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RESONANT-TRANSFER-AND-EXCITATION FOR HIGHLY CHARGED IONS ($16 \leq Z \leq 23$ IN COLLISIONS WITH HELIUM

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Abstract

Significant new evidence is presented for resonant-transfer-and-excitation (RTE) in ion-atom collisions. This process occurs when a target electron is captured simultaneously with the excitation of the projectile followed by de-excitation via photon emission. RTE, which is analogous to dielectronic recombination (DR), proceeds via the inverse of an Auger transition, and is expected to be resonant for projectile velocities corresponding to the energy of the ejected electron in the Auger process. RTE was investigated by measuring cross sections for projectile K x-ray emission coincident with single electron capture for 15-200 MeV $_{16}S^{13+}$, 100-360 MeV $_{20}Ca^{16+,17+,18+}$ and 180-460 MeV $_{23}V^{19+,20+,21+}$ ions colliding with helium. Strong resonant behavior, in agreement with theoretical calculations of RTE, was observed in the coincidence cross sections.

Introduction

In an ion-atom collision, resonant-transfer-and-excitation[1,2] (RTE) takes place when capture of a bound target electron is accompanied by simultaneous excitation of the projectile, followed by de-excitation of the resulting intermediate excited state via photon emission. RTE is qualitatively analogous to dielectronic recombination (DR), except that, in the case of DR, the captured electron is initially free. Simultaneous capture-and-excitation involving a free electron is the inverse of an Auger transition and hence is resonant for incident electron energies (in the rest frame of the ion) equal to the outgoing electron energy in the Auger process. In the case of RTE, simultaneous capture-and-excitation is also expected to be resonant for incident ion energies (in the rest frame of the target) which correspond to the ejected Auger electron energies. For both RTE and DR many intermediate resonance states are possible, each one corresponding to an allowed Auger transition. A formal theoretical treatment of simultaneous charge transfer and excitation in ion-atom collisions has recently been developed by Feagin, Briggs and Reeves.[3]

Experimentally, observation of a resonant behavior in the cross section for x rays (resulting from the decay of the intermediate excited state) coincident with electron capture identifies the RTE mechanism and distinguishes it from competing processes such as nonresonant-transfer-and-excitation (NTE)[4] in which uncorrelated electron capture and K-shell excitation occur in a single collision. Since the velocity component of the target electrons (due to their orbital motion) along the beam axis contributes to the relative velocity, the widths of the resonance states in the RTE process reflect the distribution of target electron momenta, i.e., their Compton profile. This distribution is sufficiently large to produce an overlapping of the separate intermediate resonance states such that individual states are not resolved. Instead, a broad resonant-like structure composed of the sum of the contributions from many states is expected.[5]

Correlated two-electron processes such as RTE and DR are of fundamental interest. In addition, RTE, through its connection to DR, may have important applications in astrophysical investigations as well as provide information concerning radiative energy losses in nuclear fusion plasmas[6], particularly for highly ionized ions. Cross sections for both RTE[2] and DR[7] have been measured only recently.

The first experimental evidence for the existence of RTE was obtained in S^{13+} + Ar collisions.[2] As expected for RTE, resonant behavior was observed in the cross section for K x-ray emission coincident with single electron capture. The position of the maximum and the width of the peak are in good agreement with theoretical calculations[5] of the RTE process. However, the theoretical interpretation of the results is complicated by the complexity of the argon target with its 3 electronic shells including the tightly bound 1s electrons. In addition, a relatively large nonresonant contribution, possibly due to the NTE process, was present in the coincidence cross section for these S^{13+} + Ar measurements.

Investigation of RTE in collisions of ions with helium targets promises a simpler interpretation since there are only 2 target electrons, both weakly bound compared to the relative kinetic energy between the projectile and the target. Furthermore, the 2 electron system of helium is expected to give a narrower "resonant" width due to the smaller electron momentum distribution for the target electrons compared to argon[2].

In the following we present significant new evidence[8,9] for the resonant-transfer-and-excitation process for sulfur (Z=16), calcium (Z=20) and vanadium (Z=23) ions incident on helium. Strong resonant behavior, in good agreement with theoretical RTE calculations[5,10] was observed for all three ions in the energy dependence of the cross section for projectile K x rays coincident with single electron capture.

Experimental Procedure

This work was performed at the University of California, Lawrence Berkeley Laboratory using the SuperHILAC and at the Brookhaven National Laboratory using the MP Tandem Van de Graaff. In each case the apparatus has been described elsewhere[2,11].

