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Use of Spectra from Foil-Excited Heavy-Ion Beams to Interpret Radiation from Plasmas

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MASTER

USE OF SPECTRA FROM FOIL-EXCITED HEAVY-ION BEAMS TO INTERPRET RADIATION FROM PLASMAS*

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Abstract

Spectra from foil-excited heavy ion beams can be used to investigate the relative abundance and charge state composition of heavy metal contaminants which cause severe radiative energy losses in tokamak-produced plasmas. The degree of ionization of these metals in the tokamak plasma is not well known because of uncertainties in ionization and recombination rates and particle confinement times. Only a few stages of ionization are typically prominent in foil-excited spectra, however, and both the most probable charge state and distribution width are well known. Highly ionized heavy ions (e.g., Ti, Mo, W and Au) which span the range of charge states found in present tokamaks were produced by passing beams from the Brookhaven MP tandem Van de Graaff accelerator facility through 20 ug/cm^2 carbon stripping foils. EUV radiation was recorded with a grazing incidence spectrometer. Comparisons of the beam-foil spectra with radiation from plasmas, and recent direct determinations of atomic oscillator strengths for principal resonance lines of such highly ionized species as Li-like iron (Fe^{23+}), Na-like bromine (Br^{24+}), and Cu-like iodine (I^{24+}) are discussed.

Introduction

The important atomic data needs for progress toward fusion power have been stressed in recent committee reports.[1,2] Among the needs cited are wavelengths of atomic transitions, line identifications, atomic transition probabilities, and absorption oscillator strengths (f values). Of particular urgency are the atomic data for highly ionized metals such as Sc, Ti, Cr, Fe, Ni, Zr, Nb, Mo, Ta, W, Re, Pt, and Au. These elements possess various desirable physical or chemical properties as construction materials in tokamak-type plasma devices; but the very high radiation efficiency of the heavy ions can cause prohibitively high radiative energy losses from the plasmas. The relevant parameters for producing highly ionized atoms in a tokamak discharge are the high central electron temperatures T_e (1.5 to 3 keV in existing machines) and the product of the electron density and particle confinement time. The presence of highly ionized heavy atoms, even in small quantities, adversely affects the achieved temperature and confinement times in tokamak discharges.[3,4] The identification and quantitative analysis of heavy ion impurities is thus crucial to fusion research.

The study of spectra from foil-excited ion beams, beam-foil spectroscopy (BFS),[5,6] has proved to be a valuable source of atomic data for fusion. For example, Wiese and Younger[7] have discussed the important contributions to the direct determination of f values. Until recently, most BFS experiments were performed at small accelerator facilities and were thereby limited to light ions and relatively low ionization stages of heavier atoms. This prompted the belief that since such high beam energies were required, the direct determination of f values for the very highly ionized heavy ions expected in future generation tokamaks would be beyond the scope of the BFS method.[7] A plot of the maximum mean charge states versus atomic number for several types of existing and future accelerators is shown in Fig. 1. The estimated range of ionic charges produced in previously constructed, next generation, and fusion reactor tokamaks is indicated. This comparison demonstrates that the investigation of radiation from the highly ionized species expected in future plasma devices will not be beyond the range of the BFS method. A graphical overview of recent BFS survey scans and f value determinations is included in Fig. 1.

The BFS technique can also be used to elucidate the types of transitions and the states of ionization for heavy-metal contaminants in tokamak-produced plasmas. Beam foil excitation produces a narrow distribu-

