Density-Sensitive Dielectronic Satellite Lines in Microballoon Neon Spectra

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It is suggested that the 12.3-Å feature in the spectra from compressed neon-filled microballoons, previously identified as the second-order silicon Lyman-α line, is actually a blend of neon dielectronic satellite lines. The relative intensities of these satellite lines, some of which are strong functions of electron density, agree with a numerical model of collisional mixing of the Ne IX $2l2l'$ doubly excited levels.

The neon Lyman-series spectral lines have been used to diagnose the laser-compressed core region of neon-filled microballoons.[1-4] Stark broadening of the L_β and L_γ lines indicates that electron densities in the range 2×10^{22} to 9×10^{22} cm^{-3} have been achieved. Typical electron temperatures, determined from line ratios and from the slope of the neon recombination continuum, are 300 to 400 eV. These plasma conditions have been achieved using various neon-seeding ratios and using Nd-glass and CO_2 laser irradiation.

A spectral feature at 12.3 Å, on the long-wavelength side of the neon L_α line, has been previously identified as the second-order silicon L_α line.[1,2,4] In this paper, evidence is presented that suggests that the 12.3-Å feature in the compressed-core spectra is actually a blend of neon dielectronic satellite lines. The relative intensities of these satellite lines agree with a numerical model for electron collisional mixing of the Ne IX $2l2l'$ doubly excited levels. The relative intensities of some of the satellite lines are calculated to be strong functions of electron density in the range 10^{21} to 10^{24} cm^{-3}. This is the first identification of density-sensitive dielectronic satellite lines in compressed-core spectra, and the first validation of a numerical satellite intensity model at supercritical densities.

The identification of the density-sensitive satellite lines in the compressed-core spectra permits the application of a density diagnostic technique[5,6] based on the ratios of optically thin satellite lines. This technique has the potential of providing accurate values of electron density at extremely high pellet densities where Stark broadening, because of reabsorption and overlapping of the higher Lyman-series lines,[7] becomes difficult to utilize.

For the following reasons, it is unlikely that the 12.3-Å feature in the compressed-core spectra is the second-order silicon L_α line:

(1) The spectral feature is centered at wavelength[4,8] 12.32 ± .01 Å. This is inconsistent with the measured[9] second-order Si XIV L_α doublet wavelengths 12.360 and 12.372 ± 0.002 Å.

(2) As the neon fill pressure is increased from 2 to 32 atm,[2,3] the intensities of the neon Lyman-series lines increase relative to the sodium resonance lines and to the second-order Si XIII $1s^2$-$1s3p$ line. The intensity of the 12.3-Å feature increases along with the neon lines.

(3) The widths of the 12.3-Å feature and the nearby neon lines are comparable and are much greater than the width of the second-order Si XIII $1s3p$ line.[2]

(4) In space-resolved spectra from microballons irradiated with a CO_2 laser, the 12.3-Å feature is absent in the glass-shell spectrum.[1]

(5) In two published core spectra,[1,3] the 12.3-Å feature appears to be resolved into two lines. These two lines cannot be accounted for on the basis of Lyman-α doublet splitting (12 mÅ in second order) or reabsorption at the line center. These effects would not be observable with the estimated[1] instrumental and source broadening (22 mÅ full width).

Let us now consider the possibility that the 12.3-Å feature in the compressed-core spectra is a blend of neon dielectronic satellite lines. These spectral lines result from the radiative decay of doubly excited levels. Two electrons occupy excited states, and the doubly excited levels are above the ionization limit on the energy-level diagram. The doubly excited levels may spontaneously autoionize, producing an unexcited ion of the next-higher ionization stage and a free electron. The doubly excited levels are normally populated by dielectronic recombination, the process inverse to autoionization, in which an electron is captured into an excited level and another electron is simultaneously excited.

