Resonant transfer excitation in collisions of F^{6+} and Mg^{9+} with H_2

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Experimental and theoretical investigations of resonant transfer excitation (RTE) for $F^{6+}+H_2$ and $Mg^{9+}+H_2$ collisions have been made. For both collision systems good agreement is obtained between the measured cross sections for *K*-shell x-ray emission coincident with electron-capture and theoretical RTE calculations. For F^{6+} the present calculations are about 10% lower than previous results of Bhalla and Karim [Phys. Rev. A **39**, 6060 (1989); **41**, 4097(E) (1990)]; the measured cross sections are a factor of 2.3 larger than earlier measurements of Schultz *et al.* [Phys. Rev. A **38**, 5454 (1988)]. The previous disagreement between experiment and theory for F^{6+} is removed.

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I. INTRODUCTION

Resonant transfer excitation (RTE) followed by x-ray stabilization (RTEX) in collisions of highly charged lithiumlike ions with H_2 and He has been the subject of much theoretical [1,2] and experimental [3] interest. RTEX occurs when electron capture and projectile excitation take place simultaneously in a collision due to the electron-electron interaction followed by subsequent x-ray emission. For almost all collision systems studied to date there is generally good agreement between the measured and theoretical cross sections. Little work has been done, however, for low-*Z* ions due to the small-energy separation between intermediate states and the resulting poor resolution of the resonances, and the difficulty of detecting low-energy x rays. Recently, Schulz *et al.* [4] reported on experimental RTEX cross sections involving *K*-shell excitation for collisions of 15–33-MeV F^{6+} ions with H_2. These cross sections were subsequently found to be about a factor of 2 smaller than theory [5]. Additionally, Schulz *et al.* [4] found evidence of a contribution on the high-energy side of the expected RTEX resonance at energies where KMn $(n \geq M)$ and higher [$KNn(n \geq N)$, etc.] excitations could contribute to the doubly excited intermediate state. It was suggested [4] that this extra contribution on the high-energy side of the resonant maximum might be due to a process [6] called uncorrelated transfer excitation (UTE) or two-electron transfer excitation (2*e* TE). In the UTE process, the projectile is excited by one of the target electrons while the second target electron is captured. Here the capture and excitation events are independent and, hence, UTE (or 2*e* TE) is not a resonant process.

In the present work experimental and theoretical studies of RTEX for collisions of F^{6+} and Mg^{9+} with H_2 have been undertaken in an effort to clarify the situation for RTEX in low-*Z* ions.

II. THEORY

The AUTOSTRUCTURE package [7,8] was used to carry out configuration-mixing *LS*-coupling and intermediate-coupling (IC) calculations for RTEX cross sections for $F^{6+}+H_2$ and $Mg^{9+}+H_2$. The RTEX calculations for KLn $(n \geq L)$ transitions were made exactly as before for higher atomic number lithiumlike ions [2] and, in addition, we now also include contributions from KMn $(n \geq M)$ transitions.

Figure 1 shows the present calculated RTEX cross sec-

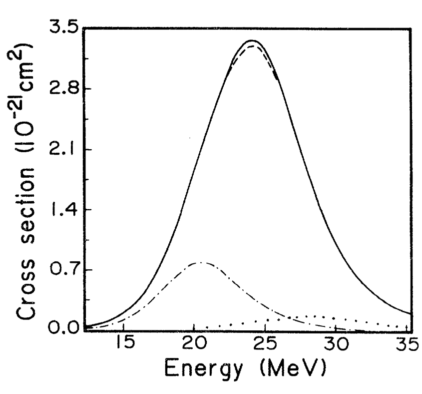

FIG. 1. Theoretical RTEX cross sections for $F^{6+}+H_2$. ——, intermediate coupling for $KLn+KMn$ $(n \geq L)$; — — —, LS coupling for $KLn+KMn$ $(n \geq L)$; —·—·—·, intermediate coupling for *KLL*; · · · ·, intermediate coupling for *KMn*; all this work. The projectile energy is in the laboratory system.