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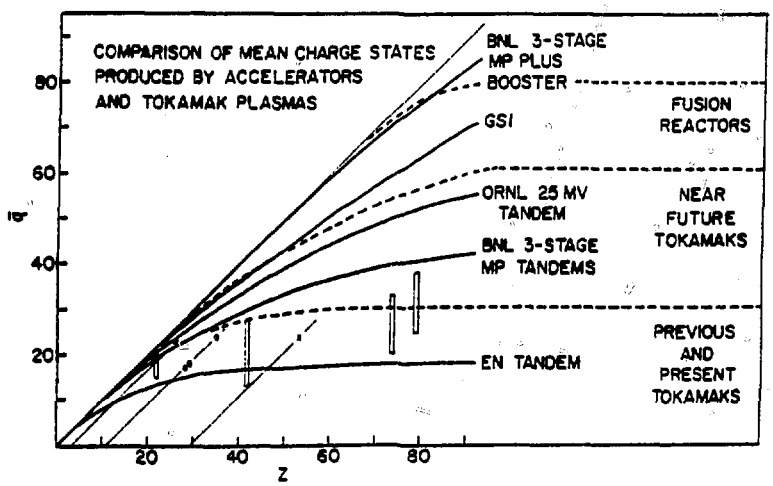

Fig. 1. Plot of maximum mean charge states $\bar{q}$ versus atomic number Z for (——) heavy ion accelerators and (---) tokamaks. The ORNL 25 MV tandem (under construction) and the BNL booster (proposed) are future accelerators. The dashed curves are drawn for tokamak electron temperatures T_e of 1-2 keV (present), 7-10 keV (future), and 30-100 keV (fusion reactors). Recent BFS data: (▯) survey spectral scans, and direct determinations of f values for (m) Li, (o) Na, and (x) Cu sequences.

tion of charge states for a single known ion, and both the mean charge state and distribution width are accurately predictable from experimental parameters. In contrast, the degree of ionization of these metals in the tokamak plasma is not well known in relation to T_e because of lack of knowledge of ionization and recombination rates and competition between ion loss and volume recombination. The experiments to be described here, collaborators involved, and the capabilities of the BNL three-stage tandem facility have been reviewed recently by Jones.[8] The present discussion will concentrate on the relation of the experimental results to fusion research.

Experimental Methods

Most of the experiments were performed using beams of heavy ions from the Brookhaven National Laboratory dual MP tandem Van de Graaff accelerator facility. The beams, after collimation, were passed through thin (typically 20 $\mu g/cm^2$) carbon stripper foils which were used to further strip and excite the beam at a well-defined position in space. In this method, the beam-foil-excitation technique,[5,6] both the mean charge state (maxima for the BNL facility are shown in Fig. 1.) and distribution width (approximately Gaussian with a typical FWHM of about 2 charge states) are accurately predictable from experimental parameters by means of empirically established relationships.[9,10] For most of the work, the extreme-ultra-violet (EUV) radiation emitted perpendicular to the beam axis was recorded with a 2.2 m grazing incidence spectrometer (Minuteman 322G) equipped with a gold coated (300 g/mm) [illegible] grating with a blaze angle of 2°13' (blaze wavelength 29 nm at 87° angle of incidence). With entrance and exit slits set to 300 μm the viewing length of the beam was less than 1 mm and the spectral resolution obtained was ~0.4 nm FWHM with an estimated uncertainty in the determination of peak centroids of ±0.02 nm. Radiation which passed through the exit slit of the spectrometer was detected with a channel electron multiplier (CEM) with a dark current counting rate of less than 0.2 Hz. Radiative lifetimes were measured by translating the foil in discrete steps parallel to the beam axis and measuring the spatial decay in intensity of wavelength selected transitions.

Direct Determination of Oscillator Strengths

Absorption oscillator strengths, f values, for principal resonance lines (i.e., strongly radiating "in-shell" transitions) can be determined directly from BFS radiative lifetime measurements using the simple relationship:

$$f_{ik} = 1.44 \times 10^{-14} \lambda^2 \frac{g_k}{g_i} A_{ki},$$

where λ is the transition wavelength in nm, g_k and g_i are the statistical weights of the upper and lower levels, respectively, and A_{ki} is the transition probability. For ns - np transitions and other unbranched decay, $A_{ki} = 1/\tau_k$, where τ_k is the measured mean life (in seconds) of the upper level. Quantitative analysis of the impurity problem in plasmas depends on the determination of f values and excitation rate coefficients (which can be determined from f values). The most promising source of a reliable data base is the combined theoretical and experimental effort to determine the systematic trends of f values along isoelectronic sequences. This approach and previous BFS results have been reviewed by Wiese and Younger.[7]

