Measurement of the $3d \rightarrow 2p$ resonance to intercombination line-intensity ratio in neonlike Fe XVII, Ge XXIII, and Se XXV

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Measurements of the $3d \rightarrow 2p$ resonance and intercombination lines were made on the PLT tokamak for the neonlike ions Fe XVII, Ge XXIII, and Se XXV at several electron temperatures. The observed ratios agree with measurements of the ratios of the electron-impact excitation cross sections measured at the Livermore EBIT-II electron beam ion trap indicating that the effects of indirect excitation processes active in a plasma environment are minor for this line pair. However, the measured ratios are significantly smaller than theoretical predictions of their relative oscillator strengths or electron-impact excitation rates, illustrating the need to use laboratory measurements to calibrate this line pair at the level necessary for spectral diagnostics.

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I. INTRODUCTION

The $n=3 \rightarrow n=2$ L-shell spectrum of mid-Z neonlike ions dominates the x-ray emission over a wide range of plasma conditions in tokamak plasmas, laser-produced plasmas, the Sun, and a variety of cosmic sources. As a result, the spectrum is of great importance for plasma diagnostics and has been used, for example, for impurity transport studies, electron temperature and density measurements, ion and elemental abundance determinations, and opacity measurements (see [1–9]). The L-shell spectrum from neonlike ions rivals the diagnostic utility of the K-shell emission from helium ions and, because of its increased complexity, has the potential to surpass it.

Two of the strongest, most distinct $n=3 \rightarrow n=2$ L-shell spectral features are the $2p^5 3d_{3/2}\ ^1P_1 \rightarrow 2p^6\ ^1S_0$ and $2p^5 3d_{5/2}\ ^3D_1 \rightarrow 2p^6\ ^1S_0$ resonance and intercombination lines, commonly labeled $3C$ and $3D$, respectively. The two lines are well resolved yet close enough together for observation with typical high-resolution x-ray spectrometers. The intensity ratio of this line pair in Fe XVII has been employed as a density diagnostic of flares in the solar corona [10]. The idea behind this diagnostic is that the stronger $3C$ line is more prone to resonant scattering than the weaker $3D$ line, which has a half an order of magnitude lower radiative rate than the $3C$ line. As the hydrogen plasma density and proportionally the iron density increases, resonance scattering was thought to have the effect of preferrentially decreasing the intensity of the $3C$ line. A smaller ratio of the intensity of the $3C$ line relative to that of $3D$, therefore, is associated with a higher hydrogen density. From an observed $3C$ to $3D$ ratio of 1.90 ± 0.21 Waljeski *et al.* inferred a hydrogen column density of $1.05 \times 10^{20}\ \mathrm{cm}^{-2}$ [10]. These evaluations require knowledge of the resonant-scattering-free, low-density value of the $3C$ to $3D$ intensity ratio. For this the authors relied on the theoretical values of the $3C$ to $3D$ ratio given by Bhatia and Doscheck [11], Zhang *et al.*[12], and Hagelstein and Jung [13] ranging from 3.78 to 4.74. The value of 3.9 they adopted is close to the value recently calculated by Mohan, Sharma, and Eisner [14] who predicted a low-density limit of $I(3C)/I(3D)=4.0$ using the R-matrix method.

Measurements of the low-density value of the Fe XVII $3C$ to $3D$ line ratio were performed on the Livermore EBIT-II electron beam ion trap under conditions where electron-impact excitation was the only line formation process [15]. These measurements have shown that the ratio is only 3.04 ± 0.12, i.e., 25% less than the R-matrix value calculated by Mohan, Sharma, and Eisner [14]. Starting with a 25% lower ratios means that the solar hydrogen density is far less than inferred by Waljeski *et al.* A systematic assessment of the predictions of various Fe XVII $3C$ to $3D$ line ratio calculations was carried out by Brown *et al.* [15] and found to scatter by a factor of 2. Ironically, the two oldest calculations [16,17] provided the best agreement [18] with the EBIT-II measurement; the newest calculations differed in the range of 25%–50%. This investigation demonstrated unequivocally that a reliable and commonly accepted low-density limit of this line ratio adequate for diagnostic applications has not been produced by theory. A recent extension of electron beam ion trap measurements to other mid-Z neonlike ions demonstrated that electron-impact excitation calculations are equally challenged in reproducing the relative $3C$ to $3D$ cross sections for a range of atomic numbers $Z=24$–36 [19].