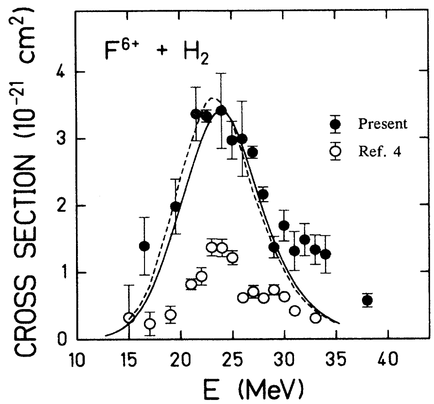

FIG. 2. Cross sections for K-shell x rays coincident with electron capture for $F^{6+}+H_2$. The present measurements are indicated with solid points; the previous results from Ref. [4] are shown with open circles. Relative uncertainties are indicated. The present theoretical IC RTEX calculations are shown by the solid curve, and the IC calculations of Bhalla and Karim (Ref. [5]) are shown with the dashed curve.

tions for collisions of F^{6+} with H_2. The energy plotted is that of the projectile ion in the laboratory frame. The IC results for the KLn peak are only 2% greater than the LS-coupling results. The large enhancement (up to 35%) found previously [2] due to spin-orbit mixing of LS-allowed and LS-forbidden autoionizing terms in more highly charged ions does not occur here as the spin-orbit interaction is too weak compared to the electrostatic interaction, even though higher n values contribute as evidenced by the fact that the KLL peak is only 25% of the KLn ($n>L$) total. We also see that the KMn excitations only make a small contribution (4%) to the total RTEX cross section.

The RTEX cross sections for $F^{6+}+H_2$ obtained here using IC are about 10% lower at the maximum than the IC results of Bhalla and Karim [5] (see Fig. 2). The only difference between the two sets of calculations appears to be in the atomic structure. We use radial functions generated in a Slater-type-orbital model potential while Bhalla and Karim [5] use Hartree-Fock-Slater functions. The resulting $\sim 10\%$ difference indicates the typical theoretical uncertainty.

III. EXPERIMENTAL PROCEDURE

Beams of F^{6+} and Mg^{9+} ions were produced by the Western Michigan University EN tandem Van de Graaff accelerator. The Mg beam was obtained by injection of MgH_2^- or MgH_3^- ions from a cesium sputter-ion source.

Except for the highest energy Mg^{9+} ions, the beams were passed through an external carbon stripping foil, after analysis in a 90° magnet, in order to obtain the charge state of interest. A switching magnet following the external stripper directed the projectiles into a differently pumped H_2 gas target.

The experimental techniques and arrangement are very similar to those used previously [3,9]. RTEX events were isolated by detecting projectile K-shell x rays coincident with single-electron capture for 16.5–38-MeV F^{6+} and 33–60-MeV $Mg^{9+}+H_2$ collisions. A 28-mm^2 Si(Li) detector with a 7.6-μm beryllium window mounted at 90° to the beam was used to detect the x rays. The beam, after emerging from the gas cell, was magnetically analyzed into its charge-state components, and ions which captured an electron were detected in a surface-barrier detector while the non-charge-changed ions were collected in a Faraday cup. K x rays coincident with electron capture were registered using a time-to-amplitude converter. All yields were measured as a function of target gas pressure to obtain the desired cross sections and to ensure that single-collision conditions prevailed.

The efficiency of the x-ray detector was calculated from the detector properties and the geometry of the experimental arrangement. For F^{6+} the dependence of the effective detector efficiency on the ratio of $K_\beta+K_\gamma$ to $K\alpha$ x rays, which changes with projectile energy, was taken into account. The theoretical ratio calculated here for RTEX was used to determine the effective detector efficiency at each incident energy. The ratio varied from about 0.055 to 0.110 resulting in an 11% difference in the efficiency over the projectile energy range studied.

The major source of uncertainty in the absolute values of the coincidence cross sections is from uncertainties in the corrections for absorption of the x rays in the detector beryllium window, the gold layer, and the silicon dead layer. The uncertainties in the absolute coincidence cross sections are estimated to be $\pm 30\%$ for F^{6+} projectiles and $\pm 25\%$ for Mg^{9+} projectiles.

