MASTER

CONF-810868--2

**SEARCH FOR PROMETHIUMLIKE GOLD LINES
AND OTHER TRANSITIONS OF INTEREST TO FUSION RESEARCH**

B.M. Johnson and K.W. Jones
Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

T.H. Kruse
Rutgers University, Piscataway, New Jersey 08903, U.S.A.

L.J. Curtis and D.G. Ellis
The University of Toledo, Toledo, Ohio 43606, U.S.A.

DISCLAIMER

This work was prepared as part of the work of the United States Government, sponsored by the United States Government, and is, therefore, in the public domain in the United States of America. It is not to be distributed outside the United States of America without the approval of the United States Government. It is not to be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or by any information storage or retrieval system, without the prior written permission of the United States Government. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Presented At
Sixth International Conference
On Fast Ion Beam Spectroscopy
Universite Laval, Quebec, Canada
August 17-20, 1981

The submitted manuscript has been authored under contract DE-AC02-76CH00016 with the Division of Basic Energy Sciences, 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.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EAB

SEARCH FOR PROMETHIUMLIKE GOLD LINES
AND OTHER TRANSITIONS OF INTEREST TO FUSION RESEARCH*

B.M. Johnson and K.W. Jones
Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

T.H. Kruse
Rutgers University, Piscataway, New Jersey 08903, U.S.A.

L.J. Curtis and D.G. Ellis
The University of Toledo, Toledo, Ohio 43606, U.S.A.

EUV spectra in the range $\lambda = 13-40$ nm were measured for foil-excited gold ions at 31-238 MeV. Data was recorded at the higher energies to extend and to complement previous measurements and at the lowest energy to see if the recently predicted 5s - 5p resonance lines in the Pm-like ion, Au XIX, could be seen in beam-foil excitation. The experimental results are presented, previous beam-foil measurements are reviewed, and the contributions and relations to fusion research are discussed.

*Work supported by the Division of Basic Energy Sciences of the U.S. Department of Energy under Contract Nos. DE-AC02-76CH00016 and DE-AS05-80ER10676, and by the U.S. National Science Foundation.

1. Introduction

This paper presents the latest results of a continuing program to study extreme-ultraviolet (EUV) radiation from highly-stripped heavy ions. The mechanism used to produce high-ionization stages is the familiar beam-foil excitation. Although the systems chosen are of interest to basic atomic-structure research, the main thrust of the program has been to determine what contributions can be made to fusion research.

The importance of atomic processes in high-temperature plasmas and the fact that much can be learned from the comparison of heavy-ion radiation produced by various sources is now widely recognized [1-3]. In 1978 the first direct comparisons of beam-foil and tokamak-discharge spectra for highly-ionized gold and tungsten were reported [4]. Next came the comparison of molybdenum radiation from both sources [5], and last year beam-foil spectra for zirconium and iron were presented and the current status of absorption-oscillator-strength (f -value) determinations was reviewed [3,6].

Alkalilike systems such as members of the H, Li, Na, and Cu sequences exhibit strong resonance transitions which have been observed and studied in both beam-foil and tokamak-discharge spectra. The characteristic bright lines from highly-ionized members of these sequences are often strong contributors to radiative energy losses from heavy-element impurities in tokamak plasmas and provide important information for plasma diagnostics [2]. In sharp contrast to the large discrepancies between experimental and calculated f values reported at the 1975 Beam-Foil Conference by Wiese and Younger [7], it was shown in [6] that good

agreement exists, and systematic trends are well established along the Li, Na and Cu sequences. From the standpoint of plasma research, f values for these sequences are now well in hand, even though many interesting experiments remain, and some apparent anomalies [8] are yet to be resolved.

Recently, the first theoretical investigation of the promethiumlike isoelectronic sequence was reported [9]. Hartree-Fock calculations [10] showed that for $Z \geq 74$, ions isoelectronic to Pm are alkalilike with a ground-state configuration of $4f^{14} 5s$, and that the $5s - 5p$ doublet lines in the range $\lambda=10-40$ nm are the dominant transitions. The leading relativistic corrections to the wavelengths were calculated using the Pauli approximation. For the $5s \ ^2S_{1/2} - 5p \ ^2P_{1/2,3/2}$ transitions in Au XIX, the approximate wavelengths, mean lives, and line strength were predicted to be 29.7 and 19.9 nm, 56 and 16 psec, and 0.86 a.u., respectively. Hot plasmas contaminated with heavy elements should exhibit these strong resonance lines, and these systems should be amenable to study by beam-foil excitation methods.