Recent BFS results[11-15] for ns-np transitons in highly ionized atoms are compared with relatavistic calculations[16-19] in Table I. The experiments were performed using a 491 MeV Fe beam from the Berkeley Super HILAC, and 64 MeV Ni, 75 MeV Cu, 80 MeV Br, and 75 MeV I beams from the Brookhaven MP tandems. The measured decay curves were fit to a sum of at most three exponentials by curve-peeling and use of the program HOMER.[21] Care was taken to follow the decay curves for many meanlives of the primary transition to avoid errors caused by overlooking contributions from long-lived cascade tails.[22] In the Li-like Fe experiment,[11] good agreement was obtained with relatavistic multi-configuration-Hartree-Fock (MCHF) "length gauge" calculations.[16,17] This agreement is typical of the Li sequence where theoretical calculations are simplified and measured decay curves are routinely fit to a single or at most three exponentials. For Na and Cu sequences, measured oscillator strengths are generally lower than theoretical results. Previous studies on less highly ionized species have indicated a (10-15)% discrepancy for the sodium sequence[22] and a 30% discrepancy for the copper sequence.[7] On the theoretical side, relatavistic effects and core polarization increase calculational uncertainty, but accuracies of ±5% are usually quoted and the disagreemnt is attributed to problems associated with extracting primary meanlives from measured decay curves.

The main experimental complication for n≥3 and higher levels is the usual presence of a long-lived tail attributed primarily to the "yrast" (l=n-1) decay chain. Younger and Wiese[23] have demonstrated the dominant effect of this type of cascading via theoretical simulation of the measured decay curve of the 4p ^2P level in Kr VIII.[24] The "yrast" decay chain is often approximated as a single exponential component. If the decay curve is followed for many primary meanlives, there is no reason to believe that an exponential decomposition is more likely to undercorrect for cascading than to overcorrect for it.[25] This contention is consistent with the comparisons shown in Table I. For the 3s $^2S_{\frac{1}{2}}$ - 3p ^2P_j, transitions of the Na sequence, the experimental results are in agreement for the 1/2-1/2 transition in Ni^{17+} and the 1/2-3/2 transition in Cu^{18+}, overestimate for the 1/2-1/2 transition in Cu^{18+}, and underestimate the theoretical values for the remaining transitions. The results for Cu-like iodine underestimate the theoretical calculations by some 30%.

Table I. A comparison of recent experimental and theoretical oscillator strength determinations for ns $^2S_{\frac{1}{2}}$ - np ^2P_j, resonance lines of the lithium (n=2), sodium (n=3), and copper (n=4) isoelectronic sequences.

n	ion	1/2 - 1/2 exp.	1/2 - 1/2 theory	1/2 - 3/2 exp.	1/2 - 3/2 theory
2	Fe^{24+}	0.018[a]	0.018[w]	0.047[a]	0.048[w]
3	Ni^{17+}	0.114[b]	0.113[x] 0.113[y]	0.237[b]	0.252[x] 0.256[y]
3	Cu^{18+}	0.16[c]	0.12[z]	0.26[c]	0.25[z]
3	Br^{24+}	0.072[d]	0.090[x] 0.089[z]	0.17[d]	0.22[x] 0.22[z]
4	I^{24+}	0.16[e]	0.22[y]	0.29[e]	0.41[y]

Experimental (BFS) determinations: (a) Ref. 11, (b) Ref. 12, (c) Ref. 13, (d) Ref. 14, and (e) Ref. 15. Relatavistic calculations: (w) Refs. 16 and 17, (x) Ref. 18, (y) Ref. 19, and (z) Ref. 20.

