Tokamak-generated tungsten radiation identified in Ag I isoelectronic sequence (W XXVIII)

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A new interpretation of the tungsten spectrum observed in 1.5-keV tokamak plasmas at Oak Ridge (the ORMAK) and Princeton (the PLT) is given. An isoelectronic extrapolation of the Ag I sequence from newly observed data through Ho XXI strongly suggests that the tokamak radiation belongs to the transition array $4d^{10}4f$-$4d^{9}4f^{2}$ of W XXVIII. This is well supported by comparison with a calculation of the spectrum. An earlier interpretation incorrectly attributed the radiation to a superposition of complex transition arrays from much higher ionization stages.

Radiation losses from heavy ions are considered to be a serious limitation to the achievable temperature in tokamak plasmas.[1] For the present, lighter metals such as titanium or stainless steel are used exclusively for the interior construction of these machines. Knowledge of the ionization stages and specific energy levels giving rise to impurity radiation is necessary for a correct calculation of the radiation losses, for an understanding of the plasma dynamics, and for future design considerations. Heretofore, the tungsten impurity spectrum observed in tokamaks[2,3] was attributed to a superposition of thousands of lines arising mainly from W XXXI-W XXXIV.[2] We here present strong experimental and theoretical evidence that show that it arises primarily from W XXVIII, and that single transitions may be recognized. Thus, the tungsten ionization appears to be much lower than expected for a 1.5-keV plasma.

The new interpretation of the tungsten radiation follows from a detailed study of the Pd I and Ag I isoelectronic sequences, whose ground states are $4d^{10}\,{}^1S_0$ and $4d^{10}5s\,{}^2S_{1/2}$. The latter changes to $4d^{10}4f\,{}^2F$ at Sm XVI due to the rapid contraction of the $4f$ shell with increasing nuclear charge. The identifications of the Pd I resonance transitions $4d^{10}$-$4d^{9}5p$ and $4d^{10}$-$4d^{9}4f$ were previously reported[4] for Cs X through Nd XV, and many lines in the Ag I sequence were identified for Cs IX through Sm XVI. In the present study these observations were extended through Dy XXI in the Pd I sequence and Ho XXI in the Ag I sequence. The ions were excited by a triggered high-voltage spark discharge[5] and photographed with the NBS 10.7-m grazing incidence spectrograph used at both 80° and 85° angles of incidence. We here make use of preliminary wavelength measurements for isoelectronic sequence curves. The data through Sm XVI are from Refs. 4 and 6–9 while the rest are new identifications.

Figure 1 shows all of the known resonance lines of the Pd I isoelectronic sequence that arise from the $4d^{9}5p$ and $4d^{9}4f$ configurations. It is a plot of the energy (in rydbergs) of the transitions divided by the effective charge on the residual ion. Extrapolations of the curves to W XXIX provide predictions for the wavelengths of the expected strong lines arising from the $^1P_1$ levels, as given in Fig. 1. The error of these predictions is not expected to exceed ±1.0 Å.

At the position of the predicted line of W XXIX at 49.3 Å, the spectrum from tokamak plasmas at Oak Ridge (ORMAK) shown in Fig. 2 (taken from Ref. 2) contains a complex blend of lines; two more blends appear at 45 and 60 Å. The spectrum was again observed with the tokamak at Princeton (PLT),[3] but a significant difference was found; in this case the structure near 45 Å was missing. The missing feature was attributed to gold that lined the ORMAK.[3]

We have found that identification of the tungsten spectral structure at 50 and 60 Å follows naturally from our observations of the Ag I isoelectronic sequence through Ho XXI. This sequence begins with the ground state $4d^{10}5s\,{}^2S$, but as the nuclear charge Z increases along the sequence the $4f$ orbit

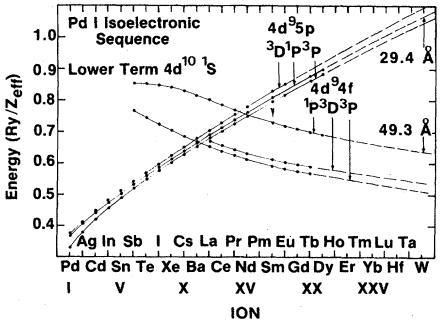

FIG. 1. Transitions of the Pd I isoelectronic sequence: $4d^{10}\,{}^1S_0$-$4d^{9}4f\,{}^1P$, ^3P, ^3D, and $4d^{10}\,{}^1S_0$-$4d^{9}5p\,{}^1P_1$, $^3P_1$, $^3D_1$. Extrapolated values (in Å) of the $^1S_0$-$^1P_1$ lines for W XXIX are given.

