Electron collisional excitation in F-like selenium

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Electron collisional excitation of the low-lying $1s^22s^22p^5$ and $1s^22s2p^6$ states of F-like selenium to the singly excited M-shell states is studied using a relativistic distorted-wave model and multiconfigurational relativistic Hartree-Fock bound states. Results are presented for all 2-3 transitions from the low-lying $2s^22p^5\ {}^2P_{3/2}$ and ${}^2P_{1/2}$ levels, and also the $2s2p^6\ {}^2S_{1/2}$ level. We find a number of strong dipole-allowed $2p$-$3d$ cross sections with peak values near threshold in excess of 10^{-20} cm^2, and derive Gaunt factors which are in good agreement with values used in the literature (0.15—0.20) for most strong transitions. Very strong monopole $2p$-$3p$ excitation cross sections have been important in soft-x-ray laser theory, and are found to be as strong as the largest dipole-allowed cross sections for F-like selenium. Theoretical output powers for the strong lines of the $2p$-$3s$, $2p$-$3d$, and $2s$-$3p$ transition arrays are computed and presented for plasma conditions of $N_e=3\times10^{20}$ cm^{-3} and $T_e=1.0$ keV. These results are compared in detail for proportionality against gf values for each array separately, as a test of how well line intensities might be judged from gf values in the absence of detailed theoretical intensity results. We find that for the $2p$-$3s$ and $2p$-$3d$ arrays, the intensities are in fair agreement with gf values within the array, while the agreement is much poorer in the case of the $2s$-$3p$ array. The two weaker arrays $2p$-$3s$ and $2s$-$3p$ are found to radiate more per unit gf than the $2p$-$3d$ transition array, in agreement with earlier observations in the Ne-like sequence. Theoretical line positions are tabulated for all strong 2-3 lines, and found to be in good agreement with experimental results for most strong transitions. Gains on the 3-3 transitions in between 2 and 4 cm^{-1} are predicted for four lines under the plasma conditions quoted. Such conditions are similar to those of the recent extreme-uv laser experiments at the Lawrence Livermore National Laboratory, yet no F-like 3-3 amplification has yet been observed for F-like transitions. The discrepancy is currently a mystery.

I. INTRODUCTION

More than a decade after the initial proposals suggesting electron collisional excitation as a mechanism to pump lasers in the extreme-uv (xuv) and soft-x-ray regimes,[1–6] and following extensive examination and modeling efforts,[7–16] theoretical and experimental efforts at the Lawrence Livermore National Laboratory lead to the experimental observation of $3p$-$3s$ amplification in Ne-like selenium at 206 and 209 Å (Ref. 17) using a laser-driven exploding-foil target.[18] The early proposals suggested that the dominant excitation mechanism in pumping this type of laser should be direct $2p$-$3p$ electron collisional excitation by ambient hot thermal electrons. While there is still little reason to believe that such direct excitation does not occur (this direct excitation drives a line near 182 Å with high theoretical gain), it is currently thought that recombination plays the dominant role in the development of population inversions of the highest-gain lines at 206 and 209 Å. The 182-Å line is observed routinely in recent experiments. However, the experimentally determined gain is still less than that predicted at the time of optimum target conditions for both gain and plasma uniformity.

Although direct experimental determination of sequence abundances and overall ionization balance is not yet in hand, our theoretical model predicts very substantial F-like populations, and such a model is not inconsistent with the strong 3-2 L-shell spectra observed experimentally. In order to obtain comparisons between the detailed kinetics model of selenium and the observed experimental spectra, it has been necessary to develop a kinetics model of the complex F-like ion. Our earlier comparisons of this model against low-resolution 3-2 spectra taken from an exploding-foil target were presented in Ref. 18, and further comparisons will be published elsewhere.

Having developed a kinetics model for F-like selenium, it is natural to enquire whether $3p$-$3s$ population inversions occur among the singly excited F-like levels. The question becomes even more relevant, given the comments above concerning the large abundance (40—50%) of F-like ions calculated to be present during much of the lifetime of the plasma. For example, if theoretically large gains are predicted for F-like $3p$-$3s$ transitions, and if it is established by 3-2 x-ray spectroscopy that substantial F-like population is present, then either F-like $3p$-$3s$ amplification should be observed experimentally, or else there must be an excellent reason as to why such amplification is absent.

The situation at present appears to be that a large F-like population exists over much of the plasma's lifetime and spatial extent, and that theoretically the resulting gain on F-like $3p$-$3s$ transitions should be high enough to be manifestly obvious, and that no such amplification has yet been observed experimentally.[19] Precisely why this is true is not well understood, although candidate explanations include possible resonant line absorption and plasma turbulence effects.

One further anomaly which may perhaps provoke some thought is that when the theoretical xuv spectrum is produced, using the results of the plasma hydrodynamic simulations and detailed atomic physics models, the resulting spectra in the vicinity of the 3-3 lines of F-like to Na-like selenium are calculated to be very rich, due to contributions from many Ne-like and F-like 3-3 lines. Many lines are calculated to be fully as bright, when viewed on-axis, as the dominant Na-like selenium resonance lines, including lines which are inverted as well as noninverted lossy lines. Once again the experimental spectra are at variance with the theoretical modeling results, for reasons which remain poorly understood. Many of the lines which seem to be missing have optical depths (or gain lengths) of near or less than unity axially (the laser plasmas have dimensions of one to several centimeters axially, and of roughly 100 μm transversely).

The problems with missing lines in the axial spectra have eluded quantitative explanation for several years now, and we shall not explain it in the present paper. One cannot help but wonder if possibly some nonselective absorption or scattering mechanism is not present which has the effect of simply removing all of the relatively weak lines of low optical depth from the spectrum. If scattering due to small-scale density fluctuations were present with a scattering coefficient of 5—10 cm^{-1} at early times, and much less later on, then one might envision a scenario wherein the Ne-like lines emerge late in time (400—500 psec after the peak of the 450-psec optical pulse) where little or no F-like gain remains. Theoretically, the Ne-like gain outlasts the F-like gain considerably. Due to the high theoretical F-like gain, which is considered near the end of the present paper, one seems pressed towards concluding that something is not quite right with axial xuv beam propagation in the exploding-foil plasma while the optical laser pulse is present.

The purpose of the present paper is to examine the electron collisional excitation process in F-like selenium, to begin exploring the 2-3 x-ray spectra theoretically, and to discuss briefly the development of $3p$-$3s$ population inversions and gain under conditions relevant to the selenium exploding-foil amplifier. We shall not explore radiative emission in the 3-3 spectra in this paper, although such a study is now within our grasp theoretically.

In Sec. II we discuss theoretical methods used in our structure calculations, and present results for wavelengths and oscillator strengths for the strong 2-3 transitions. The relativistic distorted-wave model is reviewed briefly in Sec. III, and the 2-3 collisional excitation cross sections are tabulated and discussed in Sec. IV. Section V is devoted to an investigation of theoretical output powers of the 2-3 transitions, and gain predictions for $3p$-$3s$ candidate laser transitions are explored briefly in Sec. VI.

II. STRUCTURE CALCULATIONS, WAVELENGTHS, AND OSCILLATOR STRENGTHS

The structure calculations described here are based on multiconfigurational relativistic Hartree-Fock wave functions with the Breit interaction included in the $\omega=0$ limit. We have employed YODA, an atomic physics package of Hagelstein and Jung,[20] which calculates energy levels, oscillator strengths, photoionization cross sections, collisional cross sections, and Auger rates for a restricted angular-momentum coupling scheme. YODA has been used extensively for the support of non—local-thermal-equilibrium (NLTE) kinetics model development at Lawrence Livermore National Laboratory (LLNL) for several years, and was employed in the construction of models used for the design efforts described in Ref. 18.

The multiconfigurational wave functions which serve as the starting point for the distorted-wave collisional calculations were computed using a single set of basis orbitals $(1s_{1/2}, 2s_{1/2}, \ldots, 3d_{5/2})$ computed from a single spherically averaged relativistic Hartree-Fock self-consistent field calculation with fractional orbital occupation. The specific configuration used in this calculation was the fictitious configuration with occupation numbers given as follows:

$$1s_{1/2}\ ,\ 2.00\ ;\ 2s_{1/2}\ ,\ 1.27\ ;\ 2p_{1/2}\ ,\ 1.27\ ;$$
$$2p_{3/2},\ 3.82\ ;\ 3s_{1/2}\text{-}3d_{5/2}\ ,\ 0.127\ . \tag{2.1}$$

The use of these particular fractional occupational numbers deserves a modicum of comment. The total L-shell occupation for the ground states $1s^2 2s^2 2p^5$ and $1s^2 2s 2p^6$ is 7, and for the singly excited M-shell states is 6. If our structure calculations were based on nonorthogonal single-electron wave functions, then we should do well to include L-shell orbitals computed both with 6 and 7 L-shell electrons present, and include configurations corresponding to the appropriate single-electron orbitals. This approach would be able to include relaxation effects more accurately than the present model. If the orbitals must be orthonormal, then a choice must be made as to precisely which orbitals are to be used, as the final answers will show some sensitivity to the choice. One possibility is to put 6.5 electrons in the L shell, and split the remaining half electron between the M-shell states, giving 0.10 electrons per M-shell orbital. The above choice of occupation numbers gives 6.36 electrons in the L shell and 0.64 electrons in the M shell, which is not so far from a 50%-50% split. Beyond this, it makes little sense to discuss the algorithm by which YODA computes default fractional occupations, and our results will be slightly biased towards the states with more $2s$ and $2p_{1/2}$ vacancies, although effects on cross sections are no more than a few percent.

The multiconfigurational structure calculation includes 113 states, which is the total for all L-shell and M-shell ground and singly excited states of F-like selenium. In order to check whether a larger configuration-interaction (CI) calculation would change the results given the basis orbitals, we calculated energy levels for 1622 states which included the 113 low-lying states as well as all $3l3l'$ doubly-excited states. Although some shift in optimized total energies was observed, relative level shifts were about 0.1 eV. In comparing against experimentally determined wavelengths (which we shall discuss shortly), we found a systematic shift of about 1 eV for most 2-3 transitions, and this shift seemed most likely to be due to correlation

TABLE I. Level definitions for the lowest 113 states of F-like selenium. Tabulated are the state configurations, total angular momenta J, and energies relative to the F-like $2s^22p^5\,{}^2P_{3/2}$ ground state.