The measurements on the Livermore electron beam ion trap so far have tested calculations of electron-impact excitation only. Application of these results to low-density plasma observations is justified by predictions that indirect excitation processes, such as innershell ionization, dielectronic recombination, and radiative electron capture, are negligible when considering the intensity ratio of the $3d \rightarrow 2p$ transitions. Indeed, these predictions were validated in measurements of neonlike barium [20]. Nevertheless, a measurement of the $3C$ to $3D$ line ratio in a low-density plasma where all direct and indirect processes are active is warranted. If tokamak observations of the $3C$ to $3D$ line ratio yield the same values as those found in the Livermore electron beam ion trap, such observations would provide a direct and independent confirmation that indirect excitation processes are negligible. Moreover, low-density plasma observations would be directly applicable to observations of sources such as the coronae of the Sun, Capella, or HR1099.

In the following we provide such a confirmation by presenting tokamak measurements of the 3C to 3D ratio in neonlike Fe, Ge, and Se that are in excellent agreement with the trend set by the electron beam ion trap measurements.

II. MEASUREMENTS

Our measurements were performed at the PLT tokamak, a medium-size device with very well diagnosed plasma parameters, including electron and ion temperature profiles, density, ion confinement time, and radial diffusion [21]. The measurements were carried out during the ohmic heating phase. The central electron density was about 5×10^{13} cm^{-3}; the central electron temperature ranged from about 1 to 2 keV. A laser-ablation system enabled the injection of any desired trace element [22]. This system was used to inject germanium and selenium. Iron was an indigenous trace element in PLT, and no additional injection was needed to observe its line emission. Tokamak plasmas have provided accurate information on atomic parameters and processes [23–27]. The PLT tokamak, in particular, has been used to study the x-ray spectra of K-shell [28,29], L-shell [30–32], and M-shell ions [33].

Neonlike transitions of mid-Z ions fall into the ultra-soft x-ray range from 5 to 25 Å. The present measurements were enabled by the implementation of two different vacuum Bragg crystal spectrometers. The first was a rotating flat-crystal spectrometer with microchannel-plate readout. The resolving power of the instrument was about 300 at a Bragg angle of 45° and limited by the angular aperture of the Soller slots used for collimation. A description of the instrument was given by von Goeler *et al.* [34]. For the present measurements, the instrument viewed the plasma along a radial sight line in the horizontal midplane. A thallium hydrogen phthalate crystal with lattice spacing of 12.88 Å was used to record the L-shell emission of Fe XVII. An ammonium dihydrogen phosphate crystal with lattice spacing of 5.33 Å was used to measure the L-shell spectra of Ge XXIII and Se XXV.

A typical spectrum of Ge XXIII obtained with the rotating flat-crystal spectrometer is shown in Fig. 1. Spectra from 30 similar tokamak discharges were added to increase the signal to noise ratio. This was necessary because of the intrinsically low throughput of the flat-crystal geometry and the small x-ray detection efficiency of the microchannel plate detectors. Data obtained with this instrument, therefore, represent not only averages over the observation chord through the plasma but also over different, though similar plasma discharges (between 10 and 100) during a given run period. Data were obtained in different run periods several months apart.