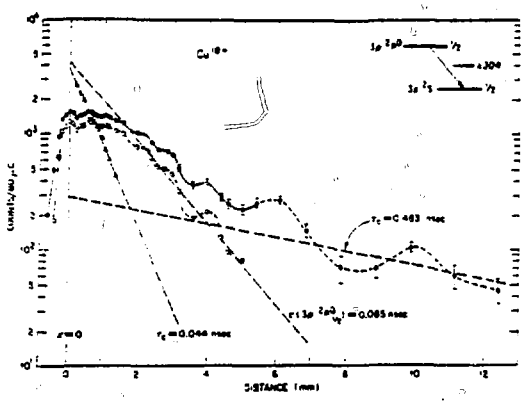

Fig. 2. Time-of-flight-intensity decay curve for the $3s^2S_{1/2} - 3p^2P_{1/2}$ transtion in Cu^{18+}. A long-lived "yrast" tail (τ_c=0.48 nsec), a "growing in" cascade (τ_c=0.044 nsec), and unexplained intensity modulations are shown to complicate the extraction of the meanlife (τ=0.085 nsec).

An additional complication in these experiments was the presence of unexplained intensity modulations[26] on most of the decay curves. A decay curve which is typical of the problems caused by an "yrast" tail and a "growing in" cascade (i.e., one of the exponential coefficients is negative causing a maximum in the curve), and shows the most extreme case of intensity modulations yet encountered is shown in Fig. 2. Although the origin of these oscillations which were also present in the measured decay curves for Ni^{17+} and Br^{24+} remains an interesting puzzle, for the prupose extracting accurate meanlives their presence is merely a nuissance which increases the experimental uncertainties. Accuracies of only ±10-20% are quoted for the sodium sequence measurements.[12-14] Younger and Wiese[23] and Curtis[25,27] have discussed in detail the problems associated with atomic meanlife measurements. Promising new procedures which should provide accurate determinations are being developed.[25,27] Further experimental and theoretical work is expected to firmly establish systematic trends along isoelectronic sequences and thereby provide plasma experimenters with accurate f values for principal resonance lines of any impurity ion.

Direct Comparison of Foil-Excited and Plasma Spectra

The measurement of absolute concentrations of individual impurity ions in tokamak plasmas depends on more than f value determinations alone. First, the resonance lines of the particular ionic species of interest must be identified and resolved from other (often overlapping) transitions. A typical plasma discharge can contain several highly ionized metals from current aperture limiters and vacuum vessel walls in addition to light ion impurities such as O or C which may radiate in the same wavelength region. Furthermore, the degree of ionization of the impurity ion is in general not well known in relation to the electron temperature due to uncertainties in plasma confinement times and competition between ion loss and volume recombination.

Recently, BFS has been used[28] to resolve differences observed in PLT[29] and Ormak[30] experiments. Results of an average ion model[31] indicated that tungsten ions with charge states q = 16 to 33 should exist in both devices (Au ions with similar charge states were also expected in Ormak) and theoretical studies[19] indicated that large numbers of spectral lines would overlap to form broad spectral features in the 40-70 Å region. Foil-excited spectra which span the range of charge states produced in present tokamaks (See Fig. 1.) were measured in this wavelength region for tungsten and gold ions with $\bar{q}$ ranging from 20-33 and 25-38, respectively. The spectra, the four beam energies used in each case and the corresponding $\bar{q}$ are shown in Fig. 3. As expected,[29,30] the isoelectronic spectra show the same features with the gold lines displaced toward lower wavelengths by about 7 and 10 Å for bands prominent at lower and higher beam energies, respectively.