Level	State	J	Energy (eV)
1	$[2s^22p_{1/2}^22p_{3/2}^3]_{3/2}$	3/2	0
2	$[2s^22p_{1/2}2p_{3/2}^4]_{1/2}$	1/2	42.8
3	$[2s2p_{1/2}^22p_{3/2}^4]_{1/2}$	1/2	212.4
4	$[2s^22p_{1/2}^22p_{3/2}^2]_23s$	5/2	1500.5
5	$[2s^22p_{1/2}^22p_{3/2}^2]_23s$	3/2	1505.2
6	$[2s^22p_{1/2}^22p_{3/2}^2]_03s$	1/2	1519.7
7	$[2s^22p_{1/2}2p_{3/2}^3]_13s$	3/2	1541.4
8	$[2s^22p_{1/2}2p_{3/2}^3]_13s$	1/2	1545.1
9	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{1/2}$	3/2	1545.3
10	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{1/2}$	5/2	1547.1
11	$[2s^22p_{1/2}2p_{3/2}^3]_23s$	5/2	1554.2
12	$[2s^22p_{1/2}2p_{3/2}^3]_23s$	3/2	1555.5
13	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{3/2}$	1/2	1555.9
14	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{3/2}$	5/2	1556.7
15	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{3/2}$	7/2	1557.5
16	$[2s^22p_{1/2}^22p_{3/2}^2]_03p_{1/2}$	1/2	1566.0
17	$[2s^22p_{1/2}^22p_{3/2}^2]_23p_{3/2}$	3/2	1571.9
18	$[2s^22p_{1/2}^22p_{3/2}^2]_03p_{3/2}$	3/2	1577.4
19	$[2s^22p_{1/2}2p_{3/2}^3]_13p_{1/2}$	1/2	1584.8
20	$[2s^22p_{1/2}2p_{3/2}^3]_13p_{1/2}$	3/2	1589.7
21	$[2s^22p_{1/2}2p_{3/2}^3]_13p_{3/2}$	5/2	1596.8
22	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{1/2}$	5/2	1599.1
23	$[2s^22p_{1/2}2p_{3/2}^3]_13p_{3/2}$	1/2	1599.9
24	$[2s^22p_{1/2}2p_{3/2}^3]_13p_{3/2}$	3/2	1600.5
25	$[2s^22p_{3/2}^4]_03s$	1/2	1602.8
26	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{3/2}$	7/2	1609.4
27	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{3/2}$	3/2	1610.2
28	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{3/2}$	5/2	1612.4
29	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{3/2}$	3/2	1612.8
30	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{5/2}$	7/2	1613.5
31	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{3/2}$	5/2	1613.8
32	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{3/2}$	1/2	1614.4
33	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{1/2}$	3/2	1615.4
34	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{5/2}$	9/2	1616.8
35	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{3/2}$	7/2	1617.7
36	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{5/2}$	1/2	1622.4
37	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{5/2}$	3/2	1626.1
38	$[2s^22p_{1/2}2p_{3/2}^3]_23p_{3/2}$	1/2	1628.3
39	$[2s^22p_{1/2}^22p_{3/2}^2]_23d_{5/2}$	5/2	1629.3
40	$[2s^22p_{1/2}^22p_{3/2}^2]_03d_{3/2}$	3/2	1635.3
41	$[2s^22p_{1/2}^22p_{3/2}^2]_03d_{5/2}$	5/2	1637.9
42	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{3/2}$	1/2	1651.1
43	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{3/2}$	3/2	1655.1
44	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{5/2}$	7/2	1655.8
45	$[2s^22p_{3/2}^4]_03p_{1/2}$	1/2	1656.9
46	$[2s^22p_{3/2}^4]_03p_{3/2}$	3/2	1658.9
47	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{5/2}$	5/2	1659.6
48	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{3/2}$	5/2	1661.2
49	$[2s^22p_{1/2}2p_{3/2}^3]_13d_{5/2}$	3/2	1661.8
50	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{3/2}$	7/2	1666.4
51	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{5/2}$	9/2	1668.0
52	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{5/2}$	5/2	1671.2
53	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{3/2}$	1/2	1671.3
54	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{5/2}$	7/2	1674.0
55	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{3/2}$	3/2	1674.4
56	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{3/2}$	5/2	1675.9
57	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{5/2}$	3/2	1683.3
58	$[2s^22p_{1/2}2p_{3/2}^3]_23d_{5/2}$	1/2	1685.8
59	$[2s2p_{1/2}^22p_{3/2}^3]_23s$	5/2	1688.9
60	$[2s2p_{1/2}^22p_{3/2}^3]_23s$	3/2	1697.1
61	$[2s2p_{1/2}^22p_{3/2}^3]_13s$	3/2	1713.4
62	$[2s2p_{1/2}^22p_{3/2}^3]_13s$	1/2	1713.9
63	$[2s^22p_{3/2}^4]_03d_{5/2}$	5/2	1718.7
64	$[2s^22p_{3/2}^4]_03d_{3/2}$	3/2	1722.9
65	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{1/2}$	3/2	1733.0
66	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{1/2}$	5/2	1736.4
67	$[2s2p_{1/2}2p_{3/2}^4]_03s$	1/2	1737.2
68	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{3/2}$	7/2	1744.2
69	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{3/2}$	3/2	1746.8
70	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{3/2}$	5/2	1749.5
71	$[2s2p_{1/2}^22p_{3/2}^3]_23p_{3/2}$	1/2	1754.4
72	$[2s2p_{1/2}^22p_{3/2}^3]_13p_{1/2}$	3/2	1756.8
73	$[2s2p_{1/2}^22p_{3/2}^3]_13p_{1/2}$	1/2	1757.9
74	$[2s2p_{1/2}^22p_{3/2}^3]_13p_{3/2}$	5/2	1766.7
75	$[2s2p_{1/2}2p_{3/2}^4]_13s$	3/2	1766.8
76	$[2s2p_{1/2}^22p_{3/2}^3]_13p_{3/2}$	3/2	1767.7
77	$[2s2p_{1/2}2p_{3/2}^4]_13s$	1/2	1770.2
78	$[2s2p_{1/2}^22p_{3/2}^3]_03p_{1/2}$	1/2	1773.6
79	$[2s2p_{1/2}2p_{3/2}^4]_13p_{1/2}$	1/2	1785.4
80	$[2s2p_{1/2}2p_{3/2}^4]_03p_{3/2}$	3/2	1791.2
81	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{3/2}$	1/2	1796.0
82	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{3/2}$	3/2	1798.3
83	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{5/2}$	9/2	1800.4
84	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{3/2}$	5/2	1801.6
85	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{3/2}$	7/2	1801.9
86	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{5/2}$	5/2	1807.6
87	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{5/2}$	7/2	1808.9
88	$[2s2p_{1/2}2p_{3/2}^4]_13p_{1/2}$	3/2	1811.3
89	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{5/2}$	3/2	1812.3
90	$[2s2p_{1/2}^22p_{3/2}^3]_23d_{5/2}$	1/2	1820.2
91	$[2s2p_{1/2}2p_{3/2}^4]_13p_{3/2}$	1/2	1820.8
92	$[2s2p_{1/2}2p_{3/2}^4]_13p_{3/2}$	5/2	1822.1
93	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{3/2}$	5/2	1824.4
94	$[2s2p_{1/2}2p_{3/2}^4]_13p_{3/2}$	3/2	1824.7
95	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{3/2}$	3/2	1825.3
96	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{3/2}$	1/2	1825.7
97	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{5/2}$	7/2	1825.9
98	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{5/2}$	5/2	1826.0
99	$[2s2p_{1/2}2p_{3/2}^4]_13p_{1/2}$	1/2	1827.7
100	$[2s2p_{1/2}^22p_{3/2}^3]_13d_{3/2}$	3/2	1832.8
101	$[2s2p_{1/2}2p_{3/2}^4]_03d_{5/2}$	5/2	1849.9
102	$[2s2p_{1/2}2p_{3/2}^4]_03d_{3/2}$	3/2	1853.1

TABLE I. (*Continued*).

Level	State	J	Energy (eV)	Level	State	J	Energy (eV)
103	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{3/2}$	5/2	1878.7	109	$[2p_{1/2}^2 2p_{3/2}^4]_0 3s$	1/2	1935.5
104	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{5/2}$	7/2	1879.7	110	$[2p_{1/2}^2 2p_{3/2}^4]_0 3p_{1/2}$	1/2	1977.7
105	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{5/2}$	3/2	1881.7	111	$[2p_{1/2}^2 2p_{3/2}^4]_0 3p_{3/2}$	3/2	1988.5
106	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{5/2}$	5/2	1884.7	112	$[2p_{1/2}^2 2p_{3/2}^4]_0 3d_{3/2}$	3/2	2043.4
107	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{3/2}$	1/2	1885.1	113	$[2p_{1/2}^2 2p_{3/2}^4]_0 3d_{5/2}$	5/2	2045.6
108	$[2s2p_{1/2}2p_{3/2}^4]_1 3d_{3/2}$	3/2	1885.4				

effects (orbital relaxation) not included in our CI expansions. In order to attempt to account for this additional shift, we recalculated the three low-lying F-like states in a 1622-state CI calculation using L-shell orbitals taken from a $1s^2 2s^2 2p_{1/2}^2 2p_{3/2}^3$ calculation. The ground-state energy dropped by about 0.9 eV, relative to our calculations with the fractional occupation discussed above.

The energy levels in Table I are taken mostly from the calculations described in the above paragraphs. The ground-state energy was taken from the ground-state optimized calculation, and the $^2P_{1/2}$ state was revised by 0.1 eV to agree with the extrapolated results of Edlen.[21] The excited states were taken from the 1622-state calculation with our fractional occupation numbers (2.1).

Wavelengths for F-like selenium have been published by a number of workers.[22–25] In Tables II–IV we have tabulated both theoretical and experimental wavelengths, and theoretical oscillator strengths for a number of strong x-ray transitions. The agreement between theory and experiment is quite good for many of the transitions.

A number of identified transition pairs exist wherein the upper level is shared while the lower levels differ, which may be used as an additional test of consistency on the data. For example, the experimentally observed pair at 8.485 and 8.237 Å connect the two lowest levels $2s^2 2p^5\,{}^2P_{3/2}$ and $^2P_{1/2}$ with the same M-shell $3s$ level. Subtraction of the two line energies yields a value for the $^2P_{3/2}$ and $^2P_{1/2}$ splitting of 44.0 eV. Altogether, there are 5 pairs of lines of this type tabulated in Ref. 25, and we have presented them in Table V.

A cursory inspection of Table V reveals that the $^2P_{1/2}$-$^2P_{3/2}$ level splitting is systematically overestimated through this procedure by values ranging from 0.7 to 3.3 eV, when compared against the accurate extrapolated value of 42.87 eV given by Edlen.[21] The worst case involves a pair of lines with level 55 as the excited state, and it seems unlikely that both the assignments (1-55) at 7.400 Å and (2-55) at 7.610 Å can be correct. Corresponding comments might be made in the cases of some of the other transition identifications. However, as it is certainly possible that the present theoretical results for the M-shell excited states can be off by 1 eV, we shall be satisfied at present with a simple expression of concern at the present state of understanding of this very complex spectrum. We hope that the results presented in the present work will enable further progress in the identification of many of the lines which have so far not been identified. In concluding this section, we note the existence of a number of publications concerning F-like spectra and identifications in nearby ions, and these are found under Refs. 26–34.

III. RELATIVISTIC DISTORTED-WAVE COLLISIONAL MODEL

The relativistic distorted-wave model which we have used to compute the F-like 2-3 cross sections has been

TABLE II. Wavelengths and absorption oscillator strengths for strong $2p$-$3s$ transitions in F-like Se (except for 8.478-Å line, we include transitions with oscillator strength greater than 0.010).

Transition	Configurations	J_i-J_f	λ (Å) (this work)	λ (Å) (Ref. 25)	f (this work)
2-5	$^2P_{1/2}-[2s^2p_{1/2}^2 2p_{3/2}^2]_1 3s$	1/2-3/2	8.478	8.485	0.001
3-60	$^2S_{1/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_2 3s$	1/2-3/2	8.351		0.068
3-61	$^2S_{1/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3s$	1/2-3/2	8.260		0.016
3-62	$^2S_{1/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3s$	1/2-1/2	8.257		0.040
2-8	$^2P_{1/2}-[2s^2 2p_{1/2}2p_{3/2}^3]_1 3s$	1/2-1/2	8.253	8.259	0.043
1-5	$^2P_{3/2}-[2s^2p_{1/2}^2 2p_{3/2}^2]_1 3s$	3/2-3/2	8.237	8.237	0.067
2-12	$^2P_{1/2}-[2s^2 2p_{1/2}2p_{3/2}^3]_2 3s$	1/2-3/2	8.196	8.197	0.089
1-6	$^2P_{3/2}-[2s^2 2p_{1/2}^2 2p_{3/2}^2]_0 3s$	3/2-1/2	8.159	8.156	0.013
3-67	$^2S_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_0 3s$	1/2-1/2	8.131		0.033
1-7	$^2P_{3/2}-[2s^2 2p_{1/2}2p_{3/2}^3]_1 3s$	3/2-3/2	8.044	8.042	0.017
1-8	$^2P_{3/2}-[2s^2 2p_{1/2}2p_{3/2}^3]_1 3s$	3/2-1/2	8.025	8.026	0.014
1-11	$^2P_{3/2}-[2s^2 2p_{1/2}2p_{3/2}^3]_2 3s$	3/2-5/2	7.978	7.978	0.049
3-75	$^2S_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3s$	1/2-3/2	7.976		0.033
2-25	$^2P_{1/2}-[2s^2 2p_{3/2}^4]_0 3s$	1/2-1/2	7.948	7.945	0.089

TABLE III. Wavelengths and absorption oscillator strengths for strong $2p$-$3d$ transitions in F-like Se (transitions with oscillator strength greater than 0.010).

Transition	Configurations	J_i-J_f	λ (Å) (this work)	λ (Å) (Ref. 25)	f (this work)
2-37	$^2P_{1/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_23d_{5/2}$	1/2-3/2	7.831		0.011
3-89	$^2S_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_23d_{5/2}$	1/2-3/2	7.750		0.155
3-90	$^2S_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_23d_{5/2}$	1/2-1/2	7.711		0.327
2-43	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_13d_{3/2}$	1/2-3/2	7.690		0.017
3-95	$^2S_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13d_{3/2}$	1/2-3/2	7.687		0.046
3-96	$^2S_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13d_{3/2}$	1/2-1/2	7.685		0.193
2-49	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_13d_{5/2}$	1/2-3/2	7.658	7.658	0.078
3-100	$^2S_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13d_{3/2}$	1/2-3/2	7.651		0.552
1-36	$^2P_{3/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_23d_{5/2}$	3/2-1/2	7.642	7.637	0.088
1-37	$^2P_{3/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_23d_{5/2}$	3/2-3/2	7.625	7.623	0.185
2-53	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{3/2}$	1/2-1/2	7.614	7.623	0.045
1-39	$^2P_{3/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_23d_{5/2}$	3/2-5/2	7.610	7.610	0.381
2-55	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{3/2}$	1/2-3/2	7.599	7.610	0.178
1-40	$^2P_{3/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_03d_{3/2}$	3/2-3/2	7.582		0.135
1-41	$^2P_{3/2}-[2s^22p^2_{1/2}2p^2_{3/2}]_03d_{5/2}$	3/2-5/2	7.570		0.243
2-57	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{5/2}$	1/2-3/2	7.558	7.565	0.984
3-102	$^2S_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_03d_{3/2}$	1/2-3/2	7.557		0.653
2-58	$^2P_{1/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{5/2}$	1/2-1/2	7.546	7.548	0.770
1-43	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_13d_{3/2}$	3/2-3/2	7.491	7.487	0.012
1-47	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_13d_{5/2}$	3/2-5/2	7.471	7.465	0.106
1-48	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_13d_{3/2}$	3/2-5/2	7.464		0.205
3-105	$^2S_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13d_{5/2}$	1/2-3/2	7.427		0.546
1-52	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{5/2}$	3/2-5/2	7.419		0.033
1-53	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{3/2}$	3/2-1/2	7.419	7.417	0.220
3-107	$^2S_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13d_{3/2}$	1/2-1/2	7.412		0.692
3-108	$^2S_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13d_{3/2}$	1/2-3/2	7.411		0.445
1-55	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{3/2}$	3/2-3/2	7.405	7.400	0.497
1-56	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{3/2}$	3/2-5/2	7.398	7.400	0.773
2-64	$^2P_{1/2}-[2s^22p^4_{3/2}]_03d_{3/2}$	1/2-3/2	7.380	7.379	0.979
1-57	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{5/2}$	3/2-3/2	7.366	7.368	0.130
1-58	$^2P_{3/2}-[2s^22p_{1/2}2p^3_{3/2}]_23d_{5/2}$	3/2-1/2	7.355		0.052

TABLE IV. Wavelengths and absorption oscillator strengths for strong $2s$-$3p$ transitions in F-like Se (transitions with oscillator strength greater than 0.010).

