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THE SPECTRA OF GERMANIUM AND SELENIUM IN THE 50-350 Å REGION FROM THE PLT TOKAMAK PLASMA

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ABSTRACT

Spectra of germanium and selenium injected into the PLT tokamak plasma were observed in the 50-350 Å region for GeXIV-XXV (KI to OI-like) and SeXVI-XXIV (KI to NaI-like). A number of $3p^k$-$3p^{k-1}3d$ transitions predicted by isoelectronic sequence extrapolation have been identified. Also, previously identified lines from ions in the AlI to OI-like and KI-like isoelectronic sequences have been observed in the tokamak plasma.

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I. INTRODUCTION

Recent interest in the spectra of high-Z ions has been motivated by their utility as diagnostic tools for tokamak and other high temperature fusion research plasmas (see, e.g., Refs. 1 and 2). The VUV spectra of such ions are largely known up to nickel (Z=28) due to their observation in both astrophysical (see, e.g., Refs. 3 and 4) and laboratory plasmas.[5-10] However, much less is known about the spectra of higher Z ions; these elements, which retain a significant number of electrons, will become more important in increasingly hotter plasmas.

In the present work, spectral lines have been identified in the 50 to 350 Å region of spectra of germanium (Z=32) and selenium (Z=34) injected into the PLT tokamak plasma. These results are important for transport studies of high temperature plasmas, can aid in the prediction of long wavelength forbidden transitions for ion temperature diagnostics,[2] and provide information on ionic structure which may be used to predict transitions in higher Z ions by isoelectronic sequence extrapolation.

The lines studied in this work have been divided into three groups: 1) those arising from $3p^k$-$3p^{k-1}3d$ transitions in the ArI to AlI-like ions and from $3p^6 3d$-$3p^5 3d^2$ transitions in KI-like germanium and selenium, most of which have not been previously identified, 2) 3s-3p and 3p-3d transitions in the AlI, MgI, and NaI-like ions and, 3) $2s^2 2p^k$-$2s2p^{k+1}$ transitions in FI and OI-like germanium. Extensive identifications of transitions of the first type in iron, cobalt, and nickel, as well as in lower Z elements, have been made using vacuum sparks, laser-produced, theta-pinch, and tokamak plasmas, and in the solar corona.[10-14] The most intense such transitions in copper, zinc, gallium, and those in GeXIX-XX and GeXIV have been observed in a laser-produced plasma by Fawcett and Hayes.[15] Transitions belonging to the second

group have been identified in laser-produced plasmas.[15,16] Several resonance lines of GeXXI and GeXXII and the $3s^2\ {}^1S_0$-$3s3p\ {}^3P_1$ intercombination line of GeXXI and SeXXIII, as well as other ions in the MgI-like sequence, have been observed in the PLT tokamak.[17,18] Edlén has analyzed the 3s-3p and 3p-3d transitions in the NaI-like sequence for SVI to MoXXXII.[19] Transitions belonging to the third group have been identified by Behring et al.,[20] in zinc and germanium using a laser-produced plasma. These $2s^22p^k$-$2s2p^{k+1}$ transitions in the FI and OI isoelectronic sequences have been studied by Edlén.[21]

II. EXPERIMENT

Atoms of the element under investigation were injected into the quasi-steady phase of an ohmically heated PLT discharge[22] at a predetermined time using the laser blow-off technique.[23,24] The short duration of the injection means that the time evolution of each line is characteristic of its ionization state. Typical plasma parameters at the time of injection were I_p = 450 kA, B_T = 29 kG, $\bar{n}_e$ = 2-3 x 10^{13} cm^{-3}, and Te(0) = 1.5-2 keV; although spectra were taken under various conditions to check the consistency of the identifications.