The $2l\,2l'$ doubly excited levels of Ne IX are shown in Fig. 1. At low electron densities, these levels are primarily populated by dielectronic recombination and depopulated by autoionization and radiative decay. The satellite line intensities

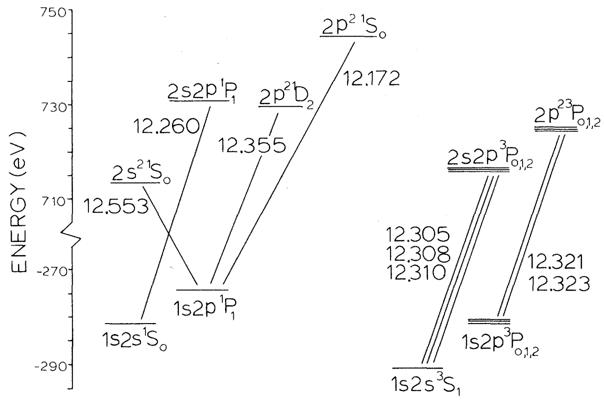

FIG. 1. The $2l2l'$ doubly excited levels of Ne IX and the wavelengths (Å) of the most intense radiative transitions. A complete list of radiative transitions is given in Table I.

are proportional to[5]

$$q_{ij} = g_i \Gamma_i A_{ij} / \lambda_{ij} (\Gamma_i + \textstyle\sum_k A_{ik}), \qquad (1)$$

where g_i is the statistical weight of the level, Γ_i is the autoionization rate, A_{ij} is the radiative decay rate, and λ_{ij} is the wavelength. As shown in Table I, the 12.355-Å satellite line is the most intense.[10]

As the electron density increases, the doubly excited levels are mixed by electron collisional transitions.[5,6] This is particularly important for the $2p^2\,{}^3P$ levels with small autoionization rates. The satellite lines originating on these levels are therefore strong functions of density. At still higher electron densities, three-body recombination from the excited hydrogenic levels, the process inverse to electron collisional ioniza-

TABLE I. The $2l2l'$ satellite transitions (Ref. 10) of Ne IX, where A is the radiative decay rate, Γ is the autoionization rate, and q is the relative intensity defined in Eq. (1) and normalized to the 12.355-Å transition.

KEY	TRANSITION	λ[Å]	q	$A[10^{12}s^{-1}]$	$\Gamma[10^{12}s^{-1}]$
1	$2p^2\,{}^1S_0 - 1s2p\,{}^3P_1$	12.087	.0002	.00014	16.6
2	$2s2p\,{}^1P_1 - 1s2s\,{}^3S_1$	12.136	.006	.00122	202
3	$2p^2\,{}^1S_0 - 1s2p\,{}^1P_1$	12.172	10.5	8.95	16.6
4	$2s2p\,{}^1P_1 - 1s2s\,{}^1S_0$	12.260	31.3	5.99	202
5	$2p^2\,{}^1D_2 - 1s2p\,{}^3P_2$	12.269	.16	.0179	372
6	$2s2p\,{}^3P_2 - 1s2s\,{}^3S_1$	12.305	36.1	5.78	13.5
7	${}^3P_1 - {}^3S_1$	12.308	21.7	5.77	13.6
8	${}^3P_0 - {}^3S_1$	12.310	7.2	5.77	13.5
9	$2p^2\,{}^3P_2 - 1s2p\,{}^3P_1$	12.321	1.6	2.90	.761
10	${}^3P_2 - {}^3P_2$	12.323	4.8	8.67	.761
11	${}^3P_1 - {}^3P_0$	12.323	0.0	3.86	0.0
12	${}^3P_1 - {}^3P_1$	12.324	0.0	2.89	0.0
13	${}^3P_0 - {}^3P_1$	12.325	.10	11.5	.0536
14	${}^3P_1 - {}^3P_2$	12.326	0.0	4.82	0.0
15	$2p^2\,{}^1D_2 - 1s2p\,{}^1P_1$	12.355	100	11.6	372
16	$2p^2\,{}^3P_2 - 1s2p\,{}^1P_1$	12.409	.007	.0126	.761
17	${}^3P_1 - {}^1P_1$	12.412	0.0	.00165	0.0
18	${}^3P_0 - {}^1P_1$	12.414	.00003	.00319	.0536
19	$2s2p\,{}^3P_1 - 1s2s\,{}^1S_0$	12.435	.004	.00116	13.6
20	$2s^2\,{}^1S_0 - 1s2p\,{}^3P_1$	12.463	.02	.00859	344
21	${}^1S_0 - {}^1P_1$	12.553	4.2	2.43	344

