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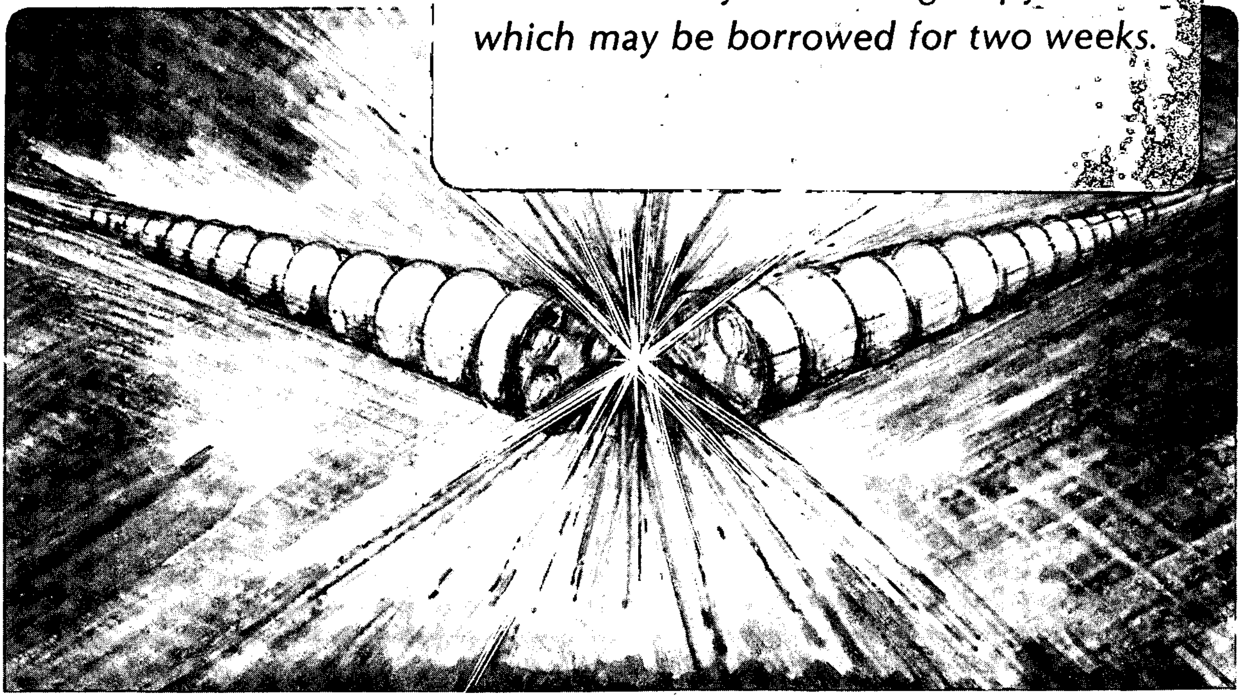

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ABSTRACT

Coincidence measurements of charge transfer and simultaneous projectile electron excitation provide insight into correlated two-electron processes in energetic ion-atom collisions. Projectile excitation and electron capture can occur simultaneously in a collision of a highly charged ion with a target atom; this process is called resonant transfer and excitation (RTE). The intermediate excited state which is thus formed can subsequently decay by photon emission or by Auger-electron emission. Results are shown for RTE in both the K shell of Ca ions and the L shell of Nb ions, for simultaneous projectile electron loss and excitation, and for the effect of RTE on electron capture.

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I. Introduction

Recent experimental studies[1,2] have shown that projectile excitation and electron capture can occur simultaneously in a single encounter of a highly charged projectile ion with a target atom through the electron-electron interaction between a projectile electron and a weakly bound target electron. This process is referred to as resonant transfer and excitation (RTE). The intermediate excited state which is formed in the RTE process can subsequently decay by photon emission or by Auger-electron emission. RTE is analogous to dielectronic recombination (DR),[3] in which the captured electron is initially free instead of bound. RTE and DR proceed via the inverse of an Auger transition and, hence, are resonant for projectile velocities, in the rest frame of the electron, corresponding to allowed Auger-electron energies.

RTE has been identified experimentally for projectile K-shell excitation by the observation of resonant behavior in the energy dependence of projectile K x rays coincident with projectiles which have captured an electron,[1,2] and of Auger-electron emission associated with electron-capture events.[4] Previous experiments with H_2 and He targets have also established the dependences of the cross sections for K-shell RTE on the projectile atomic number[5] and charge state.[6] The existing K-shell RTE data are in reasonable agreement with calculated RTE cross sections based on theoretical DR cross sections,[7] indicating a close link between RTE and dielectronic recombination.

II. Experimental Method

The measurements reported here were made at the Lawrence Berkeley Laboratory using the SuperHILAC accelerator. The experimental technique consisted of measuring projectile K or L x rays coincident with single-electron-capture or -loss events, following the passage of momentum- and charge-state-selected ions through a differentially pumped gas cell. X rays produced in collisions in the target gas were detected with a Si(Li) detector mounted at 90^0 to the beam axis. The beam, after emerging from the gas cell, was magnetically analyzed into its charge-state components. Ions undergoing electron capture or loss in the target gas were detected with solid-state detectors. The non-charge-changed component of the emerging beam was collected in a Faraday cup. Coincidences between projectile x rays and projectile ions capturing or losing an electron were measured using time-to-amplitude converters. The x-ray and coincidence yields were measured as a function of gas pressure to obtain the desired cross sections and to ensure that single-collision conditions prevailed. A capacitance manometer was used to measure the absolute pressure in the target gas cell.

