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BEAM FOIL SPECTROSCOPY OF HEAVY IONS AT ENERGIES FROM 20 TO 238 MeV

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BEAM FOIL SPECTROSCOPY OF HEAVY IONS AT ENERGIES FROM 20 TO 238 MeV*

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Résumé. Les spectres faisceau-feuilles avec des faisceaux de Ti, Cu, Ni, Br, Mo, I, W et Au ont été étudiés dans le domaine des longueurs d'onde de 5 à 60 nm pour des énergies de faisceau allant de 20 à 238 MeV. Les problèmes relatifs aux mesures des temps de vie de certains états ont été aussi étudiés.

Abstract. The beam foil spectra of beams of Ti, Cu, Ni, Br, Mo, I, W and Au have been surveyed in the wavelength region 5 to 60 nm for beam energies ranging from 20 to 238 MeV. Problems involved in making lifetime measurements for selected states have also been investigated.

INTRODUCTION

Experiments in beam-foil spectroscopy have now been going on for some twenty years and a great wealth of information has been obtained. The use of highly ionized ions has been in the past confined to relatively light ions by the low energy ion beams produced by the accelerators available for this work. Work on elements with atomic numbers greater than about twenty was for the most part restricted to the study of only low states of ionization. Within the past ten years the experimental situation has started to change with the advent of new or improved machines for production of higher energy heavy ion beams. Prominent examples are the linear accelerators at Berkeley and Darmstadt and the MP Tandem Van de Graaff accelerator. In the future one can anticipate further progress with the operation of 25 MV tandems at Oak Ridge and Daresbury and the heavy ion cyclotron, GANIL, to mention only a few. While the creation of the ultimate machine which will give U^{92+} seems far away, it is clear that we are on the threshold of a qualitative and exciting increase in the scope of experiments covered by the beam-foil technique.

The new data which can be obtained will be of interest for its own sake and should give unique results for comparison with theoretical calculations of wavelengths, lifetimes, and other effects. However, we see also that there are presently many experiments which will make possible interesting comparisons with spectra produced in high temperature plasmas in stars, by lasers, or in Tokamak type devices. The beam-foil experiments with the ability to measure lifetimes and easily control charge states should be very useful in extending and complementing the results from these other sources. The excitation mechanism for the beam foil source which involves many collisions of the ion with electrons as it traverses the foil in a time short compared to de-excitation times should produce more complex configurations than those produced in the relatively less dense plasmas. The beam-foil excitation should thus also be a unique source of spectroscopic information on complex configurations produced by many electron excitation.

The experiments that are described here were undertaken to survey the spectra of medium and heavy elements that could be produced by the Brookhaven National Laboratory (BNL) Tandem Van de Graaff facility for wavelengths less than about 50 nm. The work was started in 1975 in collaboration with S. Bashkin and J. A. Leavitt from Arizona and since then has involved a number of additional people at various times. A full list of participants is given in Table I.

EXPERIMENTAL METHODS

The experiments were carried out at the BNL Tandem Van de Graaff facility. This facility comprises two High Voltage Engineering Corporation MP Model Tandem Van de Graaffs which can be operated in normal 2 stage manner or in a three stage mode where the first machine is run negative and

Table I - Participants in Beam-Foil Spectroscopy Experiments at Brookhaven National Laboratory 1975-1978

Name	Affiliation
S. Bashkin	University of Arizona
J. A. Leavitt	University of Arizona
J. L. Cecchi	Plasma Physics Laboratory, Princeton University
T. H. Kruse	Rutgers University
D. J. Pegg	University of Tennessee and
P. M. Griffin	Oak Ridge National Laboratory
D. J. Pisano	Brookhaven National Laboratory
B. M. Johnson	Brookhaven National Laboratory
K. W. Jones	Brookhaven National Laboratory

produces a beam of negative ions which are used to inject the second machine. Higher particle energies are obtained not only because of the additional energy of the injected negative ion beam, but also because stripping to a positive ion in the terminal of the second accelerator is done at a higher energy with a resulting increase in the average charge state of the beam and a greater energy gain in the last acceleration. The heavy ions are produced with a standard sputter source [1] located in the high voltage terminal of the injector accelerator for three stage work or in the laboratory for two stage work. Operating terminal voltages are up to -7.0 MV for the injector machine and 14.0 MV for the second machine. The layout of the accelerator facility is shown in Fig. 1.

