Intensities of the neonlike iron (Fe^{16+}) $2p^5 3s$-$2p^5 3p$ and $2p^5 3p$-$2p^5 3d$ transitions in solar-flare spectra

G. A. Doschek and U. Feldman
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20375-5000

A. K. Bhatia
Laboratory for Astronomy and Solar Physics, Goddard Space Flight Center, Greenbelt, Maryland 20771
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We present relative spectral line intensities for 16 $3s$-$3p$ and $3p$-$3d$ transitions in the neonlike ion Fe^{16+}, obtained from solar-flare spectra. The spectra were obtained by a Naval Research Laboratory slitless spectrograph flown on the Skylab manned space station. The results are of relevance to x-ray-laser experiments involving collisional pumping of excited states of neonlike ions, and to the analysis of solar-flare spectra. The relative line intensities are measured to an accuracy of about 30%. The measured line intensities are compared with theoretical line intensities calculated assuming electron collisional excitation within the Fe^{16+} ion followed by deexcitation and radiative decay. The measured and theoretical intensities agree to within less than a factor of 2 for all but one line. The important $J=0$ lines ($3p\ {}^1S_0-3s\ {}^1P_1, 3s\ {}^3P_1$) at 254.87 and 204.65 Å are about a factor of 1.4 weaker than predicted, which is almost within experimental error. The $3s\ {}^3P_2-3p\ {}^3S_1$ line at 409.69 Å is 2.3 times weaker than predicted, and this is unexplained.

Several electron-impact collisional pumping schemes have been proposed for producing a soft-x-ray laser. One of the most promising of these involves pumping $2p^5 3p$ levels in neonlike ions, first proposed by Vinogradov, Sobelman, and Yukov.[1] Because the $2p^5 3p$ levels decay slowly to $2p^5 3s$, while the $2p^5 3s$ levels decay rapidly to the ground-state $2p^6\ {}^1S_0$ level, a population inversion between $2p^5 3p$ levels and $2p^5 3s$ levels can occur. Populating mechanisms for the $2p^5 3p$ levels include electron-impact excitation from the ground state, excitation from the ground state to $2p^5 3d$ levels followed by cascade into the $2p^5 3p$ levels, and radiative recombination into the $2p^5 3p$ and $2p^5 3d$ levels. Dielectronic recombination of the fluorinelike ions also contributes significantly to the populations of $2p^5 3p$ levels.[2]

Experiments successfully demonstrating gain in certain $2p^6 3s$-$2p^5 3p$ transitions have been carried out in recent years.[2,3,4] The first successful experiments involved the ion Se^{24+}.[2,3] Gain coefficients as large as 5 cm^{-1} have been reported. However, although two transitions in Se^{24+} exhibited large gain, gain in the transition expected theoretically to have the largest gain had either no gain or a very small gain. This discrepancy was noted by the experimenters and so far no completely satisfactory explanation has been proposed. The transition expected to have the largest gain is the $2p^5 3s\ {}^1P_1-2p^5 3p\ {}^1S_0$ transition,[2,5] because the collisional excitation rate from $2p^6\ {}^1S_0$ into $2p^5 3P\ {}^1S_0$ is significantly larger than the excitation rate from the ground state into other excited $2p^5 3p$ levels.[5,6] We henceforth refer to this transition as the $J=0$ transition. The transitions exhibiting largest gains are $2p^5 3s\ {}^3P_1-2p^5 3p\ {}^1D_2$ and $2p^5 3s\ {}^1P_1-2p^5 3p\ {}^3P_2$.

Recently Elton *et al.*[7] reported on spectra of neonlike Ar and Cl obtained from a θ-pinch plasma. They concluded that the relative line intensities of the relevant neonlike transitions, including the $J=0$ transition, showed no significant deviations from intensities based on a numerical model for electron-collisional excitation pumping. The numerical model is described in Ref. 7. Reference 7 also contains an energy-level diagram of the neonlike ion.

In this paper, we present relative line intensities for the significantly heavier ion Fe^{16+} derived from extreme ultraviolet spectra of solar flares. We compare the relative intensities with numerical calculations based on a simple collisional excitation model for Fe^{16+}. This model is of the same level of complexity as that used by Elton *et al.* for Ar^{8+} and Cl^{7+}.