III. RTE (K shell) for Ca ions

The existence of RTE has been demonstrated by Tanis et al.[1,2] Recent measurements[6] of K-shell RTE for 100-370 MeV ${}_{20}Ca^{q+} + H_2$ collisions for q = 10-12 and 16-19 have shown the projectile charge-state dependence and the dependence on target-electron momentum distribution. The cross sections for projectile K x rays coincident with single-electron capture, $\sigma_{K\alpha\beta}^{q-1}$, are shown in Fig. 1. These results are consistent with previous measurements for Ca^{q+} and V^{q+} + He, in which two maxima were also observed in the energy dependence of $\sigma_{K\alpha\beta}^{q-1}$. These two maxima correspond[2] to groups of intermediate resonance states in the RTE process for which the excited and the captured electrons occupy energy levels with quantum numbers (in the intermediate excited state of the two electrons which participate in the RTE process) n =2,2 or n = 2 $\geq$ 3. The results for Ca^{19+} are the first observation of RTE for a hydrogen-like ion which, of course, has an initial vacancy in the K shell. The large rise in $\sigma^{q-1}_{k\alpha\beta}$ for Ca^{19+} as the beam energy is decreased below 200 MeV is attributed to electron capture, without accompanying excitation, to an excited state (n $\geq$ 2) followed by deexcitation via photon emission to the already existing K vacancy in the incident projectile. The strong dependence of $\sigma^{q-1}_{K\alpha\beta}$ on the incident charge state of the projectile is clear. Since the lower-energy maximum in $\sigma^{q-1}_{K\alpha\beta}$ results from RTE involving n = 2,2 transitions, there must be at least two initial vacancies in the L shell of the ion (for calcium ions, charge states q $\geq$ 12+) to have a contribution to the first maximum. For the higher-energy maximum, i.e., n=2,$\geq$3 transitions, there must be at least one vacancy in the L shell (for calcium ions, q $\geq$11+) in order for for n = 2,3 to contribute to the maximum. For calcium ions in charge states q $\leq$ 10+ only n = 3, $\geq$ 3 transitions can contribute to RTE. However, the probability of occurrence of these n=3,$\geq$3 transitions is very small.[7]

The dependence of the $\sigma^{q-1}_{K\alpha\beta}$ cross-section maxima on the charge state of the incident projectile is shown in Fig. 2 for both the n=2,2 and the n=2,$\geq$3 transitions, for Ca^{q+} ions in H_2. The values for the maxima were obtained by subtracting a linear background from each of the observed n=2,2 and n=2,$\geq$3 peak heights. The lines show the calculated RTE maxima for these same transitions based on the theoretical DR cross sections of Hahn and co-workers.[7] It is seen that the predicted charge-state dependence agrees reasonably well with the data.

The measurements for $Ca^{16,17,18+} + H_2$ provide a direct comparison with earlier results for these same ions incident on He.[1] It is expected that the widths of the RTE maxima will be less for H_2, due to the smaller width of the electron momentum distribution for H_2 compared with He. The measurements indicate that this is, in fact, the case, as shown in Fig. 3 for Ca^{17+} projectiles. Each of the $\sigma_{K\alpha\beta}^{q-1}$ peaks for the H_2 target are narrower than the corresponding peak for the He target, and the minimum between the peaks is considerably more pronounced for the H_2 target, in agreement with the theoretical RTE calculations shown. To facilitate comparison between theory and experiment, and between the two data sets, all experimental and theoretical results have been normalized to the same value at the energy position of the lower-energy peak. The calculated position of the lower-energy maximum agrees reasonably well with the data for both H_2 and He, while the agreement with the calculated higher-energy maximum is not as good.

IV. RTE (L shell) for Nb Ions

Additional information concerning the RTE process and its relationship to DR can be obtained from studies of RTE involving excitation of the projectile L-shell, for which very few data presently exist. Resonant behavior for L x-ray emission coincident with projectile electron capture was observed[8] for 455-710 MeV $_{57}La^{40+}$ ions incident on H_2. While there are presently no detailed theoretical calculations to compare with these results, the energy position of the maximum in the observed coincidence cross section is consistent with that expected on the basis of specific Auger transitions. In another experiment,[9] measurements were made of the total L_α x-ray production, without coincidence, for a range of charge states for 3.6 MeV/u Sm^{q+} + Xe collisions. A maximum was observed in the x-ray-emission cross section for charge states with $46 \leq q \leq 52$. This maximum was attributed to L-shell RTE, and was found to be consistent with RTE calculations.

We have recently investigated[10] L-shell RTE for 230-610 MeV Nb^{31+} (neonlike) ions incident on H_2. The closed L-shell configuration for the projectile was chosen to simplify the theoretical analysis in order to facilitate a comparision between experiment and theory.[11] The measured cross sections, $\sigma^{q-1}_{L\alpha\beta}$, for projectile Lαβ x-ray emission coincident with single-electron capture are shown in Fig. 4. The broad maximum in $\sigma^{q-1}_{L\alpha\beta}$ near 350 MeV is attributed to RTE for L-shell excitation of ${}_{41}Nb^{31+}$. The cross section at the RTE peak is an order of magnitude larger than the largest peak values observed to date for K-shell RTE.

The vertical bars shown in Fig. 4 indicate the positions of the strongest Auger transitions in Nb^{30+} involving 2p excitations. The lines are labeled with the configurations of the excited and captured electrons in the intermediate states in the RTE process. Those states with n>6 are grouped together at 404 MeV. The height of each line is proportional to the theoretical DR cross section, obtained from a preliminary calculation by Hahn et al.[12], for the particular intermediate state or group of states. While 2p excitations dominate, additional contributions to L-shell RTE in the energy region between 260 and 410 MeV will be produced by excitation of the projectile 2s electrons.

As expected for RTE the observed maximum in $\sigma^{q-1}_{L\alpha\beta}$ occurs at energies corresponding to strong Auger transitions. We have calculated[10] the theoretical RTE cross section based on the calculated[12] DR cross sections with the 2s excitation included. This calculated RTE cross section (normalized by a factor of 0.75) is shown as the solid line in Fig. 4. The agreement between theory and experiment is reasonable.