Two grazing incidence spectrometers were used to observe the lines reported here. The first is a new time-resolving spectrograph constructed for fusion plasma diagnostics.[25] It is a one-meter 88° incidence instrument utilizing a 1200 g/mm holographic grating, 50 μm entrance slit, and covering the region from 15 to 360 Å. The detector consists of a funnelled MgF_2-coated, microchannel plate mounted tangentially to the Rowland circle, coupled via a phosphor screen and fiber optics to a 1024 element photodiode array. The photodiode array integrates the incoming flux for a period of time, which for most of the spectra taken in this work was 5.4 ms, the minimum time

resolution of the detector. The detector may be moved along the Rowland circle and simultaneously covers a 40 to 80 Å bandwidth with 0.7 Å resolution (line profile FWHM).

The instrument has been photometrically calibrated between 50 and 360 Å at the NBS SURF II synchrotron. A wavelength calibration was performed using a cubic spline interpolation procedure between well-known lines of intrinsic (C, O, Ti, and Fe) and injected impurities in the tokamak discharge; estimated uncertainty in the determination of the wavelength of an unknown line is 0.2 Å. The spectrograph is mounted on a device which moves it to view different chords of the plasma from one shot to the next, allowing radial profiles of the impurity emissions to be constructed. For most of the measurements reported here the spectrograph viewed the plasma along a line of sight through its center.

The second instrument is a two-meter extreme grazing incidence duochromator[26] with a wavelength coverage of 6 to 300 Å. It utilizes a 600 g/mm grating, a 30 μm entrance slit, and two 40 μm exit slits resulting in a 0.4 Å FWHM instrumental line profile. The detectors are two-channel electron multipliers. The instrument views the PLT plasma along a central chord.

These two instruments have complementary capabilities: the ability of the time-resolving spectrograph to view many lines during one discharge and the very fast time resolution of the duochromator. Advantage was taken of this fact in making the identifications. Initially, spectra of germanium and selenium in the 50 to 350 Å range were taken from a series of similar discharges with the time-resolving spectrograph using a 5.4 ms integration time. As an example, the spectra of germanium and selenium between 90 and 140 Å are shown in Fig. 1. These spectra show the incoming flux integrated from 3.5 to 8.9 ms after the time of injection, the period during which the

lines in this region reach their maximum intensity. The vertical scale gives the brightness as a function of wavelength. (The total brightness of a line is obtained by integrating over the line profile and subtracting an appropriate background level.) The two spectra are similar, with the lines of the germanium spectrum shifted to longer wavelengths than those of the selenium spectrum. It may be seen that there are numerous lines superimposed on a background of continuum radiation and unresolved lines of lower ionization states. The strong lines in this region are primarily due to $3p^k$-$3p^{k-1}3d$ transitions; the brightest lines are emitted by the ClI, ArI, and KI-like ions. The spectrum immediately before injection is shown in each case. Because the lines due to the injected element are so much stronger, the intrinsic impurity lines, although present, are not distinguishable on this scale.

In each spectral region, the wavelengths of the lines were measured and the known lines identified. An approximate degree of ionization was assigned to each of the unknown lines by comparing its time evolution with those of the known lines. Preliminary identifications were then made by comparison with predicted wavelengths obtained by isoelectronic sequence extrapolations performed using the wavelengths given in Refs. 10-16, and by comparing the absolute intensities of the lines in the two elements. The extrapolations were made by plotting $(\sigma/\zeta+k)$ against ζ, where σ is the transition energy in cm^{-1}, ζ-1 is the net charge of the ion, and k is a constant chosen to make the curve nearly linear; the curve was then smoothly continued to higher ζ.[27] For SeXXII 143.6 Å, SeXXII 131.6 Å, and SeXXIV 239.1 Å the predictions of Fawcett and Hayes[15] were used.

