

SEARCH FOR PROMETHIUM-LIKE GOLD LINES AND OTHER TRANSITIONS OF INTEREST TO FUSION RESEARCH*

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EUV spectra in the range $\lambda = 13\text{--}40$ nm were measured for foil-excited gold ions at 31–238 MeV. Data were 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.

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].

Alkali-like 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 ref. 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 promethium-like isoelectronic sequence was reported [9]. Hartree-Fock calculations [10] showed that for $Z \geq 74$, ions isoelectronic to Pm are alkali-like with a ground-state configuration of $4f^{14}5s$, and that the 5s–5p doublet lines in the range $\lambda = 10\text{--}40$ nm are the dominant transitions. The leading relativistic corrections to the wavelengths were calculated using the Pauli approximation. For the $5s\ ^2S_{1/2}\text{--}5p\ ^2P_{1/2,3/2}$ 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 ps, 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

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

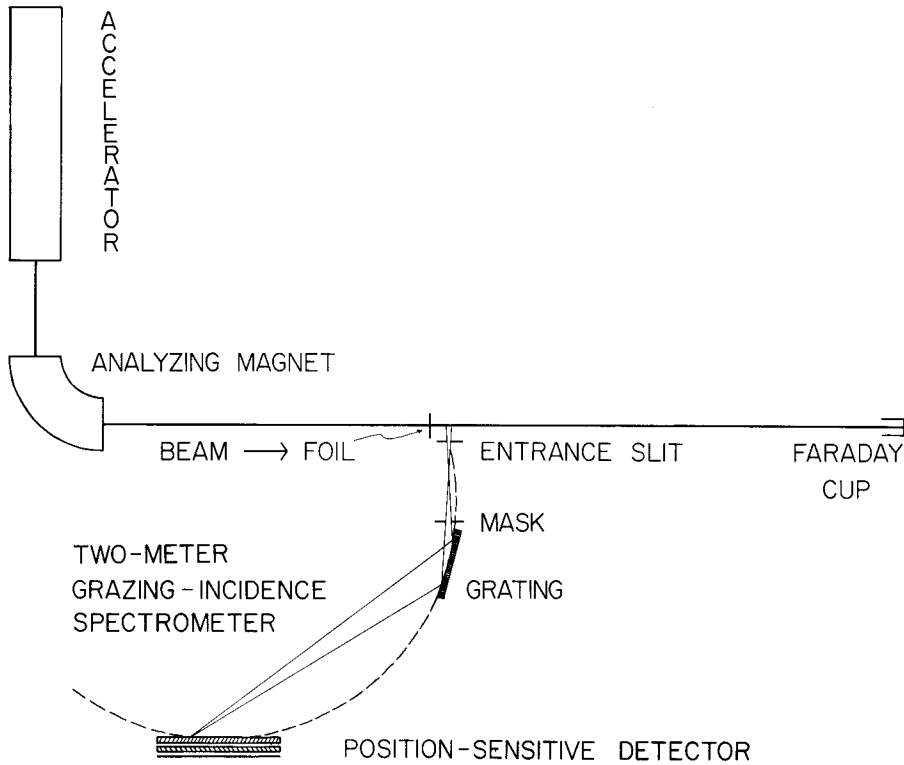


Fig. 1. Schematic representation of the experimental arrangement used to measure beam-foil spectra.

[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 $100 \mu\text{m}$, 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 $100 \mu\text{m}$. 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 $50 \mu\text{m}$ entrance slit is required. Only the central 2–3 nm of each PSD spectrum was used, because of diminished detection ef-

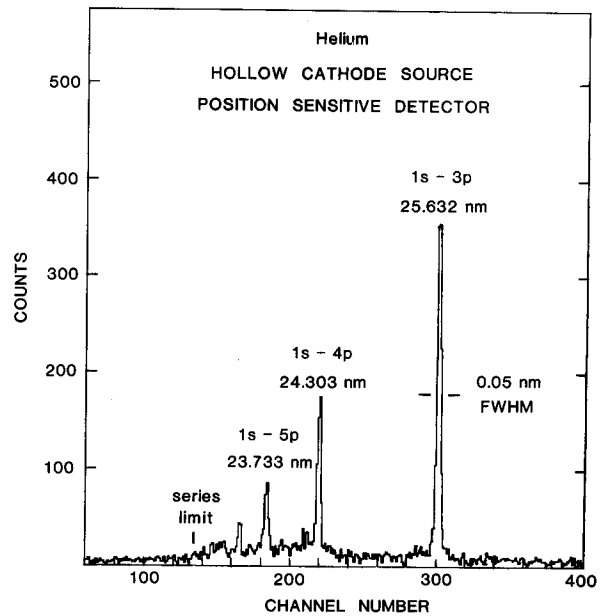


Fig. 2. EUV spectrum of the $1s-np$ lines of He II produced by hollow-cathode discharge source, which was built into the experimental chamber opposite the entrance slit of the spectrometer.

iciency 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

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

where Z is the nuclear charge, v is the beam velocity, and the constants are $v' = 3.6 \times 10^8$ cm/s, $\alpha = 0.45$, 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 eq. (1). The distribution of charge states $F(q)$ is approximately Gaussian and to within 20% is given by

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

with the width d given by

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

For gold ions at 39 MeV, eq. (1) predicts that the desired promethium-like 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 eq. (1). A somewhat lower beam energy of 31 MeV was therefore selected.