V. Electron loss and excitation

An analogous two-electron process is one in which one projectile electron is lost and another is excited in the single collision of a highly-stripped heavy ion with an atom, i.e., loss and excitation in a single collision (LE).[13] We have measured cross sections for single-electron loss, σ_{q+1}, K-shell excitation, $\sigma_{K\alpha\beta}$, and simultaneous electron loss and excitation, $\alpha_{K\alpha\beta}^{q+1}$, for 150 to 360 MeV (3.75 to 9 MeV/u) Ca^{q+} ions (q=12 to 19) in H_2 and He targets at the SuperHILAC accelerator.

Electron-capture cross sections in this energy range typically decrease rapidly with increasing projectile energy,[14] while both the electron-loss and electron-excitation cross sections have a much weaker energy dependence, generally exhibiting a broad maximum, predicted by theory, at a velocity between v_e and $2v_e$, where v_e is the velocity of the electron most likely to be lost or excited in the projectile, and v is the projectile velocity. The relative magnitudes of electron-capture and electron-loss cross sections depend strongly on the charge state of the ion.[15] However, for these measurements, the electron-loss cross sections are generally equal to or greater than the electron-capture cross sections.

The typical energy dependences of σ_{q+1}, $\sigma_{K\alpha\beta}$ and $\sigma_{K\alpha\beta}^{q+1}$ are illustrated in Fig. 5, where measurements for helium-like Ca^{18+} ions in a He target are shown. The cross sections generally exhibit similar weak energy dependencies. The ratio v/v_e varies from 0.6 to 2.0 for these measurements; v_e corresponds to projectile energies of about 84 MeV for 2s electrons and 375 MeV for 1s electrons, which accounts for the steep energy dependence of $\sigma_{K\alpha\beta}^{q+1}$ for Ca^{18+}.

The charge-state dependence of the cross sections can be illustrated by considering measurements at one energy. Cross sections for Ca^{q+} (q = 12 to 19) in H_2 and He at 250 MeV are presented in Fig. 6 . The main feature is the change in the magnitude of the electron-loss cross section at the boundary the L and K shells. We see that σ_{q+1} decreases by almost an order of magnitude in going from Li-like Ca^{17+} to He-like Ca^{18+}. Note also that σ_{q+1} decreases by approximately a factor of 2 in going from Ca^{16+} to Ca^{17+} and from Ca^{18+} to Ca^{19+}, which can be accounted for by the reduction of the number of electrons remaining in the L and K shells, respectively, from 2 to 1. This effect is also evident in $\sigma_{K\alpha\beta}$ in going from Ca^{18+} to Ca^{19+}. For charge states lower than 18+, $\sigma_{K\alpha\beta}$ decreases slowly with decreasing charge state due to the fuller L-shell for the lower charge states.

The loss-and-excitation cross section $\sigma_{K\alpha\beta}^{q+1}$ exhibits a pronounced decrease between Ca^{16+} and Ca^{17+}. This decrease must be associated with the decrease in σ_{q+1}, since $\sigma_{K\alpha\beta}$ remains relatively unchanged in going from Ca^{16+} to Ca^{17+}. However, the relative magnitude of the decrease in $\sigma_{K\alpha\beta}^{q+1}$ is much larger than that in σ_{q+1}.

An important feature of the data shown is that $\sigma_{K\alpha\beta}^{q+1}$ is significantly less than $\sigma_{K\alpha\beta}$. This indicates that, for the case shown, projectile K x-ray production is through the excitation, rather than the removal, of a 1s electron, since if a 1s electron were lost, it would be observed in the loss and excitation coincidence channel.

It is interesting to note that for Ca^{18+} (He-like) and Ca^{19+} (H-like) collisions in H_2 and He the cross section for exciting a projectile 1s electron ($\sigma_{K\alpha\beta}$) and removing a projectile 1s electron (σ_{q+1}) have the same value.

VI. RTE in Electron Capture

The RTE cross section can be sufficiently large that it appreciably adds to the normal (i.e., electron capture without excitation) cross section. This has been dramatically illustrated in the recent observation[16] of structure with energy in the electron-capture cross section for fast highly charged Ca ions in a H_2 target. The electron-capture (non-coincidence) cross section is shown in Fig. 7, along with the RTE (coincidence) cross section; the smooth curve shows the monotonic $E^{-4.2}$ energy dependence expected. The structure is attributed to RTE enhancing normal electron capture.

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Figure Captions

Fig. 1 Cross sections for projectile K x rays coincident with single-electron capture, $\sigma_{K\alpha\beta}^{q-1}$, for collisions of $_{20}Ca^{q+}$ ions with H_2. The solid curves are drawn to guide the eye. Note the scale change for the $Ca^{10,11,12+}$ data. [Tanis et al.[6]]

Fig. 2 Maximum values (less background) of the $\sigma_{K\alpha\beta}^{q-1}$ cross sections shown in Fig. 1 plotted as a function of the incident charge state of the projectile. The lines are calculated[7] RTE cross- section maxima. [Tanis et al.[6]]

Fig. 3. Comparison of the $\sigma_{K\alpha\beta}^{q-1}$ cross sections for Ca^{17+} ions in H_2 and He. Solid circles: H_2; open circles: He. Also shown are predicted RTE cross sections for these collision systems. Calculated curves and the data for He have been normalized to the lower-energy maximum of the H_2 measurements. Normalization factors for the He data, H_2 theory, and He theory are 1.51, 0.87, and 1.16 respectively. [Tanis et al.[6]]