Because the 5.4 ms time resolution of the spectrograph was sufficient to make only an approximate assignment of an unknown line to an ionization state,

the identifications were verified by observing the time evolution of each line in a series of similar discharges using the duochromator. The techniques and difficulties of line identification using the time behavior are discussed in detail by Hinnov et al.[17] The usual procedure was to observe the unknown line using one channel of the duochromator and a known line of the same or a nearby ionization state with the other channel, both for comparison of the time evolution and as a monitor of the reproducibility of the injection. Sometimes the time behavior of lines due to adjacent ionization states was very similar and could not be easily distinguished in different discharges due to statistical fluctuations in the signals and minor variations in the injection and plasma conditions. This was particularly true for the lower states of ionization having similar ionization potentials, for example, SeXVII (E_i = 657 eV) and SeXVIII (E_i = 695 eV). In some of these cases the situation could be improved by taking data during several discharges to improve the statistics but, in general, it was not possible to distinguish unambiguously two lines of these lower ionization states (GeXV-XIX and SeXVII-XXI) by comparison of their time behavior. However, it was always possible to assign an unknown line to one of two or three ionization states. Lines of different ionization states are generally well-separated in wavelength; for this reason a confident identification could be made by a combination of comparison of the measured and predicted wavelengths, the time evolution, and, in some cases, the radial distribution of the emissions.

As an example, the time histories of lines of six ionization states of germanium, XIV, XVII, XX, XXII, XXIV, and XXV obtained by the duochromator from similar discharges are shown in Fig. 2. The horizontal scale is the time elapsed from the time of injection and the vertical scale is the intensity in arbitrary units. The ionization potential is given for each ion.[28] Two

quantities are relevent in comparing the time behavior of these lines: the time from the point of injection to the peak signal and the time required for the signal to decay from its maximum value to some fraction (e.g., 1/e) of that value. In tokamak plasmas the rise time is determined primarily by the ionization rates and the decay time primarily by the recombination rates and by transport phenomena in the plasma. The rise and decay times are longer for higher ionization states than for lower ones due to longer ionization and recombination times. This trend is clearly shown in Fig. 2. The differences are quite distinct when two states of ionization differ substantially in ionization potential, as is the case for GeXVII and GeXX, and are even more obvious for the higher ionization states such as GeXXIV and GeXXV. The early rise in the GeXXIV and GeXXV signals shown in Fig. 2 is attributed to an increase in the background level and to lines of low ionization states shortly after the time of injection; in each case, the dashed line shows the probable time evolution of the signal if these effects were not present.

A further verification of the selenium identifications was provided by making radial profiles of the lines in the 80-140 Å region using the time-resolving spectrograph. The ionization states (SeXVI-XXII) of these lines have their maximum abundance at a minor radius of 25-30 cm (limiter radius = 40 cm) in PLT discharges with $T_e(0) \approx 2$ keV, beyond the 0-24 cm range of the radial scanning system. For this reason low temperature ($T_e(0) \approx 500$ eV) discharges, in which these ionization states peak within the central 10 cm of the plasma, were used. The profiles are consistent with the identifications. However, as in the case of the time behavior of the lines, it is not always possible to distinguish two adjacent states of ionization.

III. RESULTS

Table 1 lists the observed $3p^k$-$3p^{k-1}3d$ and $3p^63d$-$3p^53d^2$ transitions with their measured and predicted wavelengths. The lines of GeXIV, GeXIX, and GeXX have been previously measured[15] with greater accuracy than in the present work. These lines are listed in order to give their relative intensities in a tokamak plasma and because they should be useful for tokamak diagnostics. These previously measured values are listed in the predicted wavelength column and the value measured in this experiment is given in the measured wavelength column. With a few exceptions, the measured wavelengths agree with the predictions within ± 0.4 Å. Also given is the brightness of the lines measured by the time-resolving spectrograph. Because the detector integrates the signal for 5.4 ms, these brightnesses represent an average value from 3.5 to 8.9 ms after the time of injection, the period during which the lines listed in Table 1 reach their maximum brightness. The brightnesses are taken from several similar discharges into which approximately 8×10^{17} atoms of the element under consideration were ablated from the laser target, an estimated 30% of these entered the plasma, corresponding to an impurity density approximately 0.3% of $\bar{n}_e$, assuming a uniform impurity distribution over the plasma volume. [$T_e(0) \approx 2$ keV for these discharges.] The brightnesses may be compared to give approximate relative intensities of the lines in a tokamak plasma. Several of the lines have broad or irregularly shaped profiles when the spectra are plotted on an expanded scale. This is attributed to the blending of two or more lines due to the spectral resolution used, and is noted in Table 1. Higher resolution spectra should resolve these blends. In these cases, the major component of the peak is considered to be the one listed.

