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BY

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**PLASMA PHYSICS
LABORATORY**

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Comparison of Tungsten and Gold Radiation from
Beam-Foil Excitation and Tokamak-Produced Plasmas *

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ABSTRACT

Spectra in the 30-80 Å wavelength region of tungsten and gold ions, with charge states ranging from 20-33, and 25-38, respectively, have been measured in beam-foil excitation and compared with similar spectra from tokamak-produced plasmas. Several common features are observed. Assignment of observed features to particular states of ionization can be made with greater assurance for the beam foil spectra than for the tokamak spectra due to superior control and predictability of the ion charge states in the beam-foil experiment.

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* The submitted manuscript has been authored under contract EY-76-C-02-0016 with the Division of Basic Energy Sciences, U. S. Department of Energy and Contract EY-76-C-02-3073 of the U.S. Department of Energy. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

The present study of tungsten and gold by means of beam-foil (BF) spectroscopy has been undertaken in an attempt to elucidate the types of transitions and the states of ionization for heavy-metal contaminants in tokamak-produced plasmas and to try to resolve observed differences between Ormak¹ and PLT² spectra. The spectra and radiated energy of the ions of tungsten, gold, and other heavy elements in hot plasmas have recently received considerable attention in the magnetically confined fusion experiments.¹⁻⁶ These elements possess various desirable physical or chemical properties as construction materials of the plasma devices, but the very high radiation efficiency of the heavy ions can cause prohibitively high radiative energy losses from the plasma. Because of large uncertainties in the ionization and recombination rates for such heavy metals, as well as uncertainties in the plasma ion loss rate, the degree of ionization of these impurities in a tokamak is known only to limited accuracy. In contrast, only a few states of ionization are typically prominent in BF spectra, and both the most probable charge state and distribution width are accurately predictable from experimental parameters by means of empirically established relationships.⁷⁻⁹ The present experiment demonstrates the usefulness of comparisons between BF and tokamak spectra to interpret radiation from highly ionized heavy elements.

Tungsten beams of 50 MeV to 167 MeV and gold beams of 85 MeV to 238 MeV were produced by the Brookhaven National Laboratory MP Tandem Van de Graaff accelerator facility, using either two- or three-stage acceleration. The beams were magnetically analyzed and collimated onto 20 $\mu\text{g}/\text{cm}^2$ carbon foils. Charge state distributions were estimated from the experiment of Grodzins et al.⁷ and the formula given by Nikolaev

and Dimitriev⁸ and confirmed by Betz.⁹ The charge distribution is approximately Gaussian with an average full-width-at-half-maximum of .5 for the present experiment. The energy loss of the beam in traversing the foil of less than 2.6 MeV was negligible in all cases. The foil was sufficiently thick to ensure that the ions were in charge state equilibrium.⁷

Radiation emitted by the beam emerging from the foil was measured with a Minuteman Model 322G 2.217 m grazing-incidence spectrometer, equipped with a 300 groove/mm gold-coated grating at an 87° angle-of-incidence. The blaze wavelength for this case was 290 Å. The detection efficiency is expected to decrease rapidly at the shorter wavelengths of interest in the present experiment.¹⁰ The spectral resolution determined by 100 µm entrance and exit slit widths was about 1.7 Å. The field of view of the spectrometer covered a distance of about 1 mm along the beam (including the point of emergence), which corresponds to a flight time of 10⁻¹⁰ sec for a 100 MeV tungsten ion, i.e., a time much longer than most of the radiative lifetimes of interest.

The measured spectra for four energies of the tungsten beam are shown in Fig. 1a. Values for the most probable charge $\bar{q}$ are shown for each energy. The photon counts for each run have been normalized to the ion flux of the beam measured downstream from the spectrometer in a Faraday cup. This normalization is accurate to within a factor of 2 as a function of energy and has negligible uncertainty for points in a given spectrum. The ground configuration and approximate ionization potentials of the tungsten ions in the measured spectra corresponding to $\bar{q}$ values of 20, 24, 28 and 33 are: (4f⁸, 570 eV), (4f⁴, 750 eV), (4d¹⁰, 900-1160 eV), and (4d⁵, 1420 eV), respectively. (The two values of E_i in the case $\bar{q} = 28$ are those for removing the last 4f, and the first 4d electron.)

The gold spectra, normalized in the same way, measured for charge states isoelectronic with the tungsten scans are shown in Fig. 1b. As expected, the

spectra clearly show the same features as tungsten, displaced toward shorter wavelengths.^{1,6} The displacement is about $7 \text{ \AA}$ in the features prominent at lower beam energies, and about $10 \text{ \AA}$ in the features appearing at higher beam energies. The magnitude of the shift agrees with theoretical calculation.¹

The only substantial difference in the pairs of isoelectronic spectra is the absence of the $46 \text{ \AA}$ feature in the gold spectra at $\bar{q} = 33$ and 38 , while the $51 \text{ \AA}$ feature in the tungsten spectra at $\bar{q} = 28$ and 33 is still evident. This difference is attributed to the rapidly decreasing spectrometer efficiency in the wavelength region around $50 \text{ \AA}$ which obscures the relatively weak structure expected at about $46 \text{ \AA}$ in the gold spectra for $\bar{q} = 33$ and 38 .