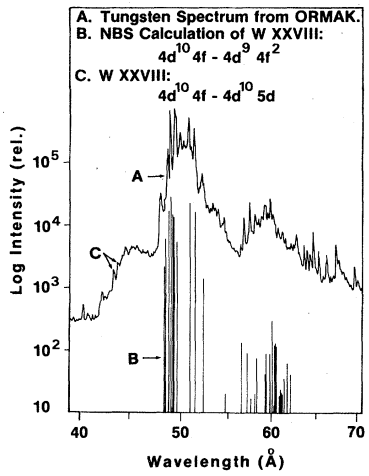

FIG. 2. Comparison of the calculated $4d^{10}4f$-$4d^{9}4f^{2}$ transition array (B) of W XXVIII with the tungsten spectrum (A) produced by ORMAK. It includes the identification of the $4^{10}4f$-$4d^{10}5d$ doublet (C).

undergoes a dramatically increasing relative binding energy (Fig. 3). The dashed portion of the $4f$ curve where no experimental data are known occurs in the region where it crosses $5d$, and is due to the lack of sufficiently long wavelength observations of the $4f$-$5d$ doublet. At Sm XVI $4f\ ^2F$ finally becomes the ground state.

A consequence of the great increase in binding energy of the $4f$ orbit is that $4d$-$4f$ transitions become a prominent feature of the spectrum, as the transition energy becomes less than the energy of promotion of $4f$ to a higher orbit. This trend in binding energy was demonstrated in a calculation by Cheng and Kim[10] who showed that between Pr XIII and Gd XVIII the $4d^{9}4f^{2}$ configuration drops below $4d^{10}5g$ and continues to fall, reaching $4d^{10}5d$ at Yb XXIV. Thereafter it becomes the lowest excited configuration of opposite parity from the ground state.

In the Pd I sequence at Sm XVI the prominent

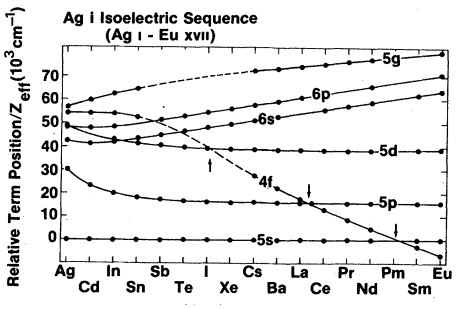

FIG. 3. Relative term energies (divided by the effective core charge Z_{eff}) in the Ag I isoelectronic sequence. Arrows indicate crossings of rapidly falling $4f\ ^2F$ term.

$4d^{10}\ ^1S_0$-$4d^{9}4f\ ^1P_1$ line begins to appear in the company of other strong lines, just at the point where it crosses the Ag I sequence doublet $4d^{10}4f$-$4d^{10}5g$. The evidence led us to calculate the transition array $4d^{10}4f$-$4d^{9}4f^{2}$ for Eu XVII and compare it with the observations; Fig. 4 shows the result. Only the short-wavelength region of the array is included, where most of the oscillator strength occurs. Although the apparent underlying weaker spectra between 70 and 71 Å distort the intensities in this region, the correspondence with the calculated spectrum is evident. A more exact fit may be obtained by scaling the electrostatic parameters of $4d^{9}4f^{2}$.

Two observations at this point are significant. (1) The strong lines of Eu XVII $4d^{10}4f$-$4d^{9}4f^{2}$ fall close to the $4d^{10}\ ^1S_0$-$4d^{9}4f\ ^1P_1$ line of Eu XVIII, and (2) the weaker lines of both arrays overlap and are displaced to higher wavelengths by the same energy. This suggests that the $4d$, $4f$ exchange interaction G^{K} dominates the level structure of both $4d^{9}4f^{2}$ and $4d^{9}4f$.

