One- and Two-Electron Excited States Produced by Electron Exchange, Excitation, and Electron Capture in Collisions of Fluorine Ions in Argon Gas at 34.8 MeV*

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High-resolution x-ray spectra have been used to obtain the relative intensities of transitions in fluorine ions that result from single collisions of F^{7+}, F^{8+}, and F^{9+} at 34.8 MeV in argon gas. Intensities of transitions resulting from direct electron capture to excited states have been compared to those produced by excitation processes. The importance of electron exchange in collisions in which inner-shell excitation occurs is indicated by the strong $(1s,2p)2\,^3P_1 \rightarrow (1s^2)1\,^1S_0$ transition obtained with incident two-electron ions.

We report the results of a high-resolution x-ray study of one- and two-electron fluorine states produced in single collisions of 34.8-MeV fluorine ions of charge states 7, 8, and 9 with argon gas. This paper demonstrates the possibilities for using high-resolution x-ray spectrometry in studying some atomic collision processes in gas targets for which both initial and final states can be readily identified.

In Fig. 1 are shown the portions of the spectra from 712 to 750 eV obtained with F^{8+} and F^{7+} ions incident on argon at 100-μm pressure in the gas cell. The transitions $2\,^1P_1 \rightarrow 1\,^1S_0$ and $2\,^3P_1 \rightarrow 1\,^1S_0$ from the singlet and metastable triplet two-electron states are observed in the two spectra. A most surprising observation in this experiment is that the $2\,^3P_1 \rightarrow 1\,^1S_0$ transition occurs with comparable intensity when produced by either F^{7+} or F^{8+} incident ions. In the latter case the excited-state population can be produced by direct electron capture, but in the former case a direct Coulomb excitation process does not permit the spin flip that is required to produce the triplet state from the two-electron ground state. We suggest that at the small impact parameters necessary for inner-shell excitation, electron-exchange probabilities may become sufficiently large to be responsible for the surprisingly strong production of the triplet state.

In Fig. 2 are shown x-ray spectra above 809 eV that were obtained for F^{9+} and F^{8+} ions incident at 34.8 MeV on argon at 100-μm pressure. In the upper spectrum, obtained with the fully stripped fluorine nuclei incident on the gas cell, allowed transitions $np \rightarrow 1s$ of the one-electron system are resolved clearly for $n \leq 5$ and are observed unresolved up to the series limit. These transitions are the most intense observed in the experiment. The excited-state distribution as observed in the x-ray spectra can be produced by electron capture processes and electron capture with subsequent cascading. At the bottom of Fig. 2, transitions in one- and two-electron fluorine ions are evident in the spectrum produced with F^{8+} ions

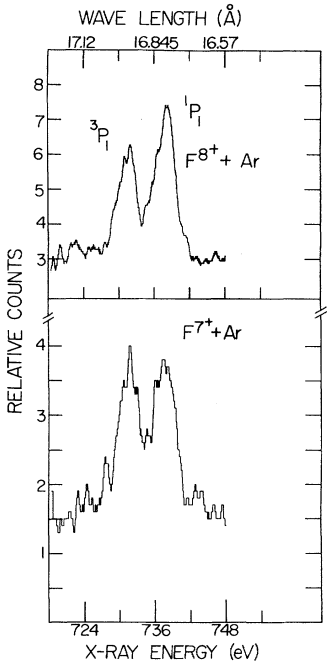

FIG. 1. X-ray spectra from 712 to 750 eV observed with F^{8+} and F^{7+} ions incident at 34.8 MeV on 100 μm of argon. The transitions to the ground state from the $2\,^3P_1$ and $2\,^1P_1$ states are indicated.

