MEASUREMENT OF WAVELENGTHS AND ABUNDANCES
FROM SOLAR FLARE X-RAY SPECTRA

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INTRODUCTION

The measurement of transition energies in highly charged ions represents an important test of quantum electrodynamics (QED) in strong fields. The QED contributions to the hydrogenic transition energies increase as $(\alpha Z)^4$, where α is the fine structure constant and Z is the atomic number. Transitions in hydrogenic ions of sulfur, chlorine, argon, and iron have previously been measured to a precision of 100 ppm or better. These measurements are in satisfactory agreement with accurate calculations of the energy levels, and this confirms the calculation of the QED contributions to the energy levels of one-electron ions.

In the case of highly charged two-electron ions, the situation at the present time is far from satisfactory. Precision measurements of the energies of several transitions in sulfur, chlorine, argon, and iron have been performed using beam foil techniques. These measurements have been compared to recent calculations, but there is not general agreement on the theoretical treatment of the QED contributions to the transition energies in two-electron ions. In three-electron ions, only the $1s^2 2s\ ^2S_{1/2} - 1s^2 2p\ ^2P_{3/2}$ transition has been measured and calculated to high precision.

We report here the measurement of wavelengths and abundances from solar flare spectra. Solar flares are bright sources of X-ray lines, and high-resolution spectra can be obtained in about 30 sec of observation time. Since the high-temperature phase of a flare typically persists for at least several minutes, spectra can be accumulated and added together to improve the signal to noise ratio. The statistics can also be improved by making measurements using data from a large number of flares.

WAVELENGTH MEASUREMENTS

Transitions in ions of argon, potassium, calcium, and iron with one, two, and three electrons have been identified. The wavelengths of the transitions in two-electron and three-electron ions are measured by using the hydrogenic transitions as references. The wavelengths are compared to recent high precision calculations, and the QED contributions to the transition energies can be determined. This work greatly expands the number of precision measurements of transitions in highly charged two-electron ions that are available for comparison with theory.

https://doi.org/10.1017/S0252921100085572 Published online by Cambridge University Press

The data were recorded by the Naval Research Laboratory crystal spectrograph on the Air Force P78-1 spacecraft. The spectrograph consists of four crystals mounted on a common rotating shaft. The wavelength regions that are covered (and the strongest resonance lines in each wavelength region) are 1.80 to 1.98 Å (Fe XXV), 2.96 to 3.10 Å (Ca XX), 3.13 to 3.25 Å (Ca XIX), and 8.23 to 8.52 Å (Mg XII). The first three wavelength regions are covered by Ge crystals (2d = 4.00068 Å), and the fourth wavelength region is covered by an ADP crystal (2d = 10.6416 Å). Dielectronic satellite lines and inner-shell transitions from lower stages of ionization generally fall on the long wavelength side of the resonance lines. These highly charged ions are produced in the hot (1.0×10^7 to 2.5×10^7 K) plasmas associated with solar flares.

On each spectral scan, the shaft rotates 450 steps in one direction and then 450 steps in the opposite direction. Both halves of the scan are over the same wavelength region, and the two halves are folded and added together to improve the signal to noise ratio. The two spectra are folded so that the centroids of the Ca XIX resonance lines in the two spectra are aligned. This eliminates any possible misregistration of the spectra due to the motion of the flare plasma. The wavelength scales are also stretched to account for the angular rotation of the shaft on each of the 900 steps. These angular displacements were measured to a precision of 1 arc sec in the laboratory before launch.

For this study, which is still in progress, we have selected for analysis the data from five flares with good signal to noise ratios. The signal to noise ratio is improved by adding together several scans near the time of peak emission for each flare.

The wavelengths of six isolated transitions in Ar XVII, K XVIII, and Fe XXV of the type $1s^2\ ^1S_0 - 1snp\ ^1P_1$ (n=3-8) are measured. The line profiles of these isolated transitions are found to be nearly Gaussian in shape and with full widths at half maximum of 1 to 3 mÅ. Gaussian profiles are expected when thermal Doppler broadening is the dominant broadening mechanism. The wavelengths are measured by fitting Gaussian profiles to the spectral features. For each flare spectrum, the precision of the Gaussian fit to a spectral feature is typically 0.05 mÅ. The standard deviation of the wavelength measurements of a given spectral feature in the five flare spectra is typically between 0.05 and 0.5 mÅ. The Ca XIX and Fe XXV transitions to the $1s^2\ ^1S_0$ level from the $1s2p\ ^1P_1$, $1s2s\ ^3S_1$, $1s2p\ ^3P_1$, and $1s2p\ ^3P_2$ levels (transitions designated w,x,y, and z respectively) are blended with dielectronic satellite lines from lower stages of ionization. Using theoretical line intensities, these dielectronic satellite lines are numerically removed from the data, and the wavelengths of the w,x,y, and z transitions are measured in the resulting spectra. A synthetic satellite spectrum is produced by using the theoretical wavelengths and by convolving the theoretical intensities with Gaussian profiles. The wavelength and intensity scales of the synthetic spectrum are normalized to the data, and the synthetic spectrum is subtracted from the spectral data.

https://doi.org/10.1017/S0252921100085572 Published online by Cambridge University Press

We have compared the measured transition energies with the calculated values for five transitions of the type $1s^2\ ^1S_0 - 1snp\ ^1P_1$ (n=2-5) in argon, potassium, calcium, and iron. Ermolaev and Jones (1974) have calculated all of these transitions, and Safronova (1981) has calculated the n=2 transitions. For n>2, we also compare the measurements to the transition energy obtained by using Safronova's ground state energy and the excited state energy of Ermolaev and Jones. Drake (1984) has calculated the transitions from the n=2 and 3 levels. For four of the five transitions, the measurements agree best with the calculations of Safronova and of Drake.

ABUNDANCES

In addition to providing accurate wavelengths, the intensities of lines of Fe XXV, Ca XX, Ca XIX, K XVIII, and Ar XVII can be used to determine their relative solar abundances. This can be done because Fe XXV and Ca XX are formed at nearly the same temperature, and a similar comment applies to the lines of Ca XIX, K XVIII, and Ar XVII. The relative intensities of these lines therefore depend primarily on the relative abundances, assuming that ionization equilibrium occurs in the flare plasma. Accurate collisional excitation rate coefficients and other necessary atomic data for the lines are available in the literature. Preliminary values of the relative abundances are: A(K)/A(Ca) = 0.11, A(Ar)/A(Ca) = 0.73, and A(Ca)/A(Fe) = 0.10. A more detailed discussion will be published elsewhere.

ACKNOWLEDEMENTS

Steven W. Daniels wrote the computer program that corrects for the nonlinearity in the angular rotation of the crystals during a spectral scan and that folds and adds the scan data. We would like to thank Dr. W.C. Martin for helpful discussions. We also thank Dr. G.W.F. Drake for communicating recently calculated transition energies. A detailed description of this work will be published in the Astrophysical Journal.

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https://doi.org/10.1017/S0252921100085572 Published online by Cambridge University Press