Identification of the lines of ions isoelectronic with AlI, SiI, ClI, and ArI is straightforward because the extrapolations should be reliable for these relatively simple systems. Particularly when a transition is already known in germanium, the extrapolation to selenium is more certain. This is the case for the AlI, SiI, and ArI-like ions: the agreement between the predicted and measured wavelengths in selenium is quite good. The GeXX $3p\ ^2P_{1/2}$-$3d\ ^2D_{3/2}$ transition at 146.6 Å is blended, accounting for its unusually high brightness compared to the $3p\ ^2P_{3/2}$-$3d\ ^2D_{5/2}$ transition at 157.5 Å. In the ClI-like sequence agreement between the extrapolated and measured wavelengths is quite good for germanium, in selenium the measured values are 0.4 Å less than the predicted ones. Because these are expected to be the two most intense lines in the selenium spectrum near the predicted wavelengths, the identifictions are secure. The SeXVIII 109.9 Å line is brighter than the SeXVIII 109.1 Å line, the opposite would be expected for these $^2P_{1/2}$-$^2D_{3/2}$ and $^2P_{3/2}$-$^2D_{5/2}$ transitions, as is observed in germanium. This is attributed to a blending of the 109.9 Å line with the $3p^63d\ ^2D_{5/2}$-$3p^53d^2\ ^2F_{7/2}$ transition of SeXVI predicted at 110.3 Å. The wavelength of this last transition is given in Table 1 as approximately 109.9 Å. No brightness is given because it is difficult to estimate its contribution to the SeXVIII 109.9 Å line. This identification is supported by the fact that the $3p^63d\ ^2D_{5/2}$- $3p^53d^2\ ^2F_{7/2}$ transition would otherwise be missing from the selenium spectrum but is present in the germanium spectrum. With this exception, and the exception of the GeXX 146.6 Å line, the lines of the AlI, SiI, ClI, and ArI-like ions are strong and unblended, which should make them quite useful as tokamak diagnostics.

Identifications in the PI, SI, and KI-like ions are more difficult, in part because the isoelectronic sequence extrapolations are less sure for these

complex ions and, for the PI and SI-like ions, because the time behavior is similar to that of the SiI and ClI-like ions, respectively. An additional problem is that many of the lines are blended. In the PI-like sequence agreement between the predicted and measured wavelengths for the GeXVIII 136.7 Å, GeXVIII 131.3 Å, and SeXX 123.3 Å lines is close but these lines are blended, reducing their utility as diagnostic lines. The measured wavelength of the SeXX 119.7 Å line differs by 0.8 Å from its predicted value. But because it is the strongest line in that region, the identification is reasonably certain.

A similar problem with blending arises in the lines of ions isoelectronic with SI. There the GeXVII 126.4 Å, SeXIX 112.5 Å, and SeXIX 114.0 Å lines are blended. The GeXVII 125.0 Å line is strong and unblended, making it a useful diagnostic line.

The SeXVI 102.6 Å line of the KI-like isoelectronic sequence has a broad structure consisting of a main peak, identified as the $3p^6 3d\ {}^2D_{5/2}$-$3d^5 3d^2\ {}^2D_{5/2}$ transition, unseparated from a peak at 102.2 Å, tentatively identified as the $3p^6 3d\ {}^2D_{3/2}$-$3p^5 3d^2\ {}^2D_{3/2}$ transition predicted at 101.6 Å. The brightness given for this line is estimated. In some spectra the two lines appear blended with a third line.

Table 2 lists the observed transitions in the AlI, MgI, NaI, FI, and OI-like ions. With the exception of the SeXXIV $3s\ {}^2S_{1/2}$-$3p\ {}^2P_{1/2}$ transition predicted at 239.10 Å[15] and observed here at 239.1 Å, these transitions have been previously observed with greater wavelength accuracy than in the present work. For this reason, these previously measured values are listed in Table 2 with the source of the measurement noted. The maximum brightness of each line is also given, taken from similar discharges with the same plasma parameters and injected quantity as in Table 1. The time behavior of these high

ionization states can be quite different, as seen in Fig. 2; the brightness does not generally correspond to the same time after injection.

