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# Additions to the Spectra of Highly Ionized Molybdenum, Mo XXIV–Mo XXVIII

C. Jupén[1], B. Denne-Hinnov[2], I. Martinson and L. J. Curtis[3,*]

[1] Atomic Spectroscopy, Lund University, Box 118, SE-221 00 Lund, Sweden
[2] Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08543-0451, USA
[3] Department of Physics and Astronomy, University of Toledo, Toledo OH 43606-3390 USA

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## Abstract

We have observed radiation from highly charged molybdenum ions in the JET tokamak plasmas. Spectra were recorded in the wavelength range 70–110 Å, resulting in the classification of 15 new $n = 3$, $\Delta n = 0$ transitions in Mo XXIV–Mo XXVIII.

## 1. Introduction

Spectra of highly charged molybdenum ions have been studied for over 25 years, largely because of data needs in fusion research [1–3]. A favored aperture limiter material in the early days of fusion research, molybdenum rapidly fell out of favor due to its detrimental radiative effects on the plasma. However, in recent years molybdenum has attracted new interest as a possible candidate for reactor first-wall material [4]. In addition to tokamak plasma spectroscopy, the spectra of Mo ions have also been investigated by means of other light sources, including laser-produced plasmas, vacuum sparks and beam-foil experiments. However, despite such activity as well as various theoretical analyses the knowledge of the energy level structure of several highly charged Mo ions is still fragmentary. A critical compilation of spectral data for Mo VI – Mo XLII has appeared recently [5].

In the present work we report spectroscopic studies of $n = 3$, $\Delta n = 0$ transitions in Mo XXIV–Mo XXVIII. These systems have 19–15 electrons and they thus belong to the K I through P I isoelectronic sequences. The spectroscopic work was carried out at the JET tokamak. In particular, we studied some disruptive plasma discharges, associated with heavy influx of Mo into the plasma. The line identification was facilitated by time-resolved plasma spectroscopy.

## 2. Experimental setup

Spectra were recorded during neutral beam injection (NBI) of 4 MW power. The particular discharge has been described in more detail elsewhere [6]. Due to a burst of Mo entering the discharge, the central electron temperature, $T_e(0)$, rapidly decreased from 4.2 to 0.7 keV and then rose to 3.6 keV as the plasma reheated. During this period of about 3 s the intensity variations of spectral lines were followed. In such time-resolved spectra, lines of e.g. Mo XXVII and XXIV with similar wavelengths could be separated.

Spectra were recorded with a 2 m grazing incidence spectrometer [7], equipped with a 600 grooves/mm grating and two microchannel plate image intensifier/convertor detector systems, fibre optically coupled to 1024 element photodiode arrays. Experimental details and analysis methods can be found in Refs [6,8,9].

As already described in Ref. [6] the temporal variations of the Mo line intensities were used to distinguish between different charge states, aiding the line identification.

## 3. Results and discussion

An example of a partial JET spectrum is shown in Fig. 1. The spectrum was recorded in second order, in the interval 156–162 Å. The strongest Mo lines are indicated. The first order spectral resolution varies from 0.20 to 0.27 Å, which results in measured wavelength uncertainties of 0.01–0.02 Å. We estimate that plasma rotation, introduced by the neutral-beam-injection, gives rise to a wavelength shift of less than a few thousands of an Å, which is well within our stated measurement accuracy.

The identified transitions of Mo XXIV–Mo XXVIII are listed in Table I. In Table II we list our measured energy level values. The accuracy of the measured values is better than 300 cm$^{-1}$. We have kept the *LS* notation for the level designations although *jj*-coupling gives a somewhat better description of the energy-level structure in these ions. Below we compare our results for each ion with data obtained at the Princeton PLT tokamak by Finkenthal *et al.* [10], Hinnov *et al.* [11] and Wouters *et al.* [12] and at the Texas TEXT tokamak by Kaufman, Rowan and Sugar [13–17].

### 3.1. *Mo XXIV*

In K-like Mo XXIV the ground configuration is $3p^6 3d$ and the lowest excited configuration is $3p^5 3d^2$. Six transitions between these configurations were first reported by Finkenthal *et al.* [10] and subsequently by Kaufman *et al.* [14] with improved wavelength accuracy. In the present work we have identified two additional transitions. A study of the time-resolved spectra reveals that a blended line at 77.369 Å consists of two components, a Mo XXIV line at 77.354 Å and a Mo XXVI line at 77.387 Å, respectively. One of the strongest lines in our spectra is a line at 79.613 Å (Fig. 1 and Table I), which has been assigned to the $3p^6 3d\ ^2D_{3/2}$–$3p^5 3d^2(^3P)\ ^2D_{5/2}$ transition. Additionally we have identified a line at 73.300 Å as the $3p^6 3d\ ^2D_{3/2}$–