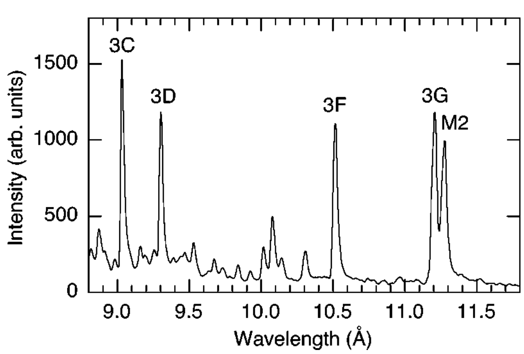

FIG. 1. L-shell emission spectrum of Ge XXIII recorded with the vacuum flat-crystal spectrometer. The spectrum represents the sum of 30 similar discharges. The lines are labeled in standard notation, where 3C, 3D, 3F, and 3G denote the electric dipole transitions from upper levels $2p_{1/2}^5 3d_{3/2}\ ^1P_1$, $2p_{3/2}^5 3d_{5/2}\ ^3D_1$, $2p_{1/2}^5 3s_{1/2}\ ^1P_1$, and $2p_{3/2}^5 3s_{1/2}\ ^3P_1$, respectively, to the $2p^6\ ^1S_0$ ground level. $M2$ denotes the magnetic quadrupole transition $2p_{3/2}^5 3s_{1/2}\ ^3P_2 \rightarrow 2p^6\ ^1S_0$.

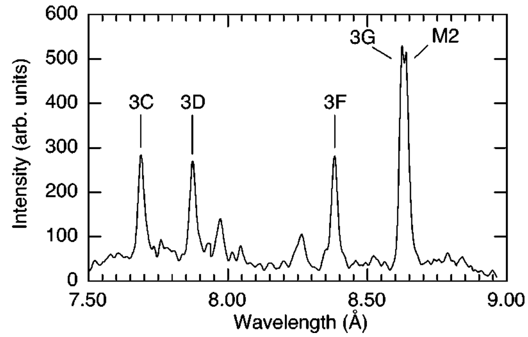

FIG. 2. L-shell emission spectrum of Se XXV recorded with the vacuum flat-crystal spectrometer. The spectrum represents the sum of 17 similar discharges.

Spectra showing the Se XXV and the Fe XVII L-shell emission are shown in Figs. 2 and 3, respectively. The resolving power of the flat-crystal spectrometer was smaller for these two ions than for germanium because these were recorded at smaller Bragg angles. The resolving power in these two cases was too small to resolve blends with lines from neighboring charge states. These blends appeared to be the reason for the variation in the iron line ratios observed during different runs.

The second instrument was a curved crystal spectrometer in the Johann geometry. The spectrometer employed a microchannel plate-intensified one-dimensional charge coupled device for readout and an ammonium diphosphate crystal bent to a 57.3 cm radius for studying the L-shell emission of Se XXV. A description of the instrument was given by Beiersdorfer *et al.* [3].

A typical spectrum showing the 3C and 3D lines in

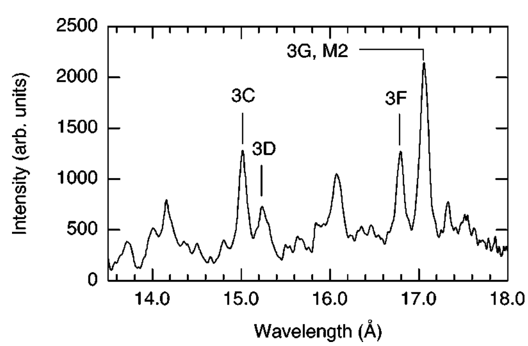

FIG. 3. L-shell emission spectrum of Fe XVII recorded with the vacuum flat-crystal spectrometer. The spectrum represents the sum of four similar discharges.

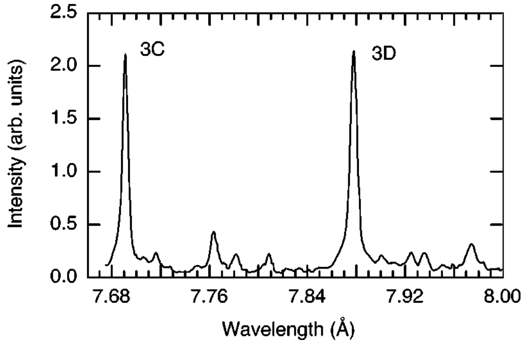

FIG. 4. *L*-shell emission spectrum of Se XXV obtained with the high-resolution Johann crystal spectrometer showing lines 3*C* and 3*D*. The spectrum was obtained from a single discharge.