This structure has been encountered before in absorption by lanthanide metals and compounds near the $4d$ edge, which was interpreted as $4d^{10}4f^{N}$-$4d^{9}4f^{N+1}$ transitions.[11] For Ce (ground state $4d^{10}4f$) and Pr (ground state $4d^{10}4f^{2}$) the breakup of absorption into a strong and weak region separated by $\sim 2G^{1}$ was observed.

In the tungsten spectrum produced by ORMAK the strong blend at 50 Å falls exactly at the predicted position of the $4d^{10}\ ^1S_0$-$4d^{9}4f\ ^1P_1$ line of W XXIX, shown in Fig. 1, and the group at 60 Å coincides with the extrapolated energy of the triplets of the same array. A calculation of the $4d^{10}4f$-$4f^{9}4f^{2}$ array in intermediate coupling for W XXVIII (without scaling), gave results strikingly similar to the spectrum from ORMAK. Figure 2 shows a fitted version of the calculation. In this

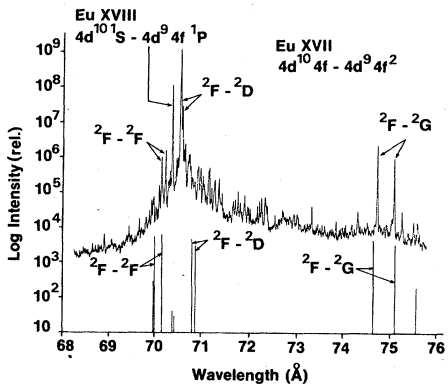

FIG. 4. Spectrum of Eu showing correspondence of calculated $4d^{10}4f$-$4f^{9}4f^{2}$ transition array (strong region only) with observed lines.

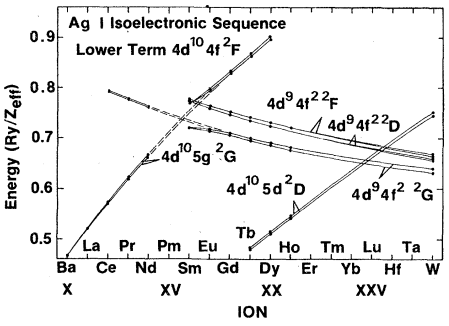

FIG. 5. Transitions in the Ag I isoelectronic sequence between the $4d^{10}4f$ ground term and the upper terms indicated. The perturbation at the crossing of ^2G terms is evident at Sm XVI. The dashed portions of the curves indicate their unperturbed positions.

case the spin-orbit parameter for the $4d^9$ core ζ_{4d} was fit along with G^1, and the rest of the electrostatic integrals of $4d^94f^2$ were reduced by 20% in accordance with experience in fitting Hartree-Fock (HF) calculations to observed levels. The adjusted value of G^1 is 87% of the HF value, while ζ_d is 7% greater than HF.

The strong portion of the transition array $4d^{10}4f$-$4d^94f^2$ has now been identified for the spectra Ce XII through Ho XXI (Fig. 5). The W XXVIII lines are included and are seen to follow smoothly the experimental points obtained from our observations. A perturbation of the ^2G term occurs where it crosses the $4d^{10}5g$ configuration. It is most severe in Sm XVI where the doublet splittings are compressed and the ^2G terms are strongly displaced. It is less severe in Eu XVII but sufficient to produce an anomalously large fitted value of G^1.

An extension of the $4d^{10}4f$-$4d^{10}5d$ sequence to tungsten leads to a tentative identification of this doublet in the ORMAK spectrum (see Fig. 2), which is unfortunately blended with the gold impurity lines. An extension of the $4d^{10}4f$-$4d^94f^2$ curves to gold leads us to assign the blend at 45 Å to the same array in Au XXXIII. The remaining weak structure underlying the 50-Å group probably includes the W XXVII array $4d^{10}4f^2$-$4d^94f^3$ that should also split into two similarly placed groups of lines.

The spark discharge used in the present work appears incapable of providing spectra in this sequence beyond Ho XXI. We are undertaking observations with a laser-produced plasma in an attempt to reach W XXVIII and verify the present analysis with high-resolution spectra.

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