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K- AND L-SHELL RESONANT TRANSFER AND EXCITATION IN ION-ATOM COLLISIONS

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Recent experimental studies of resonant transfer and excitation (RTE) in ion-atom collisions are reviewed. In the RTE process correlated electron capture and projectile excitation occur together in a single encounter with a target atom. Measurements of $Ca^{q+} + H_2$ (q=10 to 19) from 100 to 370 MeV establish the projectile charge-state dependence of K-shell RTE and provide a detailed test of the theory. Structure due to RTE is observed in the energy dependence of the total electron-capture cross sections for this collision system. A comparison of the $Ca^{17+} + H_2$ data with previous results for Ca^{17+} + He demonstrates the effect of the target-electron momentum distribution on the RTE process. Studies of 230 to 610 MeV $Nb^{31+} + H_2$ provide information about RTE involving projectile L-shell excitation. All the measurements are in reasonable agreement with theoretical calculations.

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1. Introduction

Experimental[1,2] and theoretical[3,4,5] studies have established the existence of resonant transfer and excitation (RTE) in ion-atom collisions. RTE occurs when projectile excitation and capture take place simultaneously in a single encounter with a target atom through the electron-electron interaction between a projectile electron and a target electron. The intermediate state which is formed in the RTE process can subsequently decay by photon emission or electron emission (Auger decay). RTE is analogous to dielectronic recombination (DR), 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 is identified experimentally by the observation of resonant behavior in the energy dependence of (1) the yield of deexcitation photons coincident with projectiles which have captured an electron, or (2) the yield of Auger electron emission associated with capture events.[6]

Having established the existence of RTE and its close relationship to DR, it is of interest to determine the dependence of RTE on various collision parameters. The projectile Z dependence of RTE over the range $16 \leq Z \leq 23$ has already been investigated.[7] In the following we present a review of recent experiments which (1) establish the charge-state dependence of RTE for Ca ions with incident charge states ranging from q = 10 + (neonlike) to q = 19 + (hydrogenlike), (2) demonstrate the effect of the target electron momentum distribution on RTE, (3) report the observation of structure in the energy dependence of high energy total electron-capture cross sections, and (4) investigate RTE involving excitation of the projectile L-shell for Nb^{31+}.

2. Results and Discussion

The work reported here was carried out at the Lawrence Berkeley Laboratory using the SuperHILAC. Details concerning the experimental set-up are given elsewhere.[2,7,8]

Measurements[8] were made for $Ca^{q+} + H_2$ (q=10,11,12,16,17,18,19) from 100 to 370 MeV. Fig. 1 shows the cross sections for projectile K x rays coincident with single electron capture $\sigma^{q-1}_{K\alpha\beta}$. The strong dependence of $\sigma^{q-1}_{K\alpha\beta}$ on the incident energy and charge state is obvious. The two maxima observed for the higher charge states correspond[2] to groups of intermediate resonance states in the RTE process for which the excited and captured electrons occupy energy levels with principal quantum numbers n = 2,2 (near 210 MeV) or n = 2,$\geq$3 (near 270 MeV). For q = 11 and 12 only n = 2,$\geq$3 states are observed while for q = 10 no structure is evident. These results can be understood in terms of the initial number of L-shell vacancies present for the different charge states. For q = 11 the n = 2,2 states cannot be formed since this charge state has only one L-shell vacancy. While the q = 12 charge state does have two L-shell vacancies, the probability[4] of forming n = 2,2 states for q = 12 is much smaller than the probability of forming n = 2,$\geq$3 states. Since the q = 10 (neonlike) charge state has no L vacancies, only n = 3,$\geq$3 states, which would be very close in energy to the n = 2,$\geq$3 states, could contribute to RTE. However, calculations[4,9] indicate that the probability of occurrence of n = 3,$\geq$3 transitions is very small.

Fig. 2 shows the dependence of the $\sigma^{q-1}_{K\alpha\beta}$ maxima on the charge state of the incident projectile. The experimental values were determined by subtracting a linear background, obtained by interpolating the nonresonant yield near 150 and 370 MeV, from the maximum cross sections in Fig. 1. The errors shown in Fig. 2 are relative errors. The absolute uncertainty in the data is estimated to be ± 20%. The lines in Fig. 2 are theoretical RTE calculations based on the theoretical DR cross sections of Hahn and co-workers[4,10]. It is seen that the data agree reasonably well with the calculations.