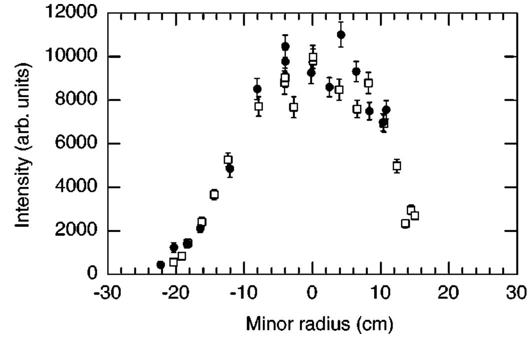

FIG. 5. Emissivities of the lines 3*C* (solid circles) and 3*D* (open squares) of as a function of the minor radius of the plasma. Error bars denote statistical uncertainties.

Se XXV is shown in Fig. 4. The nominal resolving power of this instrument is an order of magnitude higher than that of the rotating flat-crystal spectrometer. Moreover, the curved-crystal geometry provided high throughput and allowed us to collect a single spectrum in a 4.3 ms time interval. For the present measurements, the detector was slightly defocused in order to get a broader wavelength coverage, and the resolving power was about 1500.

Unlike the flat-crystal spectrometer, the plane of dispersion of this instrument was oriented perpendicular to the horizontal midplane. A pivot point near the tokamak vacuum vessel enabled us to perform radial scans of the plasma. The spectrometer was moved to a different radial sightline between each tokamak discharge. A total of 20 spectra were recorded at as many different radial chords. We used this capability to collect spectra for different radial chords that were then inverted to provide true line emissivities as a function of plasma radius. Details of this procedure were given in [3]. The radial profiles of the 3*C* and 3*D* lines are shown in Fig. 5.

III. RESULTS AND COMPARISON WITH THEORY AND ION-TRAP MEASUREMENTS

The results of the intensity ratios of 3*C* and 3*D* from our different measurements are given in Table I. Maximum and minimum values are given together with the average of the measurements carried out in separate run periods.

The radial emission measurements of the selenium lines allowed us to correlate the emission of the 3*C* to 3*D* intensity ratios to the electron temperature. The electron temperature in a tokamak plasma typically peaks at the center and falls off toward the edge. Laser scattering measurements showed that the electron temperature decreases monotonically from about 2.2 keV in the center to less than 1.0 keV near the edge of the radial extent from which Se XXV was observed in our Johann spectrometer measurements. The radial profiles of 3*C* and 3*D* track each other closely, as seen in Fig. 5. They track each other despite the variation in electron temperature by a factor of 2 in this range, indicating that there is little sensitivity of their intensity ratio to the temperature. A correlation of the radial variation of the intensity ratio with the electron temperature is shown in Fig. 6. As expected, the ratio of the 3*C* and 3*D* line intensities is independent of electron temperature within the scatter of the measurements.

The fact that the intensity ratio of 3*C* and 3*D* is independent of the plasma radius and thus of the electron temperature demonstrates that the line ratio is unaffected by excitation processes that are strongly temperature dependent. In other words, the excitation rates for each line scale the same way as a function of temperature.

Based on the radially resolved spectral data, we can safely presume that the intensity data from the flat-crystal spectrometer, which is integrated along the radial sightline through the plasma and thus over different temperature regions, is a good representation of the intensity ratio of 3*C* and 3*D*. Indeed, the ratio for Se XXV obtained with the flat-crystal spectrometer is in good agreement with the ratio ob-

TABLE I. Measurement of the relative intensity of lines 3*C* and 3*D* in mid-*Z* neonlike ions. Both the range of ratios observed in different run periods with 10 to 100 tokamak discharges each and their average are given.