Fig. 4 Cross sections for projectile L-shell x rays coincident with single-electron capture, $\sigma_{L\alpha\beta}^{q-1}$, for collisions of $_{41}Nb^{31+}$ with H_2. The vertical bars give the theoretical positions and relative intensities of the strongest Auger transitions involving 2p excitations. The configurations of the excited and captured electrons in the intermediate state are indicated. The solid curve is a theoretical RTE calculation based on DR cross-section calculations. [Bernstein et al.[10]]

Fig. 5 Energy dependence of cross sections for Ca^{q+} in He: closed squares: single-electron loss, σ_{q+1}; circles: projectile K x-ray production, $\sigma_{K\alpha\beta}$; open squares: projectile electron loss and excitation, $\sigma_{K\alpha\beta}^{q+1}$. [Graham et al.[13]]

Fig. 6. Charge-state dependence of cross sections for 250-MeV Ca^{q+} in H_2 and He. Solid symbols, H_2 target; open symbols, He target. Lines are to guide the eye:--, σ_{q+1}; - - - -, $\sigma_{K\alpha\beta}$; -. -. -., $\sigma^{q+1}_{K\alpha\beta}$. [Graham et al.[13]]

Fig. 7 Cross section for $Ca^{17+} + H_2$. Closed circles: single-electron capture, $\sigma_{q,q-1}$; open circles: single-electron capture coincident with K-x-ray emission, σ^{q-1}_{Kx}. The solid line are drawn to guide the eye. The dashed line shows an $E^{-4.2}$ energy dependence normalized at 150 MeV. [Graham et al.[16]]