Transition	Configurations	J_i-J_f	λ (Å) (this work)	λ (Å) (Ref. 25)	f (this work)
2-72	$^2P_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{1/2}$	1/2-3/2	7.234		0.012
2-76	$^2P_{1/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{3/2}$	1/2-3/2	7.188	7.190	0.026
1-66	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_23p_{1/2}$	3/2-5/2	7.140	7.138	0.045
2-79	$^2P_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13p_{1/2}$	1/2-1/2	7.115	7.116	0.078
2-80	$^2P_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_03p_{3/2}$	1/2-3/2	7.091	7.085	0.072
1-70	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_23p_{3/2}$	3/2-5/2	7.087	7.085	0.069
1-72	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{1/2}$	3/2-3/2	7.057	0.057	0.058
1-73	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{1/2}$	3/2-1/2	7.053	7.057	0.063
3-110	$^2S_{1/2}-[2p^2_{1/2}2p^4_{3/2}]_03p_{1/2}$	1/2-1/2	7.023		0.054
1-74	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{3/2}$	3/2-5/2	7.018	7.015	0.062
1-76	$^2P_{3/2}-[2s2p^2_{1/2}2p^3_{3/2}]_13p_{3/2}$	3/2-3/2	7.014		0.019
2-88	$^2P_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13p_{1/2}$	1/2-3/2	7.011	7.015	0.085
3-111	$^2S_{1/2}-[2p^2_{1/2}2p^4_{3/2}]_03p_{3/2}$	1/2-3/2	6.981		0.112
2-91	$^2P_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13p_{3/2}$	1/2-1/2	6.973	6.988	0.073
2-94	$^2P_{1/2}-[2s2p_{1/2}2p^4_{3/2}]_13p_{3/2}$	1/2-3/2	6.958	6.963	0.073
1-92	$^2P_{3/2}-[2s2p_{1/2}2p^4_{3/2}]_13p_{3/2}$	3/2-5/2	6.805	6.808	0.018

TABLE V. Wavelengths (Å) for pairs of transitions which share an excited state based on identifications of Hobby *et al.* (Ref. 25). From the wavelength values one may deduce $^2P_{3/2}$ and $^2P_{1/2}$ level splittings $\Delta E(^2P_{1/2}-^2P_{3/2})$ (tabulated in eV), which is compared to the accurate extrapolated result of Edlen (Ref. 21).

Excited state	J	Level	$\lambda(^2P_{3/2})$	$\lambda(^2P_{1/2})$	$\Delta E(^2P_{1/2}-^2P_{3/2})$
$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3s$	3/2	5	8.237	8.485	44.0
$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3s$	1/2	8	8.026	8.259	43.6
$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{3/2}$	1/2	53	7.417	7.623	46.2
$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{3/2}$	3/2	55	7.400	7.610	45.2
$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{5/2}$	3/2	57	7.368	7.565	43.8
Edlen extrapolation					42.87

described previously in Ref. 35, and we shall describe it only briefly here. The model is based on multiconfigurational jj-coupled bound states $\Psi(\Gamma_i j_i)$, which are composed of combinations of single-configuration basis states $\Phi(\Gamma' j_i)$ through

$$\Psi(\Gamma_i J_i)=\sum_{\Gamma'} C(\Gamma_i J_i,\Gamma' J_i)\Phi(\Gamma' J_i)\ , \tag{3.1}$$

where the expansion coefficients $C(\Gamma_i J_i,\Gamma' J_i)$ are determined from diagonalization of the Hamiltonian in the structure calculation. In order to compute the transmission matrix elements of the collision problem, we construct the bound-plus-continuum states from the multiconfigurational states via

$$\Psi(\Gamma_i J_i j;J)=\sum_{\Gamma'} C(\Gamma_i J_i,\Gamma' J_i)\Phi(\Gamma' J_i j;J)\ , \tag{3.2}$$

where $\Psi(\Gamma_i J_i j;J)$ is the multiconfigurational bound state $\Psi(\Gamma_i J_i)$, with a single continuum electron of angular momentum j, coupled to give a total angular momentum for the bound-plus-continuum state J.

The continuum orbitals used for the construction of these continuum states are computed in the relativistic distorted-wave approximation without exchange, where the distorted-wave potential used is the spherically averaged potential of the nucleus plus bound electrons of the bound state $\Psi(\Gamma_i J_i)$. From these continuum states, the transmission matrices are computed

$$T^J(\Gamma_i J_i j,\Gamma_f J_f j') = 4i\left\langle \Psi(\Gamma_i J_i j;J)\left|\frac{1}{r_{12}}\right|\Psi(\Gamma_f J_f j';J)\right\rangle . \tag{3.3}$$

In terms of the single-configuration continuum basis states $\Phi(\Gamma_i J_i j;J)$, the transmission matrix becomes

$$T^J(\Gamma_i J_i j,\Gamma_f J_f j') = 4i\sum_{\Gamma'}\sum_{\Gamma''} C(\Gamma_i J_i,\Gamma' J_i)C(\Gamma_f J_f,\Gamma'' J_f) \times\left\langle \Phi(\Gamma' J_i j;J)\left|\frac{1}{r_{12}}\right|\Phi(\Gamma'' J_f j';J)\right\rangle , \tag{3.4}$$

which we evaluate using standard numerical and angular-momentum algebra techniques.[35–37] Aside from the relativistic distorted-wave approximation without exchange, we make two additional approximations in our calculations; that no account is taken of the unitarity condition (which should be a very good approximation for such a highly stripped system), and that the summation of (3.4) is truncated such that all terms with

$$|\,C(\Gamma_i j_i,\Gamma' j_i)C(\Gamma_f J_f,\Gamma'' J_f)\,| < 0.0001$$

are not included. The truncation has the feature that the calculations take much less time, since as in most problems, the majority of terms in the summation are quite small due to the negligible magnitude of the product of the expansion coefficients. Errors do, however, arise in the case of weak transitions which are very nearly forbidden, and whose total contribution is dominated by contributions from basis states with small expansion coefficients. Such transitions where errors might arise are not expected to play much of a role in kinetics or intensity calculations.

The partial collision strength $\Omega_{if}^J(E)$ is computed from the transmission matrix through

$$\Omega_{if}^J(E)=\tfrac{1}{2}\sum_{j,j'}(2J+1)\,|\,T^J(\Gamma_i J_i j,\Gamma_f J_f j')\,|^2\ , \tag{3.5}$$

and the total collision strength is found from summing over partial collision strengths

$$\Omega_{if}(E)=\sum_J \Omega_{if}^J(E)\ . \tag{3.6}$$

Although the summation of (3.6) may sometimes be slowly converging, for the present calculations the summations converged fairly rapidly, with contributions from no more than about 30 different values of J required for convergence.

The cross section $\sigma_{if}(E)$ is related to the collision strength $\Omega_{if}(E)$ through

$$\sigma_{if}(E)=\frac{\pi a_0^2}{2J_i+1}\frac{1}{p^2}\Omega_{if}(E)\ , \tag{3.7}$$

where the subscripts i and f refer to initial and final states, a_0 is the Bohr radius, $2J_i+1$ is the statistical weight of the initial state, E is the incident electron energy, and p is the relativistic momentum of the incident electron in units of $1/a_0$.

TABLE VI. Electron collisional excitation cross sections (cm^2) for all 2-3 transitions from the $2s^2 2p^5\,^2P_{3/2}$ state in F-like selenium. The cross sections are tabulated at five different energies (in eV) above threshold. The level indices for the transition are given under the heading Levels: *I*, *F*, where *I* stands for the initial level and *F* for the final level. The cross sections are tabulated such that 3.350[−22] is to be read as 3.350×10^{-22}.

Levels		Energy (eV) above threshold				
I	*F*	200.0	500.0	1000.0	2000.0	4000.0
1	4	3.350[−22]	2.642[−22]	1.922[−22]	1.245[−22]	7.988[−23]
1	5	4.145[−22]	4.289[−22]	4.521[−22]	4.719[−22]	4.653[−22]
1	6	1.333[−22]	1.208[−22]	1.096[−22]	9.892[−23]	8.925[−23]
1	7	1.503[−22]	1.405[−22]	1.323[−22]	1.240[−22]	1.147[−22]
1	8	8.600[−23]	8.628[−23]	8.799[−23]	8.930[−23]	8.699[−23]
1	9	5.478[−22]	4.142[−22]	2.795[−22]	1.551[−22]	7.487[−23]
1	10	8.049[−22]	6.340[−22]	4.598[−22]	2.931[−22]	1.740[−22]
1	11	3.187[−22]	3.235[−22]	3.344[−22]	3.446[−22]	3.414[−22]
1	12	1.200[−22]	9.991[−23]	8.016[−23]	6.214[−23]	5.062[−23]
1	13	3.534[−22]	2.753[−22]	1.953[−22]	1.188[−22]	6.547[−23]
1	14	7.905[−22]	6.237[−22]	4.542[−22]	2.923[−22]	1.762[−22]
1	15	7.895[−22]	5.805[−22]	3.758[−22]	1.946[−22]	8.540[−23]
1	16	1.840[−22]	1.384[−22]	9.306[−23]	5.194[−23]	2.581[−23]
1	17	1.519[−21]	1.340[−21]	1.125[−21]	8.597[−22]	5.917[−22]
1	18	6.051[−22]	4.850[−22]	3.592[−22]	2.331[−22]	1.372[−22]
1	19	4.342[−22]	3.747[−22]	3.058[−22]	2.252[−22]	1.490[−22]
1	20	1.531[−21]	1.310[−21]	1.054[−21]	7.569[−22]	4.822[−22]
1	21	4.103[−22]	3.206[−22]	2.290[−22]	1.411[−22]	7.924[−23]
1	22	6.594[−22]	5.527[−22]	4.362[−22]	3.098[−22]	2.001[−22]
1	23	2.223[−22]	1.812[−22]	1.373[−22]	9.196[−23]	5.583[−23]
1	24	7.707[−22]	6.591[−22]	5.319[−22]	3.862[−22]	2.520[−22]
1	25	9.500[−24]	8.426[−24]	7.432[−24]	6.527[−24]	5.807[−24]
1	26	5.514[−22]	4.677[−22]	3.791[−22]	2.855[−22]	2.033[−22]
1	27	1.139[−21]	9.706[−22]	7.768[−22]	5.540[−22]	3.508[−22]
1	28	1.120[−21]	7.940[−22]	4.833[−22]	2.216[−22]	7.821[−23]
1	29	7.800[−22]	5.541[−22]	3.385[−22]	1.565[−22]	5.629[−23]
1	30	1.353[−21]	9.478[−22]	5.637[−22]	2.440[−22]	7.400[−23]
1	31	3.441[−22]	2.766[−22]	2.073[−22]	1.395[−22]	8.824[−23]
1	32	4.000[−22]	2.865[−22]	1.783[−22]	8.698[−23]	3.655[−23]
1	33	1.731[−20]	1.523[−20]	1.267[−20]	9.480[−21]	6.273[−21]
1	34	1.105[−21]	7.775[−22]	4.702[−22]	2.171[−22]	8.183[−23]
1	35	8.896[−22]	6.870[−22]	4.923[−22]	3.217[−22]	1.627[−22]
1	36	1.592[−21]	1.460[−21]	1.309[−21]	1.121[−21]	9.173[−22]
1	37	3.100[−21]	2.859[−21]	2.578[−21]	2.222[−21]	1.824[−21]
1	38	1.193[−22]	9.504[−23]	7.004[−23]	4.574[−23]	2.796[−23]
1	39	5.894[−21]	5.612[−21]	5.237[−21]	4.665[−21]	3.917[−21]
1	40	2.173[−21]	2.011[−21]	1.822[−21]	1.582[−21]	1.310[−21]
1	41	4.049[−21]	3.755[−21]	3.410[−21]	2.964[−21]	2.456[−21]
1	42	1.192[−22]	8.610[−23]	5.466[−23]	2.828[−23]	1.371[−23]
1	43	3.670[−22]	3.035[−22]	2.397[−22]	1.787[−22]	1.322[−22]
1	44	5.983[−22]	4.304[−22]	2.700[−22]	1.342[−22]	5.835[−23]
1	45	2.911[−23]	2.187[−23]	1.451[−23]	7.676[−24]	3.332[−24]
1	46	2.228[−23]	1.714[−23]	1.187[−23]	6.878[−24]	3.496[−24]
1	47	1.626[−21]	1.516[−21]	1.382[−21]	1.208[−21]	1.003[−21]
1	48	2.972[−21]	2.805[−21]	2.592[−21]	2.296[−21]	1.930[−21]
1	49	3.911[−22]	2.929[−22]	1.975[−22]	1.138[−22]	6.286[−23]
1	50	4.474[−22]	3.119[−22]	1.842[−22]	7.946[−23]	2.585[−23]
1	51	5.704[−22]	4.552[−22]	3.410[−22]	2.333[−22]	1.526[−22]
1	52	9.285[−22]	7.824[−22]	6.329[−22]	4.861[−22]	3.694[−22]
1	53	3.207[−21]	3.091[−21]	2.916[−21]	2.636[−21]	2.246[−21]
1	54	4.444[−22]	3.379[−22]	2.355[−22]	1.467[−22]	8.335[−23]
1	55	6.459[−21]	6.259[−21]	5.940[−21]	5.403[−21]	4.629[−21]
1	56	1.040[−20]	1.011[−20]	9.628[−21]	8.782[−21]	7.538[−21]
1	57	1.898[−21]	1.809[−21]	1.689[−21]	1.515[−21]	1.288[−21]
1	58	7.606[−22]	6.997[−22]	6.289[−22]	5.438[−22]	4.518[−22]
1	59	1.412[−22]	1.012[−22]	6.275[−23]	3.014[−23]	1.180[−23]

TABLE VI. (*Continued*).