The measurements for Ca^{17+} + H_2 provide a direct comparison with our earlier results[2,7] for Ca^{17+} + He. It is expected that the widths of the RTE maxima will be less for H_2, due to the smaller electron momentum distribution of H_2 compared with He. As seen in Fig. 3 each of the $\sigma^{q-1}_{K\alpha\beta}$ peaks for the H_2 target is 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[3,10] 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 high-energy maximum is not as good. This same high-energy discrepancy has been observed in RTE measurements for $_{16}S^{13+}$ + He collisions.[7] The origin of the discrepancy is not understood at present. It should be noted that the relative peak heights of the calculated RTE cross sections in Fig. 3 for the n=2,2 and n=2,≥3 transitions are not the same as those shown in Fig. 2 for q=17+. This difference is apparently due to the approximate manner[9] in which the calculated RTE maxima were obtained from the theoretical DR cross sections. The RTE calculations shown in Fig. 3, which are based on the method of Brandt[3], represent a more accurate method of accounting for the energy distribution of the DR transitions and the effect of the target electron momentum distribution.

Structure in the energy dependence of single-electron-capture cross sections in fast ion-atom collisions was observed[11] for $Ca^{16,17,18,19+}$ + H_2. This nonmonotonic energy dependence is attributed to substantial contributions to electron capture from RTE. For all four charge states the structure occurs at the same energies as the maxima in $\sigma_{K\alpha\beta}^{q-1}$ and has the same general shape as $\sigma_{K\alpha\beta}^{q-1}$. However, the magnitude of the structure in the capture cross sections is somewhat larger than that expected by simply adding the RTE contribution to the interpolated nonresonant capture cross sections. While this discrepancy may reflect an underestimate in the absolute uncertainties in the measured cross sections, another possibility may be that the RTE and electron-capture processes interfere, thereby resulting in cross sections which are not simply additive. The present data are insufficient to determine the origin of the discrepancy.

RTE involving excitation of the projectile L-shell has been measured[12] 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 at which the maximum occurs in the observed cross section for L x-ray emission coincident with projectile electron capture can be related to specific Auger transitions. In another experiment measurements[13] were made of the total $L\alpha$ x-ray production, without coincidence requirements, for a range of charge states for 3.6 MeV/u Sm^{q+} + Xe collisions. A maximum observed in the x-ray emission cross section for charge states with $46 \leq q \leq 52$ was attributed to L-shell RTE and was found to be consistent with RTE calculations.

More recently we have investigated[14] 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.[9] The measured cross sections, $\sigma_{L\alpha\beta}^{q-1}$, for projectile $L\alpha\beta$ x-ray emission coincident with single electron capture are shown in Fig. 4. Relative uncertainties in the data points are indicated by the error bars. Absolute uncertainties are estimated to be ± 20%. The maximum in $\sigma_{L\alpha\beta}^{q-1}$ near 350 MeV is attributed to RTE involving L-shell excitation of $_{41}Nb^{31+}$. The cross section at the RTE peak is nearly an order of magnitude larger than the largest peak values observed to date for K-shell RTE.

The vertical bars shown on the energy scale in Fig. 4 indicate the positions of the strongest Auger transitions in Nb^{30+} involving 2p excitations. Using theoretical DR cross sections obtained from a preliminary calculation by Hahn et al.,[15] we have calculated[3] the theoretical RTE cross section. This calculated RTE cross section (normalized by a factor of 0.75) with the 2s excitation included is shown as the solid curve in Fig. 4. The strong maximum predicted near 160 MeV corresponds to the formation of intermediate states where both the excited and captured electrons have n=3. Unfortunately, we were not able to investigate this region since a Nb^{31+} beam was not available from the SuperHILAC at these energies. In the region covered by the measurements the agreement between theory and experiment is reasonable, although the theory overestimates the measurements by about 25% at the maximum near 350 MeV. More precise measurements are needed to determine if the structure predicted near 350 MeV by the calculations is real. However, it should be noted that the minimum in the calculated curve near 350 MeV may arise, at least in part, as an artifact of the present calculation since the DR cross sections from a group of nearby states are concentrated at a single mean energy. Thus, more detailed calculations of the energies and DR cross sections for individual states are needed. At the higher energies the theory falls more rapidly than the data. This difference between experiment and theory is similar to previous results obtained for K-shell

RTE as seen in Fig. 3.