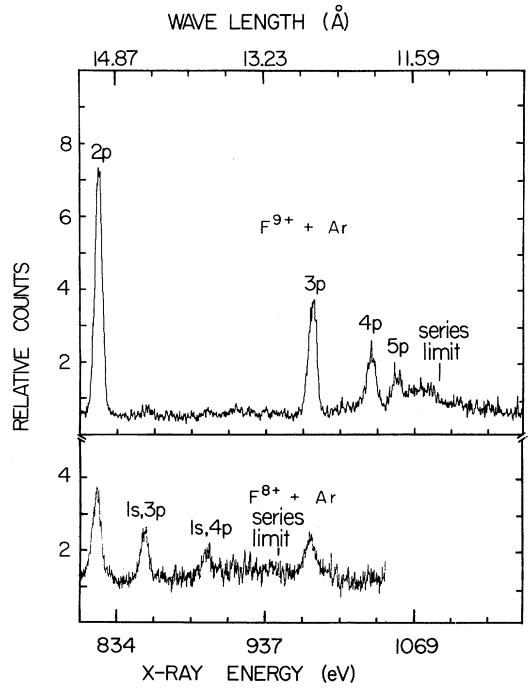

FIG. 2. X-ray spectra above 809 eV observed with F^{9+} and F^{8+} ions incident at 34.8 MeV on 100 μm of argon. Transitions between one-electron states are indicated on the upper spectrum; between two-electron states, on the lower spectrum.

incident on argon. The one-electron states can be produced by excitation processes and electron exchange. These transitions to the ground state were observed with about $\frac{1}{10}$ the intensity that was seen with the F^{9+} ions. Transitions of two-electron states formed by electron capture by F^{8+} ions were observed with intensity comparable to the intensity of the corresponding transitions (for the running electron) between the one-electron states whose formation we have attributed to excitation and exchange processes.

In this experiment, fluorine ions at 34.8 MeV from the Kansas State University tandem Van de Graaff accelerator were selected by the beam-switching magnet in a specific charge state from +7 to +9, and directed through a differentially pumped gas cell to a large, suppressed Faraday cup. A 4-in. curved-crystal spectrometer[1] with a rubidium acid phthalate (RAP) crystal was mounted with the 1-cm entrance slit inside the gas cell parallel to the beam. Over the photon energy range from 700 to 1100 eV, the x-ray lines emitted by the fluorine ions were observed with a resolution of about 3 eV full width at half-maximum. The dispersed x rays were detected in a thin-window proportional counter. Multichannel spectra were accumulated in a PDP-15 analysis system with the number of x rays counted at a particular setting for a fixed amount of integrated beam multiscaled over fixed wavelength intervals. Data were stored in steps of 4.13 mÅ per channel, with typically (3 to 10) $\times 10^9$ ions collected in the integration at each setting. The sources of error in the intensities of the lines include statistics, pressure variation in the gas cell, beam transmission through the gas cell, crystal reflectivity, detector-window absorption, and variations in the beam-dependent background.

Single-collision conditions for this experiment were examined by studying the intensity of transitions as a function of thickness of the argon-gas target. In particular, the linearity of the intensity of the $2p \rightarrow 1s$ line observed with F^{9+} ions at pressures from 20 to 150 μm gave us confidence that pressures up to more than 100 μm represent single-collision conditions for fluorine K x-ray production following electron capture.

The metastable content of the incident F^{7+} beam is not known, but this source of the two-electron triplet states was ruled out by taking x-ray spectra by accelerating F^{6+} and post stripping to charge 7 at 34.8 MeV, and alternatively by stripping to the F^{7+} ion at the 4.4-MV terminal and directly accelerating to the same final energy. It is probable that the different energy at which conversion to charge 7 occurred, plus the additional flight path after direct acceleration of F^{7+}, would substantially change the metastable fraction in the incident beam. However, the intensity of the $^3P_1 \rightarrow {}^1S_0$ and the $^1P_1 \rightarrow {}^1S_0$ transitions were indistinguishable with the two techniques.