Briefly, the experimental technique for measuring x rays associated with electron capture is as follows. Ions in a given charge state pass through a differentially pumped gas cell. After emerging from the cell, the beam is magnetically or electrostatically analyzed into its charge state components. Ions which undergo capture in the target gas are detected in a solid state particle detector while the x rays are detected with a Si(Li) detector mounted at 90° to the beam. Coincidences between ions and x rays are measured with a time-to-amplitude converter (TAC). The non-charge-changed-component of the emerging beam is collected in a Faraday cup. A capacitance manometer is used to measure the absolute pressure in the target gas cell. Data were obtained for 3-5 pressures in the range 0-80 microns for each beam energy and charge state studied. The total x-ray yields and the coincidence yields were found to be linear with gas pressure in the range studied indicating that single collisions conditions prevailed.

Results

RTE has been investigated for 15-200 MeV S^{13+} + He collisions[9] (Brookhaven) and for 100-360 MeV $_{20}Ca^{16+,17+,18+}$ and 180-460 MeV $_{23}V^{19+,20+,21+}$ + He collisions[8] (Berkeley). Figures 1, 2a, and 3a show the cross sections for total projectile K x-ray emission, $\sigma_{K\alpha\beta}$, and the cross sections for projectile

K x rays coincident with single electron capture, $\sigma^{q-1}_{K\alpha\beta}$. Relative uncertainties are generally less than ±5% for $\sigma_{K\alpha\beta}$ and less than ±10% for $\sigma^{q-1}_{K\alpha\beta}$. Systematic uncertainties due to x-ray detection efficiency and solid angle lead to an overall uncertainty in the absolute cross sections of about ±20%. Figs. 2b and 3b show the measured $\sigma^{q-1}_{K\alpha\beta}$ for $_{20}Ca^{17+}$ and $_{23}V^{20+}$ ions (lithiumlike in each case) along with the calculated[10] RTE cross sections based on the method of Brandt.[5] The vertical lines show the energy positions and relative contributions of the intermediate resonance states based on the dielectronic recombination cross section calculations of Hahn[12] and coworkers.

From Figs. 1-3 it is seen that $\sigma_{K\alpha\beta}$ varies monotonically with energy in all cases. On the other hand, strong resonant behavior is observed in the energy dependence of $\sigma^{q-1}_{K\alpha\beta}$ for each ion and charge state investigated and for $_{20}Ca^{q+}$ and $_{23}V^{q+}$ two maxima are evident in $\sigma^{q-1}_{K\alpha\beta}$. (For vanadium the measurements extend to 460 MeV which is the highest beam energy obtainable for ^{51}V at the SuperHILAC). Contributions to the measured $\sigma^{q-1}_{K\alpha\beta}$ for $_{20}Ca^{18+}$ and $_{23}V^{21+}$ (heliumlike) from 1s2s metastable states are expected to be small.[13]

In Fig. 1 for S^{13+} + He, $\sigma^{q-1}_{K\alpha\beta}$ shows a maximum near 130 MeV which is attributed to RTE and, in addition, there is a low energy maximum near 30 MeV which may be due to the two-step NTE process. Qualitatively, NTE is proportional to the product of the (increasing) K-shell excitation cross section and the (decreasing) single electron capture cross section.

The data in the "resonance" region in Figs. 1-3 indicate that the nonresonant contribution to $\sigma^{q-1}_{K\alpha\beta}$ is small in contrast to the previous results[2] for S^{13+} + Ar. As suggested above, this nonresonant part may be due to uncorrelated capture and excitation (i.e. NTE) in a single collision with one target atom. The smaller nonresonant yield for helium targets may be due to the lower electron capture and K-shell excitation probabilities for helium compared to heavier targets. Recent calculations by Feagin and Reeves[14] predict that for the collision systems studied here the nonresonant part of $\sigma^{q-1}_{K\alpha\beta}$ should be a factor of about 10 lower than the resonant part in the "resonance" region.

Discussion

The maxima in $\sigma^{q-1}_{K\alpha\beta}$ are attributed to RTE, which occurs as a result of the formation of intermediate resonance states (for lithiumlike ions) such as $1s^22s \rightarrow 1s2s^22p$, $1s2s2p^2$, $1s2s^23p$, 1s2s2p3p, etc. followed by K x-ray emission. The smooth curves in Figs. 1,2b, and 3b are the calculated[5,10] RTE cross sections σ_{RTE} for S^{13+}, Ca^{17+} and V^{20+} using the method of Ref. 5 based on dielectronic recombination cross sections[12]. The shape, magnitude, and energy position of the calculated RTE cross sections are observed to give reasonable overall agreement with the measured $\sigma^{q-1}_{K\alpha\beta}$ in each case. For S^{13+} + He (Fig. 1), the measurements of $\sigma^{q-1}_{K\alpha\beta}$ are in reasonable agreement with the RTE and NTE predictions (not shown) of Feagin and Reeves.[14]