The strongest of these lines are the $3s\ ^2S_{1/2}$-$3p\ ^2P_{1/2}$, $^2P_{3/2}$ transitions in GeXXII and SeXXIV and the $3s^2\ ^1S_0$-$3s3p\ ^1P_1$ transitions in GeXXI and SeXXIII. The $3s^2\ ^1S_0$-$3s3p\ ^3P_1$ intercombination line is quite strong, its intensity being within an order of magnitude of the $^1S_0$-$^1P_1$ transition in both germanium and selenium as previously reported.[18] The GeXXII 174.396 Å line has an unusually broad profile, in some spectra three peaks appear, at 174.4 Å, 174.8 Å, and a third in between these two. The peak at 174.8 Å is probably the GeXXI $3s3p\ ^1P_1$-$3s3d\ ^1D_2$ transition observed by Fawcett and Hayes.[7] The GeXXII 174.396 Å brightness given in Table 2 includes all three peaks and is therefore too large compared to the GeXXII 190.614 Å brightness; the correct ratio is seen for the same two transitions in SeXXIV. The resonance lines of FI and OI-like germanium are much less intense than those of the preceeding ionization states. This is attributed to the smaller fractional abundance of these high ionization states in a plasma with $T_e(0) \approx$ 2 keV. The resonance lines of FI and OI-like selenium have not yet been observed. In addition to the lines listed in Tables 1 and 2, a number of weaker lines were observed in the region around 200 Å in both germanium and selenium. These are probably due to $3s^23p^k$-$3s3p^{k+1}$ transitions, which are expected to lie at longer wavelengths than the $3p^k$-$3p^{k-1}3d$ transitions.

IV. CONCLUSION

The most intense lines emitted by a wide range of ionization states of germanium and selenium have been observed in a tokamak plasma and their brightnesses measured. In particular, many new $3p^k$-$3p^{k-1}3d$ transitions have been identified. These lines should prove useful in the diagnostics of tokamak plasmas.

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Table 1. $3^2 3p^k - 3s^2 3p^{k-1} 3d$ and $3s^2 3p^6 3d - 3s^2 3p^5 3d^2$ Transitions in Germanium and Selenium

Isoelectronic Sequence	Transition		Germanium Ion	Germanium λ meas.	Germanium λ pred.	Germanium B	Selenium Ion	Selenium λ meas.	Selenium λ pred.	Selenium B
KI	$3p^6 3d - 3p^5 3d^2$	$^2D_{5/2} - {}^2F_{7/2}$	XIV	122.8	122.82[a]	850	XVI	~109.9(bl.)[T]	110.3[c]	
		$^2D_{5/2} - {}^2D_{5/2}$		114.0	113.93[a]	1600		102.6(bl.)	102.9[c]	1300
		$^2D_{3/2} - {}^2D_{3/2}$		113.0	112.96[a]	710		102.2[T]	101.6[c]	~ 740
ArI	$3p^6 - 3p^5 3d$	$^1S_0 - {}^1P_1$	XV	117.2	117.25[a]	1300	XVII	105.9	105.9[c]	1500
ClI	$3p^5 - 3p^4 3d$	$^2P_{1/2} - {}^2D_{3/2}$	XVI	121.8	121.7[c]	1200	XVIII	109.9(bl.)	110.3[c]	1500
		$^2P_{3/2} - {}^2D_{5/2}$		120.9	120.9[c]	1400		109.1	109.5[c]	1400
SI	$3p^4 - 3p^3 3d$	$^1D_2 - {}^1P_3$	XVII	126.4(bl.)	126.0[c]	1100	XIX	114.0(bl.)	114.3[c]	1200
		$^3P_2 - {}^3D_3$		125.0	125.2[c]	910		112.5(bl.)	113.1[c]	700
PI	$3p^3 - 3p^2 3d$	$^4S_{3/2} - {}^4P_{5/2}$	XVIII	136.7(bl.)	136.8[c]	240	XX	123.3(bl.)	123.6[c]	290
		$^2D_{5/2} - {}^2F_{7/2}$		131.3(bl.)	131.3[c]	580		119.7	118.9[c]	390
SiI	$3p^2 - 3p3d$	$^3P_2 - {}^3D_3$	XIX	143.0	143.04[a]	960	XXI	129.5	129.5[c]	500
AlI	$3p - 3d$	$^2P_{3/2} - {}^2D_{5/2}$	XX	157.5	157.55[a]	790	XXII	143.6	143.57[b]	760
		$^2P_{1/2} - {}^2D_{3/2}$		146.6(bl.)	146.61[a]	800		131.6	131.61[b]	470

