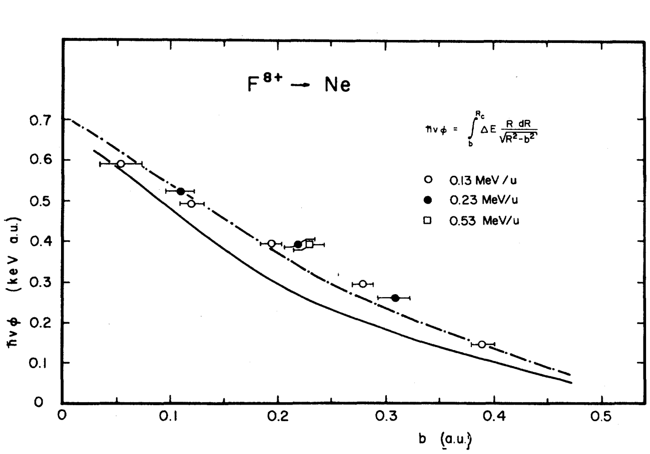

FIG. 10. Comparison of experimental values for the phase integral $\hbar v\phi$ as a function of impact parameter b with theoretical models for the molecular orbital (MO) energies of the two levels.

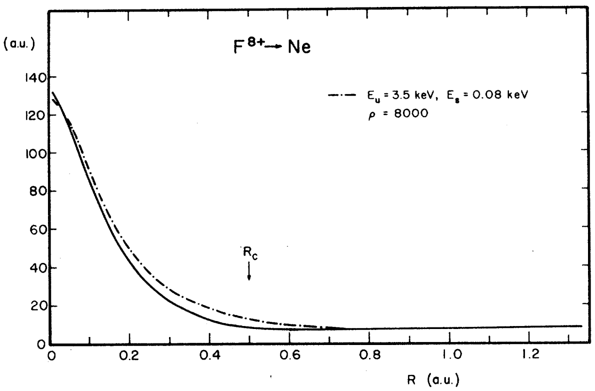

FIG. 11. Energy difference for the two active potential energy curves from HF calculations and model fits to present data (straight line and dashed curve, respectively).

In a previous systematic study of triply differential cross sections for δ-electron emission in 0.53-MeV/u F^{9+} + Ne, it was shown[15] that independent of electron-emission angle and electron energy, the impact-parameter dependence of δ-electron production showed a maximum at $b \approx 0.15$ a.u. and an exponential decrease with impact parameter for impact parameters above the maximum in qualitative agreement with SCA theory for L-shell ionization (see Fig. 12). Following established scaling laws for ionization, the smaller adiabatic radius for smaller collision energies leads to a much sharper drop for larger impact parameters for δ-electron production probability at 0.23 MeV/u and 0.13 MeV/u.

The experimental situation represents itself in spite of the limited amount of data in a very complex manner. For both collision energies we have data only for 90° observation angle and electron energy windows at $\langle E_\delta \rangle = 630$ eV (below Ne KLL), and at $\langle E_\delta \rangle = 790$ eV (between KLL and KLM), and we recall that data taken at 0.53 MeV/u did not show any discontinuities in either observation angle or electron energy. For the lower collision velocities, i.e., 0.23 and 0.13 MeV/u collision energy, a fraction of the fluorine K Auger electrons emitted after double outer-electron capture (but no simultaneous K-K capture) may appear in the electron spectrum at approximately 630 eV directly below the Ne KLL Auger lines due to Doppler broadening. Only fluorine Auger lines from decay of $|1s2l4l\rangle$, $|1s2l5l\rangle$, and $|1s2l6l\rangle$ have, however, a sufficiently high rest-frame energy so that to a small fraction they can be superimposed on the continuous δ-electron spectrum due to the finite size of the spectrometer acceptance angle. These excited projectile states must be populated in a collision

$$F^{8+}(1s)+\mathrm{Ne}(1s^2 2s^2 2p^6) \rightarrow F^{6+}(1s2lnl;\ 4 \le n \le 6) + \mathrm{Ne}^{i+}(1s^2 2l^{8-i}) + (i-2)\varepsilon l' , \quad (8)$$

where no Ne K vacancy is created, because the K-K charge transfer is the dominant mechanism to create a K vacancy in Ne. It follows that at impact parameters where the K-K charge-transfer probability takes on values close to one, the channel for projectile K Auger emission is closed and cannot contribute in the window at $\langle E_\delta \rangle = 630$ eV. If, however, electrons emitted at 630 eV should be dominantly attributed to projectile (fluorine) K Auger decay, there should be a structure in the $P(b)$ dependence like the complement of the $P(b)$ for K-K charge transfer. For 0.23 MeV/u an impact-parameter range between 0.09 and 0.45 a.u. is covered. At $b < 0.3$ a.u. the δ-electron probability is decreasing in qualitative agreement with SCA. At large impact parameters $b \ge 0.3$ a.u., however, we observe a constant or possibly even increasing probability in clear disagreement with an expected exponential decrease. The SCA calculation is performed with screened hydrogenic wave functions and Rutherford trajectories for the projectile. Recoil effects were taken into account and binding effects were simulated by united-atom wave functions assuming a fully stripped projectile. Since this formulation of the SCA ionization theory was originally formulated for the case of asymmetric collision systems, we also did calculations within the Briggs model approach which is more appropriate for the symmetric case. However, it turns out that the total ionization cross section is very similar to the above-mentioned results. They are therefore not shown in the figures. From the aforementioned it may be argued that this rise in the emission probability for electrons with $\langle E_\delta \rangle = 630$ eV at large impact parameters is due to a decreasing K-K charge-transfer probability and thus an opening of the fluorine K Auger emission channel at large impact parameters, but the comparison with δ electrons at $\langle E_\delta \rangle = 790$ eV shows the strong similarity in the shape of the $P(b)$ curve for both electron energies, and at 790 eV laboratory energy no interference with projectile Auger electrons is possible. Projectile K Auger electrons thus

