Applications of EBITs to Spectra of Multi-Electron Ions, some Solved and some Unsolved Problems

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20 Years of Spectroscopy with the
Electron Beam Ion Trap

November 12 - 16, 2006
Berkeley, California

outline

a) X ray Spectroscopy of highly charged but multi-electron Barium, and some side issues

b) Spectroscopy of Pm-like Tungsten, is this a multi-electron system or not ?

a) X ray spectroscopy of highly charged but multi-electron Barium, basically N-, O- and F-like Ba

This study was done using the original Livermore EBIT

how was this study done and what was the aim ?

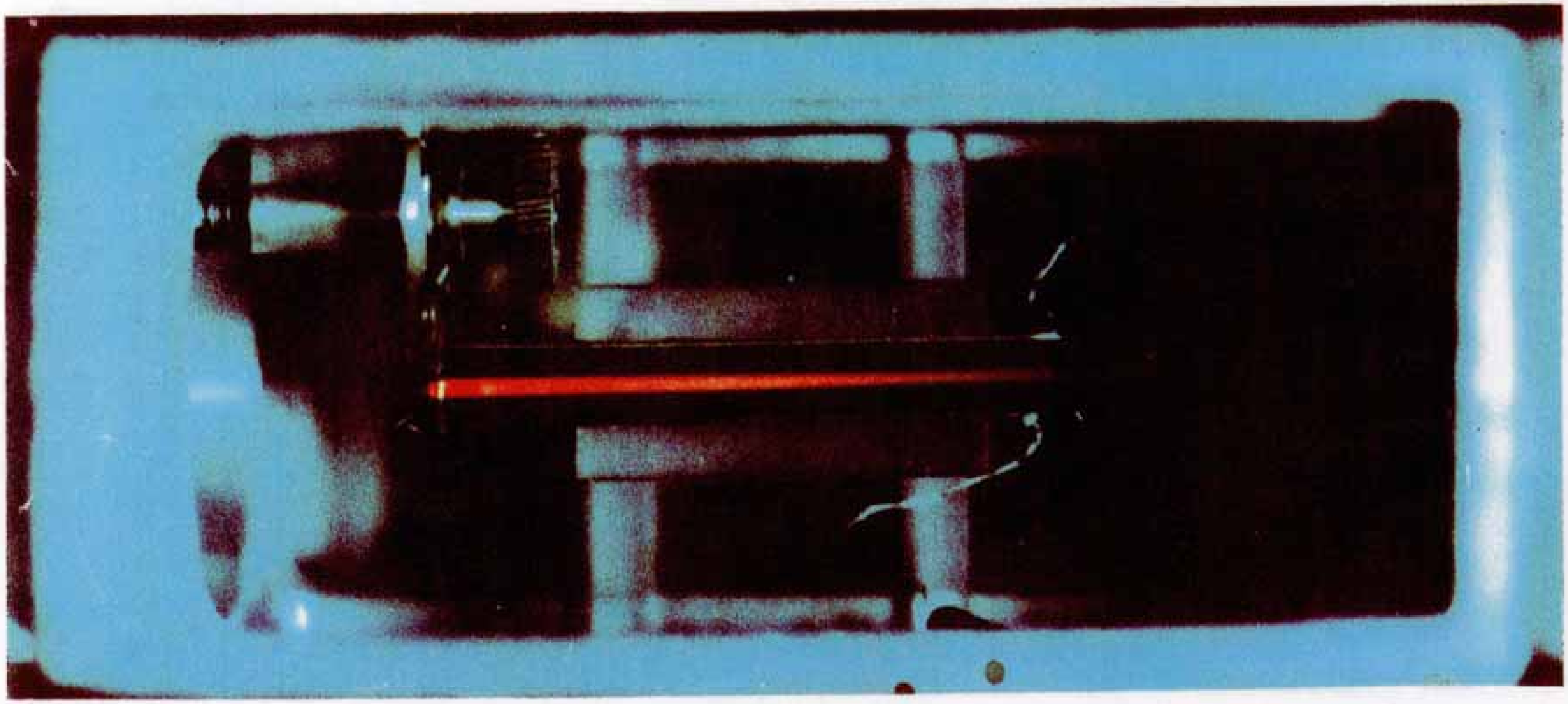
Barium is just there !!!

Sometimes Tungsten is there too !