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[*] e-mail: ljc@physics.utoledo.edu

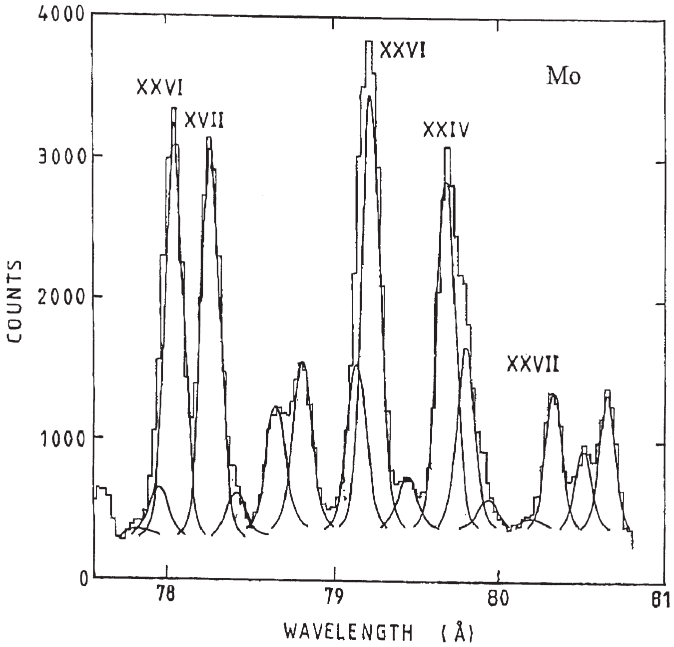

*Fig. 1.* Spectrum recorded in second order showing Mo XXIV – Mo XXVII lines between 78 and 81 Å.

$3p^53d^2(^1S)^2P_{3/2}$ transition. Thus eight levels of the $3p^53d^2$ configuration have now been established experimentally. The ground term separation, $3p^63d\,^2D(5/2 \rightarrow 3/2)$, has been determined accurately by Suckewer *et al.* [18] who observed the M1 transition at 2686.5 ± 0.3 Å.

### 3.2. *Mo XXV*

The resonance transitions $3p^6\,^1S_0 - 3p^53d\,^1P_1$ and $3p^6\,^1S_0 - 3p^53d\,^3D_1$ in Ar-like ions have been classified by Sugar *et al.* [13] for several spectra through Mo XXV. In their work they found a blended line at 91.301 Å.

By using our time-resolved spectral data, we have found two lines, at 91.329 and 91.269 Å. The estimated uncertainties are ±0.01 Å. The 91.329 Å line has been assigned to the Mo XXV $^1S_0$–$^3D_1$ transition, consistent with an isoelectronically determined value of 91.328 Å [13]. The 91.269Å line has been assigned to the $3s^2\,3p\,^2P_{1/2} - 3s3p^2\,^2S_{1/2}$ transition in Al-like Mo XXX, observed by Hinnov *et al.* [11]. Returning to the $^1S_0 - {}^3D_1$ transition, Sugar *et al.* [13] noted that the wavelength of this transition in Ni XI, as reported from solar spectra at 186.976 Å [19], is inconsistent with the isoelectronic trend. We have identified a line at 186.896 Å in JET spectra of Ni as this transition. For the $3p^6\,^1S_0 - 3p^5\,3d\,^3P_1$ transition in Mo XXV, a line at 108.254 Å in our spectra confirms the previously-reported value at 108.25 Å by Wouters *et al.* [12]. From JET spectra, we have also identified this transition in Kr XIX, at 137.02 Å. Table III summarizes the observations of this transition from Ti V through Mo XXV. We have compared the observed wavenumbers to Hartree-Fock calculations using the Cowan code [20]. The wavenumber difference was fitted to a polynomial which allowed us to obtain isoelectronically-smoothed wavelengths. Our results indicate that the data for Ge XV and Se XVII [12] differ more from the smoothed wavelengths than the experimental uncertainties.