Levels		Energy (eV) above threshold				
I	*F*	200.0	500.0	1000.0	2000.0	4000.0
1	60	2.401[−21]	2.157[−21]	1.839[−21]	1.419[−21]	9.722[−22]
1	61	5.584[−21]	4.999[−21]	4.242[−21]	3.248[−21]	2.206[−21]
1	62	1.125[−22]	9.748[−23]	8.015[−23]	6.005[−23]	4.093[−23]
1	63	9.385[−23]	8.265[−23]	7.049[−23]	5.747[−23]	4.541[−23]
1	64	3.114[−23]	2.302[−23]	1.509[−23]	8.198[−24]	4.165[−24]
1	65	1.031[−22]	8.044[−23]	5.733[−23]	3.621[−23]	2.265[−23]
1	66	2.294[−22]	2.233[−22]	2.195[−22]	2.201[−22]	2.187[−22]
1	67	1.783[−23]	1.575[−23]	1.321[−23]	1.007[−23]	6.926[−24]
1	68	1.693[−22]	1.278[−22]	8.447[−23]	4.333[−23]	1.763[−23]
1	69	2.662[−22]	2.736[−22]	2.828[−22]	2.978[−22]	3.121[−22]
1	70	3.396[−22]	3.536[−22]	3.722[−22]	4.053[−22]	4.370[−22]
1	71	6.367[−23]	5.880[−23]	5.400[−23]	5.026[−23]	4.668[−23]
1	72	2.465[−22]	2.612[−22]	2.779[−22]	2.996[−22]	3.204[−22]
1	73	2.065[−22]	2.316[−22]	2.601[−22]	2.932[−22]	3.278[−22]
1	74	2.524[−22]	2.637[−22]	2.776[−22]	2.950[−22]	2.999[−22]
1	75	8.096[−22]	7.255[−22]	6.174[−22]	4.749[−22]	3.249[−22]
1	76	1.156[−22]	1.132[−22]	1.117[−22]	1.120[−22]	1.107[−22]
1	77	2.756[−23]	2.329[−23]	1.861[−23]	1.351[−23]	9.057[−24]
1	78	2.146[−23]	1.765[−23]	1.374[−23]	1.005[−23]	7.542[−24]
1	79	1.326[−23]	1.239[−23]	1.171[−23]	1.136[−23]	1.110[−23]
1	80	1.856[−24]	1.524[−24]	1.163[−24]	7.839[−25]	4.806[−25]
1	81	1.162[−22]	8.731[−23]	5.789[−23]	3.057[−23]	1.332[−23]
1	82	3.022[−22]	2.362[−22]	1.670[−22]	9.920[−23]	5.153[−23]
1	83	6.555[−22]	5.050[−22]	3.489[−22]	1.987[−22]	9.695[−23]
1	84	4.363[−22]	3.394[−22]	2.382[−22]	1.396[−22]	7.114[−23]
1	85	6.148[−22]	5.085[−22]	3.959[−22]	2.812[−22]	1.894[−22]
1	86	8.948[−22]	8.185[−22]	7.235[−22]	5.972[−22]	4.515[−22]
1	87	1.265[−21]	1.177[−21]	1.063[−21]	8.978[−22]	6.915[−22]
1	88	2.619[−23]	2.387[−23]	2.174[−23]	2.005[−23]	1.885[−23]
1	89	5.476[−22]	4.961[−22]	4.338[−22]	3.535[−22]	2.643[−22]
1	90	2.343[−22]	2.075[−22]	1.762[−22]	1.384[−22]	9.981[−23]
1	91	8.873[−24]	7.246[−24]	5.529[−24]	3.836[−24]	2.646[−24]
1	92	6.906[−23]	7.023[−23]	7.191[−23]	7.408[−23]	7.394[−23]
1	93	7.840[−22]	7.412[−22]	6.812[−22]	5.874[−22]	4.605[−22]
1	94	2.930[−23]	2.775[−23]	2.655[−23]	2.598[−23]	2.544[−23]
1	95	7.502[−22]	7.294[−22]	6.911[−22]	6.161[−22]	4.969[−22]
1	96	5.560[−22]	5.463[−22]	5.229[−22]	4.707[−22]	3.820[−22]
1	97	1.122[−21]	1.074[−21]	1.001[−21]	8.780[−22]	7.007[−22]
1	98	5.258[−22]	4.808[−22]	4.261[−22]	3.554[−22]	2.737[−22]
1	99	1.487[−23]	1.115[−23]	7.401[−24]	3.873[−24]	1.528[−24]
1	100	2.305[−22]	1.967[−22]	1.593[−22]	1.180[−22]	8.123[−23]
1	101	8.497[−23]	7.354[−23]	5.994[−23]	4.353[−23]	2.801[−23]
1	102	2.713[−22]	2.401[−22]	2.021[−22]	1.541[−22]	1.055[−22]
1	103	1.598[−22]	1.445[−22]	1.263[−22]	1.037[−22]	7.892[−23]
1	104	2.920[−22]	2.733[−22]	2.487[−22]	2.136[−22]	1.686[−22]
1	105	1.233[−22]	1.053[−22]	8.358[−23]	5.694[−23]	3.085[−23]
1	106	1.516[−22]	1.354[−22]	1.166[−22]	9.443[−23]	7.136[−23]
1	107	3.876[−23]	3.163[−23]	2.411[−23]	1.660[−23]	1.085[−23]
1	108	1.045[−22]	9.397[−23]	8.161[−23]	6.665[−23]	5.070[−23]
1	109	1.455[−24]	1.401[−24]	1.337[−24]	1.248[−24]	1.119[−24]
1	110	2.086[−24]	1.716[−24]	1.315[−24]	9.041[−25]	5.880[−25]
1	111	4.543[−24]	3.793[−24]	2.946[−24]	2.025[−24]	1.262[−24]
1	112	6.755[−24]	5.700[−24]	4.581[−24]	3.440[−24]	2.523[−24]
1	113	3.365[−23]	3.143[−23]	2.879[−23]	2.539[−23]	2.137[−23]

IV. DETAILED 2-3 CROSS-SECTION CALCULATIONS

We have tabulated the cross sections in cm^2 from 2-3 transitions from the $2s^2 2p^5\,^2P_{3/2}$ state in Table VI at five energies above threshold. Results for cross sections from the $2s^2 2p^5\,^2P_{1/2}$ state are presented in Table VII, and from the $2s2p^6\,^2S_{1/2}$ state are given in Table VIII. We have not found previous published works in the literature considering 2-3 electron-ion collisional transitions in F-

TABLE VII. Electron collisional excitation cross sections (cm^2) for all 2-3 transitions from the $2s^2 2p^5\,{}^2P_{1/2}$ state in F-like selenium. The cross sections are tabulated at five different energies (in eV) above threshold. The level indices for the transition are given under the heading Levels: I, F, where I stands for the initial level and F for the final level. The cross sections are tabulated such that 1.036[−23] is to be read as 1.036×10^{-23}.

Levels		Energy (eV) above threshold				
I	*F*	200.0	500.0	1000.0	2000.0	4000.0
2	4	1.036[−23]	7.683[−24]	4.953[−24]	2.418[−24]	8.491[−25]
2	5	8.205[−24]	8.019[−24]	7.825[−24]	7.739[−24]	7.309[−24]
2	6	1.395[−23]	1.141[−23]	8.739[−24]	6.226[−24]	4.410[−24]
2	7	2.157[−22]	1.650[−22]	1.129[−22]	6.456[−23]	3.371[−23]
2	8	2.496[−22]	2.685[−22]	2.880[−22]	3.101[−22]	3.074[−22]
2	9	2.563[−23]	2.007[−23]	1.429[−23]	8.700[−24]	4.687[−24]
2	10	3.426[−23]	2.639[−23]	1.836[−23]	1.077[−23]	5.533[−24]
2	11	2.967[−22]	2.208[−22]	1.427[−22]	6.953[−23]	2.392[−23]
2	12	4.432[−22]	4.741[−22]	5.073[−22]	5.457[−22]	5.419[−22]
2	13	3.791[−23]	3.234[−23]	2.590[−23]	1.853[−23]	1.181[−23]
2	14	3.910[−23]	3.127[−23]	2.311[−23]	1.507[−23]	9.007[−24]
2	15	6.030[−23]	4.704[−23]	3.323[−23]	1.979[−23]	1.014[−23]
2	16	4.767[−23]	3.827[−23]	2.823[−23]	1.808[−23]	1.019[−23]
2	17	2.093[−22]	1.693[−22]	1.261[−22]	8.139[−23]	4.604[−23]
2	18	1.076[−22]	7.970[−23]	5.200[−23]	2.711[−23]	1.166[−23]
2	19	3.316[−22]	2.435[−22]	1.552[−22]	7.492[−23]	2.626[−23]
2	20	9.508[−22]	7.554[−22]	5.501[−22]	3.461[−22]	1.944[−22]
2	21	1.465[−21]	1.183[−21]	8.861[−22]	5.842[−22]	3.486[−22]
2	22	7.980[−22]	6.647[−22]	5.251[−22]	3.820[−22]	2.622[−22]
2	23	3.674[−22]	2.819[−22]	1.940[−22]	1.102[−22]	5.294[−23]
2	24	3.151[−21]	2.637[−21]	2.059[−21]	1.419[−21]	8.619[−22]
2	25	2.978[−22]	2.840[−22]	2.720[−22]	2.635[−22]	2.468[−22]
2	26	2.172[−21]	1.696[−21]	1.200[−21]	7.127[−22]	3.637[−22]
2	27	1.861[−21]	1.507[−21]	1.123[−21]	7.205[−22]	4.009[−22]
2	28	5.169[−23]	3.633[−23]	2.194[−23]	1.010[−23]	3.781[−24]
2	29	6.806[−23]	5.657[−23]	4.501[−23]	3.420[−23]	2.564[−23]
2	30	4.393[−23]	3.005[−23]	1.726[−23]	7.068[−24]	1.973[−24]
2	31	2.321[−21]	1.920[−21]	1.483[−21]	1.015[−21]	6.285[−22]
2	32	3.108[−23]	2.591[−23]	2.055[−23]	1.530[−23]	1.101[−23]
2	33	4.583[−22]	3.630[−22]	2.652[−22]	1.704[−22]	1.015[−22]
2	34	2.884[−23]	2.001[−23]	1.175[−23]	4.976[−24]	1.458[−24]
2	35	1.665[−23]	1.292[−23]	9.302[−24]	6.000[−24]	3.681[−24]
2	36	2.836[−23]	2.090[−23]	1.371[−23]	7.451[−24]	3.723[−24]
2	37	1.823[−22]	1.693[−22]	1.548[−22]	1.357[−22]	1.136[−22]
2	38	1.904[−21]	1.712[−21]	1.466[−21]	1.143[−21]	7.966[−22]
2	39	4.861[−23]	3.364[−23]	1.984[−23]	8.760[−24]	3.118[−24]
2	40	9.547[−23]	7.185[−23]	4.936[−23]	2.986[−23]	1.803[−23]
2	41	1.427[−22]	9.926[−23]	5.862[−23]	2.520[−23]	7.728[−24]
2	42	6.404[−22]	4.599[−22]	2.870[−22]	1.393[−22]	5.642[−23]
2	43	1.192[−21]	8.982[−22]	6.144[−22]	3.654[−22]	2.136[−22]
2	44	9.752[−22]	6.800[−22]	4.029[−22]	1.751[−22]	5.598[−23]
2	45	4.295[−21]	3.803[−21]	3.197[−21]	2.426[−21]	1.641[−21]
2	46	8.627[−22]	6.853[−22]	5.040[−22]	3.286[−22]	2.015[−22]
2	47	9.125[−22]	6.346[−22]	3.733[−22]	1.579[−22]	4.542[−23]
2	48	5.805[−22]	4.758[−22]	3.741[−22]	2.808[−22]	1.939[−22]
2	49	1.712[−21]	1.499[−21]	1.278[−21]	1.044[−21]	8.329[−22]
2	50	9.072[−22]	7.251[−22]	5.449[−22]	3.741[−22]	2.442[−22]
2	51	1.264[−21]	8.832[−22]	5.228[−22]	2.234[−22]	6.604[−23]
2	52	8.158[−22]	5.892[−22]	3.733[−22]	1.897[−22]	8.441[−23]
2	53	1.319[−21]	1.127[−21]	9.285[−22]	7.231[−22]	5.509[−22]
2	54	6.434[−22]	4.789[−22]	3.241[−22]	1.921[−22]	1.100[−22]
2	55	2.997[−21]	2.721[−21]	2.416[−21]	2.051[−21]	1.674[−21]
2	56	6.248[−22]	4.555[−22]	2.953[−22]	1.610[−22]	7.895[−23]
2	57	1.361[−20]	1.317[−20]	1.249[−20]	1.129[−20]	9.582[−21]
2	58	1.021[−20]	9.885[−21]	9.382[−21]	8.477[−21]	7.187[−21]
2	59	6.281[−23]	5.332[−23]	4.248[−23]	3.009[−23]	1.905[−23]

TABLE VII. (*Continued*).