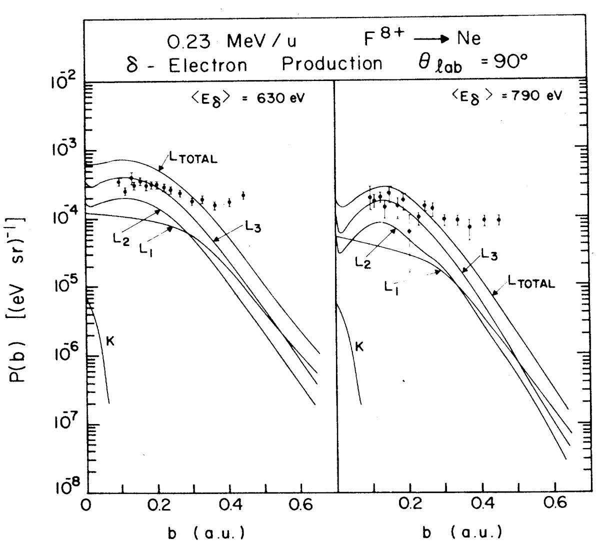

FIG. 12. Impact-parameter dependence $P(b)$ for two groups of δ electrons adjacent to the Ne K Auger groups for 0.23-MeV/u projectile energy. Data are compared with SCA calculations by D. Trautmann and co-workers for K, L_1, L_2, and L_3 ionization.

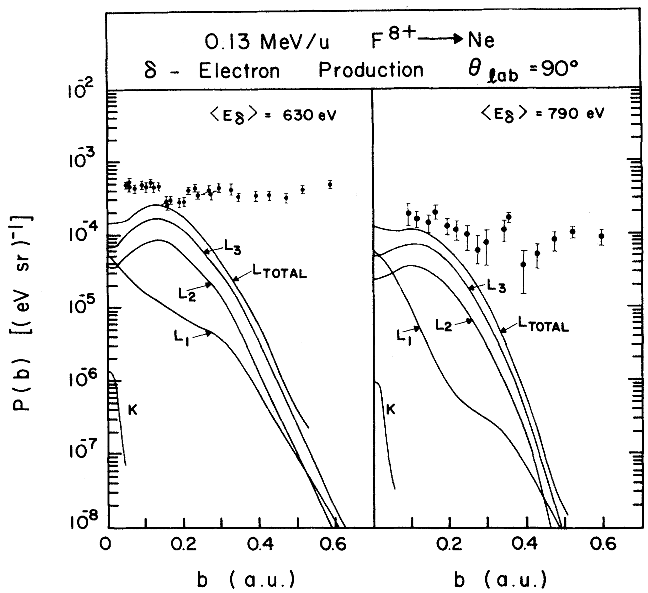

FIG. 13. Impact-parameter dependence $P(b)$ for two groups of δ electrons adjacent to the Ne K Auger groups for 0.13 MeV/u projectile energy. Data are compared with SCA calculations for K, L_1, L_2, and L_3 ionization.

cannot be the explanation for the shape of the $P(b)$ curve at very large b for the continuous electron spectra.

An even more dramatic behavior is displayed for 0.13 MeV/u where in first order the δ-electron production probability may be called b independent for both electron windows (see Fig. 13). However, the significant drop in electron-production probability at $\langle E_\delta \rangle = 630$ eV and $b \approx 0.2$ a.u. coincides with a maximum in the K-K transfer probability; this variation does not appear for the higher electron energy and may here indeed be interpreted as due to the inhibition of F K Auger decay due to K-K charge transfer (see Fig. 8). In this case the value of the electron-production probability in the minimum would represent the true continuum electron-production probability and from the depth of the minimum follows then the F K Auger production probability following two-electron capture. On the other hand, $P(b)$ for electrons at 790 eV show, except for the nonexisting valley, the same tendency as for 630 eV. We note as very interesting that for $\langle E_\delta \rangle = 790$ eV the absolute probabilities for 0.23 and 0.13 MeV/u excitation energy are very closely the same. However, a more detailed analysis requires data from more forward and backward scattering angles to compare δ-electron emission and projectile K Auger decay probabilities. From the coincident electron spectra as given in Fig. 4 in comparison with Fig. 3, it follows that even the dominant contribution to the cross section of δ-electron production must come from impact parameters outside the range of the present experiment. In fact, the electron spectra coincident with particles scattered under $b = 0.58$ and 0.52 a.u. bear the most resemblance to the singles spectrum of Fig. 3. It might appear exciting to speculate about quasimolecular electron emission in the context of the data just discussed, however, before doing so, we intend to begin a systematic study of continuous electron emission for this collision system at these low velocities.

IV. CONCLUSION AND SUMMARY

We have measured the impact-parameter dependence $P(b)$ for quasiresonant K-K charge transfer for 0.23-MeV/u and 0.13-MeV/u $F^{8+} + Ne$. At the higher collision velocity agreement with theory may now be called very good, where at the low velocity theory fails to reproduce the damping effect in the amplitude whereas the position of extrema are agreeing satisfactorily with experimental data. Furthermore, the derived potential curves are only in qualitative agreement with Hartree-Fock calculations.

A highly interesting and unexpected byproduct of this experiment is the strong enhancement of δ-electron production probabilities at large impact parameters in clear disagreement with present ionization theories.

ACKNOWLEDGMENTS

This work was supported in part by the Division of Chemical Sciences, Office of Basic Energy Sciences, Office of Energy Research, U.S. Department of Energy, and Deutsche Forschungsgemeinschaft.

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