In principle it is possible to produce beams of all elements. In practice this can be done with a success which depends on the actual element used. Table II lists the beams which have actually been accelerated and the magnitude of the beam in particles/sec after momentum analysis. Approximately half the beam is lost in transmission through collimators before impinging on the final target.

There are two particular problems evident in the acceleration process which bear on the experiments. First, it is desireable to use foils for stripping the beam since the resulting average charge state is higher than when a gas is used. There are restrictions on the use of foils, however, because of short foil lifetimes and the finite number of foils that can be placed in the terminal of the accelerator. We have found foil lifetimes of only a few minutes when using Wolfram beams so that it was necessary to use gas stripping and accept lower beam energies. The second problem is evident from Table II: the beam currents are very low, and light intensity can generally be expected to be weak for any beam-foil experiment.

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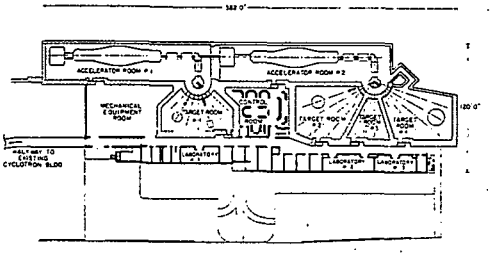

Fig. 1 - Layout of three stage tandem Van de Graaff facility at Brookhaven National Laboratory.

Table II - Typical Beams Produced by BNL Tandems.

Element	Energy (MeV)	i (nA)	Q	n (particles/sec.)
S	215	4	15	1.7×10^{9}
Cl	200	150	14	6.7×10^{10}
Ti	190	70	15	2.9×10^{10}
Fe	260	4	19	1.3×10^{9}
Ni	230	15	18	5.2×10^{9}
Cu	268	6	20	1.9×10^{9}
Br	226	12	18	4.2×10^{9}
I	290	30	24	7.8×10^{9}
W	167	3	13	1.4×10^{9}

The maximum ion energies which can be achieved with our accelerators are in the range of 100-250 MeV. The actual energy is, of course, not of as much interest to us as the degree of ionization. This is shown as a function of atomic number in Fig. 2. The curves show the values for the BNL tandems, 5 MV and 25 MV tandems, the GSI and GANIL. It can be seen that the machines that are now or will soon be available make possible investigations in a large region of charge states not previously accessible.

The actual experimental arrangement that we have used is simple. The beam is collimated with a 3mm aperture and then passes through a carbon stripping foil and is finally collected in a Faraday cup $\sim$ 20 cm from the spectrometer entrance slits. The spectrometer is a 2.2 m grazing incidence spectrometer [2] positioned at 90° to

the incident beam with the entrance slits approximately 4 cm away. In this geometry entrance and exit slit widths of 300 μm give a viewing length on the beam of less than a millimeter. For most of the survey work reported here the grazing angle was 87°, and 300 g/mm gold coated grating with a blaze angle of 2°13' and, hence, a blaze wavelength of 29.0 nm was used. A hollow cathode source is used to produce the He Lyman series lines from He II for calibration of the wavelength scale. With 300 μm slits which were used for much of this work the resolution (full width at half maximum) was 0.4 nm with an estimated uncertainty of ± 0.01 nm. The exact angle of observation was determined from the second order Doppler shift of the 25.666 nm line in S XIII. The UV radiation was detected with a channeltron detector [3] with a dark current counting rate less than 0.2 HZ. Lifetime data was taken by moving the exciter foil in typically 2.5 μm increments with a stepping motor. Spectral scans were also made by use of a stepping motor programmed to move the detector in preset increments. In both cases the data was stored directly in a computer ready for further analysis. Most of the lifetime data was analyzed using the program HOMER [4].