Levels I	F	200.0	500.0	1000.0	2000.0	4000.0
2	60	8.885[−23]	7.368[−23]	5.678[−23]	3.813[−23]	2.240[−23]
2	61	7.337[−23]	5.988[−23]	4.603[−23]	3.218[−23]	2.093[−23]
2	62	7.791[−22]	6.992[−22]	5.968[−22]	4.616[−22]	3.175[−22]
2	63	1.397[−21]	1.034[−21]	6.838[−22]	3.791[−22]	1.942[−22]
2	64	1.302[−20]	1.253[−20]	1.183[−20]	1.068[−20]	9.108[−21]
2	65	7.277[−24]	5.784[−24]	4.276[−24]	2.865[−24]	1.531[−24]
2	66	4.784[−24]	3.820[−24]	2.852[−24]	1.952[−24]	1.101[−24]
2	67	2.939[−21]	2.612[−21]	2.202[−21]	1.677[−21]	1.134[−21]
2	68	5.066[−24]	3.750[−24]	2.458[−24]	1.326[−24]	6.701[−25]
2	69	1.615[−23]	1.317[−23]	9.986[−24]	6.710[−24]	4.175[−24]
2	70	1.824[−24]	1.449[−24]	1.075[−24]	7.360[−25]	4.145[−25]
2	71	4.135[−23]	4.029[−23]	3.932[−23]	3.838[−23]	3.677[−23]
2	72	8.253[−23]	7.844[−23]	7.489[−23]	7.228[−23]	6.949[−23]
2	73	1.213[−23]	9.230[−24]	6.327[−24]	3.659[−24]	1.952[−24]
2	74	6.656[−23]	4.980[−23]	3.247[−23]	1.604[−23]	5.635[−24]
2	75	1.571[−22]	1.222[−22]	8.738[−23]	5.532[−23]	3.294[−23]
2	76	1.165[−22]	1.199[−22]	1.251[−22]	1.322[−22]	1.352[−22]
2	77	4.338[−21]	3.910[−21]	3.348[−21]	2.596[−21]	1.786[−21]
2	78	5.457[−23]	4.302[−23]	3.114[−23]	1.998[−23]	9.346[−24]
2	79	3.283[−22]	3.470[−22]	3.664[−22]	3.839[−22]	3.811[−22]
2	80	3.538[−22]	3.500[−22]	3.478[−22]	3.483[−22]	3.400[−22]
2	81	2.189[−22]	1.912[−22]	1.571[−22]	1.150[−22]	7.413[−23]
2	82	1.441[−22]	1.255[−22]	1.027[−22]	7.503[−23]	4.840[−23]
2	83	5.733[−25]	5.133[−25]	4.397[−25]	3.468[−25]	2.523[−25]
2	84	1.015[−22]	8.938[−23]	7.450[−23]	5.621[−23]	3.834[−23]
2	85	5.221[−23]	4.574[−23]	3.790[−23]	2.839[−23]	1.927[−23]
2	86	5.851[−23]	4.854[−23]	3.760[−23]	2.599[−23]	1.654[−23]
2	87	1.676[−23]	1.451[−23]	1.183[−23]	8.675[−24]	5.777[−24]
2	88	3.945[−22]	4.091[−22]	4.264[−22]	4.466[−22]	4.487[−22]
2	89	1.671[−22]	1.457[−22]	1.202[−22]	8.967[−23]	6.030[−23]
2	90	6.922[−23]	5.664[−23]	4.280[−23]	2.820[−23]	1.657[−23]
2	91	2.505[−22]	2.762[−22]	3.062[−22]	3.410[−22]	3.583[−22]
2	92	1.743[−22]	1.310[−22]	8.589[−23]	4.296[−23]	1.591[−23]
2	93	2.717[−22]	2.360[−22]	1.965[−22]	1.524[−22]	1.107[−22]
2	94	3.145[−22]	3.314[−22]	3.525[−22]	3.791[−22]	3.901[−22]
2	95	1.191[−22]	9.296[−23]	6.566[−23]	3.909[−23]	2.057[−23]
2	96	1.639[−23]	1.205[−23]	7.672[−24]	3.714[−24]	1.356[−24]
2	97	2.359[−22]	1.788[−22]	1.213[−22]	6.866[−23]	3.573[−23]
2	98	5.537[−22]	5.100[−22]	4.551[−22]	3.813[−22]	2.943[−22]
2	99	5.430[−23]	4.178[−23]	2.871[−23]	1.631[−23]	8.482[−24]
2	100	2.166[−22]	1.777[−22]	1.367[−22]	9.551[−23]	6.315[−23]
2	101	1.202[−21]	1.078[−21]	9.344[−22]	7.593[−22]	5.731[−22]
2	102	1.299[−21]	1.200[−21]	1.072[−21]	8.936[−22]	6.808[−22]
2	103	1.158[−21]	1.077[−21]	9.741[−22]	8.301[−22]	6.506[−22]
2	104	6.082[−22]	4.537[−22]	2.959[−22]	1.491[−22]	5.764[−23]
2	105	9.043[−22]	8.496[−22]	7.755[−22]	6.652[−22]	5.210[−22]
2	106	1.470[−21]	1.404[−21]	1.304[−21]	1.140[−21]	9.067[−22]
2	107	1.447[−22]	1.059[−22]	6.674[−23]	3.128[−23]	1.036[−23]
2	108	8.594[−22]	8.030[−22]	7.294[−22]	6.239[−22]	4.891[−22]
2	109	3.188[−24]	3.080[−24]	2.977[−24]	2.882[−24]	2.733[−24]
2	110	4.574[−24]	3.675[−24]	2.694[−24]	1.680[−24]	9.169[−25]
2	111	7.625[−24]	6.316[−24]	4.875[−24]	3.352[−24]	2.123[−24]
2	112	5.159[−23]	4.921[−23]	4.610[−23]	4.145[−23]	3.517[−23]
2	113	8.498[−24]	6.533[−24]	4.519[−24]	2.621[−24]	1.370[−24]

(Column heading over 200.0–4000.0: Energy (eV) above threshold)

like selenium. However, there are some results available for other nearby ions. Davis *et al.*[38] listed fitting coefficients for rate coefficients for a number of 2-3 transitions in F-like iron. The annotated bibliography of Itikawa *et al.*[39] lists several papers dealing with excitation in F-like ions. None of the references listed gives results for 2-3 cross sections in a Coulomb-Born, distorted-wave, or other relatively sophisticated approximation.

TABLE VIII. Electron collisional excitation cross sections (cm^2) for all 2-3 transitions from the $2s2p^6\,{}^2S_{1/2}$ state in F-like selenium. The cross sections are tabulated at five different energies (in eV) above threshold. The level indices for the transition are given under the heading Levels: I, F, where I stands for the initial level and F for the final level. The cross sections are tabulated such that 7.060[−24] is to be read as 7.060×10^{-24}.

Levels		Energy (eV) above threshold				
I	F	200.0	500.0	1000.0	2000.0	4000.0
3	4	7.060[−24]	5.524[−24]	3.967[−24]	2.463[−24]	1.378[−24]
3	5	7.259[−24]	5.922[−24]	4.494[−24]	2.996[−24]	1.780[−24]
3	6	9.702[−24]	8.083[−24]	6.319[−24]	4.396[−24]	2.728[−24]
3	7	2.318[−24]	1.820[−24]	1.314[−24]	8.254[−25]	4.708[−25]
3	8	7.426[−25]	5.601[−25]	3.787[−25]	2.150[−25]	1.165[−25]
3	9	2.674[−24]	2.424[−24]	2.210[−24]	2.004[−24]	1.824[−24]
3	10	2.081[−24]	1.518[−24]	9.785[−25]	5.140[−25]	2.069[−25]
3	11	5.378[−24]	4.636[−24]	3.847[−24]	2.972[−24]	2.134[−24]
3	12	4.041[−24]	3.631[−24]	3.190[−24]	2.534[−24]	1.959[−24]
3	13	1.386[−24]	1.206[−24]	1.041[−24]	9.053[−25]	7.866[−25]
3	14	2.599[−24]	1.917[−24]	1.252[−24]	6.622[−25]	2.677[−25]
3	15	1.422[−24]	1.011[−24]	6.465[−25]	3.535[−25]	1.834[−25]
3	16	4.403[−24]	4.242[−24]	4.033[−24]	3.795[−24]	3.389[−24]
3	17	1.152[−23]	1.112[−23]	1.047[−23]	9.543[−24]	8.131[−24]
3	18	3.698[−24]	2.950[−24]	2.231[−24]	1.611[−24]	1.186[−24]
3	19	1.826[−24]	1.401[−24]	9.709[−25]	5.608[−25]	2.738[−25]
3	20	3.187[−24]	2.833[−24]	2.550[−24]	2.387[−24]	2.255[−24]
3	21	5.593[−24]	4.827[−24]	4.044[−24]	3.352[−24]	2.739[−24]
3	22	2.284[−24]	1.778[−24]	1.310[−24]	8.401[−25]	4.238[−25]
3	23	3.026[−24]	2.624[−24]	2.201[−24]	1.733[−24]	1.254[−24]
3	24	3.536[−24]	3.206[−24]	2.867[−24]	2.521[−24]	2.106[−24]
3	25	6.781[−24]	5.566[−24]	4.277[−24]	2.928[−24]	1.806[−24]
3	26	3.113[−24]	2.393[−24]	1.718[−24]	1.115[−24]	6.844[−25]
3	27	9.769[−24]	1.055[−23]	1.128[−23]	1.197[−23]	1.161[−23]
3	28	3.924[−24]	3.178[−24]	2.405[−24]	1.625[−24]	1.003[−24]
3	29	6.393[−23]	5.395[−23]	4.271[−23]	3.009[−23]	1.877[−23]
3	30	3.894[−24]	3.412[−24]	2.863[−24]	2.221[−24]	1.581[−24]
3	31	1.472[−24]	1.121[−24]	7.868[−25]	4.995[−25]	2.441[−25]
3	32	5.335[−23]	4.502[−23]	3.561[−23]	2.500[−23]	1.540[−23]
3	33	3.347[−23]	3.301[−23]	3.181[−23]	2.979[−23]	2.582[−23]
3	34	1.086[−25]	7.980[−26]	5.442[−26]	3.394[−26]	2.121[−26]
3	35	5.458[−24]	4.729[−24]	3.886[−24]	2.902[−24]	1.964[−24]
3	36	2.681[−23]	2.239[−23]	1.748[−23]	1.206[−23]	7.286[−24]
3	37	4.686[−23]	3.965[−23]	3.149[−23]	2.228[−23]	1.390[−23]
3	38	3.648[−23]	3.749[−23]	3.794[−23]	3.770[−23]	3.460[−23]
3	39	5.568[−23]	4.839[−23]	3.986[−23]	2.977[−23]	2.001[−23]
3	40	2.264[−23]	1.952[−23]	1.600[−23]	1.197[−23]	8.133[−24]
3	41	1.455[−22]	1.233[−22]	9.818[−23]	6.984[−23]	4.434[−23]
3	42	3.786[−21]	3.210[−21]	2.550[−21]	1.798[−21]	1.113[−21]
3	43	7.178[−21]	6.092[−21]	4.845[−21]	3.423[−21]	2.128[−21]
3	44	1.871[−21]	1.622[−21]	1.330[−21]	9.875[−22]	6.636[−22]
3	45	7.232[−24]	6.224[−24]	5.153[−24]	4.050[−24]	3.044[−24]
3	46	1.476[−23]	1.360[−23]	1.234[−23]	1.105[−23]	9.529[−24]
3	47	4.367[−21]	3.746[−21]	3.025[−21]	2.192[−21]	1.423[−21]
3	48	1.728[−23]	1.533[−23]	1.302[−23]	1.020[−23]	7.335[−24]
3	49	7.602[−22]	6.485[−22]	5.190[−22]	3.698[−22]	2.324[−22]
3	50	1.263[−24]	1.067[−24]	8.572[−25]	6.361[−25]	4.429[−25]
3	51	3.619[−25]	2.691[−25]	1.860[−25]	1.175[−25]	7.397[−26]
3	52	6.472[−23]	5.595[−23]	4.560[−23]	3.338[−23]	2.183[−23]
3	53	8.474[−23]	7.238[−23]	5.797[−23]	4.130[−23]	2.596[−23]
3	54	4.946[−23]	4.224[−23]	3.394[−23]	2.450[−23]	1.600[−23]
3	55	4.559[−23]	3.862[−23]	3.061[−23]	2.153[−23]	1.336[−23]
3	56	2.614[−22]	2.231[−22]	1.788[−22]	1.282[−22]	8.241[−23]
3	57	8.625[−22]	7.343[−22]	5.855[−22]	4.144[−22]	2.587[−22]
3	58	2.209[−22]	1.873[−22]	1.486[−22]	1.044[−22]	6.441[−23]
3	59	3.077[−22]	2.285[−22]	1.474[−22]	7.186[−23]	2.523[−23]

TABLE VIII. (*Continued*).