The intensities of all the transitions observed in Fig. 1 and Fig. 2 are summarized in Table I. Because the intensities were corrected for the reflectivity of the RAP crystal and the absorption in the proportional-counter window, the attenuation parameters used to correct the data for each line are given in the table. Although absolute yields for the lines were not determined in this experiment, the intensities of all lines are normalized relative to the yield (in x rays per incident ion per target atom) of the $2p \rightarrow 1s$ line observed with F^{9+} incident, taken as unity for the normalization. For the relative intensities given in Table I, we estimate that the uncertainty ranges from about 10% for the stronger lines up to 50% for the weakest lines.

An examination of the intensities of the lines observed in this experiment leads to several con-

TABLE I. Summary of transitions, x-ray energies, and relative intensities observed in this experiment with 34.8-MeV F^{9+}, F^{8+}, and F^{7+} ions. The parameters used to normalize the line intensities for the detection efficiency are included.

Transition	Energy[a] (eV)	Relative intensity F^{9+}	Relative intensity F^{8+}	Relative intensity F^{7+}	X-ray detection efficiency Reflectivity $\times 10^5$ [b]	X-ray detection efficiency Window transmission[c]
$2p \rightarrow 1s$	827	1.0	0.12	...	7.6	0.30
$3p \rightarrow 1s$	981	0.26	0.025	...	9.1	0.47
$4p \rightarrow 1s$	1035	0.12	...	...	9.6	0.52
$5p \rightarrow 1s$	1059	0.08	...	...	9.9	0.55
$(1s,2p)2\,^3P_1 \rightarrow 1\,^1S_0$	731	...	0.075	0.073	6.6	0.25
$(1s,2p)2\,^1P_1 \rightarrow 1\,^1S_0$	738	...	0.089	0.075	6.6	0.25
$(1s,3p)3\,^1P_1 \rightarrow 1\,^1S_0$	858	...	0.054	...	7.8	0.35

[a]The energy calibration is based on measurements by F. Tyren, Nova Acta Regiae Soc. Sci. Upsal. 12, 1 (1940).
[b]The crystal reflectivity is based on measurements by R. L. Blake (Enrico Fermi Institute), unpublished.
[c]The window used was 2-μm Macrofoil, Siemens Corp., Karlsruhe.

clusions concerning electron capture to excited states, the relative strength of excitation and capture mechanisms in producing projectile excited states, and the importance of electron exchange in inner-shell excitation.

Electron capture to excited states has been a subject of discussion[2] for a long time, and indirect experimental evidence[3,4] for these processes in the MeV/amu energy range with heavy ions has been reported previously. The transitions $np \rightarrow 1s$ observed in the present experiment following electron capture by the F^{9+} incident ion are found to have relative intensities (listed in Table I) that are represented by a n^{-3} dependence. Such a relation for capture by protons to excited states has been obtained in calculations based on capture only to s states.[2,5] For very large principal quantum numbers it has recently been predicted that the distribution of excited states produced by electron capture falls as n^{-2} in the limit of large n.[6] Although the branching ratios for all one-electron states are well known,[7] no unfolding of the cascading processes to obtain the excited-state distribution produced by electron capture has been undertaken in this work. However, since cascading should preferentially enhance the intensities of lines originating from low-n states, our data suggest that the excited-state distribution for electron capture to bare fluorine nuclei falls off less rapidly with principal quantum number than n^{-3} for $n \leq 5$.

The intensity of transitions observed with F^{8+} incident ions between one-electron states is a measure of the importance of excitation processes in producing inner-shell vacancies. Although these one-electron states could be produced after electron loss followed by electron capture to the excited state in a subsequent event, this mechanism can account for only about 8% of the observed yield because the stripping cross section $\sigma_{89} = 1.3 \times 10^{-18}$ cm^2/atom [8] limits the fraction of F^{9+} to less than 1% of the incident F^{8+}. From the relative intensities of the $2p \rightarrow 1s$ and $3p \rightarrow 1s$ transitions with F^{8+} and F^{9+} ions we conclude that the cross section for direct excitation is only $\frac{1}{10}$ as large as that for electron capture by the bare nucleus in producing the one-electron excited state population.