The solar-flare spectra were recorded by a Naval Research Laboratory (NRL) slitless spectrograph flown on the Skylab manned space station in 1973. The instrument was part of a group of solar instruments known collectively as the Apollo Telescope Mount (ATM). The instrument was designed to produce monochromatic images of flares, rather than spectral lines. These images were recorded on uv-sensitive film. The different shapes of the images were frequently useful in identifying the responsible spectral transitions. A complete description of the instrument is given by Tousey *et al.*[8]

Feldman, Doschek, and Seely[9] have previously used the solar-flare Fe^{16+} spectra to review the Fe^{16+} identifications given by Jupen[10] and Jupen and Litzen.[11] Figure 1 in Feldman, Doschek, and Seely[9] is a halftone reproduction of representative images of the flare in transitions in Fe^{16+} and other ions. In Figs. 1 and 2 of this paper we show microdensitometer traces through the photographically most dense region of typical flare images.

The entire wavelength region covered by the slitless spectrograph could not be covered with one grating setting and still optimize spatial and spectral resolution. Therefore the total spectral range of the instrument was divided into two spectral regions: a short-wavelength region, 180–345 Å, and a long-wavelength region, 320–630 Å. The Fe^{16+} lines are found in both spectral regions. The Fe^{16+} lines found in the region of spectral overlap were used to relate the intensities of the short-wavelength lines to the intensities of the lines found in the long-wavelength range.

Film-calibration curves were constructed for the Fe^{16+} spectra so that the photographic densities in Figs. 1 and 2 could be converted to true relative intensities. An instrumental calibration curve is available from previous work. The wavelengths, transitions, and relative intensities of the lines, for which reasonably accurate intensities could be derived, are given in Table I. The measured line intensities are normalized to the $2p^5 3s\ ^3P_1 - 2p^5 3p\ ^1D_2$ line at 340.40 Å. Experimental uncertainties in the intensities are estimated to be about 30%.

As discussed by Elton *et al.*,[7] the breakdown of *LS* coupling leads to some ambiguities in level designations. We have used the same *LS* designations as given in Jupen and Litzen[11] and Feldman, Doschek, and Seely.[9] Some of these differ from the *LS* designations given by Bhatia, Feldman, and Seely,[6] e.g., $2p^5 3s\ ^1P_1$ and $2p^5 3s\ ^3P_1$ are interchanged, $2p^5 3p\ ^1D_2$ and $2p^5 3p\ ^3P_2$ are interchanged, $2p^5 3p\ ^3D_1$ and $2p^5 3p\ ^3P_1$ are interchanged. However, the transitions in Ref. 9 can be unambiguously related to those in Ref. 6 by referring to the experimental energies given in both of these references.

The electron density in the solar-flare plasma responsible for Fe^{16+} line emission is sufficiently high ($\sim 10^{11}$ cm^{-3}), and the time scale for significant flare evolution is sufficiently long, so that the assumption of ionization equilibrium is a reasonable one during most of the flare lifetime. At least departures from equilibrium should not be large. It is therefore reasonable to expect the Fe^{16+} spectrum to be produced primarily by electron collisional excitation, as is the case for the Ar^{8+} and Cl^{7+} θ-pinch