Levels I	F	200.0	500.0	1000.0	2000.0	4000.0
		Energy (eV) above threshold				
3	60	4.095[−22]	4.208[−22]	4.371[−22]	4.540[−22]	4.416[−22]
3	61	2.556[−22]	2.188[−22]	1.820[−22]	1.469[−22]	1.184[−22]
3	62	2.300[−22]	2.403[−22]	2.539[−22]	2.663[−22]	2.595[−22]
3	63	3.565[−23]	3.086[−23]	2.563[−23]	1.980[−23]	1.425[−23]
3	64	9.444[−23]	8.244[−23]	6.826[−23]	5.126[−23]	3.474[−23]
3	65	8.569[−22]	6.439[−22]	4.266[−22]	2.226[−22]	9.138[−23]
3	66	7.459[−22]	5.991[−22]	4.491[−22]	3.034[−22]	1.938[−22]
3	67	2.137[−22]	2.188[−22]	2.280[−22]	2.438[−22]	2.582[−22]
3	68	1.644[−21]	1.251[−21]	8.506[−22]	4.705[−22]	2.170[−22]
3	69	1.432[−21]	1.148[−21]	8.443[−22]	5.322[−22]	2.941[−22]
3	70	1.319[−21]	1.084[−21]	8.322[−22]	5.714[−22]	3.621[−22]
3	71	5.146[−22]	4.295[−22]	3.358[−22]	2.337[−22]	1.468[−22]
3	72	5.924[−22]	4.616[−22]	3.275[−22]	1.981[−22]	1.074[−22]
3	73	1.644[−21]	1.395[−21]	1.112[−21]	7.877[−22]	4.978[−22]
3	74	1.368[−21]	1.094[−21]	8.065[−22]	5.150[−22]	2.950[−22]
3	75	3.911[−22]	3.880[−22]	3.907[−22]	3.917[−22]	3.751[−22]
3	76	1.731[−21]	1.461[−21]	1.158[−21]	8.184[−22]	5.215[−22]
3	77	1.064[−22]	8.160[−23]	5.630[−23]	3.256[−23]	1.767[−23]
3	78	1.255[−21]	1.092[−21]	8.982[−22]	6.647[−22]	4.391[−22]
3	79	8.732[−22]	7.507[−22]	6.095[−22]	4.452[−22]	2.927[−22]
3	80	4.928[−22]	4.006[−22]	3.050[−22]	2.097[−22]	1.358[−22]
3	81	6.557[−22]	4.631[−22]	2.790[−22]	1.234[−22]	3.862[−23]
3	82	1.126[−21]	7.943[−22]	4.782[−22]	2.120[−22]	6.716[−23]
3	83	1.340[−21]	9.334[−22]	5.506[−22]	2.349[−22]	6.969[−23]
3	84	1.093[−21]	7.630[−22]	4.515[−22]	1.936[−22]	5.713[−23]
3	85	9.214[−22]	6.613[−22]	4.166[−22]	2.120[−22]	9.666[−23]
3	86	8.573[−22]	6.169[−22]	3.890[−22]	1.964[−22]	8.659[−23]
3	87	7.789[−22]	6.342[−22]	4.910[−22]	3.525[−22]	2.396[−22]
3	88	6.187[−22]	4.815[−22]	3.410[−22]	2.054[−22]	1.101[−22]
3	89	2.559[−21]	2.346[−21]	2.110[−21]	1.813[−21]	1.478[−21]
3	90	4.859[−21]	4.653[−21]	4.382[−21]	3.971[−21]	3.589[−21]
3	91	6.320[−22]	5.321[−22]	4.196[−22]	2.935[−22]	1.826[−22]
3	92	9.615[−22]	8.104[−22]	6.492[−22]	4.786[−22]	3.305[−22]
3	93	6.375[−22]	4.552[−22]	2.841[−22]	1.419[−22]	6.317[−23]
3	94	7.387[−22]	5.895[−22]	4.312[−22]	2.699[−22]	1.477[−22]
3	95	1.292[−21]	1.063[−21]	8.353[−22]	6.146[−22]	4.453[−22]
3	96	3.255[−21]	3.010[−21]	2.726[−21]	2.350[−21]	1.916[−21]
3	97	8.545[−22]	6.003[−22]	3.626[−22]	1.677[−22]	6.403[−23]
3	98	8.655[−22]	6.804[−22]	4.992[−22]	3.321[−22]	2.116[−22]
3	99	5.652[−21]	5.067[−21]	4.319[−21]	3.337[−21]	2.291[−21]
3	100	7.805[−21]	7.458[−21]	7.008[−21]	6.276[−21]	5.274[−21]
3	101	7.553[−22]	5.754[−22]	4.013[−22]	2.461[−22]	1.438[−22]
3	102	9.053[−21]	8.676[−21]	8.180[−21]	7.352[−21]	6.206[−21]
3	103	6.830[−22]	4.902[−22]	3.057[−22]	1.488[−22]	6.077[−23]
3	104	8.621[−22]	6.727[−22]	4.871[−22]	3.170[−22]	1.974[−22]
3	105	7.565[−21]	7.149[−21]	6.648[−21]	5.911[−21]	4.980[−21]
3	106	4.922[−22]	3.378[−22]	1.945[−22]	7.940[−23]	2.227[−23]
3	107	8.806[−21]	8.509[−21]	8.091[−21]	7.334[−21]	6.242[−21]
3	108	5.663[−21]	5.434[−21]	5.131[−21]	4.620[−21]	3.914[−21]
3	109	2.489[−21]	2.227[−21]	1.892[−21]	1.459[−21]	9.999[−22]
3	110	2.887[−22]	2.834[−22]	2.806[−22]	2.796[−22]	2.742[−22]
3	111	5.711[−22]	5.632[−22]	5.604[−22]	5.623[−22]	5.552[−22]
3	112	1.629[−21]	1.471[−21]	1.285[−21]	1.054[−21]	8.019[−22]
3	113	2.433[−21]	2.195[−21]	1.917[−21]	1.572[−21]	1.196[−21]

There are unpublished results for 2-3 transitions in F-like iron calculated in the distorted-wave approximation (with exchange) by Mann.[40] As opposed to the subset of results given by Davis *et al.*, Ref. 40 presents a complete set of *LS*-coupled results for transitions from the $2s^2 2p^5\,{}^2P$ ground state. Our results are most closely related to those of Ref. 40, although it is worthwhile to comment on some of the differences. The results of Mann are in *LS* coupling (not *LSJ* coupling), while the present results are in intermediate *jj* coupling, hence our results must be summed to be compared against the LS results. Mann's calculations treated the various singly excited manifolds as degenerate, while in the present calculations each transition is treated one at a time, and continuum waves are computed at the energies appropriate to each multiconfigurational state (this statement implies no criticism of the method used by Mann, which should be very good here, but rather is a remark concerning different approaches). The present results are fully relativistic, as both our bound and continuum orbitals are two-component Dirac orbitals, while the results of Ref. 40 are based on a nonrelativistic collision problem.

Inspection of Table VI reveals some interesting points about the near-threshold collisional process. For many years workers modeling spectra would use empirical cross sections based on Gaunt factors for dipole-allowed transitions,[41–45] where detailed collisional cross-section results were lacking. By far the strongest oscillator strengths from the $^2P_{3/2}$ level are for $2p$-$3d$ transitions, and the strongest of these are transitions from level 1 ($^2P_{3/2}$) to levels 55 and 56 with absorption oscillator strengths of 0.497 and 0.773, respectively. Perusal of Table VI shows very large excitation cross sections to these levels, with values of 6.5×10^{-21} and 1.0×10^{-20} cm^{-2}, respectively. Other $2p$-$3d$ dipole-allowed transitions with oscillator strengths of 0.100 or more have substantial near-threshold excitation cross sections, including transitions to levels 37, 39, 40, 41, 47, 48, 52, 53, and 57.

With the advent of more powerful computers and the development of high-quality atomic physics programs, the Gaunt factor approximation in kinetics modeling may yield to more accurate collisional models. Nevertheless, we are in a position to compute excitation Gaunt factors from our data, simply out of curiosity as to what the results might be, and whether they compare at all with threshold values of between 0.15 and 0.20 as found in the literature. We shall define our Gaunt factor in terms of the excitation cross section through the standard nonrelativistic formula

$$\sigma_{ij}(E)=\frac{8\pi}{\sqrt{3}}\pi a_0^2\frac{I_H}{\Delta E_{ij}}\frac{I_H}{E}f_{ij}G_{ij}(E)\ , \qquad (4.1)$$

where $G_{ij}(E)$ is our energy-dependent and transition-dependent Gaunt factor. The results are presented in Table IX and one observes that, for many $2p$-$3d$ transitions with large oscillator strengths, the utilization of Gaunt factors often used is a good approximation in F-like selenium. Also in agreement with earlier experiences with Gaunt factors, one finds substantial variations for transitions with small oscillator strengths, and the $2p$-$3s$ transitions are an excellent example of this. Based on these results, it is very probable that the empirical collision strengths for F-like S, Ca, Fe, and Ni $2p$-$3s$ transitions published by Kato in Ref. 46, which are based on the Gaunt factor prescription of Ref. 47, are too high by a factor of 2—3.

The occurrence of strong dipole electron collisional cross sections for transitions with large oscillator strengths is also observed for transitions from the

TABLE IX. Gaunt factors derived from the oscillator strengths and distorted-wave collisional cross sections for selected $2p$-$3s$ and $2p$-$3d$ dipole-allowed transitions from the $2s^22p^5\,^2P_{3/2}$ state. The threshold energies ΔE_{ij} are listed in eV, the cross sections are in cm^2, and both the oscillator strengths f_{ij} and the derived Gaunt factors G_{ij} are dimensionless. The cross sections and Gaunt factors are for incident electron energies 200 eV above threshold. Numbers in square brackets indicate the power of ten; for example, 4.15[−22] is to be read 4.15×10^{-22}.

Transition	ΔE_{ij}	f_{ij}	$\sigma_{ij}(\Delta E_{ij}+200$ eV)	$G_{ij}(\Delta E_{ij}+200$ eV)
		$2p$-$3s$ transitions		
1-5	1519.7	0.013	4.15[−22]	0.068
1-6	1519.7	0.013	1.33[−22]	0.114
1-7	1541.4	0.017	1.50[−22]	0.101
1-8	1545.1	0.014	8.60[−22]	0.070
1-11	1554.2	0.049	3.19[−22]	0.075
		$2p$-$3d$ transitions		
1-36	1622.4	0.088	1.59[−21]	0.228
1-37	1626.1	0.185	3.10[−21]	0.212
1-39	1629.3	0.381	5.89[−21]	0.196
1-40	1635.3	0.135	2.17[−21]	0.206
1-41	1637.9	0.243	4.05[−21]	0.213
1-43	1655.1	0.012	3.67[−21]	0.400
1-47	1659.6	0.106	1.63[−21]	0.201
1-48	1661.2	0.205	2.97[−21]	0.191
1-52	1671.2	0.033	9.29[−22]	0.380
1-53	1671.3	0.220	3.21[−21]	0.194
1-55	1674.4	0.497	6.46[−21]	0.174
1-56	1675.9	0.773	1.04[−21]	0.180
1-57	1683.3	0.130	1.90[−21]	0.197
1-58	1685.8	0.052	7.61[−22]	0.198

$2s^22p^5\,^2P_{1/2}$ and $2s2p^6\,^2S_{1/2}$ states in Tables VII and VIII. Cross sections in excess of 10^{-20} cm^2 are observed for near-threshold excitation of two dipole-allowed transitions with large f values, and these are (2-57) and (2-58) with oscillator strengths of 0.984 and 0.770, respectively.

In short-wavelength-laser research, electron monopole transitions play a key role (at least theoretically) in the production of $\Delta n = 0$ population inversions. For example, in neonlike selenium, the excitation of a $2p$ electron from the ground state $2s^22p^6\,^1S_0$ to $2s^22p^53p\ J=0$ states is calculated to drive population inversions on a number of $3p$-$3s$ transitions. The strongest of these transitions is near 182 Å, and amplification has been observed now on this line. The mechanism by which gain is produced on this line is believed to be direct excitation, in contrast to that of the 206- and 209-Å lines, which are believed to be populated predominantly through recombination channels. The question might be asked as to whether analogs of this strong monopole excitation exist in F-like selenium, and, if so, whether collisionally pumped $3p$-$3s$ transitions in F-like selenium might be observed.

The monopole transitions in question would occur from the $2s^22p^5\,^2P_{3/2}$ level to states of the form $2s^22p^43p\ J=3/2$. There are eight such states (levels 9, 17, 18, 20, 24, 27, 33, and 46). Of these states, one of them is amply favored in terms of collisional strength, and that is level 33 ($[2s^22p_{1/2}2p^3_{3/2}]_2 3p_{1/2}\ J=3/2$) which has a near-threshold excitation cross section of 1.7×10^{-20} cm^2 at 200 eV above threshold. This cross section is larger than the dipole cross section for (1-56) of 1.0×10^{-20} cm^2 discussed above. One should expect level 33 to be the upper $3p$ state of a monopole-excited $3p$-$3s$ inversion driven from the ground state $^2P_{3/2}$.