Spectra from the tokamak discharges with central electron temperatures T_e of about 500-600 eV for PLT and 400 eV for Ormak are shown in Fig. 4. The PLT spectrum corresponds to somewhat higher states of ionization and did not change very markedly up to about 1500 eV, where it is expected[31] that tungsten ions with $\bar{q}$=31 will be produced. The two tokamak spectra shown in Fig. 4 are very similar except for the absence of the band around 46 Å in the PLT spectrum. All of

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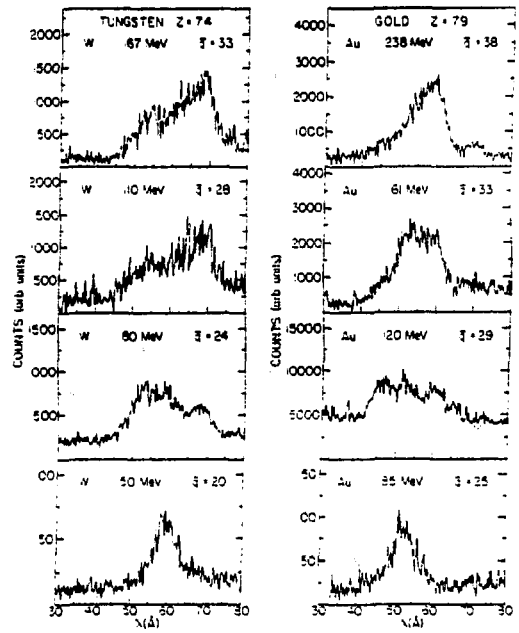

Fig. 3. Foil-excited spectra of tungsten (left) and gold (right) ions. Beam energies and mean charge states $\bar{q}$ are indicated.

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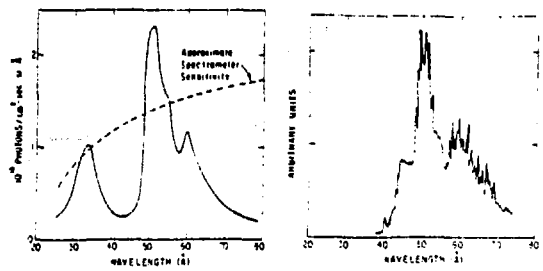

Fig. 4. Spectra from tokamak discharges in PLT (left) and Ormak (right). Radiation was attributed primarily to tungsten ions. See References 29 (PLT) and 30 (Ormak).

the transitions in the Ormak spectrum were attributed to radiation from tungsten ions,[30] even though Ormak contained a gold-plated liner (PLT does not). Comparison of the BFS spectra in Fig. 3 with the tokamak spectra in Fig. 4 indicates that the 46 Å feature in the Ormak spectrum should be assigned to gold. The two bands of lines at about 51 and 59 Å were attributed primarily to 4d-4f transitions, although other transitions may have comparable intensities in this spectral region.[19] Additional features at higher wavelengths observed in the foil-excited spectra, but which are absent from the tokamak spectra, were attributed mainly to 4d-4f transitions from multiply-excited states not produced in plasmas. This first use of BFS as an aid to identification of heavy contaminants in tokamak plasmas has shown that the method can contribute much to the identification of spectral features. More detailed comparisons are limited, however, by the differneces in reaction mechanisms in beam-foil and plasma excitation.

In a tokamak or similar plasma discharge, excitation proceeds by electron impact. The rate of collisional excitation is typically about 10^5 sec^{-1} and the typical radiative lifetime is about 10^{-12} sec. Multiple excitations are therefore not likely and singly excited $\Delta n=0$ transitions will predominate. In beam-foil excitation, the rapid passage of the beam through the foil produces effective collision frequencies of about 10^{17} sec^{-1} and concomitant multiple collisions before excitation states produced in a previous collision have deexcited. It is also possible to produce multiply excited states in a single ion-atom collision.[32] Singly excited $\Delta n=0$ transitons are also copiously produced and are often the most salient spectral features,[11-15] so that any features observed in a tokamak spectrum should in general also be observable in BFS. Additional features attributable to multiple and/or inner-shell excitation will often lie outside the wavelength region of interest. When overlapping does occur, as is apparently the case for the W and Au spectra of Fig. 2., it may be possible to isolate the spectral features peculiar to beam-foil excitation by comparison with the spectra from plasmas. Experiments which were undertaken to contribute to the understanding of plasmas might thereby serve to further the understanding of the beam-foil interaction.