As a check on the calculated x-ray-detection efficiency, measurements were made of the absolute K-shell x-ray-production cross sections for several collision systems involving low-energy x-ray emission. These cross sections are compared with the results of others [10–16] in Table I. The values given in column 3 in the table were obtained in the present experiment from measured x-ray yields versus target pressure using calculated x-ray-detection efficiencies.

The previously measured values for $F^{6+}+He$ given in Table I were deduced from interpolation of values obtained by summing the x-ray-production cross sections for the ^1P, ^3P, and ^2P states given by Tawara *et al.* [12]. These cross sections were (1) reduced to account for the lifetime of the ^3P state and (2) increased using relative yields measured [13] at 15 MeV, to account for the contributions from other transitions [13] which were unresolved in the present experiment. These changes amount to a net increase in the sum of the values given in Ref. [12] by about 11%.

For $F^{9+}+H_2$ the values listed in column 4 were obtained from electron-capture measurements made in the present experiment assuming that 90% of the total capture events for F^{9+} result in K-shell x-ray emission. This latter method was used in Ref. [4] to obtain the absolute x-ray-detector efficiency.

As seen from column 6 in Table I, there is good agreement within the experimental uncertainty between the cross sections measured here and the values obtained by

TABLE I. Comparison of absolute K-shell x-ray-production cross sections measured in the present experiment with the results of others. The last column gives the differences in percent between the present results and other measurements.

Collision system	E (MeV)	Cross section (10^{-21} cm^2) Present[a]	Others	Reference	Difference (%)
$p+Ne$	3	1.21(20)	1.37	10	−13
$p+Ar$	3	0.62(15)	0.64	11	−3
	4	0.76(15)	0.76	11	0
$F^{6+}+He$	19.5	1.26×10^2(23)	1.14×10^2 [b,c]	12,13	+10
	24	1.14×10^2(23)	1.22×10^2 [b,c]	12,13	−7
$F^{8+}+He$	19.5	1.26×10^3(20)	1.10×10^3 [c]	14,15	+13
	24	5.81×10^2(20)	4.90×10^2	14,15	+16
$F^{9+}+H_2$	30	85.2(20)	97.0[d]		−14
	34	43.4(20)	53.9[d]		−24
$F^{9+}+He$	24	1.71×10^3(20)	1.50×10^3	15	+12
	28	7.71×10^2(20)	7.30×10^2	15	+5
	32	4.50×10^2(20)	3.80×10^2	15	+16
$S^{13+}+He$	40	12.9(15)	13.6	16	−5
	50	16.4(15)	17.0	16	−4

[a] The number in parentheses gives the percent uncertainty.
[b] See the text.
[c] Interpolated value.
[d] These cross sections, which have an estimated uncertainty of 15%, correspond to 90% of the total electron-capture cross sections measured in the present experiment.

others. While this agreement includes the x-ray-production cross sections for $F^{9+}+H_2$ obtained from the electron-capture cross sections, the present results for this collision system indicate that at the incident energies measured the fraction of the total captures resulting in K-shell x rays is close to $\sim75\%$ rather than 90%.

IV. RESULTS AND DISCUSSION

Figure 2 shows the energy dependence of the measured cross sections for coincidences between K-shell x rays and electron capture for $F^{6+}+H_2$ collisions. The energy plotted is that of the projectile in the laboratory. The present measurements are indicated with the solid points while the results of Schulz *et al.* [4] are shown as open circles. Also shown in Fig. 2 are the present IC calculations of RTEX cross sections (solid curve) and the IC calculations of Bhalla and Karim [5] (dashed curve). There is no normalization of the theory to the data in this figure. As can be seen there is rather good agreement between theory and the present measurements. The excess yield measured at the higher energies is discussed below.

The absolute values of the measured coincidence cross sections reported here are about a factor of 2.3 larger than those given in Ref. [4] for the same collision system. This difference is well outside the quoted experimental uncertainties. The source of the disagreement between the two experiments is not known.

In both the present experiment and that of Ref. [4] the x rays were observed only at 90° relative to the projectile beam. The expected effect of anisotropic radiative emission on the deduced RTEX cross sections was calculated [17] to be small (+ 12%) for F^{6+} ions and has not been taken into account in the results shown in Fig. 2.