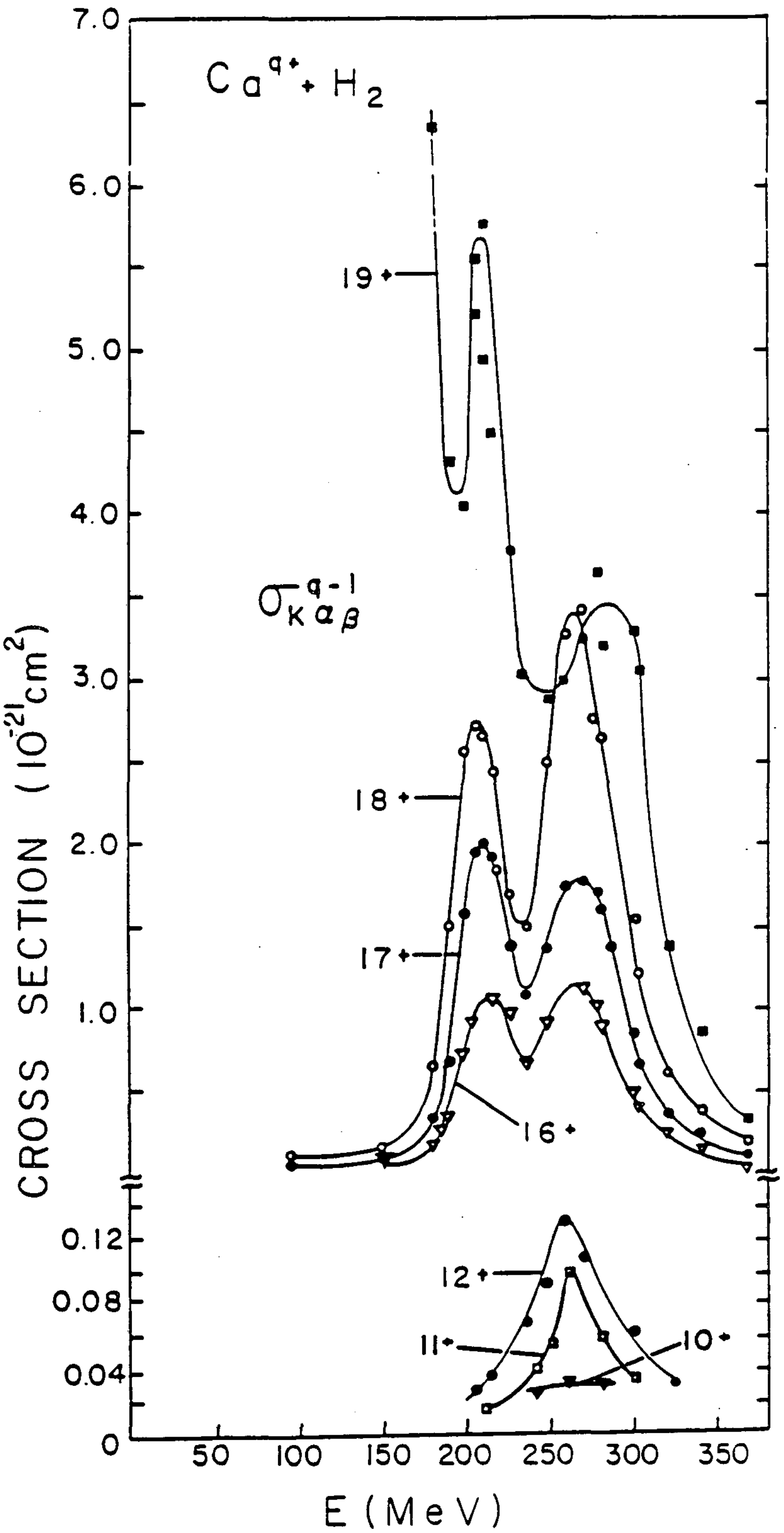

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Fig. 1

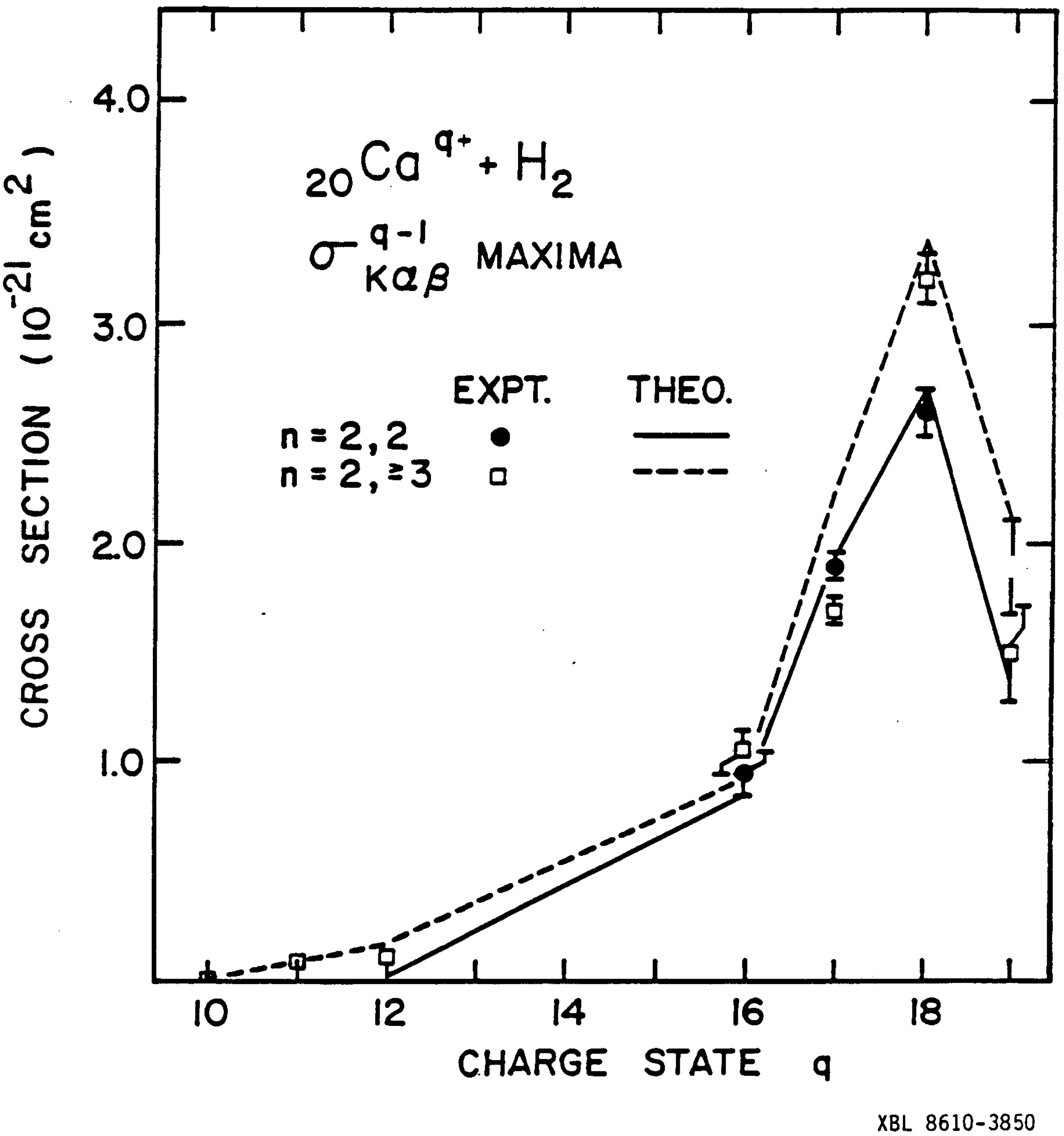
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Fig. 2