2. Experimental procedure

2.1. Beam-foil measurements

The experimental setup is shown in fig. 1, and the basic procedure has been described in detail elsewhere [6,11]. Gold ion beams were produced by the Brookhaven dual-MP-tandem accelerator facility, magnetically analyzed, passed through $20 \mu\text{g}/\text{cm}^2$ carbon and aluminum stripper foils, and

collected in a Faraday cup. Extreme-ultraviolet (EUV) radiation emitted at an observation angle of 89.6° was dispersed and detected in a 2.2 m grazing-incidence spectrometer, equipped with a 300 groove/mm gold-coated grating. The entrance slit width was 100 μm , and the angle of incidence was 87.5° .

A position-sensitive detector (PSD) consisting of a 25 mm microchannel plate [12] coupled to a resistive anode encoder (RAE) replaced the usual spectrometer exit slit and single-channel detector (SCD). To achieve a full-width-at-half-maximum resolution of about 0.1 nm in conventional SCD operation would have required entrance and exit slits of 100 μm . This would result in a band pass of about 0.02 nm and would therefore require about 250 steps to scan a 5 nm portion of an EUV spectrum. By replacing the exit slit with a 25 mm PSD, however, all radiation in this wavelength range could be recorded at the same time with comparable efficiency per incident photon and detector dark current. To achieve comparable resolution a 50 μm entrance slit is required. Only the central 2-3 nm of each PSD spectrum was used, because of diminished detection efficiency and shadowing near the edges of the detector and very non-linear dispersion in the electronics for the smaller pulses near the ends of the RAE. The estimated overall improvement in data-collection efficiency of PSD versus SCD was about a factor of 25. Other examples of and possible improvements in the position-sensitive detection of EUV photons are discussed in a recent review by Livingston [13].

The one-dimensional relative position of photons which were incident on the front face of the PSD were determined by applying charge-division encoding techniques [14]. Laboratory wavelength calibrations were

obtained by measuring the $1s - np$ lines of He II produced in a hollow-cathode source (see fig. 2). By recording spectra for small displacements in the PSD position, the non-linearity in the electronic-encoding was documented. Adjustable fitting parameters were introduced to convert channel numbers to corresponding positions along the PSD. Doppler shift corrections (0.01-0.03 nm) were obtained by comparing the laboratory and rest-frame wavelengths of the $2s^2 1s - 2s 2p 1p$ line of S XIII, recorded for a 55 MeV sulfur ion beam.

2.2. Charge-state distributions

The usual prescription for selecting the appropriate beam energy to produce the desired atomic species in a beam-foil experiment is to use the semi-empirical formula of Nikolaev and Dimitriev [15]. If the foil thickness is sufficient to produce an equilibrium charge distribution, the most probable or mean charge state $\bar{q}$ is given by

$$\bar{q} / Z = [1 + (Z^{-\alpha} v / v')^{-1/k}]^{-k}, \quad (1)$$

where Z is the nuclear charge, v is the beam velocity, and the constants are $v' = 3.6 \times 10^8$ cm/sec, $\alpha = 0.45$, and $k = 0.6$. For this choice of constants, Betz [16] has shown that the measured $\bar{q}$ for energetic iodine and uranium beams lie within 1 of the prediction of eqn. (1). The distribution of charge states $F(q)$ is approximately Gaussian and to within 20% is given by

$$F(q) = (1 / 2\pi d^2)^{1/2} \exp[-(q - \bar{q})^2 / 2d^2], \quad (2)$$

with the width d given by

$$d = 0.5 \{ \bar{q} [1 - (\bar{q} / z)^{-1/k}] \}^{1/2}. \quad (3)$$

For gold ions at 39 MeV, eqn. (1) predicts that the desired promethiumlike 61-electron system ($q = 18$) will be the most probable species produced. The $\bar{q}$ produced by foil stripping of a gold beam at the terminal of an MP tandem (i.e., 6-14 MeV), however, has been found [17] to be 2 charge states higher than the predictions of eqn. (1). A somewhat lower beam energy of 31 MeV was therefore selected.

To confirm that an appreciable fraction of promethiumlike ions were produced at 31 MeV, charge-state distributions were measured for 20 and 100 $\mu\text{g}/\text{cm}^2$ carbon and aluminum foils. The foils were placed between a 90° analyzing magnet which selected an incident charge state ($q = 6$) and energy ($E = 31$ MeV) and a switching magnet which separated the different post-foil charge-state components of the beam. Currents were recorded for the beam collected in a Faraday cup placed after the switching magnet and in a monitor cup intermittently inserted before the foil. The measured charge-state distributions are compared in fig. 3 to the predictions of eqn. (2). The predicted $\bar{q} = 16$ from eqn. (1) does underestimate the measured $\bar{q}$ by about 2 charge states, but the width of the distribution is in good agreement. For all the foils studied, these measurements confirm that promethiumlike gold ions are copiously produced at 31 MeV.