For Ca^{17+} and V^{20+}, based on the theoretical dielectronic recombination energies[12] (see Figs. 2b and 3b), the lower energy maximum corresponds to intermediate resonance states for which the excited and the captured electrons occupy levels with principal quantum numbers n = 2,2, i.e., $1s2s^22p$ and $1s2s2p^2$. The higher energy maximum corresponds to intermediate states $1s2s^23p$, 1s2s2p3p, 1s2s2p4p, etc., for which n = 2,$\geq$3. This means that those intermediate states populated in the collision which give rise to the low energy peak decay by Kα transitions only, while the higher energy peak contains contributions due to both Kα and Kβ. For V^{20+} ions the measured ratio of Kα coincidences with single electron capture to all K x-ray (i.e. Kα + Kβ) coincidences with single capture is essentially unity in the region of 360 MeV. Thus, nearly all of the coincidences near 360 MeV are associated with Kα , indicating that the transitions which contribute to $\sigma^{q-1}_{K\alpha\beta}$ in this energy region are due to n = 2,2 states. In the region of 435 MeV about 85% of the coincidences are with Kα. A similar result is found for Ca^{17+} ions.

For $_{16}S^{13+}$ + He collisions (Fig.1) only a single maximum is observed in $\sigma^{q-1}_{K\alpha\beta}$ in the RTE region. In this case the energy separation (~20 MeV) of the n = 2,2 and the n = 2, $\geq$ 3 intermediate resonance states is less than the energy spread in σ_{RTE} due to the bound target electron momenta.

In Fig. 4 we show the calculated[10] RTE cross section for lithiumlike ions from silicon to iron incident on helium. This figure shows that the separation of the n = 2,2 states and n = 2,$\geq$ 3 states is sufficient to expect partial resolution of these groups only for incident ions with Z $\geq$ 18. Similar calculations for a neon target (not shown) indicate that no resolution of the n = 2,2 and n = 2$\geq$3 groups is expected for ions up to iron.

The partial resolution of the intermediate states into the groups n = 2,2 and n = 2,$\geq$ 3 is significant since it allows both the absolute magnitudes and the relative heights of these groups to be compared with theory. The lower energy peak, corresponding to transitions with principal quantum numbers n = 2,2 for the two electrons involved, (see Figs. 2b and 3b) arises from only two intermediate resonance states and so the RTE contribution due to the sum of these two transitions, namely, $1s^2 2s \rightarrow 1s2s^2 2p$ and $1s^2 2s \rightarrow 1s2s2p^2$, can be compared directly with theory. In addition, the measured ratio between the n = 2,2 transitions and the n = 2,$\geq$3 transitions for a given charge state can be compared with theory[12]. These comparisons are made in Table I for V^{q+} ions where the agreement is seen to be quite good. It should be noted that the theoretical ratio of the high-to-low energy peak heights for q = 20+ in Table I is about 15% larger than that obtained from the RTE calculations shown in Fig . 3b. This deviation is apparently due to the different methods of accounting for the target electron momentum distribution in Refs. 10 and 12.

In Fig. 5 the experimental peak heights for $\sigma^{q-1}_{K\alpha\beta}$ are compared with the theoretical[5,10] peak heights for σ_{RTE} for the three ions investigated. For calcium and vanadium the heights of $\sigma^{q-1}_{K\alpha\beta}$ corresponding to the n = 2,2 states were used in this comparison. It is seen that the theoretical RTE cross sections σ_{RTE} for helium targets are about 15-25% larger than the measured $\sigma^{q-1}_{K\alpha\beta}$ while the theoretical cross section for S^{13+} + Ar is about half of the measured value.

The reasonable agreement, for helium targets, of the positions of the maxima and the relative heights of the peaks in $\sigma^{q-1}_{K\alpha\beta}$ with the calculations (Figs. 2b,3b and Table I) suggests that the relative probabilities for the population of groups of intermediate states with specific n values in the RTE process are nearly the same as those calculated for dielectronic recombination. Thus it would appear likely that RTE measurements will be useful in testing DR calculations, particularly for highly ionized ions.