Wavelengths are in Å with a measured accuracy of ± 0.2 Å.

B: Brightness (10^{12} photons/sec-cm^2-sr).
T: Tentative identification

a) Previously measured value from Ref. 15
b) Predicted value from Ref. 15
c) Predicted in present work

Table 2. Observed Transitions in AlI, MgI, NaI, FI, and OI-like Germanium and Selenium

Isoelectronic Sequence	Transition		Germanium Ion	Germanium λ	Germanium B	Selenium Ion	Selenium λ	Selenium B
AlI	$3s^2 3p - 3s 3p^2$	$^2P_{1/2} - ^2P_{3/2}$	XX	184.38[a]	540	XXII	165.62[a]	460
MgI	$3s^2 - 3s 3p$	$^1S_0 - ^1P_1$	XXI	196.57[a]	3900	XXIII	175.92[a]	4700
		$^1S_0 - ^3P_1$		293.4[b]	450		265.7[b]	490
NaI	3s-3p	$^2S_{1/2} - ^2P_{1/2}$	XXII	261.52[c]	1900	XXIV	239.1[d]	1700
		$^2S_{1/2} - ^2P_{3/2}$		226.505[c]	3300		201.07[c]	4300
	3p-3d	$^2P_{3/2} - ^2D_{5/2}$		190.614[c]	330		174.118[c]	660
		$^2P_{1/2} - ^2D_{3/2}$		174.396[c](bl.)	430		156.468[c]	260
FI	$2s^2 2p^5 - 2s 2p^6$	$^2P_{1/2} - ^2S_{1/2}$	XXIV	79.78[e](bl.)	30			
		$^2P_{3/2} - ^2S_{1/2}$		65.93[e]	40			
OI	$2s^2 2p^4 - 2s 2p^5$	$^3P_1 - ^3P_2$	XXV	92.56[e]	20			
		$^3P_2 - ^3P_1$		68.65[e]	20			
		$^3P_2 - ^3P_2$		75.55[e]	40			

Wavelengths are in Å

B: Brightness (10^{12} photons/sec-cm^2-sr)
a) Wavelength from Ref. 15
b) Wavelength from Ref. 18
c) Wavelength from Ref. 16
d) Wavelength measured in present work, predicted at 239.10 Å in Ref. 15
e) Wavelength from Ref. 20

FIGURE CAPTIONS

FIG. 1 Spectra of Germanium and Selenium in the 90-140 Å region. Spectra immediately before impurity injection are also shown.

FIG. 2 Time behavior of lines due to six different ionization states of germanium.