3. Results and discussion

3.1. High-energy spectra

In a previous study of tungsten and gold radiation [4], spectra for gold ions at 85-238 MeV were measured over the limited wavelength range $\lambda = 3-8$ nm.

Broad spectral features were observed near 5 and 7 nm and were attributed to the superposition of numerous 4p - 4d and 4d - 4f transitions, but few individual lines were clearly resolved. Direct comparison of these and foil-excited tungsten spectra with studies of W and Au impurity radiation from tokamak-plasma discharges was used to assign charge states, identify elements, and elucidate types of transitions.

Shown in figs. 4 and 5 are the spectra for foil-excited gold ions at 150, 120, 85, and 50 MeV. Broad features are again observed, which shift toward higher wavelengths as the beam energy and therefore mean charge state is decreased. Many individual lines are also observed, but most are not well-resolved from neighboring transitions. As in [4], these are believed to be primarily 4p - 4d and 4d - 4f transitions, although individual lines have not been identified.

3.2. 31 MeV spectra

Beam-foil spectra for 31 MeV gold ions, excited by 20 $\mu\text{g}/\text{cm}^2$ carbon (upper spectrum) and aluminum (lower spectrum) foils, are shown in fig. 6.

Similar charge-state distributions with $\bar{q} \approx 18$ were measured (see fig. 3) for the two foils, but the two spectra are quite different. Apparently, either the same distribution of excited states is not produced in the gold-carbon and gold-aluminum interactions, even though the same ionization stages are present, or substantial radiation from the C and Al foils is produced from highly ionized target atoms. For example, Cocke [16] has shown that fully ionized Ne target atoms can be produced by collisions with Ar beams. This point deserves further study, because the opposite result was obtained in calibration runs with 55 MeV sulfur beams, where very similar spectra were obtained for C, Al, and Ti foils.

The predicted positions [9] of the Pm-sequence resonance lines are indicated in fig. 6. Although several lines lie within 0.2 nm of the predicted 19.9 and 29.7 nm, dominant lines which could be readily identified as the 5s - 5p transitions are not observed. This contrasts with the observation of the analogous 3s - 3p and 4s - 4p transitions in lighter elements such as Ni, Au, Br, Zr, Mo, and I [5,8,19,20].

Of course it is possible that the lines were not observed for some experimental reason. The spectra shown in fig. 6 contain contributions from many charge states, as shown in fig. 3, and this will suppress the prominence of the 5s - 5p transitions relative to other features in the spectrum. It is also possible that the measured charge state distribution shown in fig. 3 does not truly reflect the charge state distribution of the emitting ions at the foil because of recombination processes with the accompanying electron swarm. If this were the case, the true mean charge state could be higher than believed and the optimum energy lower than the 31 MeV actually used. It is also possible that there are other sources of

radiation in the wavelength region of interest, such as from free electron bremsstrahlung or from the decay of highly ionized atoms in the stripping foil, as has been previously mentioned.

There is some evidence that these experimental problems are not crucial since, the 5s - 5p resonance lines in tungsten were not observed in tokamak-discharge spectra [21]. The problem in this experiment is that W may have too low an atomic number for the states to be truly alkalilike [9].

These apparent failures to observe strong alkalilike resonance lines in Au XIX in the predicted wavelength region under both beam-foil and tokamak excitation conditions raises interesting theoretical and experimental questions. By analogy with the copper isoelectronic sequence, it is expected that ions of the promethium sequence should assume an alkalilike structure for sufficiently high Z. A single configuration Hartree-Fock calculation with relativistic corrections has indicated that, for Au XIX, all open $n < 5$ configurations lie above $4f^{14}5s$ and only the $4f^{13}5s^2$ lies below $4f^{14}5p$.

It is expected that this type of calculation should improve in reliability with increasing Z, as the core shrinks and stiffens. On the other hand, relativistic effects increase with Z, and the Pauli approach may not be entirely valid here. A multi-configuration relativistic Hartree-Fock calculation with two or three open shells would be useful, if it were tractable. However, theoretical methods are untested for any system of comparable complexity to these 61 electron ions, and experimental measurements are essential if theoretical methods are to be applied with confidence to such systems. The promethium sequence, with

its predicted alkalilike properties for high Z , should be an exceptionally clean test within these highly complex systems. An experimental determination of the ion in this sequence for which alkalilike lines first become prominent would provide a valuable bench mark for theoretical calculations. The failure to see these lines in Au XIX therefore motivates an extension of the experimental study to isoelectronic ions of higher Z .