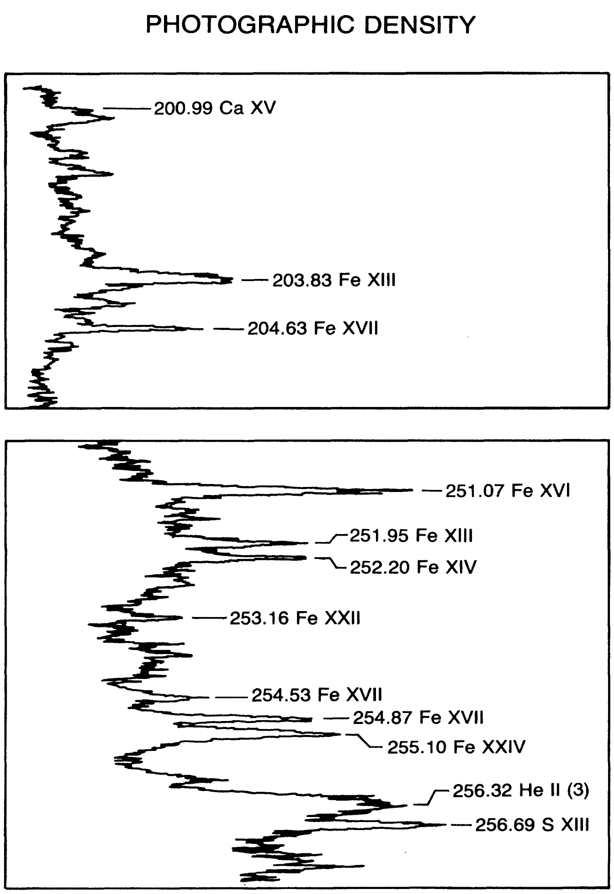

FIG. 1. Solar-flare spectra showing the $J=0$ neonlike Fe transitions. The spectra are uncorrected for film calibration and instrumental sensitivity as a function of wavelength. The lines near 204 Å appear weaker than the lines near 255 Å because the instrumental sensitivity correction has not been applied to the spectra.

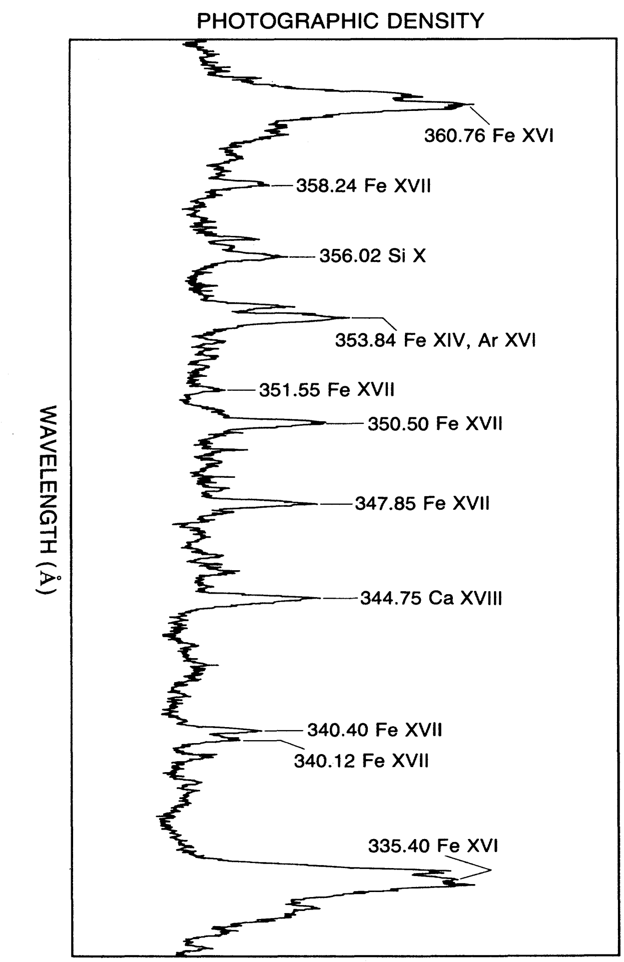

FIG. 2. Solar-flare spectra showing the long-wavelength neonlike Fe transitions. The spectra are uncorrected for film calibration and instrumental sensitivity.

TABLE I. Fe^{16+} data and theory for $2p^53s$-$2p^53p$ transitions.

Transition	Wavelength (Å)	Observed relative intensity[a]	Predicted relative intensity[b]
$3s\ ^3P_1-3p\ ^1S_0$	204.65	5.9	8.2
$3p\ ^3S_1-3d\ ^3P_2$	254.53	1.6	1.0
$3s\ ^1P_1-3p\ ^1S_0$	254.87	5.4	7.2
$3p\ ^1P_1-3d\ ^1D_2$	266.42	1.2	1.0
$3p\ ^3D_2-3d\ ^3F_3$	269.41	1.8	1.8
$3p\ ^3S_1-3d\ ^3P_0$	269.88	0.64	0.42
$3p\ ^3D_1-3d\ ^3F_2$	275.54	0.99	0.94
$3s\ ^3P_2-3p\ ^1D_2$	323.57	2.0	1.4
$3s\ ^3P_0-3p\ ^3P_1$	340.12	1.1	0.73
$3s\ ^3P_1-3p\ ^1D_2$	340.40	1.0	1.0
$3s\ ^1P_1-3p\ ^3P_2$	347.85	2.7	2.2
$3s\ ^3P_2-3p\ ^3D_3$	350.50	3.1	3.0
$3s\ ^1P_1-3p\ ^3P_1$	351.55	0.30	0.40
$3s\ ^3P_1-3p\ ^3D_1$	358.24	0.76	1.1
$3s\ ^3P_2-3p\ ^3D_2$	367.26	1.2	1.2
$3s\ ^3P_2-3p\ ^3S_1$	409.69	0.73	1.7