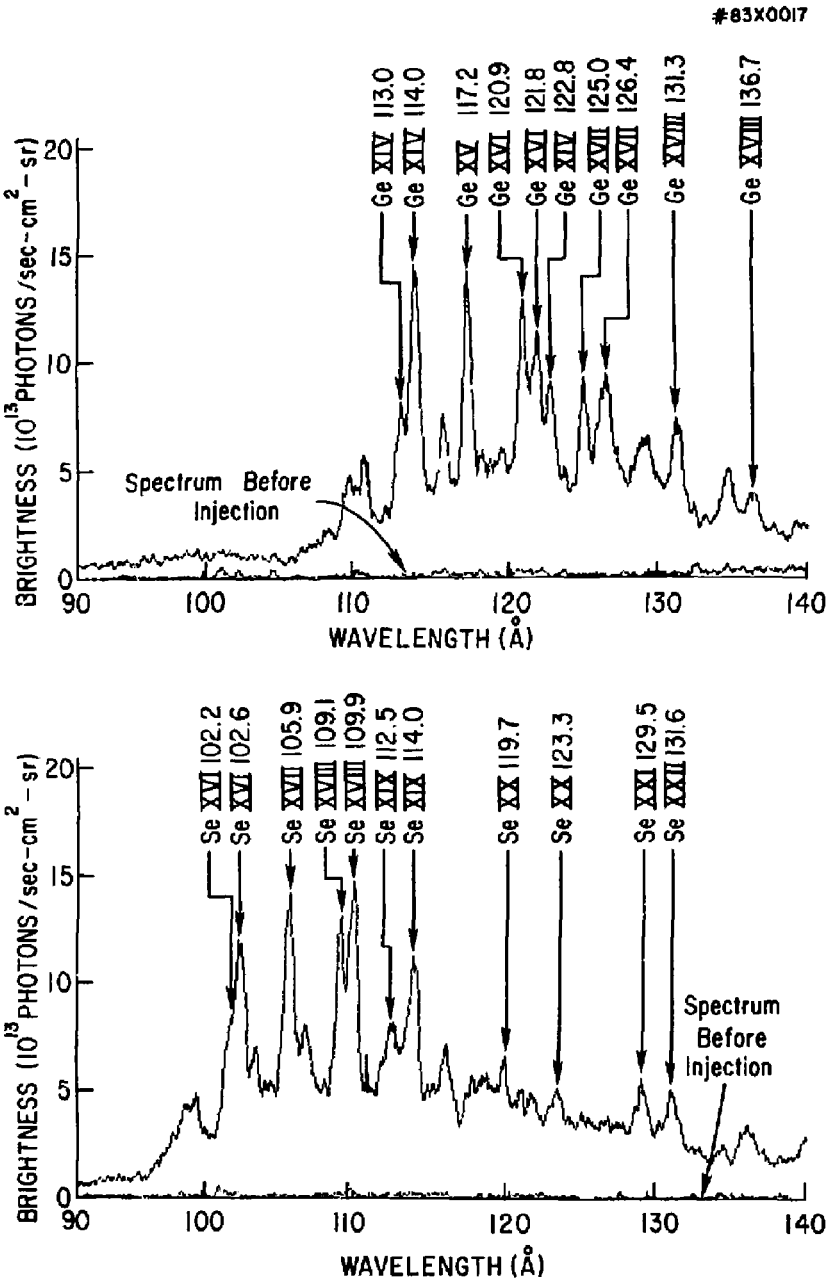
#83X0017
Ge XIV 113.0
Ge XIV 114.0
Ge XV 117.2
Ge XVI 120.9
Ge XVI 121.8
Ge XIV 122.8
Ge XVII 125.0
Ge XVII 126.4
Ge XVIII 131.3
Ge XVIII 136.7
Spectrum Before Injection
BRIGHTNESS (10^13 PHOTONS/sec-cm^2-sr)
WAVELENGTH (Å)
Se XVI 102.2
Se XVI 102.6
Se XVII 105.9
Se XVIII 109.1
Se XVIII 109.9
Se XIX 112.5
Se XIX 114.0
Se XX 119.7
Se XX 123.3
Se XXI 129.5
Se XXII 131.6
Spectrum Before Injection
BRIGHTNESS (10^13 PHOTONS/sec-cm^2-sr)
WAVELENGTH (Å)