Investigations have been initiated to provide extensive foil-excited spectra for other metals for comparison with spectra from tokamak discharges. For expample, spectra in the wavelength region from 5 to 55 nm have been measured for molybdenum ions with $\bar{q}$ = 13 to 28. Details of these recent experiments and comparisons with Mo spectra from other sources are given elsewhere.[33] In present and near future tokamaks, heavy ions such as W and Mo will be partially stripped and therefore strongly radiating.[3] Lighter ions will be nearly or completely ionized (See Fig. 1.) and consequently should radiate less power from a tokamak discharge. Titanium (Z=22) is currently the most favorable construction material for next generation tokamaks such as Princeton's TFTR.[34] To provide data for plasma diagnostics, we have begun a comprehensive study of foil-excited Ti. Preliminary spectra for $\bar{q}$ = 16 and 17 are shown in Fig. 5. The fewer electron systems are seen to produce much simpler spectra than observed for W and Au in Fig. 3. In contrast to the results for heavier ions where complex bands of lines dominate the spectrum, it will be possible to obtain Ti spectra with sufficient resolution to isolate most of the transitions and make accurate wavelength and lifetime measurements. Further measurements for higher $\bar{q}$ and over an extended range of wavelengths are now in progress.

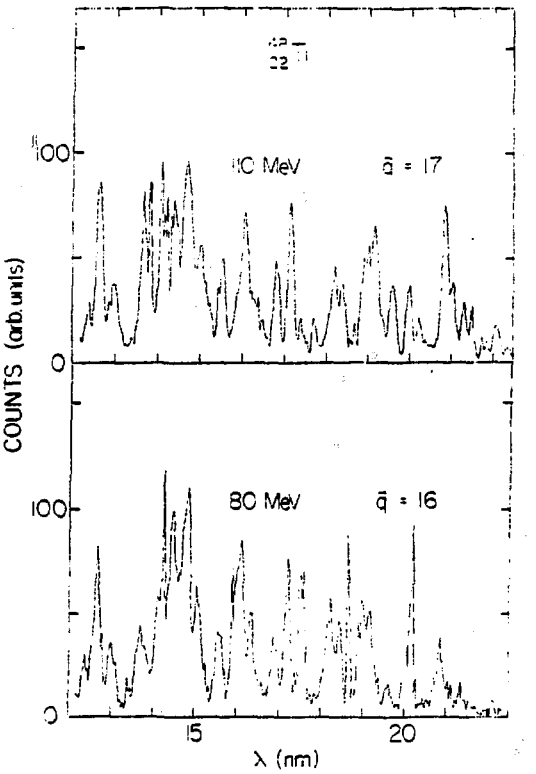

Fig. 5. Foil-excited spectra for 80 and 100 MeV Ti ions with $\bar{q}$ = 16 (C-like) and 17 (B-like).

Summary and Conclusions

Much can be learned from the comparison of spectra from highly ionized heavy ions produced by beam-foil excitation and plasma discharge. It has been shown that present and future accelerators can produce sufficiently energetic beams to span the range of charge states expected in future and even fusion reactor tokamaks. If individual transitions are well-resolved and identified in spectra from both sources, the direct determination of f values from the beam-foil experiments can be used to determine excitation rate coefficients and absolute concentrations of impurity ions in tokamak plasmas. Further experimental and theoretical work should extend and firmly establish systematic trends of f values along isoelectronic sequences. When individual lines are not identifiable, comparison with foil-excited spectra can help identify, assign charge states and elucidate the types of transitions produced in plasma discharges. Conversely, the comparison can serve to isolate transitions from excitation states which are produced strongly in BFS, but not observed in plasmas, thus furthering the understanding of the beam-foil interaction. An experimental program to investigate foil-excited spectra over a wide range of charge states and to directly determine f values for heavy ions commonly observed in plasma discharges has been initiated.

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