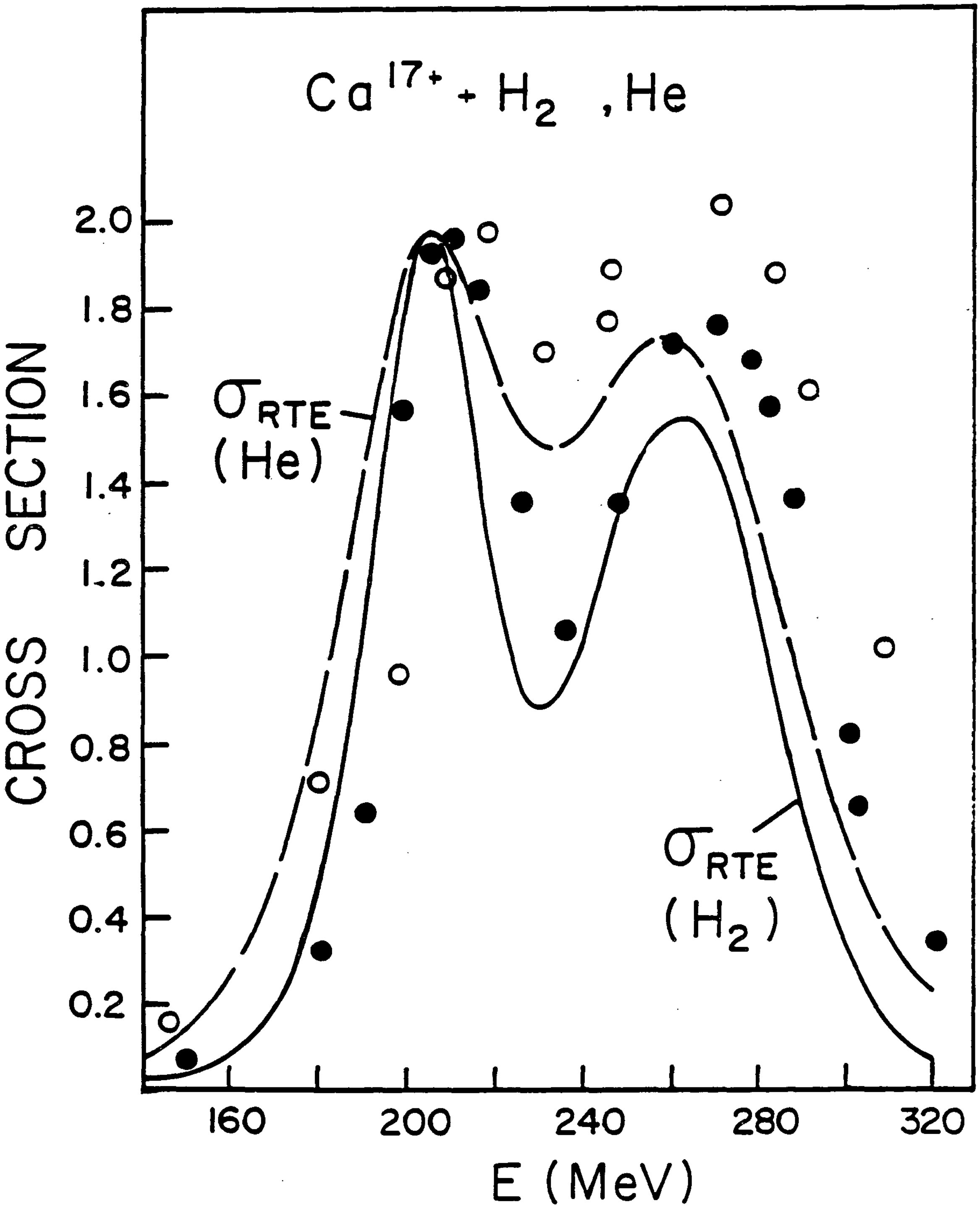

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Fig. 3

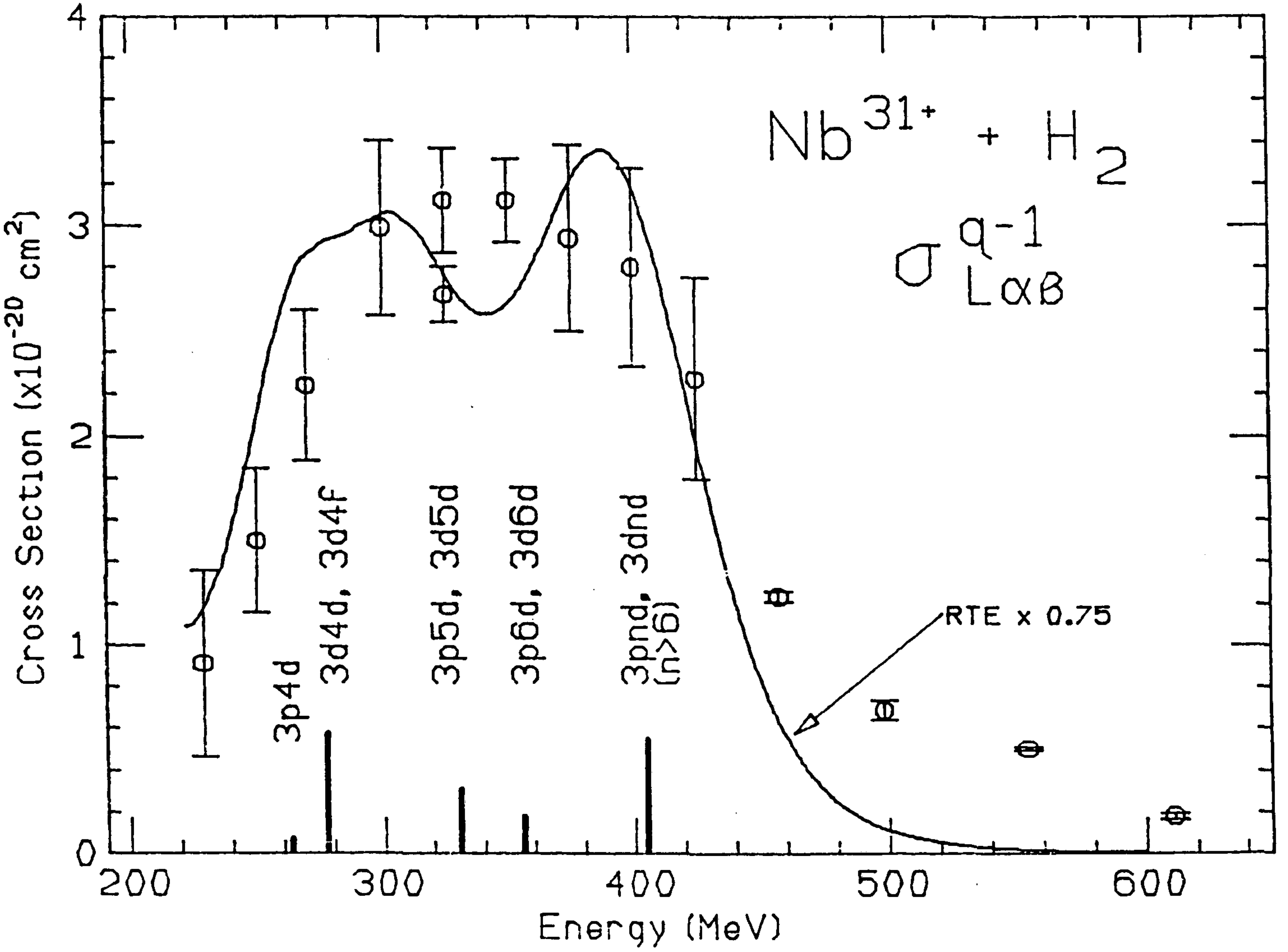

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Fig. 4