[a]The observed relative intensities have an experimental accuracy of about 30%. Intensity units are in ergs, not photons.
[b]Collisional model assuming electron temperature $=4\times10^6$ K and electron density $=10^{11}$ cm^{-3}.

spectra mentioned above. From ionization equilibrium calculations (Arnaud and Rothenflug[12]), we expect the bulk of Fe^{16+} emission to occur at a temperature of about 4×10^6 K. Spectra lines of other ions in the flare plasma indicate temperatures ranging from a few million to 20×10^6 K, so our assumption that the emitting temperature of Fe^{16+} is 4×10^6 K is probably valid.

We have computed theoretical line intensities for comparison to the data with the electron-collisional excitation model described by Elton *et al.*[7] Briefly, the equations of detailed balance (among collisions and radiative decay) were solved for the 37 levels of the $2s^22p^6$, $2s^22p^53s$, $2s^22p^53p$, $2s^22p^53d$, $2s2p^63s$, $2s2p^63p$, and $2s2p^63d$ configurations. The scattering problem was solved in the distorted wave approximation including configuration interactions by using the SUPERSTRUCTURE program developed at the University College, London.[13,14] Collision strengths were computed at five energies: 76.83, 91.53, 120.93, 179.73, and 253.23 Ry. Our collision-strength data agree quite well with the atomic data published by Zhang *et al.*,[15] Zhang and Sampson,[16] and Hagelstein and Jung.[17] In addition, because of the solar plasma composition, proton excitation among the $2s^22p^53s$ fine-structure levels was included. All of these atomic data are planned to be published separately. Radiative and dielectronic recombination from the fluorine-like ion, as well as resonance excitation of the upper levels of the neonlike ion as described by Doschek, Feldman, and Seely,[18] were neglected. The level populations were calculated as functions of electron density and temperature. Theoretical line intensities derived from the atomic data are given in Table I.

The results in Table I were obtained assuming typical flare temperatures and densities of 4.0×10^6 K and 10^{11} cm^{-3}, respectively. We also computed populations at temperatures of 7.3×10^6 K and found that these temperature variations had no significant effect on line ratios. The same result was found for density by computing populations at densities of 10^{10} and 10^{12} cm^{-3}.

A comparison of the theoretical and experimental results in Table I shows that the agreement between the data and the collisional excitation model is generally quite good. All lines intensities agree to better than a factor of 2 with the exception of the line at 409.69 Å. This line deviates significantly from the theory, and the reason for this is unknown. The $J=0$ lines are slightly weaker than predicted, but the difference is almost within experimental error. We point out that the atomic processes neglected in our collisional excitation model, i.e., recombination processes, would probably have the least effect on the $2p^53p\ ^1S_0$ level because of its small statistical weight. Therefore, including these recombination processes might reduce the predicted intensities of the $J=0$ lines relative to the other lines, and make agreement with the data even better.

In summary, we believe that the overall agreement between the experimental data and the collisional excitation model is generally good, although the discrepancy noted for the 410-Å line is disturbing. In particular, the $J=0$ lines are the most intense lines in the spectrum and their intensities are in reasonable agreement with the collisional model. We therefore conclude that inaccurate collision excitation rates are not the cause of the $J=0$ discrepancy.

Other checks on the collisional model for Fe XVII can be attempted using available solar observations of $2p$-$3s$ and $2p$-$3d$ x-ray lines of Fe XVII that fall near 15 Å. The x-ray lines of Fe XVII have been recorded by a number of solar-rocket and satellite instruments. A more comprehensive theoretical model for Fe XVII than used for this work has been published by Smith *et al.*[19] Rugge and McKenzie[20] have compared this model to spectra obtained from the SOLEX Bragg crystal x-ray spectrometers flown on the DoD P78-1 spacecraft. A further comparison of the theory to these data and data obtained from other space experiments has been published by Raymond and Smith.[21] Rugge and McKenzie[20] found significant disagreements between measured line ratios and ratios calculated using the Smith *et al.*[19] theory, but Raymond and Smith[21] report that some of the disagreement may only be apparent and could be due to the multitemperature structure of the solar atmosphere. A detailed comparison of these calculations to the x-ray spectra is given in Refs. 20 and 21, and therefore we do not comment further on the x-ray Fe XVII lines.

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