3s-3p TRANSITIONS IN Ni, Cu, AND Br

Study of the resonance transitions in Na-like ions has been extensive, at least in part because the simplicity of their electronic structure makes them a suitable testing ground for theoretical and experimental methods. Theoretical calculations have been made recently by, for example, Laughlin et al. [5], Froese-Fischer [6], Weiss[7], and Kim and Cheng [8], and Cowan [9]. Crossley et al. [10] have pointed out that experimental lifetime determinations can be affected by long-lived yrast cascades. Experimental values have recently been summarized by Wiese and Younger [11].

Our measurements have extended the range of experimental work through Ni, Cu, and Br. Some initial measurements on Cu have been reported earlier [12,13]. The experiments showed a strong field-free intensity modulation in the decay curves of the $3s_{1/2}-3p_{1/2}$ transition whose origin was unknown. Further experiments with nickel where the nuclear spin is zero and with bromine where nuclear and electronic spins are identical

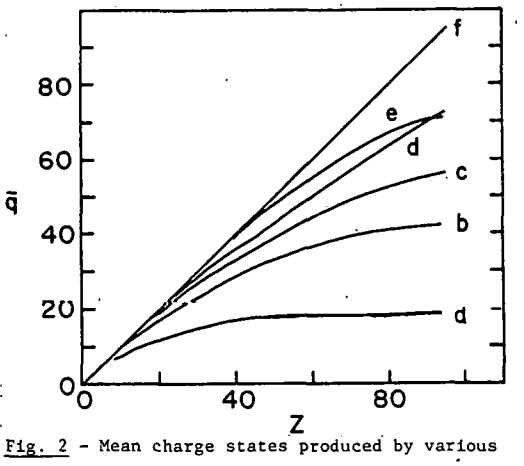

Fig. 2 - Mean charge states produced by various accelerators as a function of atomic number for: (a) 5 MV tandem, (b) BNL three stage tandems, (c) 25 MV tandem, (d) GSI, (e) GANIL, (f) ideal accelerator.

to the Cu^{18+} case also exhibited intensity modulations.

To illustrate the results that are obtained for these elements the case of Ni^{17+} can be taken as typical. A scan of the spectral region

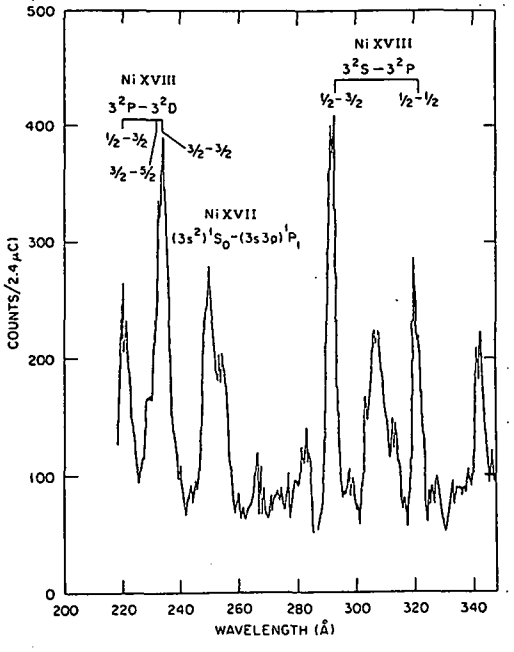

Fig. 3 - Spectral scan in region of 3s-3p transitions in Ni^{17+} at a beam energy of 64 MeV.

from 20-35 nm is shown in Fig. 3. The lines of interest and the ^2P-^2D feeding transitions are prominent. Lifetime measurements are shown in Fig. 4. Intensity modulations can be clearly seen, similar to those observed for copper and bromine.