Ion	Instrument	Number of different run periods	I_{3C}/I_{3D} (range)	I_{3C}/I_{3D} (average)
Fe XVII	flat-crystal spectrometer	5	2.05–3.33	2.48 ± 0.40
Ge XXIII	flat-crystal spectrometer	6	1.21–1.95	1.50 ± 0.14
Se XXV	flat-crystal spectrometer	1	1.05[a]	1.05 ± 0.20
Se XXV	bent-crystal spectrometer	1	1.03–1.18	1.12 ± 0.05

[a]Single run period of 17 tokamak discharges.

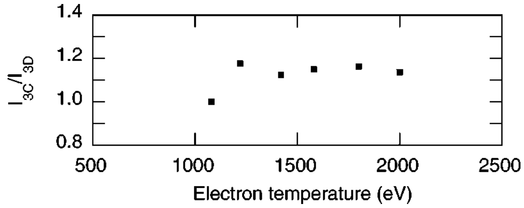

FIG. 6. Ratio of the emissivities of the Se XXV lines $3C$ and $3D$ as a function of electron temperature.

tained from the value obtained with the Johann spectrometer, the average of which is also listed in Table I.

In Fig. 7 we compare our measurements to the ratio of the electron-impact excitation cross sections measured by Brown, Beiersdorfer, and Widmann *et al.* [19]. As this figure illustrates, our data agree well within the trend set by their cross section data. This good agreement would not be expected were it not for the fact that indirect excitation and plasma processes are negligible for the $3C$ to $3D$ line ratio. Together with the lack of a temperature dependence of the line ratio, these data thus confirm the notion that the ratio is described by the relative electron-impact excitation cross sections and is essentially independent of indirect excitation and plasma processes.

As noted by Brown, Beiersdorfer, and Widmann [19] the measured $3C$ to $3D$ intensity ratio systematically differs from the values obtained from calculations. For example, the results from distorted-wave calculations of Zhang *et al.* [12] were found to be about 25% higher than measured. A nearly equal discrepancy was obtained for the calculations of Hibbert, Dourneuf, and Mohan [35], while the calculation by Cornille, Dubau, and Jacquemots [36] is about 35% larger than measured. Differences on the order of 25% are also found when comparing the measured values to the ratio of oscillator strengths given by Biémont and Hansen [37]. The least agreement is noted in the comparison of the measured ratios to those predicted by Bhatia, Feldman, and Seely [38]. For chromium and nickel they predicted ratios of 15.7 and 8.1, respectively. Differing by nearly a factor of 4 from the measured values, these values are so large that they fall outside the region depicted in Fig. 7. For iron they give a value of 4.65. Although less in agreement with the measurements than any of the other predictions, this value is in much better agreement than any of their neigboring values. Their best agreement is with the measured value of germanium, where their prediction is about 30% too large. For selenium their prediction is about 65% too large.

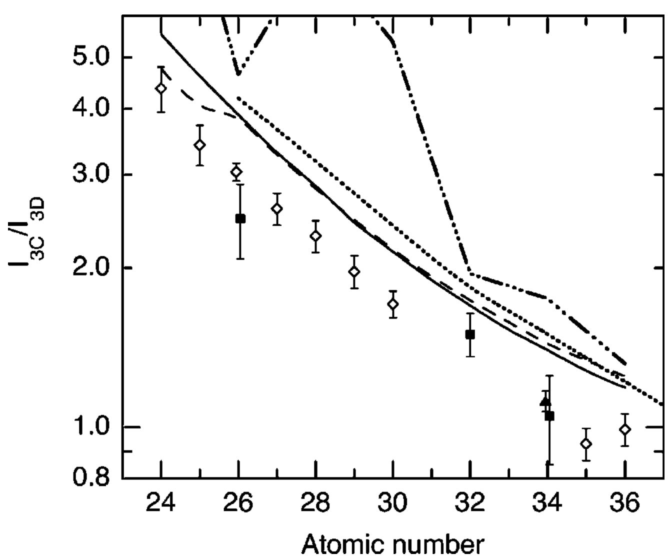

FIG. 7. Comparison of the ratios measured in the present experiments with those measured by Brown, Beiersdorfer, and Widmann on the EBIT-II electron beam ion trap (open diamonds) [19], and theory values from Zhang *et al.* (solid line) [12], Hibbert, Dourneuf, and Mohan (dashed line) [35], Cornille, Dubau, and Jacquemots (dotted line) [36], and Bhatia, Feldman, and Seely (dot-dashed line) [38].