Table I. *Identified lines of Mo XXIV – Mo XXVIII and Kr XIX.*

| Ion | Transition | Intensity | Wavelength (Å) |
|---|---|---|---|
| Mo XXIV | $3p^6\,3d\,^2D_{3/2} - 3p^53d^2(^1S)^2P_{1/2}$ | 950 | 73.300 |
| | $3p^6\,3d\,^2D_{3/2} - 3p^53d^2(^3F)^2F_{5/2}$ | 1000 | 77.354 |
| | $3p^6\,3d\,^2D_{3/2} - 3p^5\,3d^2(^3P)^2D_{5/2}$ | 2300 | 79.613 |
| Mo XXV | $3p^6\,^1S_0 - 3p^53d\,^3D_1$ | 1400 | 91.329 |
| Mo XXVI | $3p^5\,^2P_{1/2} - 3p^4\,(^3P)3d\,^2D_{3/2}$ | 800 | 77.387 |
| | $3p^5\,^2P_{1/2} - 3p^4\,(^3P)3d\,^2P_{1/2}$ | 1100 | 84.069 |
| Mo XXVII | $3p^4\,^3P_2 - 3p^3\,(^2D)3d\,^3S_1$ | 1500 | 79.212 |
| | $3p^4\,^3P_2 - 3p^3\,(^2P)3d\,^3P_2$ | 1200 | 79.761 |
| | $3p^4\,^1D_2 - 3p^3\,(^2D)3d\,^1D_2$ | 450 | 80.910 |
| | $3p^4\,^3P_2 - 3p^3\,(^2D)3d\,^3D_3$ | 1500 | 81.302 |
| | $3p^4\,^1S_0 - 3p^3\,(^2P)3d\,^1P_1$ | 800 | 86.912 |
| Mo XXVIII | $3p^3\,^2D_{3/2} - 3p^2\,(^1D)3d\,^2D_{5/2}$ | 500 | 82.773 |
| | $3p^3\,^2D_{3/2} - 3p^2\,(^1D)3d\,^2D_{3/2}$ | 350 | 82.955 |
| | $3p^3\,^4S_{3/2} - 3p^2(^3P)3d\,^2P_{3/2}$ | 2000 | 84.229 |
| | $3p^3\,^2P_{1/2} - 3p^2(^1D)3d\,^2P_{3/2}$ | 350 | 84.771 |
| Kr XIX | $3p^6\,^1S_0 - 3p^53d\,^3P_1$ | 100 | 137.02 |

Table II. *Energy levels of Mo XXIV – Mo XXVIII and Kr XIX.*

| Ion | Designation | Energy value (1000 $cm^{-1}$) |
|---|---|---|
| Mo XXIV | $3p^5\,3d^2(^3P)^2D_{5/2}$ | 1255.6 |
| | $3p^5\,3d^2(^3F)^2F_{5/2}$ | 1292.76 |
| | $3p^5\,3d^2(^1S)^2P_{1/2}$ | 1364.3 |
| Mo XXV | $3p^5\,3d\,^3D_1$ | 923.75 |
| | $3p^5\,3d\,^3P_1$ | 1094.94 |
| Mo XXVI | $3p^4\,(^3P)3d\,^2P_{1/2}$ | 1376.45 |
| | $3p^4\,(^3P)3d\,^2D_{1/2}$ | 1479.16 |
| Mo XXVII | $3p^3\,(^2D)3d\,^3D_3$ | 1204.5 |
| | $3p^3\,(^2P)3d\,^3F_2$ | 1246.1 |
| | $3p^3\,(^2D)3d\,^3S_1$ | 1262.4 |
| | $3p^3\,(^2D)3d\,^1D_2$ | 1454.0 |
| | $3p^3\,(^2P)3d\,^1P_1$ | 1577.6 |
| Mo XXVIII | $3p^2\,(^1D)3d\,^2P_{3/2}$ | 1179.6 |
| | $3p^2\,(^3P)3d\,^2P_{3/2}$ | 1187.2 |
| | $3p^2\,(^1D)3d\,^2D_{5/2}$ | 1208.1 |
| | $3p^2\,(^1D)3d\,^2D_{3/2}$ | 1362.4 |
| Kr XIX | $3p^5\,3d\,^3P_1$ | 729.82 |

Figure 2 presents a plot of the measured (where available) or fitted values for the $3s^2\,3p^53d\,^3P_1$ excitation energies from Table III. For comparison, the measured (where available) or fitted [13] values for the $3s^2\,3p^5\,3d\,^1P_1$ and $^3D_1$ excitation energies are also plotted.

### 3.3. *Mo XXVI*

In Cl-like Mo XXVI Finkenthal *et al.* [10] identified six lines as $3p^5$–$3p^4\,3d$ resonance transitions, four of which were confirmed and accurately measured by Kaufman *et al.* [15]. In addition to the line at 77.387 Å mentioned above we have now found the $3p^5\,^2P_{1/2} - 3p^4(^3P)3d\,^2P_{1/2}$ transition at 84.069 Å. However, the assignment is tentative because of the lack of experimental data in the interval Kr XX–Nb XXV. Note that the $3p^5\,^2P(3/2 \rightarrow 1/2)$ M1 transition was observed by Denne *et al.* [21] in the PLT tokamak, at 534.9 ± 0.3 Å.