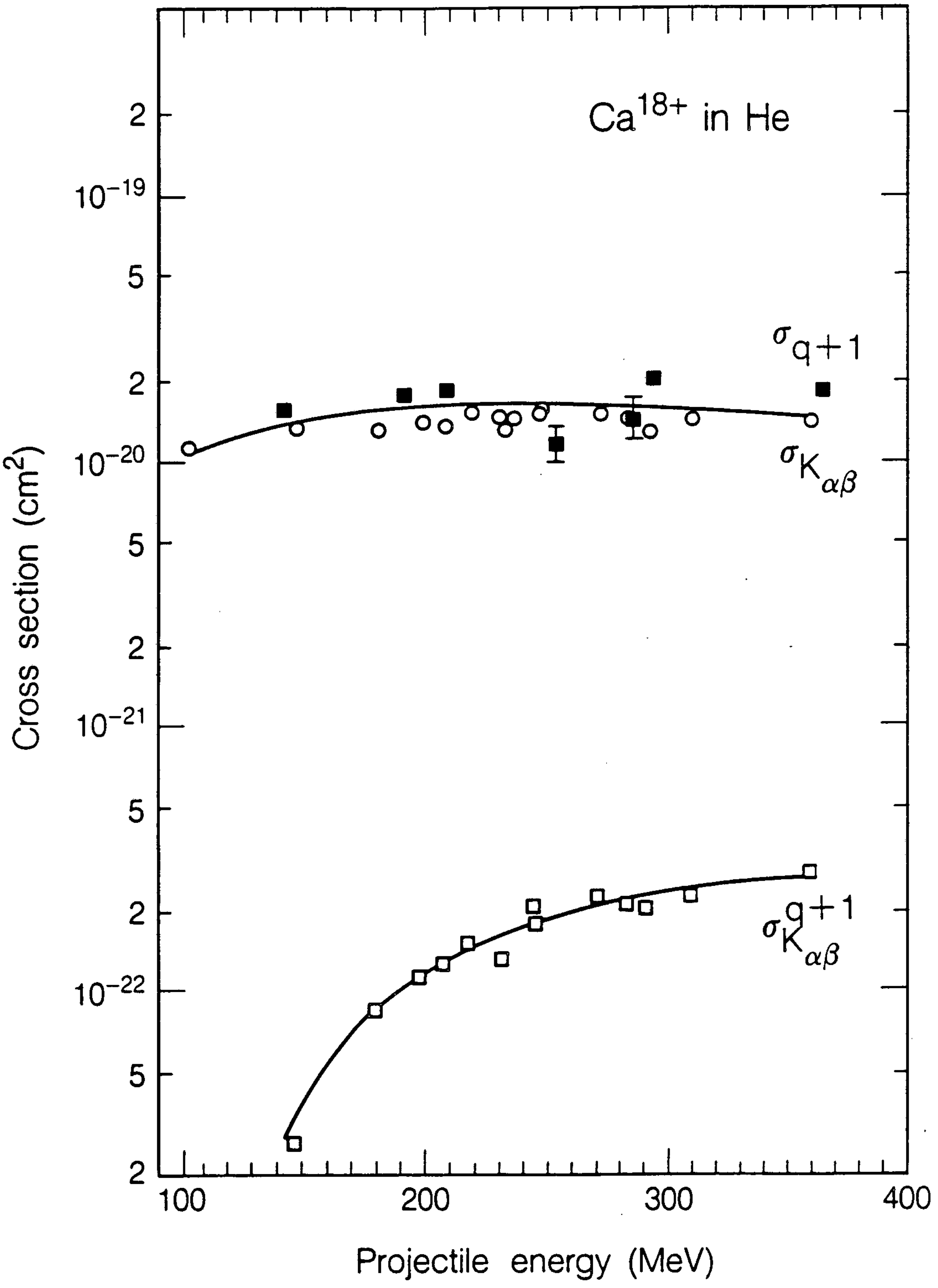

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Fig. 5

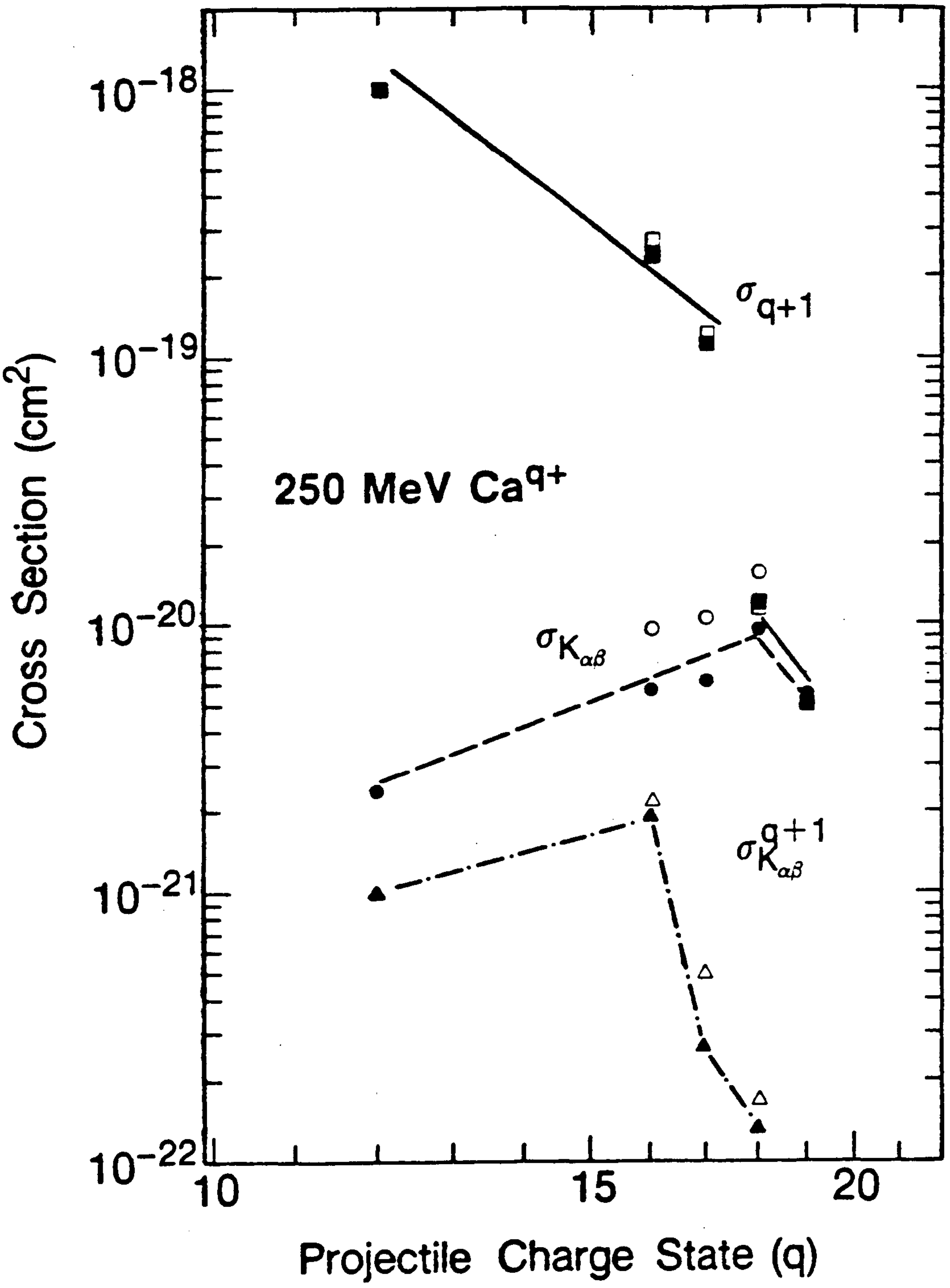