Discrepancies with theory exist, however. For example, the experimental minimum in $\sigma^{q-1}_{K\alpha\beta}$ in both Figs. 2b and 3b is lower than that calculated, the relative experimental peak heights are not reproduced exactly by the calculations, and for S^{13+} and Ca^{17+} there is an obvious deviation between σ_{RTE} and $\sigma^{q-1}_{K\alpha\beta}$ at the higher projectile energies. These differences may be due to one or more of the following reasons: (1) the electron momentum distribution used in the RTE calculation may overestimate the width of the actual distribution, (2) the relative amplitudes for formation of the various intermediate resonance states may be slightly different for dielectronic recombination and RTE, (3) the assumed Z^2 scaling[12] used to obtain the intermediate resonance state transition energies may not be exactly correct, and (4) the DR cross sections for n = 3,$\geq$3 have not been calculated and hence contributions due to these states are not included in the RTE calculations.

Conclusion

In summary, important new evidence for the existence of resonant-transfer-and-excitation has been presented. The use of a helium target, with only 2 weakly bound electrons, simplifies the theoretical interpretation of the experimental results compared to previous measurements with many-electron targets. The observation of two maxima in the cross section for K x-ray production associated with electron capture for incident calcium and vanadium ions provides a more detailed and critical test of the RTE theory and the calculated dielectronic recombination cross sections which go into the theory. The experimental results are in substantial agreement with the predictions of this theory.

Apart from any connection to dielectronic recombination the large resonant contribution to the coincidence yield due to RTE demonstrates the fundamental importance of this process and indicates the necessity of including RTE in theoretical formulations of ion-atom collision interactions.

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TABLE I. Comparison of the measured $\sigma_{K\alpha\beta}^{q-1}$ relative peak heights with theoretical RTE calculations for vanadium ions. Similar comparisons are not included for calcium ions since the DR cross sections needed to calculate σ_{RTE} for calcium are not available.

Ratio[a]	Experiment	Theory[b]
$\frac{I_2\ (20+)}{I_1\ (20+)}$	0.98	0.97
$\frac{I_2\ (21+)}{I_1\ (21+)}$	1.07	0.99
$\frac{I_1\ (21+)}{I_1\ (20+)}$	1.27	1.34
$\frac{I_2\ (21+)}{I_2\ (20+)}$	1.40	1.36

[a] I_1 refers to the maximum intensity of the lower energy peak at about 360 MeV; I_2 refers to the maximum intensity of the higher energy peak near 435 MeV (see Fig. 3); the number in parentheses is the incident charge state.

[b] Ref. 12

FIGURE CAPTIONS

Fig. 1 Projectile K x-ray cross sections for 15–200 MeV S^{13+} + He collisions. $\sigma_{K\alpha\beta}$ is the cross section for total sulfur K x-ray production and $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for sulfur K x rays coincident with single-electron capture. The maximum in $\sigma^{q-1}_{K\alpha\beta}$ near 130 MeV is due to RTE and the maximum near 30 MeV may be due to NTE (see text). The dashed curve through $\sigma^{q-1}_{K\alpha\beta}$ is the calculated (Ref. 5) RTE cross section multiplied by 0.85.

Fig. 2 (a) Projectile cross sections for 100–360 MeV Ca^{q+} + He for q = 16+, 17+, and 18+. $\sigma_{K\alpha\beta}$ is the cross section for the total calcium K x-ray production. $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for calcium K x rays coincident with single-electron capture. The solid lines are drawn to guide the eye. (b) $\sigma^{q-1}_{K\alpha\beta}$ for Ca^{17+} + He. The solid curve is the calculated (Ref. 10) RTE cross section. The vertical bars give the theoretical positions and relative intensities of the intermediate states for dielectronic recombination (Ref. 12). The notation n = 2,3 etc. refers to the principal quantum numbers of the two electrons in these intermediate states. The two states near 210 MeV are the n = 2,2 transitions.

Fig. 3 (a) Projectile cross sections for 180–460 MeV V^{q+} + He for q = 19+, 20+, and 21+. See caption for Fig. 2. (b) $\sigma^{q-1}_{K\alpha\beta}$ for V^{20+} + He. See caption for Fig. 2.

Fig. 4 RTE cross sections, σ_{RTE}, for ions in the range $14 \leq Z \leq 26$ incident on helium. The magnitudes of the DR cross sections used in these calculations were taken to be constant and equal those given for S^{13+} by McLaughlin and Hahn in Ref. 12. The DR cross sections, obtained from the information in Ref. 12, do not vary greatly over this range of Z. These calculations show the qualitative features of σ_{RTE} and the onset of structure for $Z \gtrsim 18$.

Fig. 5 Ratio of the theoretical RTE cross sections σ_{RTE} and the experimental cross sections for K x rays coincident with single electron capture $\sigma^{q-1}_{K\alpha\beta}$ for $_{16}S^{13+}$, $_{20}Ca^{17+}$, and $_{23}V^{19+,20+,21+}$ ions incident on He. Also shown is this same ratio for S^{13+} + Ar from Ref. 2. The RTE calculations for calcium and vanadium are from Ref. 10. The DR cross sections used to obtain σ_{RTE} are from Ref. 12.