IV. DISCUSSION

Tokamak plasmas are generally affected by radial ion transport, which smears out the radial location of a given charge state both toward higher and lower temperatures. As a result, both ionization and recombination are enhanced in tokamak plasmas. Moreover, there is a significant influx of neutral hydrogen from the wall which leads to charge exchange reactions. In addition, there are transient phenomema associated with the fact that two of the elements of interest were injected into the plasma via laser ablation. The observed x-ray spectra mirror all of these plasma processes.

The fact that there is very good agreement between our tokamak data with those from the EBIT-II electron beam ion trap, where excitation by electron impact was isolated as the sole line formation processes, shows that plasma processes are not of great significance for the intensity ratio of lines $3C$ and $3D$. PLT plasmas are relatively low density, and opacity effects are completely negligible for the lines of interest. As a result, our data can be compared to calculations of both relative excitation cross sections and rates.

The insignificance of indirect excitation processes make the $3C$ to $3D$ line ratio a particularly good case for testing the reliability of atomic scattering calculations. There is no need for complex excitation models to predict the ratio.

Comparing measurements with theory, we find systematic differences. The fractional differences remain nearly the same from one ion to the next. In the case of the calculations of Hibbert, Dourneuf, and Mohan [35], for example, a simple shift of the calculations by one and a half atomic numbers would restore good agreement with the measurements. This seems to indicate that calculations may be unable to adequately predict the effective nuclear charge seen by the optical electron. In particular, the screening of the nuclear charge by L-shell electrons seems underestimated. One should note that the range of atomic numbers plotted in Fig. 7 corresponds to the region where spin-orbit coupling increases and starts to dominate. In fact, for $Z \geqslant 36$ the intercombination line dominates the spectral emission, surpassing the intensity of the resonance line. The wave functions of the upper levels of the two transitions, therefore, mix considerably, making reliable predictions more difficult.

Similar discrepancies as a function of atomic number were noted by Beiersdorfer *et al.* and Smith *et al.* [39,40] when studying the relative intensities of the $1s$-$3p$ resonance and intercombination lines in heliumlike ions. Unlike the $3C$ to $3D$ ratio, the ratio of the heliumlike line pair is affected by calculations of the $1s$-$3p$ and $2s$-$3p$ radiative branching ratio, increasing the complexity of the calculations needed to predict the ratio and making the reason for the discrepancy less obvious. The present results for the resonance and intercombination line ratios in neonlike ions are not affected by such complications and clearly isolate problems in the excitation cross section calculations.

Our measurements of the $3C$ to $3D$ ratio for Fe XVII produced an average value of 2.48. This value is lower than that observed by Brown, Beiersdorfer, and Widmann. Individual measurements, however, ranged from 2.05 to 3.33. This scatter is attributed to blending of unresolved lines from neighboring charge states of iron, especially with $3D$.

The observed range of values for iron is markedly less than any recent theoretical value. Reliance on the theoretical values around 4.0 resulted in the suggestion that resonance scattering affects this line in the Sun. As Fig. 7 clearly shows, excitation calculations of this ratio, however, are too unreliable to draw such conclusions. A comprehensive modeling of resonance scattering in coronal loop structures has recently been developed by Wood and Raymond [41]. Their modeling calculations show that resonant scattering tends to average out when looking at multiple loops on the Sun or a star. They concluded based on their modeling that resonance scattering is unlikely to cause a reduction of the iron $3C$ to $3D$ ratio in these objects. Our range of values matches the range of values observed in the Sun [6,42] and recently from Capella [8,9]. As a result, a reduction is not needed for agreement with nonterrestrial observations. In other words, the range of values observed for Fe XVII in the present measurements reproduces the range observed in the nonterrestrial measurements without invoking resonance scattering.

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