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Fig. 6

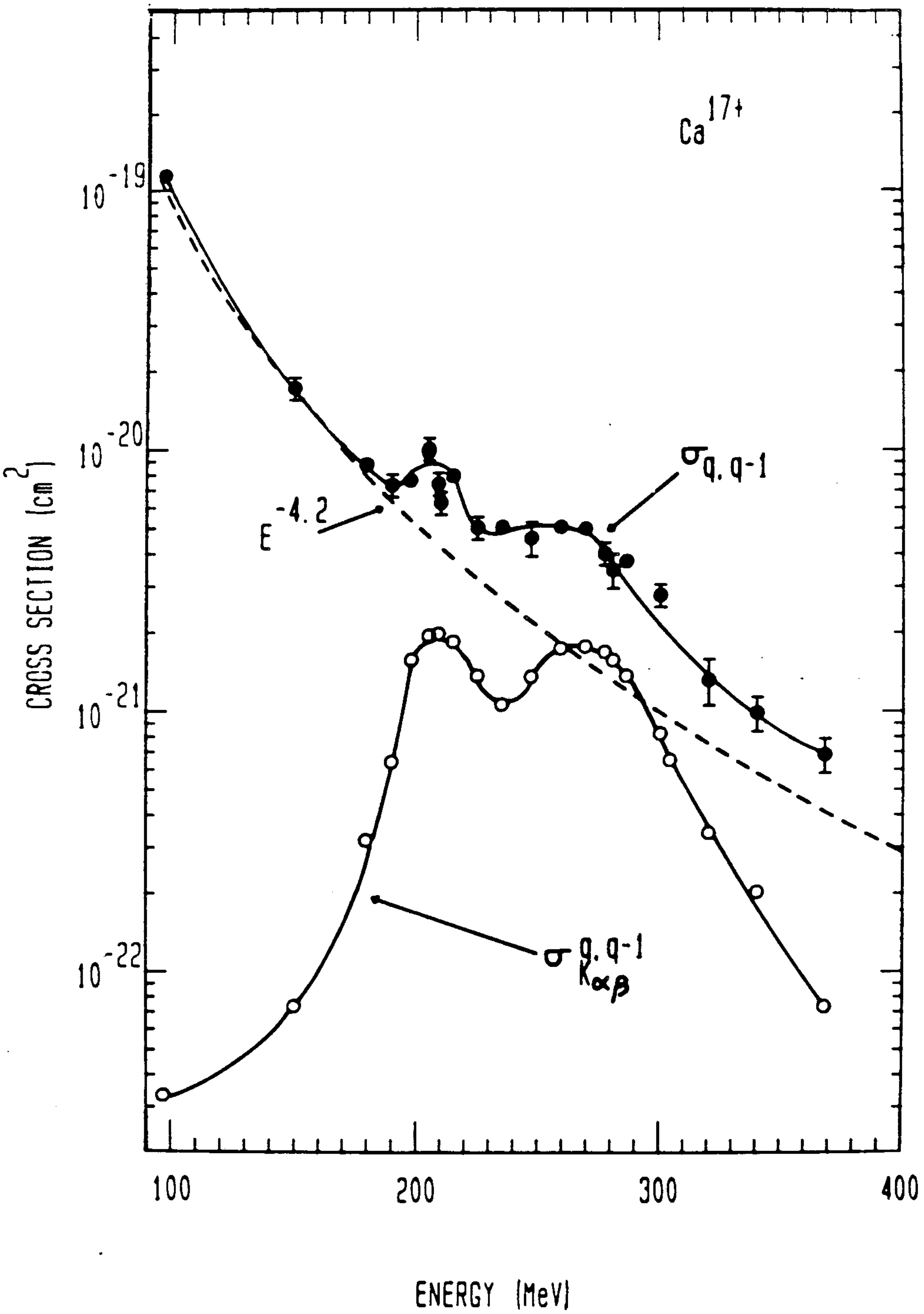

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Fig. 7

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