Identification of magnetic dipole lines above 2000 Å in several highly ionized Mo and Zr ions on the PLT tokamak

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(Received 16 April 1982)

A number of spectrum lines arising from magnetic dipole transitions in the $n=3$ shell ground configurations of molybdenum and zirconium ions have been identified. These lines are particularly suitable for spectroscopic diagnostics in tokamak-type plasmas in the 500–1500-eV temperature range.

The relatively-long-wavelength magnetic dipole lines of the $n=2$ shell of highly ionized elements from scandium to copper ($Z=21-29$) are being extensively used for plasma diagnostics in tokamaks.[1–3] The different ionization stages of such elements occur in appreciable quantities only over a limited radial range of the quasicylindrical discharge, where local electron temperature is comparable to their ionization potentials, thus allowing localized spectroscopic measurements of a variety of plasma parameters in the discharge. Furthermore, a particular diagnostic element may be selected to fit the expected temperature range, and injected at predetermined quantities and chosen times during the discharge. In this respect, lines with wavelengths above the air cutoff, $\lambda > 2000$ Å, offer special advantages because of the relative simplicity and versatility of the applicable instrumentation. However, in the new generation tokamaks, with expected peak electron temperatures above 5 keV, the $n=2$ shells of these elements are stripped over the most interesting part of the plasma, thus necessitating for diagnostic use of somewhat heavier elements, perhaps up to molybdenum ($Z=42$). In such heavier elements, the magnetic dipole transitions in the $n=3$ shell are also sufficiently intense for spectroscopic measurements, thus providing the means of simultaneous diagnostics of the outer lower-temperature region of the plasma. Also, in the presently operating tokamaks, with $T_e(0) \sim 1-3$ keV, it may be of interest to compare measurements in the same location with two elements of significantly different mass, e.g., the $n=3$ states of Mo or Zr and the $n=2$ states of Ti or Sc.

In the present paper we report the identification of a number of $n=3$ shell magnetic dipole lines, with wavelengths above the air cutoff, of various Mo and Zr ions, which were introduced into the PLT (Princeton Large Torus) tokamak discharges for diagnostic purposes.

Figure 1 shows the measured wavelengths (in boxes) and the transitions in the molybdenum ions, which we consider fairly reliably identified. The saga of discovery of these lines is too varied to be recounted here, but it consists of a combination of isoelectronic extrapolations (which are more vague and unreliable than in the relatively simple $n=2$ shell) from available data in lower-Z elements,[4–7] measurement of time-evolution and radial profiles of the emissivities of these lines, some of which will be presented below, and finally the internal consistency of the corresponding transitions in molybdenum and zirconium ions. One exception to this process was the $3p^6 3d^8\,{}^3F_3 \rightarrow {}^3F_4$ transition, which had been established from the shorter wavelength measurements of Reader and Ryabtsev,[8] with which our results are in excellent agreement.

The experimental procedure is qualitatively similar to the $n=2$ shell measurements.[9] The element in question is introduced by the laser blowoff method at a preselected time during the discharge, and, as a consequence of the relatively slow radial transport, the increasing ionization stages appear successively in time, and in quasicylindrical shells in radial distribu-

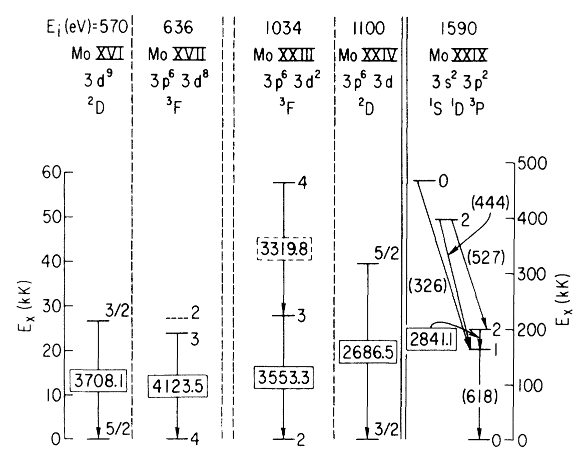

FIG. 1. Measured wavelengths (in angstroms) and transitions ascribed to several molybdenum ions. E_i are the approximate ionization potentials of these ions. The wavelengths in parentheses for Mo XXIX are predicted values.

tion, determined primarily by the ionization potentials of the ions (and hence their collisional ionization rates). Helpful bounds for the time and space variations are provided by the well-established resonance lines of the magnesium or sodium sequences on one side and the zinc or copper sequences on the other side, for the ions in question.

A sample of the time behavior of some of these lines is shown in Fig. 2, with the sodiumlike Mo XXXII resonance line given for comparison. (The ~4-msec-period modulation on the Mo XXIV 2686-Å line is caused by a vibrating LiF plate, which sweeps the line image repeatedly across the exit slit. This allows determination of the Doppler width and hence ion temperature at a radial location established from spatial emissivity scan described below.) The time sequence, for both appearance and disappearance, clearly occurs in the ascribed order, although in adjacent states, e.g., Mo XXIII and XXIV, the differences are quite small. Thus the time-behavior alone is often not sufficient for precise assignment of an unknown line, especially a weak one, to a particular ionization state although the range of uncertainty is rather limited.