Six states of the form $2s^22p^43p\ J=1/2$ occur which might serve as candidates for strong monopole excitation, including levels 13, 16, 19, 23, 38, and 45. In this case, the strong monopole excitation is split between two levels, namely levels 38 ($[2s^22p_{1/2}2p^3_{3/2}]_2 3p_{3/2}\ J=1/2$) and 45 ($[2s^22p^4_{3/2}]_0 3p_{1/2}\ J=1/2$), for which the near-threshold excitation cross sections are 1.9×10^{-21} and 4.3×10^{-21} cm^2, respectively, from level 2. In terms of candidate monopole excited $3p$-$3s$ laser transitions, one might look for levels 38 and 45 as potential upper laser states. However, the quantity which is more important in terms of driving a population inversion than the excitation cross section is the product of the lower-state statistical weight g_i and the cross section $\sigma_{ij}(E)$. This product for excitation to levels 38 and 45 is less than one-fifth of that for the transition (1-33) considered above. One would expect that level 33 would be a much better candidate upper laser state than either levels 38 or 45, based on this simple consideration alone.

One might enquire about monopole excitation from the third F-like level (the $2s2p^6\,^2S_{1/2}$), given the set of cross sections of Table VIII. From the point of view of xuv lasers and $3p$-$3s$ inversions, the monopole excitation process is not of particular interest, as the upper $3p$ electron will be able to radiatively decay rapidly back to the L shell, by virtue of the initial $2s$ hole. But it is this difference which makes it interesting in terms of dielectronic recombination physics. The reason for this can be seen from a consideration of quantum-defect theory, from which a linear relation exists between the threshold excitation cross section and the dielectronic capture rate into states corresponding to the excited state plus an additional highly excited Rydberg electron. If one starts from the ground state $2s^22p^6$ Ne-like level, then the capture process is dominated by $2p$-$3d$ excitation leading to Na-like states of the form $2s^22p^53dnl$, and these states may be stabilized by $3d$-$2p$ radiative decay. Although there is a large monopole $2p$-$3p$ excitation cross section, and a correspondingly large capture rate into $2s^22p^53pnl$ doubly excited levels, no stabilizing $3p$-$2s$ radiative decays are possible because the $2s$ shell is already fully occupied.

The situation starting from the F-like $2s^22p^5\,^2P$ levels is similar, in that although substantial capture occurs into the $2s^22p^43pnl$ doubly excited neonlike levels, no stabilizing $3p$-$2s$ decay may occur. From the $^2S_{1/2}$ state, however, the capture into $2s2p^53pnl$ levels can be followed by $3p$-$2s$ radiative decay, and hence a new capture channel is opened. Based on this, one might expect the dielectronic recombination rate coefficients from the $^2S_{1/2}$ level to be larger than the recombination rate coefficients from the ^2P levels, simply due to the existence of an additional strong recombination channel.

The largest collisional excitation cross section from the $2s2p^6\,^2S_{1/2}$ level is a $2p_{1/2}$-$3p_{1/2}$ monopole transition to level 99 ($[2s2p_{1/2}2p^4_{3/2}]_1 3p_{1/2}\ J=1/2$), with a near-threshold cross section of 5.7×10^{-21} cm^2. This cross section is comparable in magnitude to that of any dipole cross section from the $^2S_{1/2}$ level.

V. THEORETICAL INTENSITIES OF F-LIKE 2-3 LINES

From the 2-3 electron collisional cross sections presented in Sec. IV, one can compute theoretical values for absolute line emission. In Tables X—XII, we present results for the strong 2-3 transitions of F-like selenium under conditions similar to those found in the selenium exploding-foil laser target when the plasma is thought to be near optimal conditions for the development of xuv gain. The electron density is taken to be 3.0×10^{20} cm^{-3} and the electron temperature assumed is 1.0 keV. The calculation was carried out using our current selenium xuv laser design model, which incorporates the F-like collisional data which is the subject of the present work, as well as the detailed Ne-like cross sections presented in Ref. 48. The model includes very detailed atomic physics for the F-like through Na-like sequences, and multicore "hydrogenic" physics in the neighboring sequences, computed originally using Morgan's XATOM code,[49] and upgraded substantially over the years with improved rate coefficients from YODA[20] and a variety of other sources. The dielectronic recombination model is based on Refs. 50 and 51, and has been extended to all sequences modeled in a detailed and consistent fashion (Hagelstein). Direct dielectronic recombination into the F-like excited states is included in the intensity results under discussion. This design model will be documented at greater length elsewhere.

TABLE X. Output power (in units of W/cm^3) radiated by strong $2p$-$3s$ transitions in F-like selenium. The plasma conditions are chosen to have an electron temperature of 1.0 keV and an electron density of 3.0×10^{20} electrons/cm^3. The selenium levels are modeled using a detailed multisequence atomic physics model, and the ionization balance is determined self-consistently, such that 5.35×10^{18} cm^{-3} F-like ions are present. Numbers in square brackets indicate the power of ten.

Transition	Configurations	J_i-J_f	λ (Å)	Output power	Normalized power	gf
2-5	$^2P_{1/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3s$	1/2-3/2	8.478	4.45[9]	0.002	0.002
3-60	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_2 3s$	1/2-3/2	8.351	4.35[11]	0.148	0.136
3-61	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_1 3s$	1/2-3/2	8.260	4.47[11]	0.152	0.032
3-62	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_1 3s$	1/2-1/2	8.257	1.11[11]	0.038	0.080
2-8	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3s$	1/2-1/2	8.253	2.17[11]	0.074	0.086
1-5	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3s$	3/2-3/2	8.237	7.87[11]	0.268	0.268
2-12	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3s$	1/2-3/2	8.196	6.90[11]	0.235	0.179
1-6	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_0 3s$	3/2-1/2	8.159	1.94[11]	0.066	0.052
3-67	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_0 3s$	1/2-1/2	8.131	1.90[11]	0.065	0.066
1-7	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3s$	3/2-3/2	8.044	5.24[11]	0.178	0.069
1-8	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3s$	3/2-1/2	8.025	1.49[11]	0.051	0.054
1-11	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3s$	3/2-5/2	7.978	1.22[12]	0.415	0.194
3-75	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_1 3s$	1/2-3/2	7.976	2.61[11]	0.089	0.148
2-25	$^2P_{1/2}$—$[2s^2 2p_{3/2}^4]_0 3s$	1/2-1/2	7.948	2.15[11]	0.073	0.077

TABLE XI. Output power (W/cm^3) radiated by strong $2p$-$3d$ transitions in F-like selenium. The plasma conditions are chosen to have an electron temperature of 1.0 keV and an electron density of 3.0×10^{20} electrons/cm^3, as in Table X. Numbers in square brackets indicate the power of ten.

Transition	Configurations	J_i-J_f	λ (Å)	Output power	Normalized power	gf
2-37	$^2P_{1/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3d_{5/2}$	1/2-3/2	7.831	2.74[10]	0.023	0.023
3-89	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_2 3d_{5/2}$	1/2-3/2	7.750	2.67[11]	0.228	0.310
3-90	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_2 3d_{5/2}$	1/2-1/2	7.711	2.60[11]	0.222	0.654
2-43	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{3/2}$	1/2-3/2	7.690	2.07[11]	0.177	0.034
3-95	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_1 3d_{3/2}$	1/2-3/2	7.687	2.32[11]	0.198	0.092
3-96	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_1 3d_{3/2}$	1/2-1/2	7.685	2.81[11]	0.240	0.385
2-49	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{5/2}$	1/2-3/2	7.658	3.52[11]	0.301	0.157
3-100	$^2S_{1/2}$—$[2s 2p_{1/2}^2 2p_{3/2}^3]_1 3d_{3/2}$	1/2-3/2	7.651	4.26[11]	0.362	1.104
1-36	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3d_{5/2}$	3/2-1/2	7.642	5.10[11]	0.436	0.353
1-37	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3d_{5/2}$	3/2-3/2	7.625	9.60[11]	0.820	0.739
2-53	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{3/2}$	1/2-1/2	7.614	1.04[11]	0.089	0.091
1-39	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_2 3d_{5/2}$	3/2-5/2	7.610	1.90[12]	1.623	1.522
2-55	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{3/2}$	1/2-3/2	7.599	3.41[11]	0.291	0.357
1-40	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_0 3d_{3/2}$	3/2-3/2	7.582	6.99[11]	0.597	0.541
1-41	$^2P_{3/2}$—$[2s^2 2p_{1/2}^2 2p_{3/2}^2]_0 3d_{5/2}$	3/2-5/2	7.570	1.30[12]	1.110	0.972
2-57	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{5/2}$	1/2-3/2	7.558	1.69[12]	1.444	1.968
3-102	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_0 3d_{3/2}$	1/2-3/2	7.557	5.49[11]	0.469	1.306
2-58	$^2P_{1/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{5/2}$	1/2-1/2	7.546	1.11[12]	0.948	1.540
1-43	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{3/2}$	3/2-3/2	7.491	3.28[11]	0.280	0.050
1-47	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{5/2}$	3/2-5/2	7.471	9.96[11]	0.851	0.423
1-48	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{3/2}$	3/2-5/2	7.464	1.20[12]	1.025	0.820
3-105	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_1 3d_{5/2}$	1/2-3/2	7.427	4.72[11]	0.403	1.092
1-52	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{5/2}$	3/2-5/2	7.419	5.37[11]	0.459	0.130
1-53	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{3/2}$	3/2-1/2	7.419	1.09[12]	0.931	0.880
3-107	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_1 3d_{3/2}$	1/2-1/2	7.412	4.15[11]	0.354	1.385
3-108	$^2S_{1/2}$—$[2s 2p_{1/2} 2p_{3/2}^4]_1 3d_{3/2}$	1/2-3/2	7.411	3.67[11]	0.313	0.890
1-55	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{3/2}$	3/2-3/2	7.405	2.06[12]	1.760	1.987
1-56	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{3/2}$	3/2-5/2	7.398	3.62[12]	3.092	3.092
2-64	$^2P_{1/2}$—$[2s^2 2p_{3/2}^4]_0 3d_{3/2}$	1/2-3/2	7.380	1.43[12]	1.221	1.092
1-57	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_2 3d_{5/2}$	3/2-3/2	7.366	4.83[11]	0.413	0.521
1-58	$^2P_{3/2}$—$[2s^2 2p_{1/2} 2p_{3/2}^3]_1 3d_{5/2}$	3/2-1/2	7.355	1.62[11]	0.138	0.208

TABLE XII. Output power (W/cm^3) radiated by strong $2s$-$3p$ transitions in F-like selenium. The plasma conditions are chosen to have an electron temperature of 1.0 keV and an electron density of 3.0×10^{20} electrons/cm^3, as in Table X. Numbers in square brackets indicate the power of ten.

Transition	Configurations	J_i-J_f	λ (Å)	Output power	Normalized power	gf
2-72	$^2P_{1/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{1/2}$	1/2-3/2	7.234	4.20[10]	0.017	0.024
2-76	$^2P_{1/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{3/2}$	1/2-3/2	7.188	1.29[11]	0.054	0.051
1-66	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_2 3p_{1/2}$	3/2-5/2	7.140	5.59[11]	0.232	0.178
2-79	$^2P_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3p_{1/2}$	1/2-1/2	7.115	1.17[11]	0.049	0.156
2-80	$^2P_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_0 3p_{3/2}$	1/2-3/2	7.091	2.42[11]	0.100	0.143
1-70	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_2 3p_{3/2}$	3/2-5/2	7.087	6.65[11]	0.276	0.276
1-72	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{1/2}$	3/2-3/2	7.057	4.35[11]	0.181	0.116
1-73	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{1/2}$	3/2-1/2	7.053	2.81[11]	0.117	0.251
3-110	$^2S_{1/2}-[2p_{1/2}^2 2p_{3/2}^4]_0 3p_{1/2}$	1/2-1/2	7.023	6.59[10]	0.027	0.110
1-74	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{3/2}$	3/2-5/2	7.018	7.52[11]	0.312	0.250
1-76	$^2P_{3/2}-[2s2p_{1/2}^2 2p_{3/2}^3]_1 3p_{3/2}$	3/2-3/2	7.014	2.08[11]	0.086	0.077
2-88	$^2P_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3p_{1/2}$	1/2-3/2	7.011	2.78[11]	0.115	0.169
3-111	$^2S_{1/2}-[2p_{1/2}^2 2p_{3/2}^4]_0 3p_{3/2}$	1/2-3/2	6.981	1.43[11]	0.059	0.225
2-91	$^2P_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3p_{3/2}$	1/2-1/2	6.973	2.15[11]	0.089	0.146
2-94	$^2P_{1/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3p_{3/2}$	1/2-3/2	6.958	2.53[11]	0.105	0.157
1-92	$^2P_{3/2}-[2s2p_{1/2}2p_{3/2}^4]_1 3p_{3/2}$	3/2-5/2	6.805	2.62[11]	0.109	0.074

We have tabulated the radiated power in units of W/cm^3, and we have also tabulated normalized output powers, where the various powers were scaled such that the power is equated with the transition gf value for the transition with largest gf. The incentive for pursuing such a normalization is that spectroscopists often use gf values as a guide to roughly estimate the expected relative line intensities, since in most interesting spectroscopic studies no detailed intensity calculations exist. Having access to both gf values and theoretical intensity values, we are in a position to assess the accuracy or reliability of this method in the case of the F-like sequence. In our first effort at this, we select the strongest $2p$-$3d$ transition (1-56) and normalized all other lines against its output power and gf value. The results were reasonable for the $2p$-$3d$ array; however, the comparison was not very useful for $2p$-$3s$ or $2s$-$3p$ lines. We therefore modified our approach, and normalized the three transition arrays against the strongest transition in each of the arrays. This process improved matters considerably for the two weaker arrays, and results in a surprisingly good match in the case of the $2p$-$3s$ array.