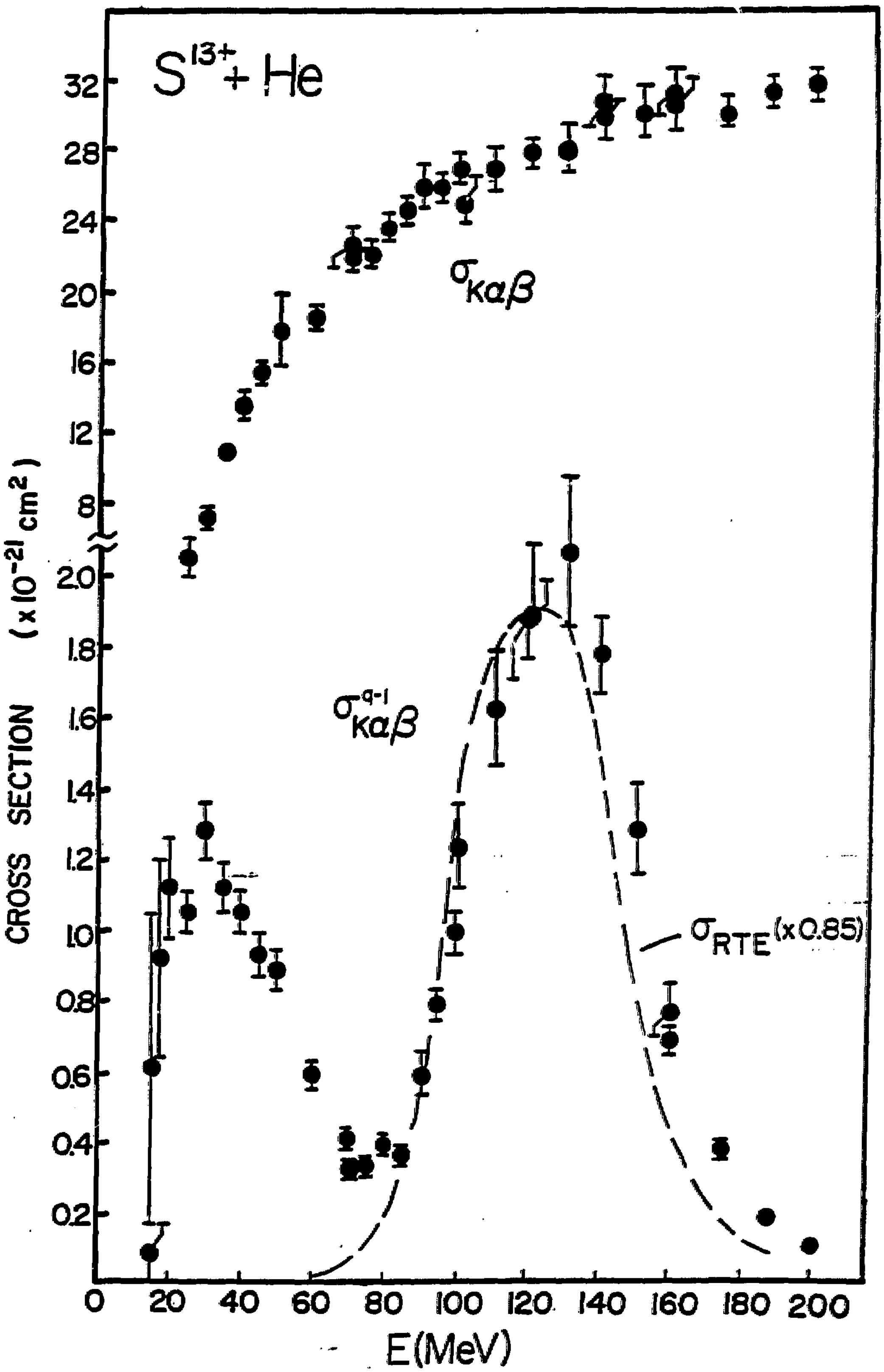
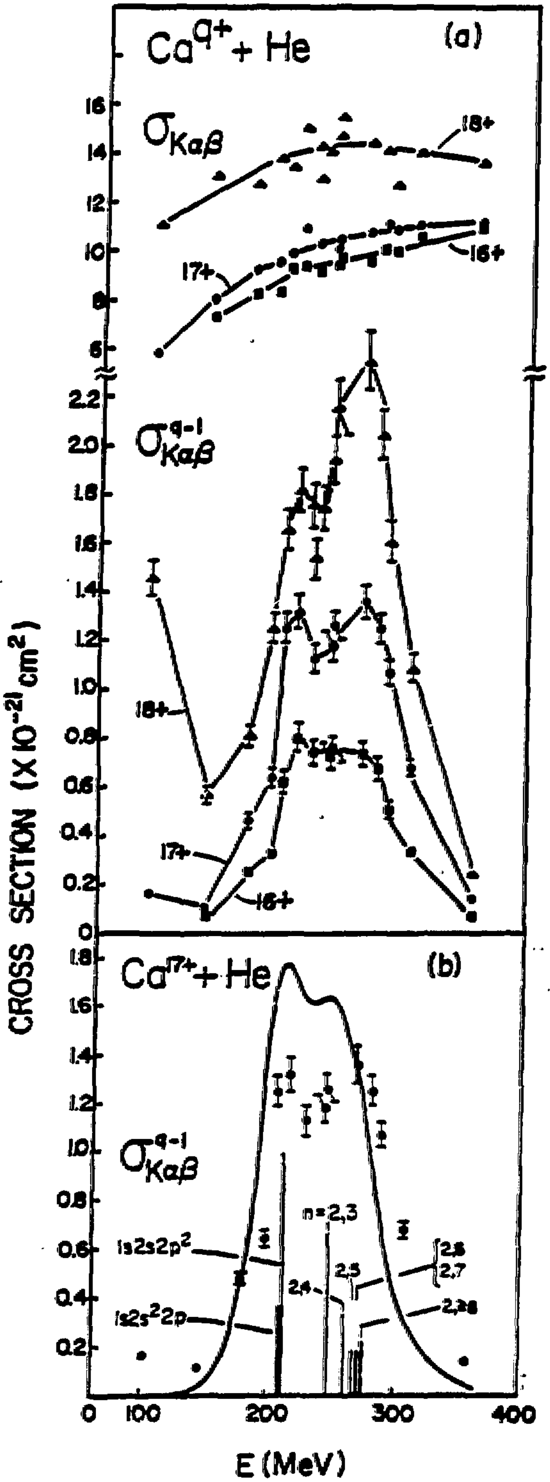