To confirm that an appreciable fraction of pro-

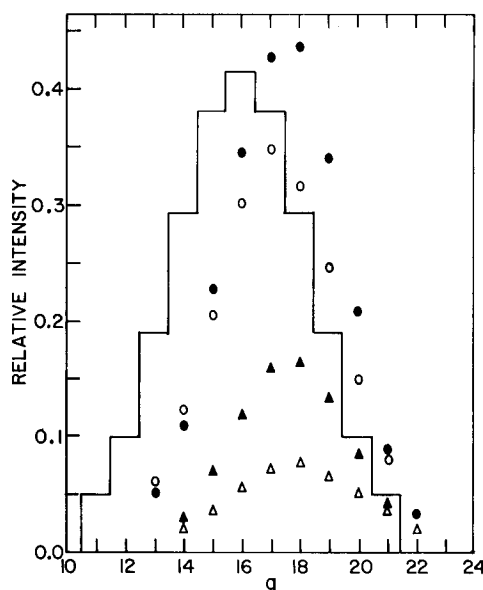


Fig. 3. Measured charge-state distributions for gold ions emerging from $20\ \mu\text{g}/\text{cm}^2$ carbon (closed circles) and aluminum (open circles) and $100\ \mu\text{g}/\text{cm}^2$ carbon (closed triangles) and aluminum (open triangles) foils. The relative particle currents are plotted vs charge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

methium-like ions was produced at 31 MeV, charge-state distributions were measured for 20 and $100\ \mu\text{g}/\text{cm}^2$ carbon and aluminium 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 eq. (2). The predicted $\bar{q} = 16$ from eq. (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 promethium-like 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 $\lambda = 3\text{--}8$ nm.

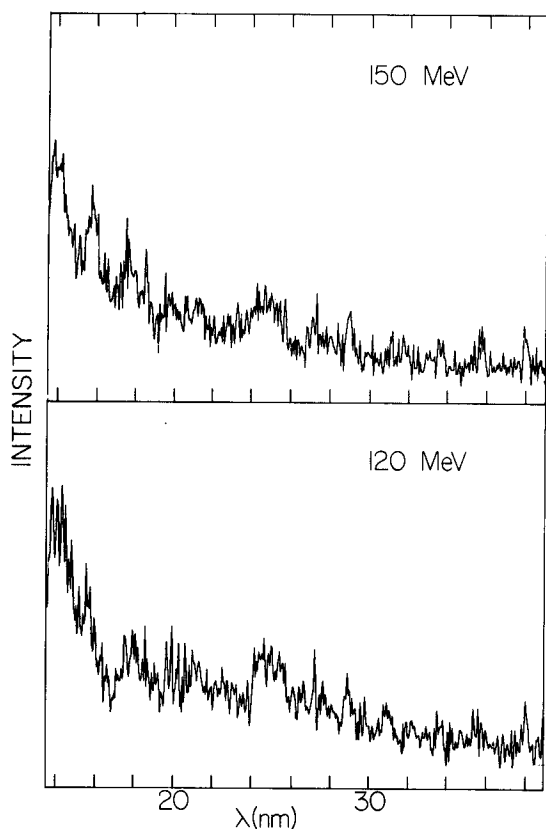


Fig. 4. EUV spectra for foil-excited gold ions at 150 and 120 MeV.

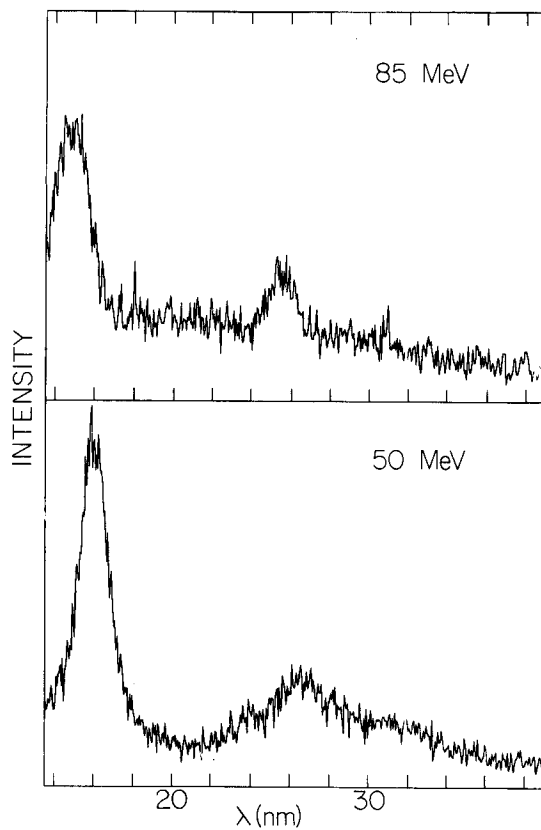


Fig. 5. EUV spectra for foil-excited gold ions at 85 and 50 MeV.