Special features of the experiment

(1) X ray spectra were recorded using a von Hamos type crystal spectrometer with a resolution ($\lambda/\delta\lambda$) of around 2500

(2) Elements to provide calibration lines were injected into the EBIT from a MEVVA.



Beam-Foil Spectroscopy

Spectra were recorded at 4 different crystal settings,

covering an x ray energy region of 4.45 to 5.8 keV (or 2.1378 – 2.7863 Å).

The energy regions, of course, overlapped allowing a full spectrum to be constructed.

1838 R. HUTTON *et al.* 44

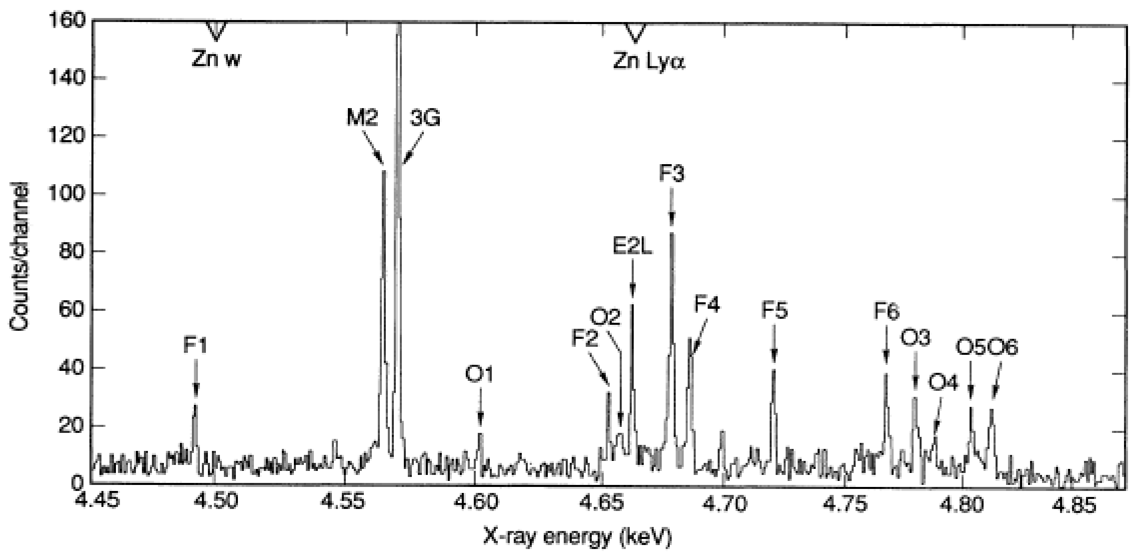


FIG. 1. Spectrum of barium in the region 4.45–4.85 keV. This region contains $3s_{1/2} \rightarrow 2p_{3/2}$ electric dipole transitions as well as several core-changing transitions. F-like lines are denoted by F, O-like lines by O. M2, 3G, and E2L denote Ne-like lines. Line N1 is not seen because of vignetting. The positions of the lines of He-like zinc (w) and H-like zinc (Ly-α) are indicated. The lines are observed in second order and serve as calibration lines.

Physical Review **A44,** 1836 (1991)

Core changing transitions ?

transition	wavelength, Å	
$(2s2p^2_{1/2}2p^4_{3/2})_{1/2}-(2p_{1/2}2p^3_{3/2}3p_{1/2})_{3/2}$	2.76135	
$(2s2p^2_{1/2}2p^4_{3/2})_{1/2}-(2s2p^2_{1/2}2p^3_{3/2}3s)_{3/2}$	2.66507	2p – 3s

The upper transition looks like a two electron-one photon transition !

Such transitions had been seen earlier by Chandler et al. using beam-foil spectroscopy here in Berkeley.

(Phys. Rev. Lett. 61, 1186 (1988))

In total 4 elements were injected from the MEVVA ion source to calibrate this spectral region

TABLE I. Calibration line energies used in the experiment. The values for the He-like resonance line $1s2p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, denoted w, are taken from calculations by Vainstein and Safranova [29] and are adjusted by an empirical correction found in [30]. The values for the hydrogenic $2p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$ Ly-α_1 lines are taken from [28]. All values are in eV.

Element	Ly-α	w
Ti	4976.89	
V	5443.63	5205.33
Cr		5682.32
Zn	9318.48	8998.97

The Zn lines were used in second order, otherwise they seem a little out of place here.

What were the results of this work ?