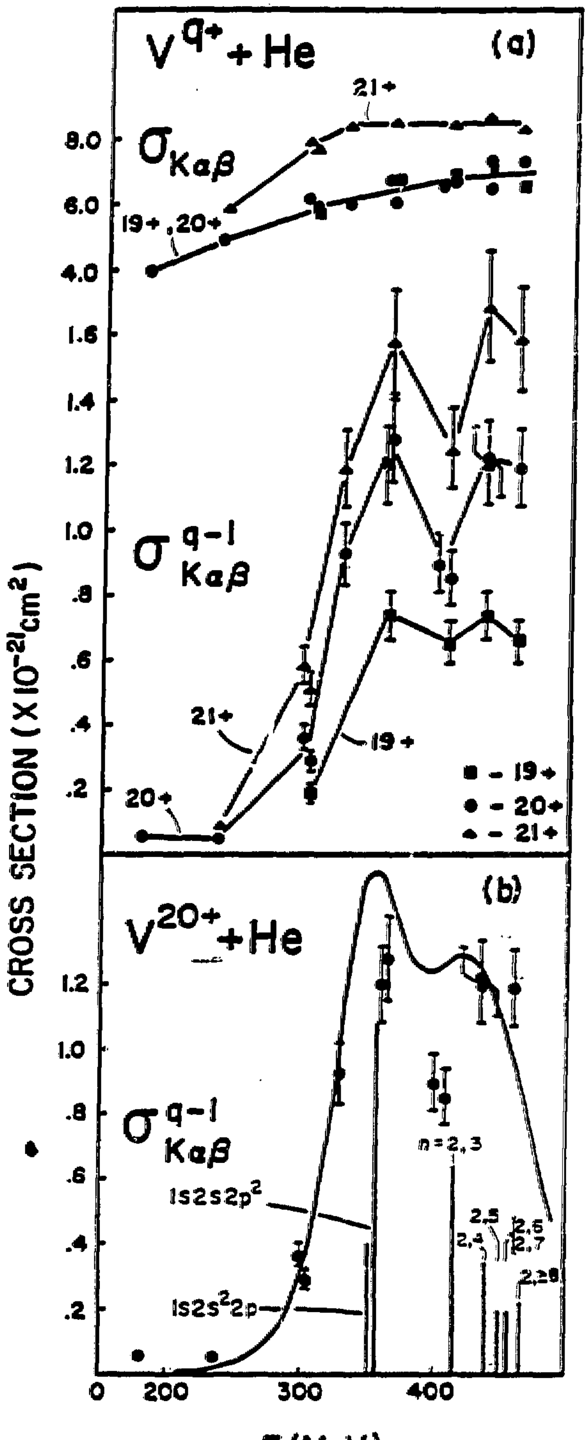