3. Conclusions

In summary, recent investigations of RTE (1) establish the projectile charge-state dependence of K-shell RTE and provide a rather detailed test of the theory, (2) demonstrate directly the effect of the target electron momentum distribution on RTE, (3) show that RTE can make an important contribution to total single-electron-capture cross sections, and (4) provide information concerning RTE involving excitation of the projectile L-shell. The measurements are in reasonable agreement with RTE calculations based on theoretical cross sections for DR although some significant discrepancies remain.

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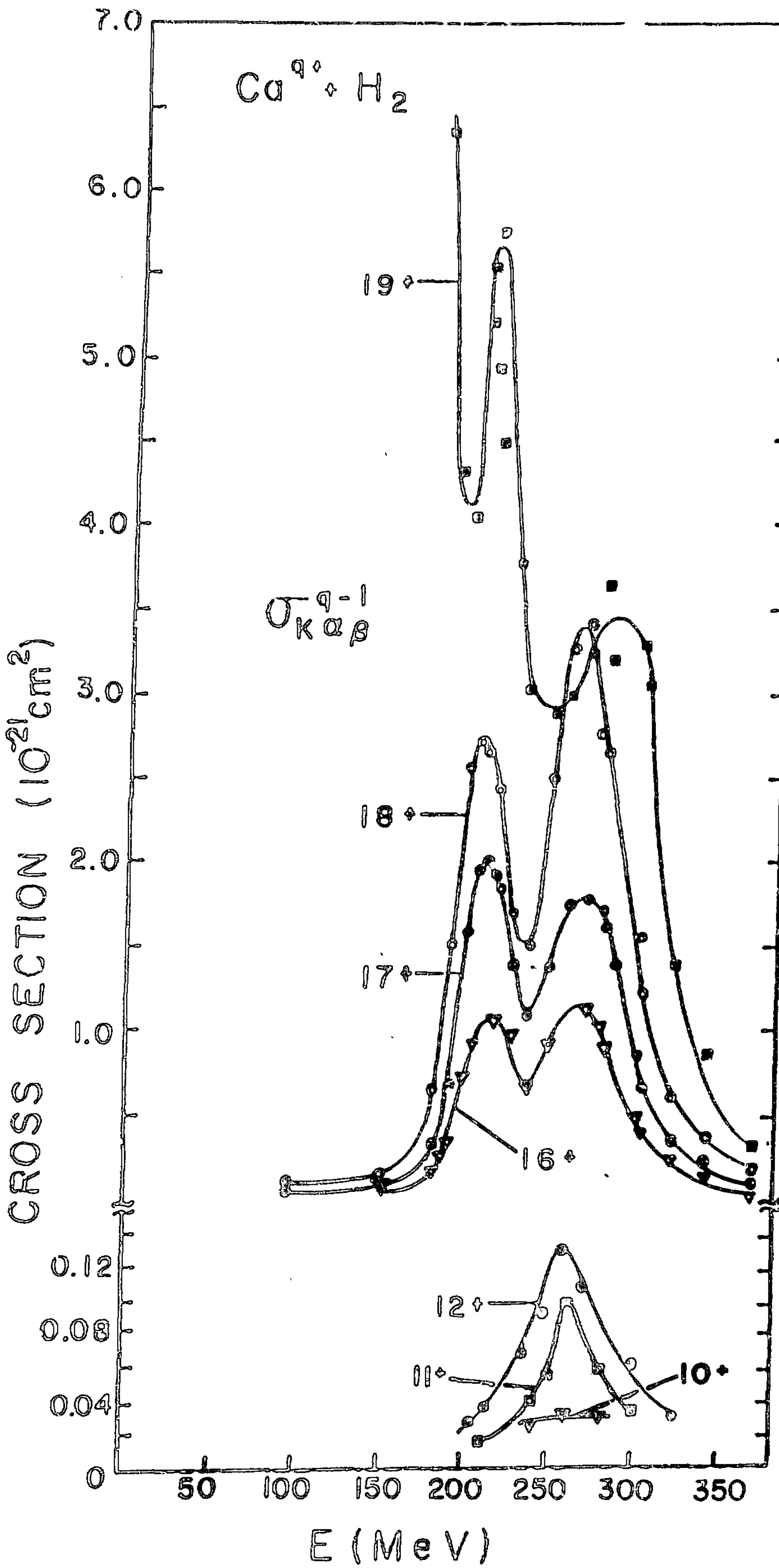
FIGURE CAPTIONS

FIG. 1. Cross sections for projectile K x rays coincident with single electron capture, $\sigma^{q-1}_{K\alpha\beta}$, for collisions of $_{20}Ca^{q+}$ ions with H_2 (q = 10,11,12,16,17,18, and 19). The solid curves are drawn to guide the eye. Note the scale change for the $Ca^{10,11,12+}$ data. Relative uncertainties in the data are typically 5-10%, and the absolute uncertainty is estimated to be ± 20%.