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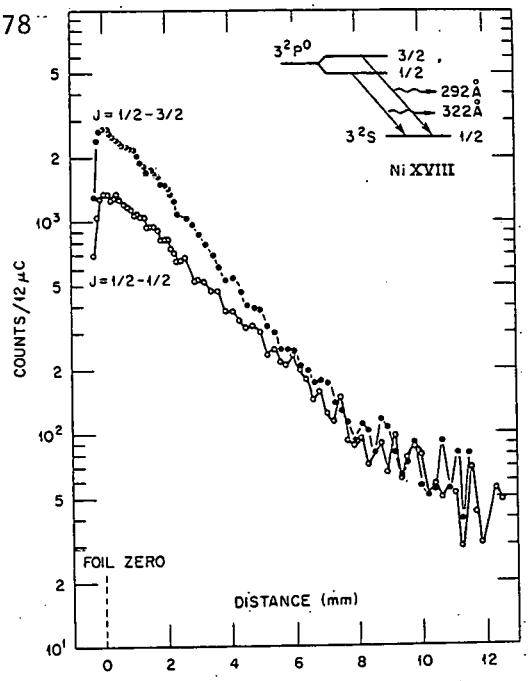

Fig. 4 - Decay curves for J = 1/2-1/2 and 1/2-3/2 transitions in Ni^{17+} showing total-intensity modulations for both transitions.

The observation of the effect for a spin zero nucleus rules out the possibility of a hyperfine interaction as a source. A typical fit to the data is shown in Fig. 5 where the contribution from the long lived yrast cascades has been subtracted. The contribution of the growing-in cascade from the $^2P^0_{1/2}$-$^2D_{3/2}$ transition is clearly visible.

Values of lifetimes and oscillator strengths from these experiments are in quite good agreement with the theoretical calculations of Weiss [7], Kim and Cheng [8], and Cowan [9] and indicate a general reliability of about ± 10%. The values are given in Table III for nickel as an illustration. Similar agreement has been found for copper and bromine. The total intensity modulations that are observed in the decay curves remain as an intriguing puzzle in these experiments. Further experiments on the effect are planned. Such experiments may consider the possible influence of a continuous background radiation under the line as well as effects caused by the use of external electric and magnetic fields.

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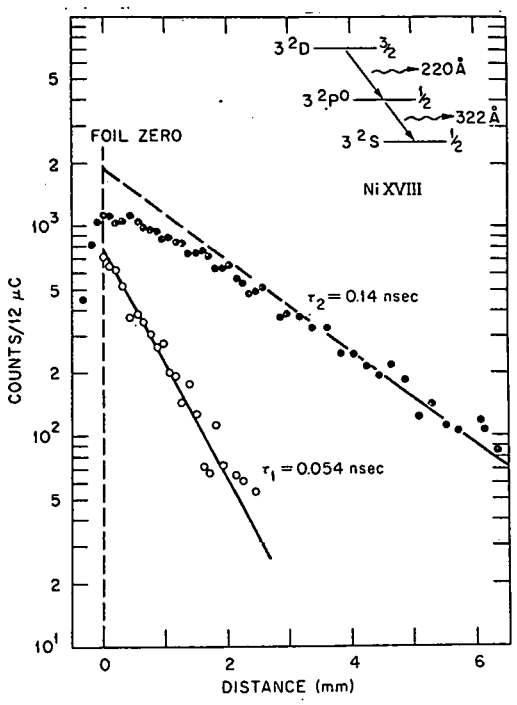

Fig. 5 - Fit to decay curve data of J = 1/2-1/2 transition. A long-lived component has been subtracted. The influence of the feeding transition is also shown.

Table III - Radiative Lifetimes and Oscillator Strengths in Ni XVIII

Wavelength(Å)	Transition	Lifetime of Upper Level(psec)	Oscillator Strengths Present	Oscillator Strengths Theory
320.76	$3s^2S_{1/2}$ - $3p^2P_{1/2}$	137 ± 14	0.114 ± 0.012	0.113[a], 0.115[b], 0.113[c]
292.00	$3s^2S_{1/2}$ - $3p^2P_{3/2}$	108 ± 11	0.237 ± 0.024	0.252[a], 0.255[b], 0.256[c]
233.79	$3p^2P_{3/2}$ - $3d^2D_{5/2}$	66 ± 7	0.187 ± 0.020	0.226[a], 0.227[b]

a. Reference 7
b. Reference 8
c. Reference 9

SURVEY OF ^{98}Mo SPECTRA FROM 22 TO 200 MeV

The study of radiation emitted by highly ionized molybdenum has practical interest and application because of its widespread use as a construction material in Tokamak fusion devices. The use of beam-foil experiments for study of these states is attractive because of the flexibility in the choice of charge states and the possibility of measuring lifetimes. On the other hand more states will be excited than in plasmas, and the comparison of the spectra will be difficult. Recent experiments have used a spark source [12,13], laser source [14] and direct observation of Tokamak plasmas [15,16] for measurements on many charge states. Ultimately, information on states up to about Mo^{+38} will be useful as the electron temperatures obtainable in Tokamaks are increased.

