Spectra from Foil-Excited Molybdenum Ions

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Abstract

The extreme-ultra-violet spectra (5-55 nm) for foil-excited molybdenum ions have been measured using 22-200 MeV beams from the Brookhaven National Laboratory MP tandem Van de Graaff accelerator facility, 20 $\mu\text{g}/\text{cm}^2$ C stripping foils, and a grazing incidence spectrometer. The mean ion charge states (13 to 28) and the narrow distribution widths (about 2 charge states) were accurately predictable from experimental parameters. Where possible, comparisons are given with Mo radiation from tokamaks, vacuum sparks, and laser-excited plasmas.

Introduction

Heavy metals such as molybdenum are commonly used in the construction of tokamak devices because of their desirable physical or chemical properties. During a plasma discharge, however, these heavy atoms are released by sputtering or evaporation and have detrimental effects on plasma behavior.¹ Heavy impurities cause increased bremsstrahlung and recombination radiation and, in the case of species not fully stripped, line radiation. In order to measure absolute concentrations of these ions it is necessary to have for a particular ionic species, lines which are identified and have known absorption oscillator strengths. The identification and subsequent analysis of radiation from individual states of particular ions is hampered by the presence of many ionization states of several impurity elements. For example, a typical tokamak discharge can contain highly ionized Mo or W from current aperture limiters, Cr, Fe, Ni (stainless steel) from vacuum vessel walls and in addition to the working gas (H or He) some light impurities such as O or C. Many other metals (e.g., Ti, Zr, Nb, Ta, Re, Pt) are under consideration as construction materials and various light ions and high-Z metals can be injected to study impurity behavior. Although many light and some medium-Z elements have been extensively studied, data is needed for heavier atoms such as Mo and W.

The use of beam foil spectroscopy (BFS) to determine absorption oscillator strengths (f values) for light ions has been reviewed by Wiese and Younger² and recent results for heavier ions are given elsewhere.³ It has also been shown^{3,4} that BFS can be used to help identify the radiating ions, stages of ionization and types of transitions for tungsten and gold contaminants in tokamak plasmas. Discrepancies between spectra from Ormak⁵ and PLT⁶ in the wavelength region from 4-8 nm were resolved, average charge states were indicated, and spectral features were assigned primarily to 4d-4f transitions. Further analysis of these spectra was prevented by the large number of overlapping lines and the scarcity of previous experimental and theoretical work.

Mo radiation from tokamaks, vacuum sparks, and laser-excited plasmas has been studied spectroscopically, but usually over limited wavelength regions. We have undertaken the present study to complement the previous investigations by providing Mo spectra over an extended wavelength region (5-55 nm) and for known charge states and narrow distribution widths.

Experimental Method

Molybdenum beams with energies of 22, 30, 67, 97, 168, and 200 MeV were produced with the BNL three-stage MP tandem Van de Graaff accelerator facility. The maximum beam current that was delivered to the experimental area was 6×10^9 particles/sec through a 3 mm defining aperture. Carbon stripping foils of 20 $\mu\text{g}/\text{cm}^2$ were used. The foils were thick enough to ensure charge equilibrium, but thin enough to ensure that multiple scattering was negligible. Mean charge states $\bar{q}$ for foil-excited ions are accurately predictable from experimental parameters using the formula of Nikolaev and Dimitriev⁷ as confirmed by Betz.⁸ The beam was collected in a Faraday cup 20 cm downstream from the foil. The number of collected particles, which was determined from the accumulated charge divided by $\bar{q}$, was used to normalize the data. The full-width-at-half-maximum (FWHM) of the charge state distribution at each energy was about 2 charge states and has an approximately Gaussian shape.⁷

Extreme-ultra-violet (EUV) radiation emitted by the beam after passage through the stripping foil was examined with a 2.2 m grazing incidence spectrometer (Minuteman model 322G). The angle of observation was 90° to the incident beam with the spectrometer entrance slits 4 cm from the beam axis. Radiation was dispersed with a gold-coated concave grating with 300 grooves/mm, a blaze angle of $2^\circ 13'$ and a corresponding blaze wavelength of 29 nm at the 87° grazing angle used in the present work. Spectrometer entrance and exit slit widths of 300 μm were used to obtain reasonable signal strength. Under these conditions the spectral resolution obtained was about 0.4 nm FWHM, and the uncertainty in the determination of the centroid of well-resolved peaks was about 0.02 nm. The EUV radiation was detected with a channeltron electron multiplier (CEM) which had a dark current counting rate of 0.2 Hz. The data were corrected for this background contribution. Spectral scans were recorded in the wavelength region from 5 to 55 nm.