tion, becomes important. The populations of the excited hydrogenic levels are enhanced by reabsorption of L_α radiation.

The ten coupled rate equations, one for each of the $2l2l'$ doubly excited levels of Ne IX, have been solved numerically for the level densities and satellite line intensities. Hydrogenic collision-rate coefficients[11] are used for the allowed dipole transitions and Mewe's[12] semiempirical expression for the spin-exchange rate coefficients. Reabsorption of neon L_α radiation is treated using the escape-factor approximation, and the hydrogenic neon ground-state density is a few percent of the total density of core ions. The calculated relative intensities of the satellite lines are shown in Fig. 2. The normally weak $2p^2\,{}^3P$ lines, with wavelengths near 12.32 Å, are strong functions of electron density above 10^{21} cm^{-3}. Because of a relatively small dielectronic recombination rate, the $2p^2\,{}^3P$ levels are primarily populated by collisional transitions from the $2s2p\,{}^3P$ and $2s2p\,{}^1P$ levels. A similar density dependence for the $2p^2\,{}^3P$ lines of C V has recently been observed in space-resolved spectra from a laser-produced carbon plasma.[13]

In two published[1,3] spectra from the compressed-core regions of neon-filled microballons, the 12.3-Å feature appears to be resolved into two lines. Referring to Fig. 2 and Table I, the longer wavelength line is the $2p^2\,{}^1D$ transition at 12.355 Å, and the shorter-wavelength line is the blend of $2p^2\,{}^3P$ and $2s2p\,{}^3P$ transitions at 12.305 to 12.326 Å. The calculated intensity of this blend, relative to the 12.355-Å intensity, is shown in Fig. 3 as a function of electron density for the two temperatures 300 and 400 eV. The temperature dependence is weak. Also shown are the two experimental intensity ratios.[1,3] The agreement is within the indicated experimental uncertainties. The higher density experimental line ratio[3] does not agree with the calculated results of Ref. 6. This calculated line ratio, which is apparently an approximate analytical result in which reabsorption of L_α radiation is neglected, falls below the observed line ratio.

At the extremely high pellet core densities that are anticipated to occur in future experiments,

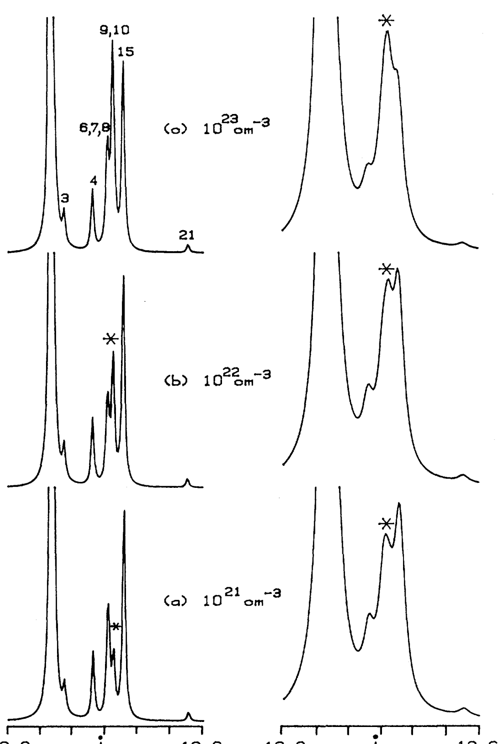

FIG. 2. The calculated relative intensities of the Ne IX $2l2l'$ dielectronic satellite transitions as functions of electron density. Lorentzian line profiles, with full-widths 10 mÅ (left) and 40 mÅ (right), have been added to simulate instrumental and Stark broadening. The neon L_α line is at 12.132 Å, and the density-sensitive dielectronic satellite line is indicated (*) at 12.32 Å. The numbers above the spectral lines in (c) refer to the key in Table I. The electron temperature is 400 eV.