References

- [1] For example, conferences on "Atomic Processes in High Temperature Plasmas," held in Knoxville, Tennessee, February 16-18, 1977 in Boulder, Colorado, January 17-19, 1979, and in Baton Rouge, Louisiana, February 25-27, 1981.
- [2] E. Hinnov, Phys. Rev. A 14 (1976) 1533; Atomic and molecular processes in controlled thermonuclear fusion, eds. M. R. C. McDowell and A. M. Ferendici (Plenum Press, New York, 1980) p. 449.
- [3] I. Martinson, Atomic and molecular processes in controlled thermonuclear fusion, eds. M. R. C. McDowell and A. M. Ferendici (Plenum Press, New York, 1980) p. 391.
- [4] B. M. Johnson, K. W. Jones, J. L. Cecchi, E. Hinnov and T. H. Kruse, Phys. Lett. 70A (1979) 320; B. M. Johnson, IEEE Trans. Nucl. Sci. NS-26 (1979) 1312.
- [5] B. M. Johnson, K. W. Jones, J. L. Cecchi and T. H. Kruse, Phys. Lett. 78A (1980) 61; IEEE Trans. Nucl. Sci. NS-26 (1979) 1317.
- [6] B. M. Johnson, K. W. Jones and D. C. Gregory, IEEE Trans. on Nucl. Sci. NS-28 (1981).
- [7] W. L. Wiese and S. M. Younger, Beam-foil spectroscopy, Vol. 2, eds. I. A. Sellin and D. J. Pegg (Plenum Press, New York, 1976), p. 951.
- [8] B. M. Johnson, D. C. Gregory, K. W. Jones, D. J. Pegg, P. M. Griffin, T. H. Kruse, J. L. Cecchi and J. O. Ekberg, IEEE Trans. on Nucl. Sci. NS-28 (1981) 1159.
- [9] L. J. Curtis and D. G. Ellis, Phys. Rev. Lett. 45 (1980) 2099.
- [10] C. Froese Fischer, Comp. Phys. Commun. 1 (1969) 151; 14 (1978) 145.
- [11] B. M. Johnson, K. W. Jones, D. C. Gregory, T. H. Kruse and E. Träbert, to be published.
- [12] Microchannel plate, model 3025-B-00M00 Chevron-CEMA, Galileo Electro-Optics Corporation, Galileo Park, Sturbridge, MA 01518, U.S.A.; J. L. Wiza, Nucl. Instr. and Meth. 162 (1979) 587.
- [13] A. E. Livingston, IEEE Trans. Nucl. Sci. NS-28 (1981) 1559.
- [14] G. M. Lawrence and E. J. Stone, Rev. Sci. Instrum. 46 (1975) 432.
- [15] V. S. Nikolaev and I. S. Dimitriev, Phys. Lett. 28A (1968) 277.
- [16] H. Betz, Rev. Mod. Phys. 44 (1972) 465.

- [17] H. F. Abendroth of the Brookhaven Tandem Operations Group, private communication.
- [18] L. C. Cocke,
- [19] B. Denne and O. Poulsen, Phys. Rev. A 23 (1981) 1229.
- [20] K. W. Jones, J. de Physique 40 (1979) C1-197.
- [21] R. C. Isler, private communication.

Figure Captions

Fig. 1. Schematic representation of the experimental arrangement used to measure beam-foil spectra.

Fig. 2. EUV spectrum of the $1s - np$ lines of He II produced by a hollow-cathode discharge source, which was built into the experimental chamber opposite the entrance slit of the spectrometer.

Fig. 3. Measured charge-state distributions for gold ions emerging from $20 \mu\text{g}/\text{cm}^2$ carbon (closed circles) and aluminum (open circles) and $100 \mu\text{g}/\text{cm}^2$ carbon (closed triangles) and aluminum (open triangles) foils. The relative particle currents are plotted versus charge state and compared to the predictions of eqn. (2) in the text (solid curve). Note that for all of the foils studied, the mean charge state $\bar{q} \approx 18$, the promethiumlike ion, two charge states higher than the $\bar{q} = 16$ predicted by eqn. (1).

Fig. 4. EUV spectra for foil-excited gold ions at 150 and 120 MeV.

Fig. 5. EUV spectra for foil-excited gold ions at 85 and 50 MeV.

Fig. 6. EUV spectra for gold ions at 31 MeV excited by $20 \mu\text{g}/\text{cm}^2$ carbon (upper spectrum) and aluminum (lower spectrum) foils. The predicted positions (from [9]) of the $5s^2S_{1/2} - 5p^2P_{1/2,3/2}$ transitions in promethiumlike gold are indicated.

RELATIVE INTENSITY

INTENSITY

150 MeV

120 MeV

20

$\lambda(\text{nm})$

30

INTENSITY