In Table X we tabulate the output power results for strong $2p$-$3s$ transitions, and as noted above, the normalized results compare well with the gf values, especially for transitions from either the $^2P_{1/2}$ or $^2P_{3/2}$ states. The $^2S_{1/2}$ state is less populated, and in general the normalized output powers for (3-i) transitions are less than corresponds to the relevant gf values. When comparing experimental spectra with gf values then, spectroscopists might do well to reduce the gf values for lines whose lower levels are expected or observed to be underpopulated relative to their statistical values.

Similar comments apply to the $2p$-$3d$ spectra, for which the theoretical output powers are tabulated in Table XI. Again, very reasonable agreement is found between normalized powers and gf values, with (3-i) transitions coming in generally low. A comparison of absolute radiated power between the $2p$-$3d$ transitions and the $2p$-$3s$ transitions shows that the $2p$-$3s$ lines are radiating more per unit gf than the $2p$-$3d$ lines by a factor of 2.51. This is interesting, as we found in the previous section that the $2p$-$3s$ collisional cross sections were low compared to their f values when we examined the derived Gaunt factors. What is occurring is that the primary excitation mechanism for singly excited $3s$ levels is indirect excitation, and not primary $2p$-$3s$ excitation. This effect has long been observed in the Ne-like sequence,[52] and actually served as the impetus for some of the early Ne-like Coulomb-Born calculations.[53,54] We have quantified the effect for F-like selenium under our particular plasma conditions. As the direct $2p$-$3s$ collisional excitation of the $3s$ levels plays only a minor role in the production of $3s$ states, one might expect an increase in the near-threshold cross section due to the presence of resonance structure[55] would not have such a large effect on our intensity estimates, although this is certainly an area where future study will be of interest.

The output powers for the $2s$-$3p$ transition array are presented in Table XII, and one notes that relative agreement between normalized output powers and gf values is degraded relative to the $2p$-$3s$ and $2p$-$3d$ cases. The $2s$-$3p$ array normalization is different from the $2p$-$3d$ normalization by a factor of 2.06, such that the $2s$-$3p$ lines are radiating more per unit gf than the $2p$-$3d$ lines (similar to the $2p$-$3s$ array, and with a similar numerical factor as well). Once again, indirect processes are important in $2s$-$3p$ line formation.

We shall compare our theoretical model with experimental results in a future publication.

VI. GAIN OF F-LIKE $3p$-$3s$ AND $3d$-$3p$ TRANSITIONS IN SELENIUM

In the previous section we noted the presence of strong $2p$-$3p$ electron collisional transitions originating from the low-lying F-like ground states, and we have remarked on the importance of such processes in the theory of collisional excitation lasers. We have discussed briefly the issue of the occurrence of substantial numbers of F-like selenium ions in the LLNL selenium exploding-foil laser experiments,[17,18] and in this section we shall examine the issue of population inversions and gain. The presence of such strong monopole excitation cross sections in the F-like sequence will lead to substantial population inversions on $3p$-$3s$ transitions, and the resulting small signal gain on the highest-gain transitions of this type will be found to be large enough that it should have been observed. Substantial population inversions will be calculated on transitions driven by other collisional processes with even higher gains. We will then be left with the mystery that the absence of any F-like 3-3 amplified emission in the LLNL experiments is not in agreement with our theory.

We consider plasma parameters similar to the conditions chosen in our study of 2-3 line intensities, including an electron density of 3.0×10^{20} electrons/cm^3, an electron temperature of 1.0 keV, and an ion temperature of 0.4 keV. We have used our detailed selenium kinetics model which we described only briefly in Sec. V, and have solved for level populations and gains using XRASER.[56] The small signal gain α_{ij} for a transition is computed assuming both Lorentz and Doppler broadening, according to

$$\alpha_{ij}=\sigma_{ij}^{\mathrm{SE}}\left[N_j-\frac{g_j}{g_i}N_i\right], \tag{6.1}$$

where N_i and N_j are the populations of the lower and upper levels, respectively, where g_i and g_j are the statistical weights, and $\sigma_{ij}^{\mathrm{SE}}$ is the stimulated-emission cross section at line center. The latter is computed through

$$\sigma_{ij}^{\mathrm{SE}}=\frac{g_i}{g_j}\frac{\dfrac{\pi e^2}{mc}f_{ij}}{\dfrac{\nu_0}{c}\left[\dfrac{2kT_i}{M_i}\right]^{1/2}}U(a,0), \tag{6.2}$$

where ν_0 is the line-center frequency in Hz, $U(a,x)$ is the Voigt function,[57] and a is the Voigt parameter

$$a=\frac{1}{4\pi}\frac{\Gamma}{\dfrac{\nu_0}{c}\left[\dfrac{2kT_i}{M_i}\right]^{1/2}}, \tag{6.3}$$

where we have included all radiative and inelastic destruction rates in the computation of the decay rate Γ.

In Table XIII we present the wavelengths, gains, inversion densities, and gf products for the lines with the highest predicts gains. We note that four lines are calculated to have gains of 2 cm^{-1} or more, and hence in principle ought to be observable in the 3-3 axial spectra of the LLNL selenium-laser experiments. To date no emission from F-like lines has been positively identified, and we are left with a mystery as to why these lines are absent from the spectra, as discussed earlier.

The wavelengths of Table XIII have been tabulated so as to include a digit after the decimal point. Our calculation is certainly not accurate to 0.1 Å and, due to the lack of positive identifications of any F-like 3-3 lines, we cannot say with certainty how good these numbers are. At worst, most of the lines should be better than about 2 Å (0.6 eV), judging from comparisons drawn from Ne-like selenium.

The strong monopole $2p$-$3p$ excitation cross section for excitation from level 1 $^2P_{3/2}$ to level 33, on which we remarked in Sec. IV, is observed to drive gain on the $3s$-$3p$ transition (11-33) at 202.6 Å. This line was commented on previously as the F-like line at 204 Å.[19] One observes a predicted gain of about 4.5 cm^{-1}, which may be compared against gains on the Ne-like $J=2$ and $J=0$ lines from the same calculation of about 6 cm^{-1}.

Perusal of Table XIII shows four weaker lines in addition to the high-gain 202.6-Å transition. The 207.0-Å line shares the same monopole-excited upper laser state (level 33) as the high-gain line, but has less gain due to a lower oscillator strength. The remaining three transitions are due to higher-J upper laser states which are pumped partially by direct excitation from the ground states, partially by indirect excitation, and partially through recombination which channels through the high-J $3d$ levels. The upper level (level 26) of the 224.2-Å line is populated predominantly through direct excitation (58%), and the upper level (level 21) of the 223.4-Å line is driven half by direct excitation (49%) and half by other mechanisms. Level 15 is populated primarily by indirect processes. Our calculation includes the effects of dielectronic recombination on the excited-state populations

Further discussion of these issues must wait for a future publication, and we shall be satisfied here with remarking once again that relatively high (2—4 cm^{-1}) gains are predicted on 3-3 transitions, in disagreement with present experimental results.

TABLE XIII. Predicted wavelengths (in Å), small signal gains α (cm^{-1}), population inversion densities $N_u=(g_u/g_l)N_l$ (cm^{-3}) and gf values (dimensionless) for the highest gain F-like selenium $3p$-$3s$ candidate laser transitions. The plasma conditions assumed are an electron density of 3.0×10^{20} cm^{-3}, an electron temperature equal to 1.0 keV, and an ion temperature of 400 eV. Numbers in square brackets indicate powers of ten, such that 1.22[16] is to be read 1.22×10^{16}.

Transition	Configurations	J_i-J_f	λ (Å)	α	$N_u-(g_u/g_l)N_l$	gf
11-33	$[2s^22p_{1/2}2p^3_{3/2}]_23s-[2s^22p_{1/2}2p^3_{3/2}]_23p_{1/2}$	5/2-3/2	202.6	4.47	1.22[16]	0.203
11-26	$[2s^22p_{1/2}2p^3_{3/2}]_23s-[2s^22p_{1/2}2p^3_{3/2}]_23p_{3/2}$	5/2-7/2	224.2	2.28	3.33[15]	0.696
12-33	$[2s^22p_{1/2}2p^3_{3/2}]_23s-[2s^22p_{1/2}2p^3_{3/2}]_23p_{1/2}$	3/2-3/2	207.0	2.06	1.25[16]	0.096
4-15	$[2s^22p^2_{1/2}2p^2_{3/2}]_23s-[2s^22p^2_{1/2}2p^2_{3/2}]_23p_{3/2}$	5/2-7/2	217.5	1.99	2.45[15]	0.723
7-21	$[2s^22p_{1/2}2p^3_{3/2}]_13s-[2s^22p_{1/2}2p^2_{3/2}]_13p_{3/2}$	3/2-5/2	223.4	1.53	2.14[15]	0.502

VII. SUMMARY AND CONCLUSIONS

We have analyzed theoretically the 2-3 electron collisional process in F-like selenium using a multiconfigurational relativistic distorted-wave model, and have tabulated a complete set of 2-3 cross sections for excitation from the $2s^22p^5\,{}^2P_{3/2}$, and $2s^22p^5\,{}^2P_{1/2}$, and $2s2p^6\,{}^2S_{1/2}$ levels. The cross sections have been used to derive Gaunt factors as a check on the accuracy of empirical methods in highly stripped F-like systems, and have found agreement with Gaunt factor values in the literature (0.15–0.20) for many of the strong $2p$-$3d$ transitions. Dipole-allowed and monopole electron collisions have the largest theoretical cross sections. A very strong monopole excitation cross section is found for the $2s^22p^5\,{}^2P_{3/2}$ $-[2s^22p_{1/2}2p^3_{3/2}]_2 3p_{1/2}\,J=3/2$ transition, with a value of 1.7×10^{-20} cm^2 at 200 eV above threshold.

We have calculated wavelengths and intensities of the 2-3 F-like selenium transitions, and have examined the use of gf values as approximations to line intensity in spectroscopic analysis. We have compared our theoretical wavelengths with the experimental results of Gorden *et al.*[25] and have found good agreement for many identified transitions. Some of the weaker lines are in disagreement with our results, and seem to be inconsistent with the accurate ${}^2P_{1/2}$-${}^2P_{3/2}$ splitting of Edlen.[21] We have tabulated predicted output powers for all strong $2p$-$3s$, $2p$-$3d$, and $2s$-$3p$ transitions, and compared in detail the output powers relative to the line strength gf. We found fair agreement within the transition arrays $2p$-$3s$ and $2p$-$3d$, and observed a systematic reduction of output power relative to gf for lines originating from the ${}^2S_{1/2}$ state. Agreement was poorer for $2s$-$3p$ lines. We noted that the two weaker arrays ($2p$-$3s$ and $2s$-$3p$) are expected to radiate more per unit gf than the strong $2p$-$3d$, in qualitative agreement with early astrophysical observations in Ne-like Fe.[52]

The gains on the 3-3 transitions in F-like selenium have been examined briefly, and four transitions are predicted to have gains between 2 and 4 cm^{-1} under conditions thought to occur near the optimum for LLNL selenium exploding-foil laser targets. Direct collisional excitation from the ground states is calculated to be the principal excitation mechanism for most of the high-gain lines. We have tabulated theoretical wavelengths and gf values for these candidate laser transitions.

The exploding-foil selenium laser experiments yield 3-2 spectra in which F-like emission is manifestly obvious, but in which there is no discernible 3-3 emission. Detailed comparisons between the present theoretical results and experimental observations will be presented elsewhere; however, the model seems to be in agreement on the 2-3 spectra. The absence of observed gain on the F-like 3-3 lines, coupled with predictions presented here and found in the design and analysis simulations of Rosen, results in a mystery.

Where are the missing lines? We simply do not know whether our theoretical models are incorrect in some fundamental way, or whether some interesting physics not modeled is at work. Possible explanations include resonant line absorption or axial beam scattering by density fluctuations. One might propose a scenario in which very strong scattering occurs while the incident optical laser pulse is present (for which there is currently no direct evidence), and which relaxes some time after the optical laser intensity has fallen. The time history of the F-like gain is such that it falls off faster than the Ne-like lines, which tend to hang up in our present model, hence one might propose that the Ne-like lines themselves emerge only very late in time, thereby providing a solution to our mystery. Forthcoming absolutely timed measurements will help to resolve these matters in the near future.

The possibility of designing a laser which amplifies F-like 3-3 transitions is of interest. Currently, the F-like 3-3 spectroscopy is not well understood in selenium, and the observation of gain on a number of easily identifiable $3s$-$3p$ or $3p$-$3d$ transitions would make a significant difference in our understanding of a very complex spectrum. Such a laser could readily be designed with current techniques, and tested in experiments similar to ongoing selenium exploding-foil work.

Note added in proof. Measurements of the absolute timing of the selenium laser emission at 206 and 209 Å have been completed as this paper was being proofed. The measurements indicate that the emission occurs early with respect to the incident laser pulse, and therefore the speculations concerning the timing of the laser pulse which appear in the text are incorrect.

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