FIGURE 1



Ca^{q+} + He
(a)
$\sigma_{K\alpha\beta}$
18+
17+
16+
$\sigma^{q-1}_{K\alpha\beta}$
CROSS SECTION (X 10^{-21} cm^2)
Ca^{17+} + He
(b)
1s2s2p^2
1s2s^{2}2p
n=2,3
2,4
2,5
2,6
2,7
2,≥8
E (MeV)

FIGURE 2



V^{q+} + He
(a)
$\sigma_{K\alpha\beta}$
21+
19+ ,20+
$\sigma^{q-1}_{K\alpha\beta}$
21+
19+
20+
■ - 19+
● - 20+
▲ - 21+
(b)
V^{20+}+He
$\sigma^{q-1}_{K\alpha\beta}$
n=2,3
$1s2s2p^2$
$1s2s^22p$
2,4
2,5
2,6
2,7
2,≥8
CROSS SECTION ($\times 10^{-21}cm^2$)
E (MeV)

FIGURE 3

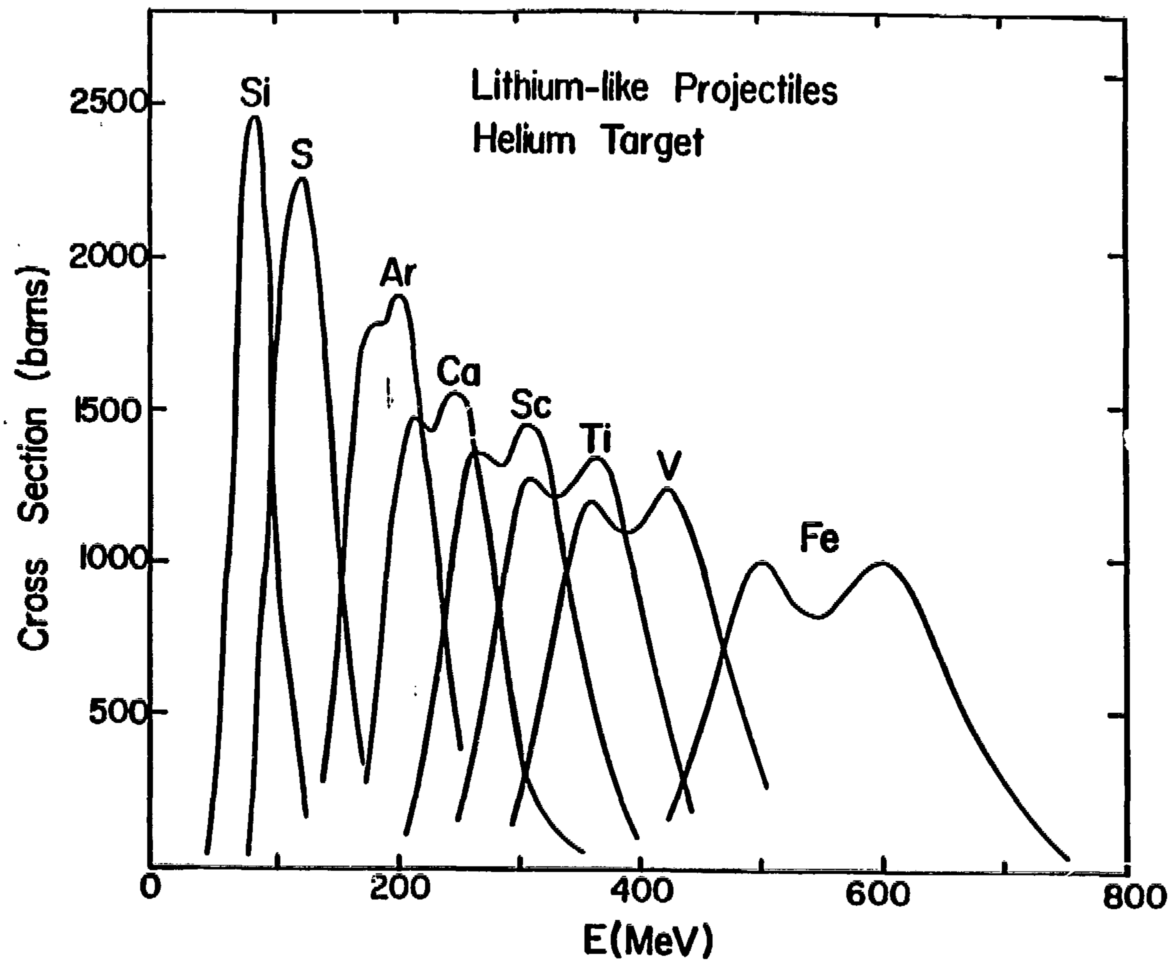
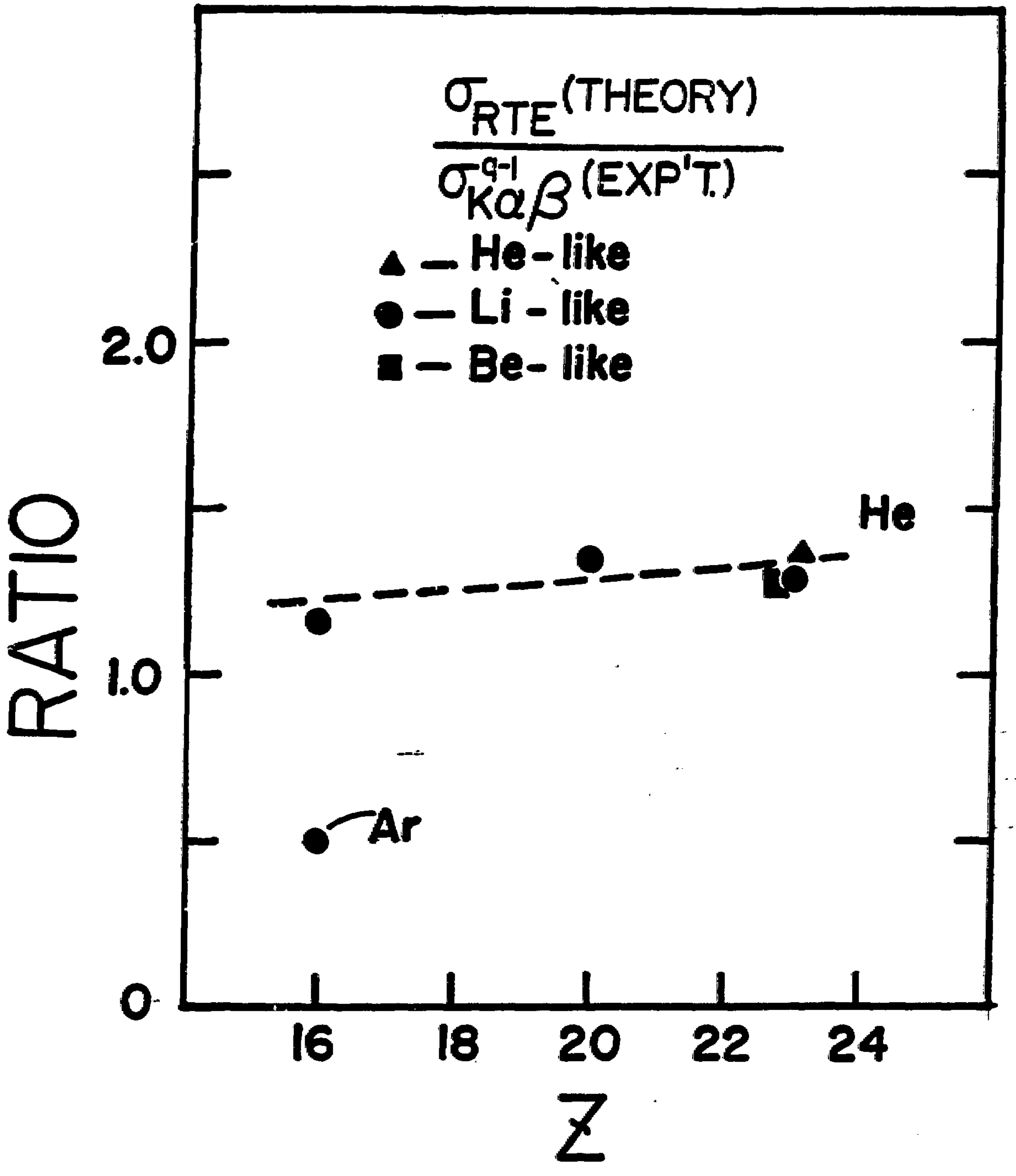

Lithium-like Projectiles
Helium Target
Si
S
Ar
Ca
Sc
Ti
V
Fe
Cross Section (barns)
2500
2000
1500
1000
500
0
200
400
600
800
E(MeV)

FIGURE 4



σRTE (THEORY)
σKαβ q-1 (EXP'T.)
He-like
Li-like
Be-like
He
Ar
RATIO
2.0
1.0
0
16
18
20
22
24
Z

FIGURE 5