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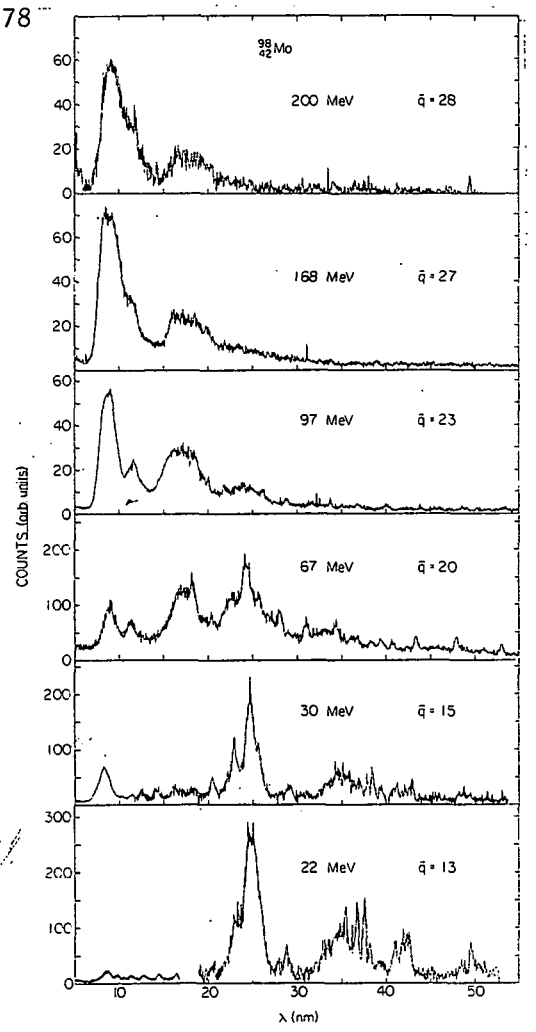

Fig. 6 - Survey of $^{98}_{42}$Mo spectra for mean charge states between 13 and 28. The beam energy used to produce each charge state is shown on the figure.

Our experimental results are shown in Fig. 6. The mean charge states, $\bar{q}$, range from 13 at 22 MeV to 28 at 200 MeV. At a given energy the charge state intensity distribution can be approximated by a Gaussian with a full-width at half-maximum of about 4. The spectrum at a given energy thus contains sizeable contributions from a number of charge states, and identification of particular lines with particular charge states is not clear. The beam-foil excitation mechanism can also reasonably be expected to excite multi-electron configurations which are not excited in the same way by other sources. Comparison of the beam-foil induced spectra with those from Tokamaks or other sources should thus be of use in picking out these more exotic states. Mansfield et al. [14] have emphasized the importance of inner-subshell excitation for the case of Mo in particular, and for heavy ions in general.

The spectra shown in Fig. 6 show that as the mean charge state of the ion is increased there is a rather striking shift in intensity from longer to shorter wavelengths and an accompanying decrease in complexity. At the lowest energy the 4s - 4p resonance lines of Mo XIV have been identified by Hinnov at 37.3 and 42.3 nm and, indeed, rather strong lines can be found there in the spectrum shown for a bombarding energy of 22 MeV where Mo XIV is produced strongly. Rather detailed comparisons can be made with the theoretical and experimental results of Curtis et al. [12], Cowan [9], and Mansfield et al. [14]. This work is in progress, and the results will be presented elsewhere [17].