Figure 3 shows the radial distribution of the measured emissivities of the three Mo ion lines, together with that of 2271-Å line of C V ($E_i = 392$ eV) for comparison, and the electron temperature profile from single-shot Thomson scattering. The emissivity profiles are determined by Abel-inverting chord brightnesses measured by means of a rotating mirror, which scans the plasma vertically with a period of about 10 msec. The emissivities clearly occur in fairly distinct radial shells, which again is helpful for the assignment of the ionization stages for the observed

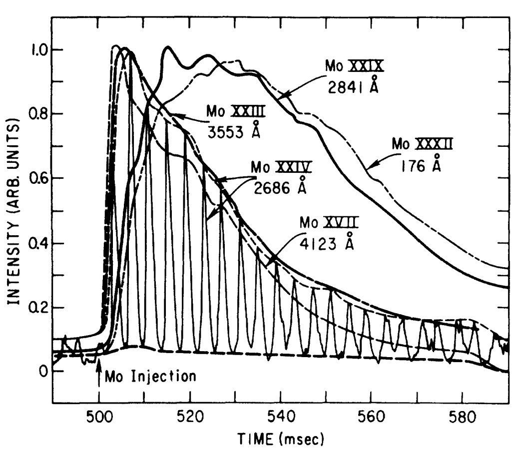

FIG. 2. Observed time behavior of several molybdenum ion lines after the injection. The rapid modulation of the Mo XXIV is described in the text. The small oscillations, e.g., on Mo XXIX line 10–30 msec are probably caused by radially localized magnetohydrodynamic plasma oscillations.

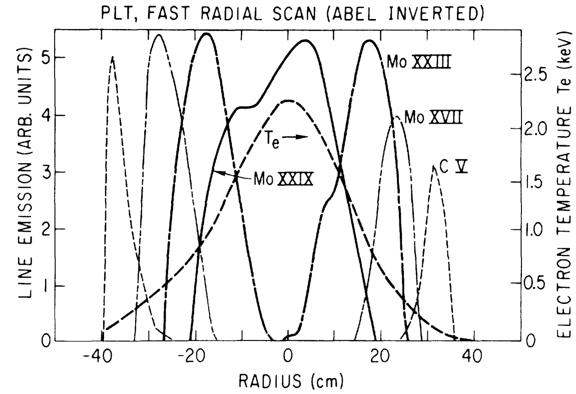

FIG. 3. Local emissivities of Mo XVII, XXIII, and XXIX ions and C V 2271-Å line, with the radial electron temperature profile from Thomson scattering. The electron density is about 2×10^{13} cm^{-3} near the center and slightly sharper than parabolic in shape within the ±40 cm limiter radius.

lines, and forms the basis for their use of radially localized diagnostics. The location and shape of these shells is nearly constant in time, provided that the electron temperature profile remains unchanged. The peaks occur at $T_e(r)$, which is slightly lower than the ionization potentials, but distinctly higher than what would correspond to coronal ionization equilibrium. There is evidence of some poloidal or up-down asymmetry both in the emissivities and the electron temperature. The significance of this has not been determined, although it is not primarily due to measurement uncertainties.

We also note that in a discharge with central $T_e(0) = 1$ keV, the Mo XXIII line emissivity was peaked on the axis, with a radial width of the profile about ±10 cm.

The temperature profile on Fig. 3 is an average of four discharges. Both the $T_e(r)$ profile and the Mo injection had some small but significant shot-to-shot variation. It is therefore not worthwhile to attempt too quantitative interpretation of these data, e.g., to derive deviations from coronal equilibrium.

The measured wavelengths (in air) together with estimated uncertainties are given in Table I. For tokamak plasma diagnostic purposes, both Mo XXIV 2686-Å line and Mo XXIII 3553-Å line are relatively strong, and free of significant interfering lines. They are thus eminently suitable for diagnostics of ~1-keV plasma. Their (2686:3554) measured intensity ratio is about 2:1, which, in view of the similarity of their radial distribution, is also their emissivity ratio. The 2841-Å line of Mo XXIX is also well separated from interfering lines, and it has typically about one-half the intensity of the 3553-Å line. Qualitatively similar statements apply to the corresponding zirconium lines, except that the 3100-Å line suffers some interference from a thus far unidentified line in the

TABLE I. Observed molybdenum and (zirconium) wavelengths (in angstroms) for transitions given by Fig. 1.

Mo XVI (Zr XIV)	Mo XVII (Zr XV)	Mo XXIII (Zr XXI)		Mo XXIV (Zr XXII)	Mo XXIX (Zr XXVII)
3708.1 ± 0.2 (4967.4 ± 0.3)	4123.5 ± 0.3 (5547.6 ± 0.3)	3553.3 ± 0.3 (4774.2 ± 0.4)	3319.8 ± 0.3	2686.5 ± 0.3 (3507.1 ± 0.2)	2841.1 ± 0.2 (3100.2 ± 0.4)

discharge. We want to emphasize here that the emissivities are only partly determined by radiative transition rates, i.e., collisional rates, including cascading, have important, indeed usually dominant, effect. Their quantitative interpretation, especially in the more complicated d^2 and d^8 configurations, is very approximate at present.

The assignment of the 3320-Å line must be regarded as more tentative than the others. It is about 4–5 times weaker than the 3553-Å line. This seems somewhat too weak, although various cascading transitions would tend to enhance rather strongly the $^3F_3$-$^3F_2$ transition. Furthermore, the corresponding zirconium line which would occur at ~4431 Å if the assignment is correct, has not yet been observed. The assignment is based on the approximately expected wavelength and the proper time dependence of the emissivity. It was too weak for reliable measurement of intensity radial distribution. In view of the small state-to-state variations of the time dependence it may possibly belong to Mo XXII or even XXI, in which case the $3d^2\,{}^3F_4$-$^3F_3$ transition is yet to be discovered.

ACKNOWLEDGMENTS

The authors wish to thank J. Hosea for supporting these measurements, F. Boody, C. Daughney, D. Dimock, and D. McNeil for providing Thomson-scattering T_e data, the Princeton Plasma Physics Laboratory surface physics group for enthusiastic cooperation, and the PLT operators for their acquiescence in the course of these experiments.

This work was supported by the U.S. Department of Energy, Contract No. AC02-76-CHO-3073.

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