FIG. 2. Maximum values less background (see text) of the $\sigma^{q-1}_{K\alpha\beta}$ cross sections shown in Fig. 1 plotted as a function of the incident charge state of the projectile. The error bars show relative uncertainties in the data. The solid and dashed curves are calculated maxima obtained from Refs. 4 and 9.

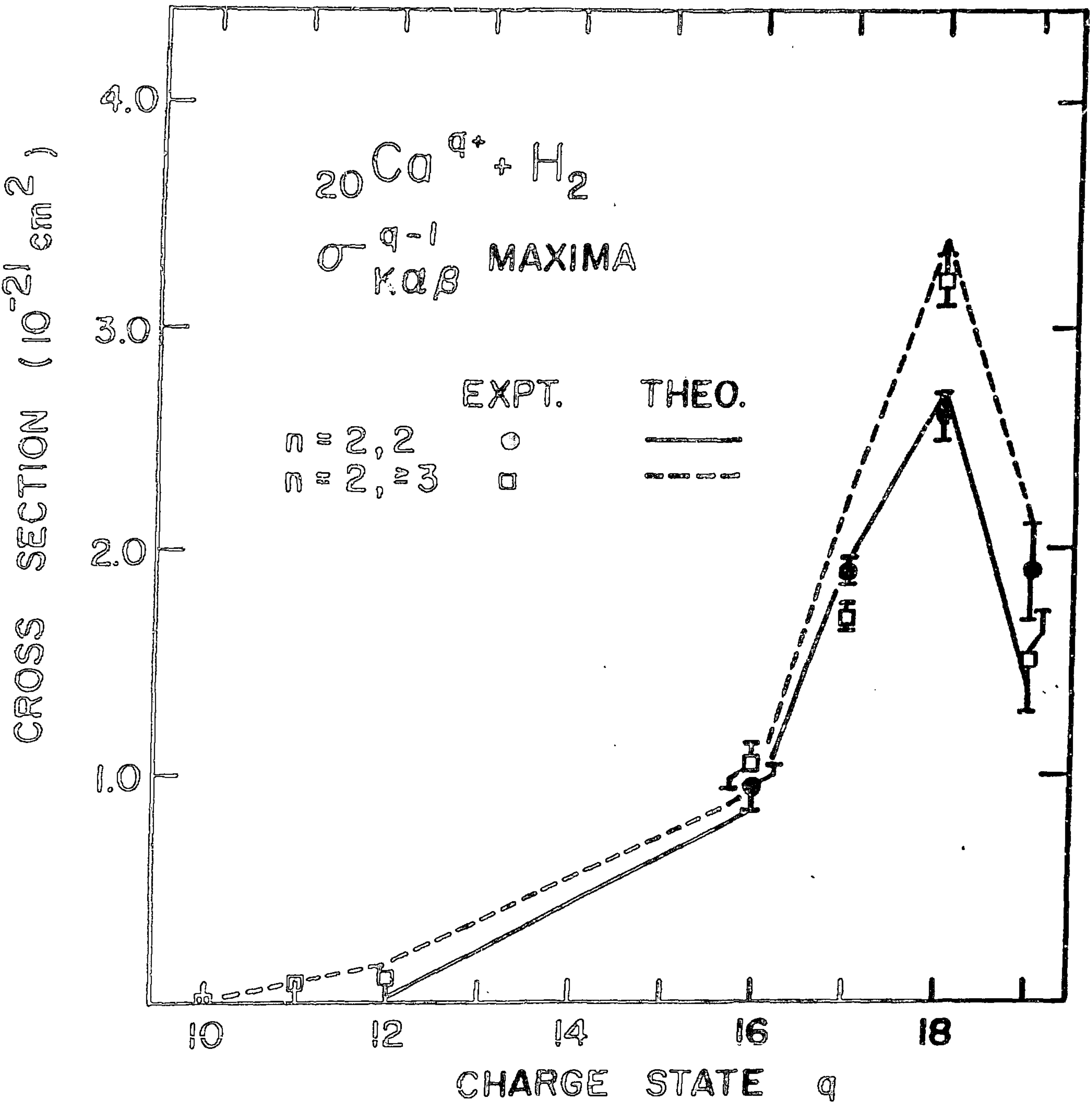
FIG. 3. Comparison of the $\sigma^{q-1}_{K\alpha\beta}$ cross sections for Ca^{17+} ions in H_2 and He. Solid circles are for H_2, and the open circles are for He. Also shown are predicted RTE cross sections. Both calculated curves and the data for He have been normalized to the lower-energy maximum 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.