STUDY OF RESONANCE STATES IN COPPER- AND ZINC-LIKE $^{127}_{-53}$I

We have also made measurements [18] of the spectra produced by iodine beams with energies of 65, 75 and 85 MeV shown in Fig. 7. The scan from 10 to 60 nm at 85 MeV shows the general features of the spectrum. At this energy the mean charge state is 23.6 so that lines from copper- and zinc-like states should be important. Three of the

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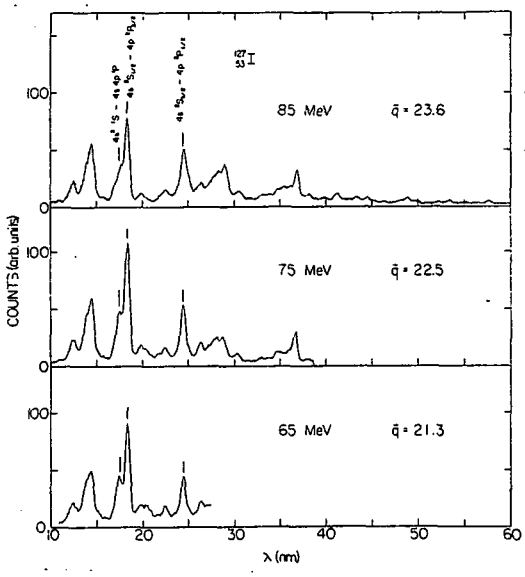

Fig. 7 - Spectra taken at 65, 75, and 85 MeV showing the copper- and zinc-like resonance lines of iodine.

strongest lines are 18.61 and 24.43, and 17.4 nm which are resonance lines in copper- and zinc-like iodine, respectively [19]. The intensities for the transitions were large at 75 MeV where the mean charge state is 22.5 and thus close to the maxima for the zinc-like and copper-like series. The above wavelength values are in good agreement with the extrapolations of 18.37, 24.32, and 17.44 nm given by Hinnov [19].

These lines are strong and seem well enough isolated to make blending relatively unimportant especially if judicious spectrometer settings are used. Preliminary lifetime measurements were therefore made on the copper-like lines at 75 MeV. The results are shown in Figs. 8 and 9. Values of 35 ps for the 18.61 nm and 57 ps for the 24.43 nm lines were found by use of the program HOMER [4]. These preliminary lifetime values lead to oscillator strengths of 0.16 and 0.29 for the 1/2-1/2 and 1/2-3/2 transitions, respectively, some 30% lower than theory [7]. This result is in agreement with earlier work summarized by Wiese and Younger [11].

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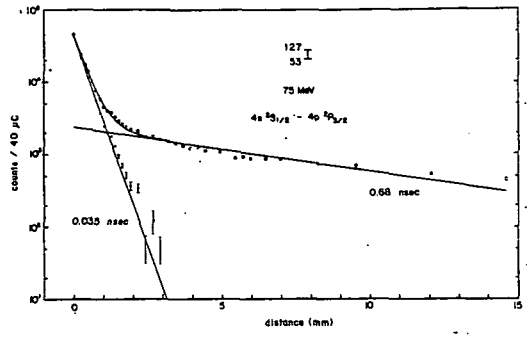

Fig. 8 - Decay curve of $4s^2S_{1/2}$-$4p^2P_{3/2}$ transition. The lifetime obtained and calculated fits to the data are shown.

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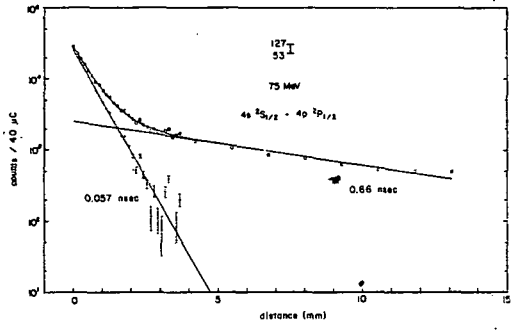

Fig. 9 - Decay curve of $4s^2S_{1/2}$-$4p^2P_{1/2}$ transition. The lifetime obtained and calculated fits to the data are shown.