In recent tokamak experiments, the principal part of the tungsten radiation has been found to occur in the wavelength range $30\text{--}70 \text{ \AA}$ ^{1,2}, in discharges where $n_e \tau$ is in the range of $1 \times 10^{11} - 3 \times 10^{12} \text{ sec cm}^{-3}$ (n_e is the electron density and τ the ion confinement time) and electron temperatures, T_e , are in the range from $400\text{--}1500 \text{ eV}$. Figs. 2a and 2b show the general appearance of the spectra from the Ormak¹ and PLT² tokamaks in this region. In the Ormak spectrum (Figure 2a) some of the peaks correspond to oxygen and carbon lines, all others were attributed to highly ionized tungsten.¹ The electron temperature was about 400 eV . In the PLT spectrum, Figure 2b, the electron temperature is $500\text{--}600 \text{ eV}$. Since the $n_e \tau$ for PLT is greater than for Ormak, the PLT spectrum corresponds to higher states of ionization than does the Ormak spectrum. Furthermore, it was found that the PLT spectrum did not change very markedly up to about $T_e = 1500 \text{ eV}$. The spectral resolution is $1.25 \text{ \AA}$ for the PLT case (compared to $\sim 0.1 \text{ \AA}$ in the Ormak spectrum), and the intensity scale

is approximately linear, although below about $35 \text{ \AA}$ the calibration uncertainty becomes very large. Clearly the two spectra are very similar, except for the absence of the band around $46 \text{ \AA}$ in the PLT spectrum. The common features of the two spectra are bands of lines at ~ 51 and $\sim 59 \text{ \AA}$. In both experiments the spectra probably arise from a considerable number, perhaps 10-20, of successive states of ionization of tungsten. The spectra are thought to arise primarily from 4f-4d type of transitions of these ions, but 4d-4p and other transitions may also be present.¹ Because Ormak contains a gold-plated liner, the Ormak plasma may also contain gold.

In comparing the BF spectra of Fig. 1 with the tokamak spectra of Fig. 2, the first point to note is that the $46 \text{ \AA}$ feature present in the Ormak spectrum and absent in the PLT spectrum should be assigned to gold and not to tungsten as assumed in Ref. 1. Secondly, the prominent band in the tokamak spectra at $\sim 51 \text{ \AA}$ first appears in the BF tungsten spectra for $\bar{q} = 24$ and persists up to $\bar{q} = 33$. This corresponds to ground configurations from about $4d^{10}4f^6$ to at least $4d^5$. Since this is the strongest feature in the tokamak spectra, the assignment of 4d-4f transitions as its origin seems well justified. The $59 \text{ \AA}$ band first appears in the $\bar{q} = 20$ BF tungsten spectrum. The lower $\bar{q}$ origin of this band is consistent with some (unpublished) observations on PLT which show that it tends to have a broader radial profile than the $51 \text{ \AA}$ band and hence originates at somewhat lower electron temperatures. However, like the $51 \text{ \AA}$ band in the tokamak spectra, it also persists to electron temperatures well over 1 keV. We are inclined to ascribe this band also to 4d-4f transitions, which appear with only a few vacancies in the 4f subshell, but diminish in intensity relative to the $51 \text{ \AA}$ band with

progressive stripping of the core. However, 4f-5g transitions (which may have intensities comparable to 4d-4f) could also be involved, especially at lower $\bar{q}$ states.¹¹

In the BF tungsten spectra there is no indication of the 34 Å band observed in PLT at temperatures similar to those required for the 51 Å band. This is probably due to the rapid decrease of the grating efficiency with the wavelength in the BF experiment. On the other hand, the most prominent feature in the BF spectra for high $\bar{q}$ does not appear at all or, at most, very weakly in the tokamak plasma. For tungsten, this band of radiation at ~ 69 Å is clearly present at $\bar{q} = 24$ and grows strongly with increasing $\bar{q}$. This latter difference between the BF and tokamak spectra may reflect differences in the excitation mechanisms in the two environments. In the tokamak plasma, where the rate of collisional excitation is $\sim 10^5 \text{ sec}^{-1}$ and the typical radiative lifetime is $\sim 10^{-12} \text{ sec}$, multiple excitations are not important and $\Delta n = 0$ transitions predominate. For the BF case, however, the rapid passage of the beam particles through the foil ($\sim 10^{-14} \text{ sec}$) produces effective collision frequencies of $\sim 10^{17} \text{ sec}^{-1}$ and concomitant multiple excitation or inner shell excitations as well as the $\Delta n = 0$ variety found in a tokamak plasma. Consequently, the most promising source of the 69 Å BF radiation would be multiply excited 4f (or 4d at higher $\bar{q}$) states or, stated in another way, vacancies in the 4d (or 4p) subshells, created during the passage of the beam through the carbon stripping foil.

In summary, this first use of BF spectroscopy as an aid to plasma diagnostics of heavy contaminants has shown that the method contributes much to the identification of spectral features. More extensive and detailed BF spectra would be useful in making more refined estimates. In the present work we were able to identify separate contributions from

Au and W and to give an independent method for assigning average charge states. In the future, BF data is needed for elements of somewhat lower Z where one can still clearly identify the transitions corresponding to the 51 Å bands of W, and yet be able to reach the end of the 4d subshell, and eventually also the 4p. Theoretically it would be helpful to the interpretation of the BF spectra to predict the probable location of transitions with one or more vacancies in the near-valence subshells which can be excited in the BF process.

We would like to acknowledge the invaluable technical assistance of Mr. George Hummer.

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FIGURE CAPTIONS

- Fig. 1. Beam-foil spectra of tungsten ions (a) and gold ions (b) emerging from a $20 \mu\text{g}/\text{cm}^2$ carbon foil, at indicated beam energies and most probable charge states $\bar{q}$.
- Fig. 2. (a) Spectrophotometer trace of ORMAK discharge, ascribed primarily to tungsten and perhaps gold ions. (b) Spectrum ascribed to tungsten ions in PLT tokamak, corrected for spectrometer sensitivity (at a lower spectral resolution of about $1.25 \text{ \AA}$). In both cases the radiation in the observed bands accounted for a substantial fraction of ohmic heating power input.

Fig. 1. 783920

Fig. 2. 784603