Fig. 4 Cross sections for projectile L-shell x rays coincident with single-electron capture, $\sigma^{q-1}_{L\alpha\beta}$, for collisions of $_{41}Nb^{31+}$ with H_2. The vertical bars along the energy axis 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 the DR cross section calculations from Ref. 15 (see text).



$Ca^{q+} + H_2$
$\sigma_{K\alpha\beta}^{q-1}$
19+
18+
17+
16+
12+
11+
10+
CROSS SECTION (10^{-21} cm^2)
E (MeV)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.12
0.08
0.04
0
50
100
150
200
250
300
350

FIG. 1



4.0
3.0
2.0
1.0
CROSS SECTION (10^{-21} cm^2)
$_{20}Ca^{q+} + H_2$
$\sigma^{q-1}_{K\alpha\beta}$ MAXIMA
EXPT.
THEO.
n = 2, 2
n = 2, ≥3
10
12
14
16
18
CHARGE STATE q

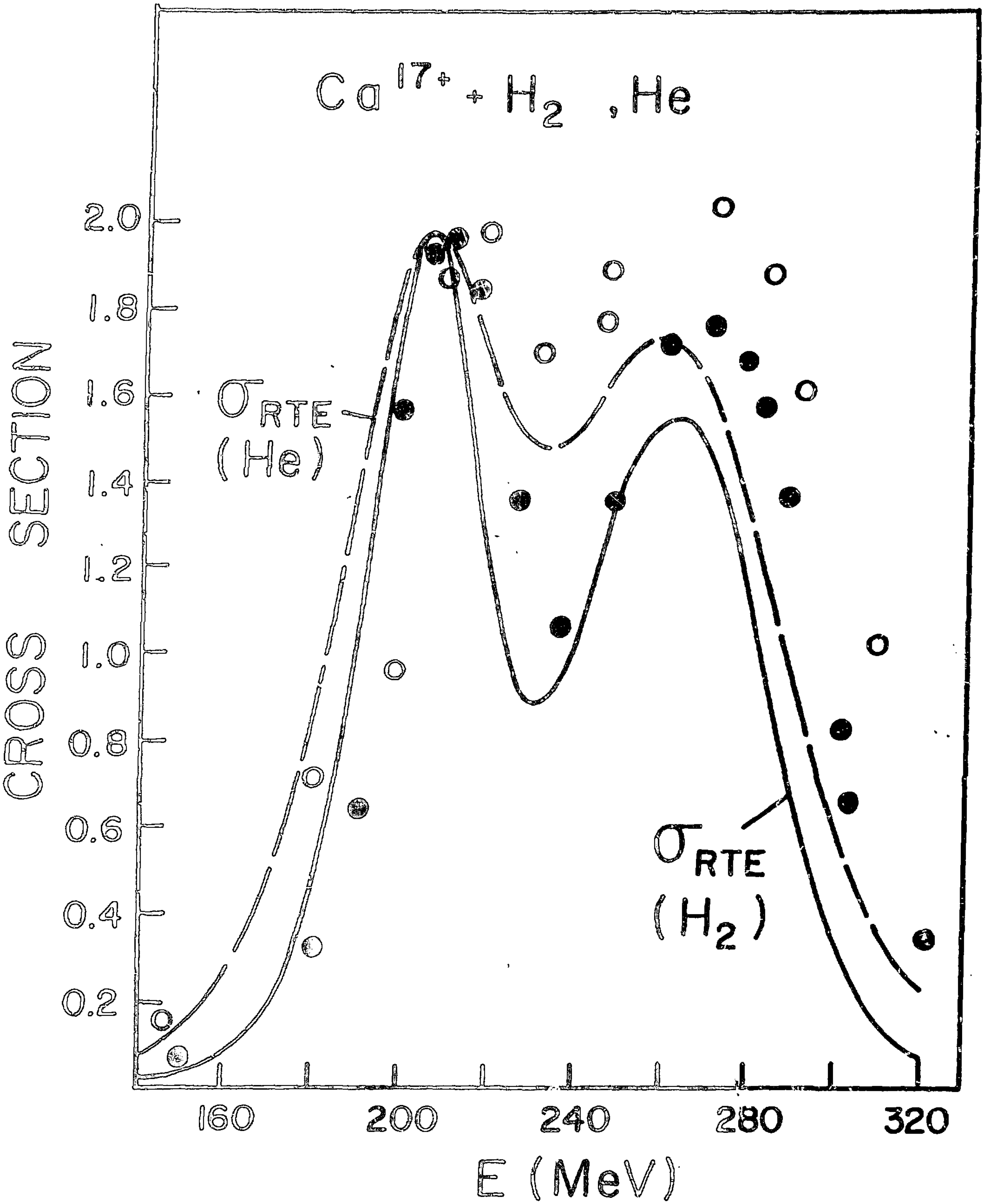
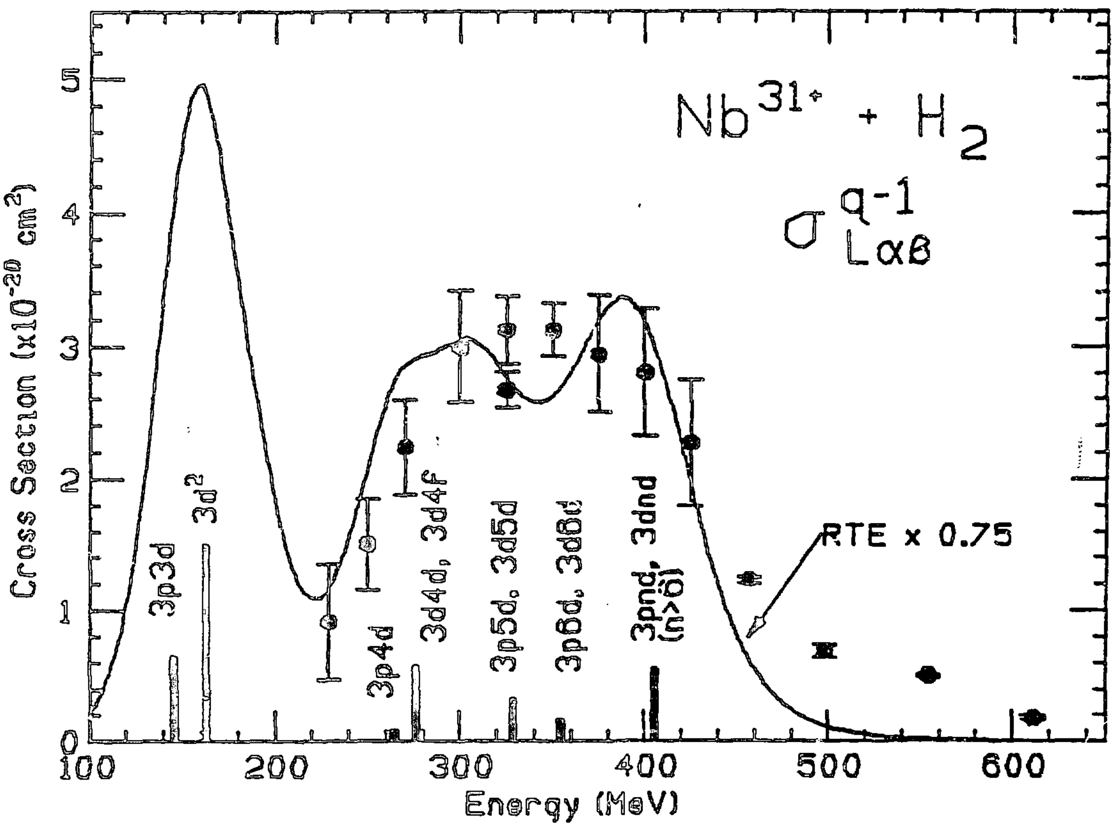

Ca 17+ + H2 ,He
CROSS SECTION
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
σRTE (He)
σRTE (H2)
160
200
240
280
320
E (MeV)

FIG. 3



Nb^{31+} + H_2
$\sigma^{q-1}_{L\alpha\beta}$
RTE x 0.75
3p3d
3d^2
3p4d
3d4d, 3d4f
3p5d, 3d5d
3p6d, 3d6d
3pnd, 3dnd (n>6)
Cross Section (x10^{-20} cm^2)
Energy (MeV)
0
1
2
3
4
5
100
200
300
400
500
600

FIG. 4