Fig. 1

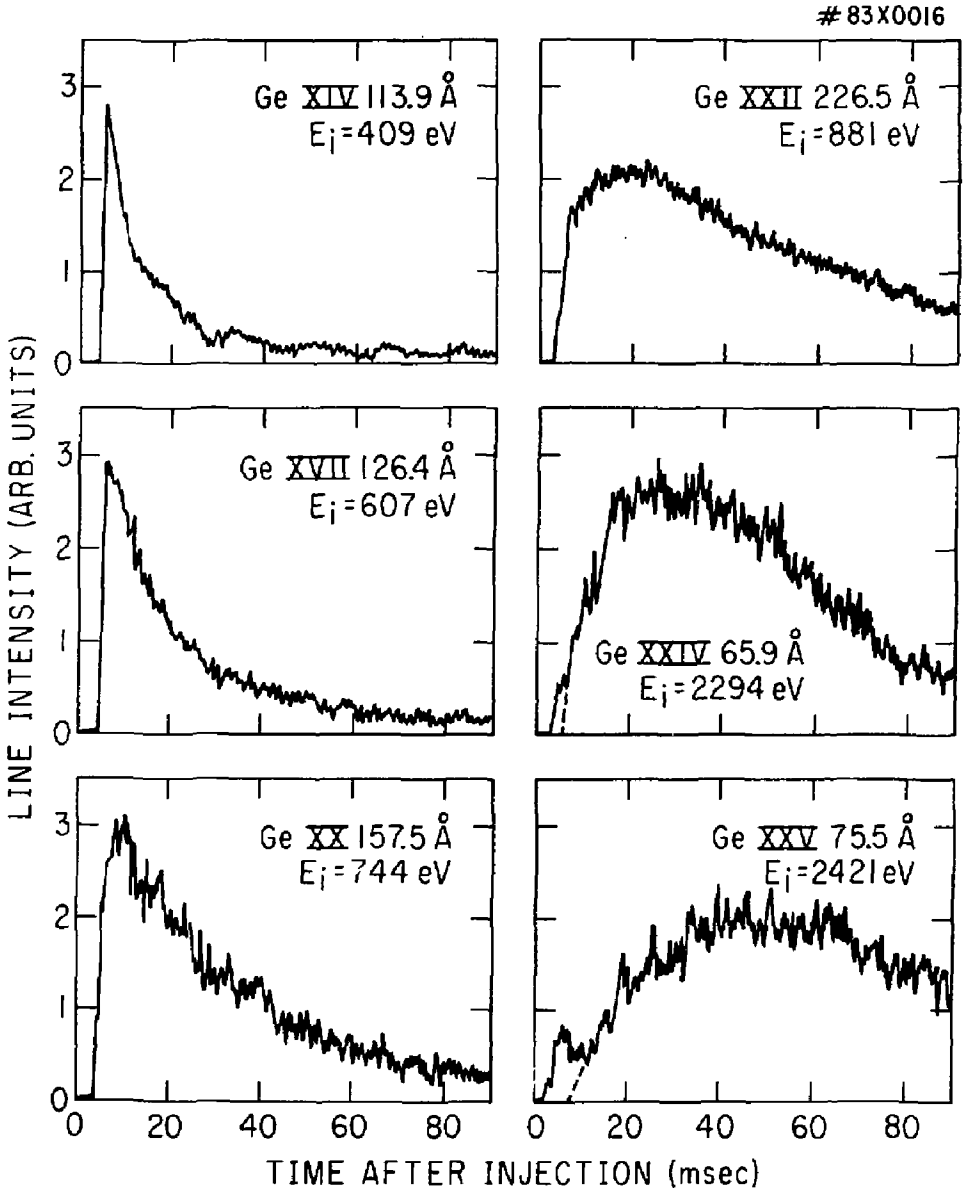
#83X0016
Ge XIV 113.9 Å
Ei=409 eV
Ge XXII 226.5 Å
Ei=881 eV
Ge XVII 126.4 Å
Ei=607 eV
Ge XXIV 65.9 Å
Ei=2294 eV
Ge XX 157.5 Å
Ei=744 eV
Ge XXV 75.5 Å
Ei=2421eV
LINE INTENSITY (ARB. UNITS)
TIME AFTER INJECTION (msec)
0
1
2
3
0
20
40
60
80

Fig. 2

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