SPECTRA OF WOLFRAM AND GOLD

The spectra of wolfram and gold have been of some interest in Tokamak experiments because of their use as construction materials and resulting appearance as contaminants in the plasma. Measurements of the UV spectrum have been made in the region up to 8 nm by Isler et al. [20] at Oak Ridge and by Hinnov and Mattioli [21] at Princeton. Theoretical calculations of the very complex spectra expected for highly ionized wolfram have been made by Cowan [9]. For the electron temperatures attained at ORMAK and PLT it should be possible to produce up to about W^{+31}. For our maximum beam energy of 167 MeV for wolfram, it is possible to produce W^{+34}; at 238 MeV for gold, it is possible to produce Au^{+39}, isoelectronic to the wolfram ion. The beam-foil technique can thus span all the

charge states of W or Au now seen in Tokamaks with the variable energy beams available from Tandem accelerators.

We measured [22] the wavelength range from 4 to 8 nm for W^{+20} to ^{33} and the corresponding isoelectronic charge states in Au. These results are shown in Fig. 10. The spectra for the two elements are very similar with the gold features appearing at shorter wavelengths. The shift, ranging from 0.7 to 1.0 nm, is in agreement with theoretical predictions [21]. Cowan [9] has pointed out that many states will contribute to the wolfram spectrum in this range and indeed it can be seen in Fig. 10 that we are not able to resolve individual lines in this experiment. From comparison of the charge state dependence of the spectra with theoretical predictions of Cowan tentative assignments for the bands observed in the wolfram spectrum can be made: 5.1 nm, 4d-4f; 5.9 nm, 4d-4f, 4f-5g; 6.9 nm, multiply excited 4f or 4d states caused by excitation of 4d or 4p subshells.

Lifetime values or oscillator strengths for these states are of importance for determining

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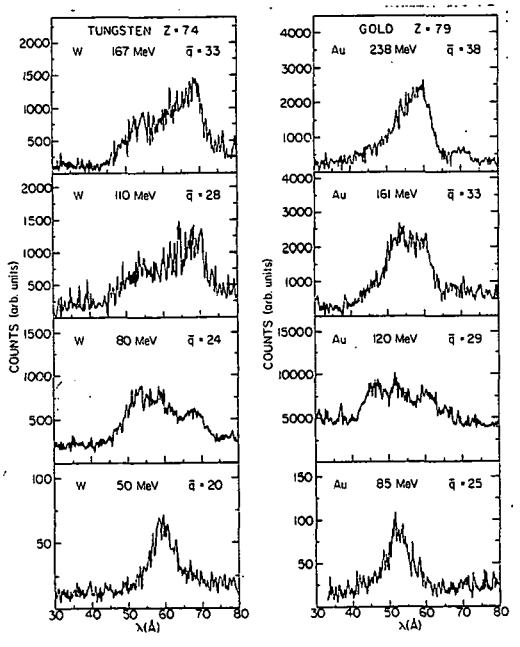

Fig. 10 - Spectra obtained for W^{+20} to W^{+33} and the isoelectronic ions Au^{+25} to Au^{+38} are shown for the wavelength region from 30-80 Å.

radiation losses in plasmas caused by them. The lifetimes are expected to be rather short [9], around 1 ps for electric dipole radiation, and measurements by the beam-foil method may be difficult because of the finite spatial resolution of the spectrometer and the effects of cascades. Measurements for a single state may be impossible, and it might be necessary to compare averages of theoretical predictions over many states with the corresponding experimental result. As a first step in the attack on this problem, we measured the decay curve for radiation produced at 6.1 nm for wolfram at 50 MeV. After subtracting the contribution from long-lived cascades, the lifetime of the short-lived component was determined to be about 50 ps. This can be taken as an upper limit on the true lifetime of the states convoluted with the effects of the finite spatial resolution of the spectrometer and unresolved cascades.

CONCLUSIONS

It has been shown that reliable data can be obtained for spectral scans in the wavelength region from 5 to 60 nm for beams from nickel to lead and at energies up to 238 MeV even with the relatively weak beam intensities which can presently be obtained from tandem accelerators. *Lifetime results in agreement with theoretical calculations have been obtained for long-lived states of simple configurations.*

In the future, as has been pointed out by Bashkin et al. [23], it will be important to use position-sensitive detectors to improve the data acquisition rate and thus make possible spectra with better statistics and resolution. Whether it is possible because of cascading problems to obtain reliable lifetime data in the region around 1 ps for heavy elements, such as wolfram, remains an open question.

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