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 ref. 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 [18] 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 analog 3s–3p and 4s–4p transitions in lighter elements such as Ni, 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

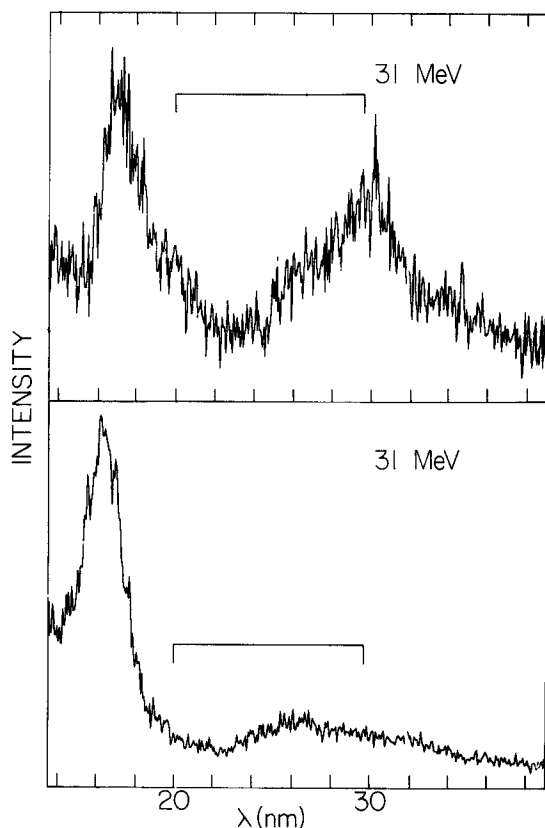


Fig. 6. EUV spectra for gold ions at 31 MeV excited by 20 $\mu\text{g}/\text{cm}^2$ carbon (upper spectrum) and aluminum (lower spectrum) foils. The predicted positions (from ref. 9) of the $5s\ ^2S_{1/2}-5p\ ^2P_{1/2,3/2}$ transitions in promethium-like gold are indicated.

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 alkali-like [9].

These apparent failures to observe strong alkali-like resonance lines in Au XIX in the predicted wavelength region under both beam-foil and tokamak excitation conditions raise interesting theoretical and experimental questions. By analogy with the copper isoelectronic sequence, it is expected that ions of the promethium sequence should assume an alkali-like 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 alkali-like 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 alkali-like lines first become prominent would provide a valuable benchmark 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 .

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Discussion

Sellin: What is the position resolution of your position sensitive detector and what is its dynamic range? What I mean by that is, if you have two lines, one very bright and one very dim on the surface of the detector at the same time, what is the intensity ratio over which you can operate and the third question is, what is the maximum counting rate you can achieve averaged of the entire face of the detector?

Johnson: I can not give you an exact answer to all three of those questions, especially the last one. We have only looked at beam-foil sources with this, and with a hollow cathode source that is reduced to be comparable to a beam-foil source. So we

have never run it at very high counting rates to determine what the maximum counting rate is. The position resolution in the helium spectrum that I showed, we can achieve with 25 μm entrance slits. We get about 0.5 \AA resolution. That is the entire spectrum on the 25 mm, so it is 1/400th of 25 mm for the resolution of a peak full-width at half-maximum. In terms of the bright and weak lines on the source at the same time, as near as we can tell, the counting rate is independent because again we have very weak sources. So our count rate in one place on a microchannel plate is not dependent on a high counting rate in another place. As you get to brighter sources that may be a problem, but for the purposes of beam-foil spectroscopy it seems to be very adequate.

Sellin: Would the lines get narrower if you narrowed your slit width further?

Johnson: As narrow as we can go with our slit widths in our particular experiment, which is down to 10 μm , these do not narrow appreciably. The set-up that this was taken in is probably at the limit of the electronic and microchannel plate resolution. Gene Livingston might be able to address your questions based on his work with position sensitive detection.

Livingston: 50 μm .

Lennard: With regard to Ivan's [Sellin] question there is a chap right down the hall by the name of J.D. Carette who can probably tell you about count rate limitations of microchannel plate detectors since he fabricates them himself. I think it is determined by resistivity per channel and that there is some limit that that puts on it.

Martinson: You mentioned that you have a better agreement with theory when it comes to Si-like systems than for Mg-like or Al-like systems. I think the reason might be that in the Si-like case you do not have $\Delta n = 0$ or $\Delta n = 1$ cascades, and of course they go down very promptly, so that you have much cleaner conditions, while in the other two cases you have $\Delta n = 0$ cascading and this just stays throughout the sequence.

Johnson: Or it could be fortuitous.

Crossley: I think if I might make a comment of my own since you have been so generous in allowing that it is experimentalists who make all the mistakes. We theoreticians can take a little of the strain. Particularly I am thinking of what Alan Hibbert said this morning about polarisation effects in the larger ions. Taking those into account would make a worthwhile difference to the theoretical results, especially in the copper sequence.