In conclusion, we repeat that the most surprising observation in this experiment is the strength of the two-electron $^3P_1 \rightarrow {}^1S_0$ transition observed with F^{7+} ions incident on argon gas. A one-electron excitation process is not expected to permit the spin flip required to produce this state from the two-electron ground state. We suggest that at the small impact parameters necessary for inner-shell excitation, electron exchange may be responsible for the strong production of the triplet state. A further question, not answered in this paper, is whether the structure of the target plays a role in the importance of this process.

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Dispersion and Attenuation of Superthermal "Monochromatic" Phonons in He II

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The propagation of phonons in He II at 0.1 K, in the frequency range (2 to 9)$\times 10^{10}$ Hz, has been studied using superconducting Al-film generators. Such superthermal waves ($\hbar\omega \gg kT$) are shown to be long-lived propagating excitations in the liquid and to have negligible dispersion (group velocity varies by less than 0.5%). These measurements reveal that the current theories of phonon lifetimes in He II are inadequate.

The pressure and temperature dependence of the attenuation of subthermal ($\hbar\omega \ll kT$) ultrasonic waves in He II has been the subject of intensive investigation recently.[1] Maris and Massey[2] and Jäckle and Kehr[3] have successfully explained several unusual features by assuming that the He II excitation spectrum $\omega(k)$ initially curves *upwards*. Experimental support for such anomalous dispersion has been obtained from heat-capacity data[4] and from sound-velocity measurements on helium films.[5] Neutron measurements[6] have so far revealed only normal dispersion, although a region of anomalous dispersion at low k ($\lesssim 0.2$ Å^{-1}) could not be ruled out.

In this Letter we present experimental results on the group velocity ($v_g = \partial\omega/\partial k$) and attenuation (as a function of pressure) for phonons of frequency $\nu \sim 2\times 10^{10}$ to $\sim 9\times 10^{10}$ Hz [$k \sim 0.04$ to 0.22 Å^{-1} at saturated vapor pressure (SVP)] at low temperatures (~0.1 K) using "monochromatic" phonon generation and detection and time-of-flight techniques.[7,8] We give strong evidence that such superthermal waves are long-lived propagating excitations in the liquid and have a relative dispersion of less than 0.5% in this low-k region with $v_g = 238$ m/sec with an absolute error of ± 4 m/sec.

The experiments were performed in a large He II cell cooled by means of a dilution refrigerator (see inset of Fig. 1). In the initial exper-

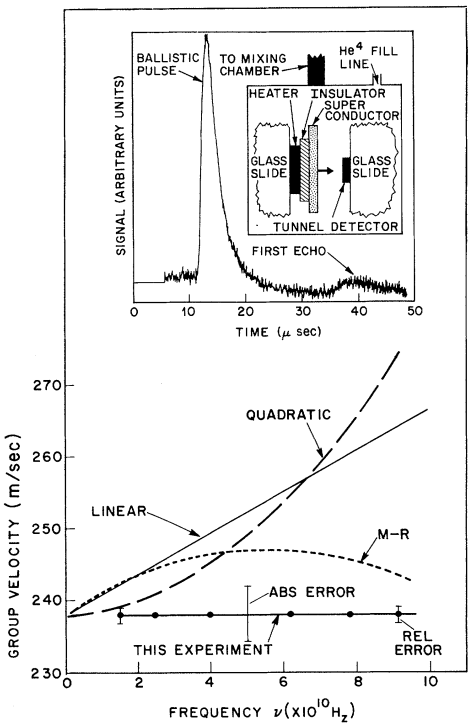

FIG. 1. Group velocity of superthermal monochromatic phonons in He II as a function of frequency at 0.1 K and SVP. The curves marked "linear," "quadratic," and "M-R" were calculated for different forms of the He excitation spectrum (see text). At the top of the figure we show a recorder tracing of a typical ballistic phonon pulse and its first echo. Path length 2.68 mm.