It has been proposed [6] that the structure claimed at high energies in the data of Ref. [4] could be due to uncorrelated transfer excitation with subsequent x-ray stabilization. There is some evidence of structure in the present date (see Fig. 2), but it is at a higher energy than that found by Schulz *et al.* [4]. The results of the calculations of Hahn and Ramadan [6] for UTE were similar to our calculated *KMn* RTEX results (see Fig. 1), i.e., too small and broadly distributed to give rise to any discernable structure. It should be noted that in some of our previous work [3] a small extra contribution at high energies not accounted for by theory was observed in the measured cross sections. However, the differences between experiment and theory at higher energies in the present results for F^{6+} appear to be more significant (see Fig. 2).

A comparison between the measured cross sections for K-shell x-ray-emission coincident with electron capture and theoretical calculations of RTEX for $Mg^{9+}+H_2$ collisions as a function of the projectile laboratory energy is

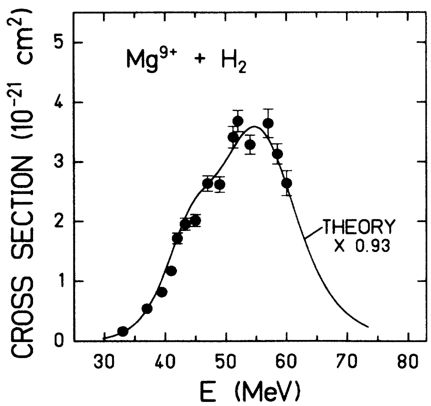

FIG. 3. Experimental cross sections (solid points) for *K*-shell x rays coincident with electron capture for $Mg^{9+}+H_2$. Relative uncertainties are indicated. The present theoretical IC RTEX calculations for this collision system (solid curve) have been multiplied by 0.93 to facilitate comparison with the data.

given in Fig. 3. The highest energy attainable was limited to 60 MeV by the maximum terminal voltage ($\sim$6 MV) of the accelerator. The theoretical curve in Fig. 3 has been multiplied by 0.93 to facilitate the comparison with the data. Again the *KLL* contribution is smaller than that from *KLn* ($n > L$) transitions; however, in this case there is a marked asymmetry in the calculated resonant maximum which exhibits structure near 45 MeV due to the *KLL* peak. There is an indication of similar structure in the data. Over the energy range of the measurements there is good agreement between the theory and experiment.

V. CONCLUSIONS

Experimental and theoretical studies of resonant transfer excitation have been made for $F^{6+}+H_2$ and $Mg^{9+}+H_2$ collisions. For $F^{6+}+H_2$ there is little difference in the calculated *KLn* RTEX cross sections in the IC and *LS*-coupling schemes, and the *KMn* RTEX cross sections contribute little to the total. Except for a small ($\sim$10%) difference attributed to the atomic structure used, the present IC calculations for F^{6+} agree with those of Bhalla and Karim [5].

The measured cross sections for *K*-shell x rays coincident with electron capture are in good agreement with the RTEX calculations for both collision systems. The experimental cross sections for $F^{6+}+H_2$ are about a factor of 2.3 larger than values previously published [4]. The origin of this discrepancy is not understood at this time.

For F^{6+} the experimental cross sections are somewhat larger than the theory at the higher energies. Contributions to the F^{6+} cross section at the higher energies from *KMn* RTEX or uncorrelated transfer excitation are not expected to produce discernable structure. Furthermore, if this excess high-energy yield were due to a broad maximum as expected [6] for UTE, the present results indicate that the energy position of such a maximum would be higher($\sim$33 MeV) than that ($\sim$28 MeV) reported in Ref. [4].

The source of the excess yield at higher energies for F^{6+} is not known at this time. However, it is noted that RTE can interfere [18] with nonresonant transfer excitation (NTE). Thus, even a relatively small NTE amplitude [4] could produce observable effects through interference. This explanation is rather speculative; further experimental and theoretical work is needed to elucidate this point and to establish the origin of the excess high-energy yield.

The present results extend the general agreement between experiment and theory for RTEX involving *K*-shell excitation [3] down to $Z=9$. The previously reported [4] disagreement between experiment and theory for F^{6+} is removed.

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