### 3.4. *Mo XXVII*

In this S-like ion Kaufman *et al.* [16] identified three lines belonging to the $3s^23p^4$–$3s^23p^3\,3d$ transition array. They

Table III. *Observed and fitted wavelengths of the* $3s^2\ 3p^6\ {}^1S_0$–$3s^2\ 3p^5\ 3d\ {}^3P_1$ *transition from Ti V up to Mo XXV. The fitted values are based on the difference between observations and Hartree–Fock calculations.*

| Ion | $\lambda_{obs}$ (Å) | $\sigma_{obs} - \sigma_{calc}$ (cm$^{-1}$) | $\lambda_{fit}$ (Å) |
|---|---|---|---|
| Ti V | 363.145 ± 0.005 | −1811 | 363.145 |
| V VI | 323.211 ± 0.005 | −2071 | 323.211 |
| Cr VII | 291.738 ± 0.005 | −2292 | 291.741 |
| Mn VIII | 266.163 ± 0.005 | −2478 | 266.169 |
| Fe IX | 244.909 ± 0.005 | −2633 | 244.906 |
| Co X | | −2762 | 226.900 |
| Ni IX | 211.439 ± 0.005 | −2867 | 211.428 |
| Cu XII | | −2952 | 197.968 |
| Zn XIII | 186.13 ± 0.01 | −3022 | 186.130 |
| Ga XIV | | −3079 | 175.655 |
| Ge XV | 166.41 ± 0.01 | −3128 | 166.290 |
| As XVI | | −3173 | 157.870 |
| Se XVII | 150.32 ± 0.03 | −3216 | 150.256 |
| Br XVIII | | −3263 | 143.337 |
| Kr XIX | 137.020 ± 0.02[a] | −3316 | 137.019 |
| Rb XX | | −3380 | 131.227 |
| Sr XXI | | −3457 | 125.897 |
| Y XXII | | −3553 | 120.977 |
| Zr XXIII | | −3670 | 116.421 |
| Nb XXIV | | −3813 | 112.190 |
| Mo XXV | 108.254 ± 0.008[a,b] | −3984 | 108.249 |

[a] This experiment.

[b] The transition has previously been identified by Wouters *et al.* [12].

further predicted the $3p^4\ {}^1S_0 - 3p^3({}^2P)3d\ {}^1P_1$ transition to lie at 86.947 Å. In present work, we have assigned a line at 86.912 Å to this transition (see Table I). Four other lines were classified as belonging to Mo XXVII and are listed in Table I. Within the ground configuration of this ion, five M1 lines have been reported [5,16,21].

### 3.5. *Mo XXVIII*

Sugar *et al.* [17] have identified four lines belonging to $3s^2 3p^3$–$3s^2\ 3p^2 3d$ transition array in P-like Mo XXVIII. They also gave predicted wavelengths for three additional transitions in this array. Our time-resolved spectra confirm these results and their predicted wavelengths for the $3p^3\ {}^2D_{3/2}$–$3p^2({}^1D)3d\ {}^2D_{3/2}$ and ${}^2D_{3/2}$–${}^2D_{5/2}$ transitions, 82.943 and 82.821 Å, agree fairly well with our experimental values of 82.955 and 82.773 Å, respectively. The predicted wavelength [17] of a line at 81.947 Å for the $3p^3\ {}^4S_{3/2}$–$3p^2({}^3P)3d\ {}^4P_{3/2}$ transition could not be verified in our work, however.

## 4. Conclusions

In the present work we report on 15 new transitions belonging to Mo XXIV-Mo XXVIII. We have also updated the experimental information along the $3p^6\ {}^1S_0$–$3p^5 3d\ {}^3P_1$ transition from Ti V up to Mo XXV adding a new identification in Kr XIX and an improved value in Mo XXV.

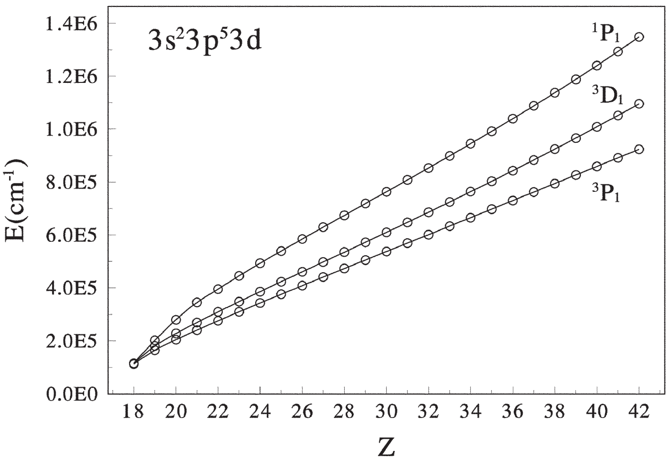

*Fig. 2.* Plot of the excitation energies of the $3s^2 3p^5 3d\ {}^3P_1, {}^3D_1$ and ${}^1P_1$ levels in the argon isoelectronic sequence.

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