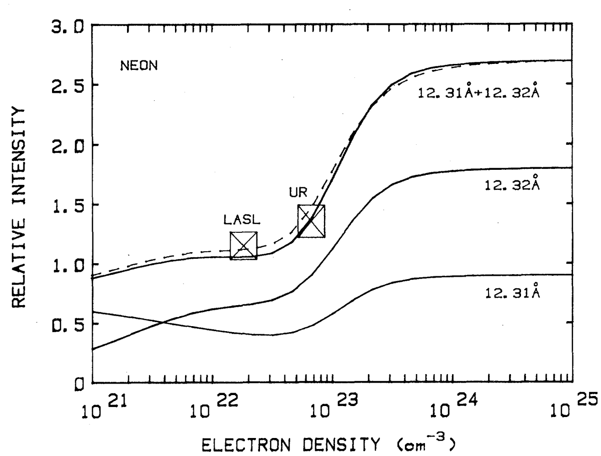

FIG. 3. Comparison of the calculated (curves) and experimental (Refs. 1 and 3) (boxes) satellite intensity ratios. The two lower curves are the intensities, relative to the 12.355-Å line, of the transitions in the wavelength ranges 12.305 to 12.310 Å and 12.321 to 12.326 Å listed in Table I. The two upper curves, and the experimental data, are the intensities of the transitions in the range 12.305 to 12.326 Å relative to the 12.355-Å line. The solid curves are for an electron temperature of 400 eV, and the dashed curve for 300 eV.

Stark broadening may prevent resolution of neon satellite lines. This problem can be overcome by using seed ions with higher atomic number Z. The Stark width[14] of the L_α line is proportional to $Z^{-5.9}$, whereas the separation between the satellite lines[10] is proportional to $Z^{-2.8}$.

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Saturation and Stark Splitting of Resonant Transitions in Strong Chaotic Fields of Arbitrary Bandwidth

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We report the solution of the problem of saturation and ac Stark splitting of a resonant transition in a strong chaotic field of arbitrary bandwidth. We present results for double optical resonance and resonance fluorescence and compare them to those obtained for a phase-diffusion field.

The role of field fluctuations and of the associated bandwidth in the resonant interaction of intense radiation with matter has been an extremely active subject in the last three years or so. A number of interesting results[1-8] have been obtained under the assumption of a bandwidth due entirely to the fluctuations of the phase (phase diffusion) of the field, whose amplitude is assumed to be constant. The phase-diffusion model is, of course, adequate for the interpretation of experiments with well-stabilized cw lasers, notably those used in recent experiments on resonance fluorescence[9,10] under intense fields. There is, however, another class of experiments —such as multiphoton experiments,[11,12] for example—performed with considerably stronger, multimode, pulsed lasers whose amplitude undergoes substantial fluctuations, often comparable to, if not stronger than, those of a chaotic field. We have therefore a more general and far more significant problem: How does an intense, stochastically fluctuating field—with both amplitude and phase fluctuations—affect the saturation and the associated Stark splitting of a resonant transition? It also is a far more difficult problem that had thus far eluded solution, although some of its aspects have been investigated.[13-18] In this Letter, we report the solution of the problem for a chaotic field and present results on saturation, resonance fluorescence, and double optical resonance.

The essential mathematical problem, which can be formulated in more than one way, basically requires the solution of the equations of motion of