Experimental Results and Discussion

The results of the experiment are shown in Fig. 1. The mean charge states $\bar{q}$ of the foil-excited molybdenum ions ranged from 13 to 28, that is, spectra with most probable ionization states ranging from zinc-like to silicon-like were observed. The most striking feature of these scans is the obvious great complexity of the broad spectral features observed. Only in a few cases, notably for $\bar{q} = 13$, are strong single lines observed. Bands of lines are seen to be centered at about 8.5, 18, 25, 35 and 42.5 nm. The last three show some evidence for individual lines which decrease in intensity as the mean charge state increases and are virtually gone at $\bar{q} = 23$ and greater. The other two features show maxima at $\bar{q} = 20$, but remain as the dominant feature of the spectra through $\bar{q} = 28$.

Resonance lines from copper- and zinc-like molybdenum have been observed in tokamaks¹ and a precision measurement of their wavelengths has been made by Reader and Acquista⁹ in a low-inductance

spark experiment, in which the wavelengths of the $4s\ 2S_{1/2} - 4p\ 2P_{1/2,3/2}$ transitions of copper-like Mo XIV ($q=13$) were measured to be 42.3576 and 37.3647 nm, respectively, and the $4s\ 2S_0 - 4s4p\ 1S_1$ transition in zinc-like Mo XIII ($q=12$) was observed at 34.0909 nm. The 37.4 nm line is clearly observed here in the $\bar{q} = 13$ spectrum, and partially resolved lines also appear at wavelengths of 42.4 and 34.1 nm in good agreement with the observations from the spark source⁹ and tokamak¹ experiments.

For higher $\bar{q}$, detailed comparisons with other experimental results obtained with spark sources or laser-excited plasmas are difficult because (a) spectral features are complex with few, if any, well-resolved lines; (b) there are differences in resolution, knowledge of charge states distributions, and spectrometer efficiencies; (c) there are differences in excitation mechanisms; and (d) few complete spectra have been displayed. Mansfield et al.¹⁰ make the point that inner-subshell excitation is of

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Fig. 1. Survey of foil-excited Mo spectra for mean charge states $\bar{q}$ between 13 and 28. The beam energy used to produce each $\bar{q}$ is shown.

importance in dense plasmas and gives greatly increased spectral complexity. This observation is in agreement with the BFs results shown in Fig. 1 where the ion-atom collisions are known to produce inner-subshell and multiple excitation.

Comparisons with theory must also be qualitative since no theoretical predictions are available which predict transition probabilities for all the very complex configurations which contribute to the experimental spectra. Curtis et al.¹¹ in an extensive analysis of Mo XIV spectra from a vacuum spark give theoretical values for the transition probabilities. Major strength is observed at about 9, 12, 18, 23, 38, and 42 nm, which is in reasonable agreement with the present experimental spectrum for $\bar{q} = 13$. A more detailed comparison would require correction of the experimental results for the wavelength dependence of the spectrometer efficiency and extension of the calculated transition probabilities to other charge states. Perhaps a more favorable possibility for comparison of theory and experiment is in the 5-50 nm region for $\bar{q} = 27$ or 28. Theoretical calculations for E1 transitions have been made by Cowan¹² for charge states from 24 to 37. The major strength observed in the highest energy spectra of Fig. 1 is concentrated in the region from 8 to 10 nm which is in good agreement with the theoretical prediction.

Finally, we compare our results with observations of molybdenum excited in tokamak plasmas. Although no published spectra are available, Hinnov¹ has reported observation of the Cu- and Zn- like lines whose wavelengths were confirmed by Reader and Acquista.⁹ Hinnov also observed radiation attributed to states of ionization higher than covered in the present experiment. The TFR group has reported rather extensive work on Mo, mainly on these higher ionization states and on forbidden lines.^{13,14} Geller et al.¹⁵ have reported observation on Alcator of a series of lines with a peak between 6.4 and 9 nm, which is somewhat lower than observed here. The reason for this discrepancy is unknown.

Conclusions

It has been shown here that it is possible to obtain beam-foil spectra of molybdenum in charge states which cover a region of current interest in tokamak applications. The complexity of the spectra suggest that theoretical predictions of average spectral behavior would be more useful rather than to attempt to resolve each line experimentally. The beam-foil excitation method is of great value in determining the charge state dependence of the spectra and in the future will be able to give lifetime information unobtainable by other means.

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