No of holes in The 2p shell	average energy difference between expt. and theor. (eV)
1	1
2	2
3	3

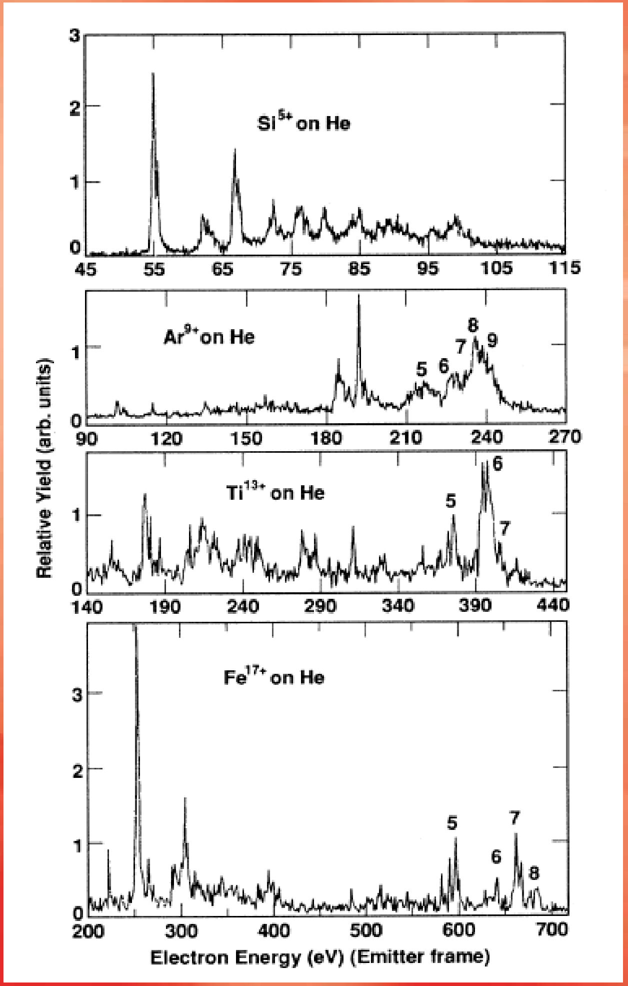
As a side issue, and a re-surfaced problem …

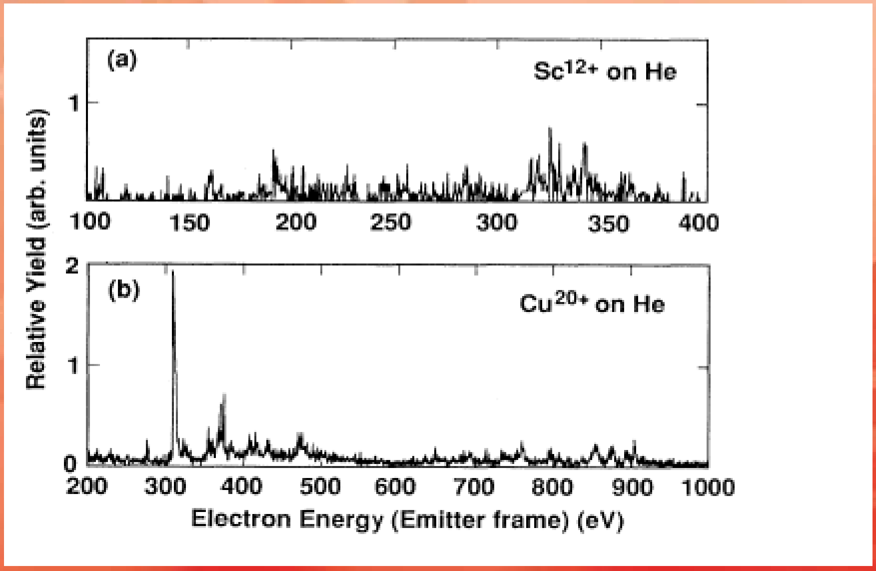
The spectroscopy of core-excited Na-like ions, this was recently brought back to life by John Tanis because of a famous $^4D_{7/2}$ level ($2p^5 3s3p\ ^4D_{7/2}$).

The level was studied here in Berkeley using the ion-atom collision set up at the ECR source at the 88 inch cyclotron.

The $^4D_{7/2}$ level is forbidden to decay via photo emission and forbidden to Coulomb Auger decay

The interesting thing about the work on this level is that it appears to show that hyperfine induced transitions decay faster than the calculations predict





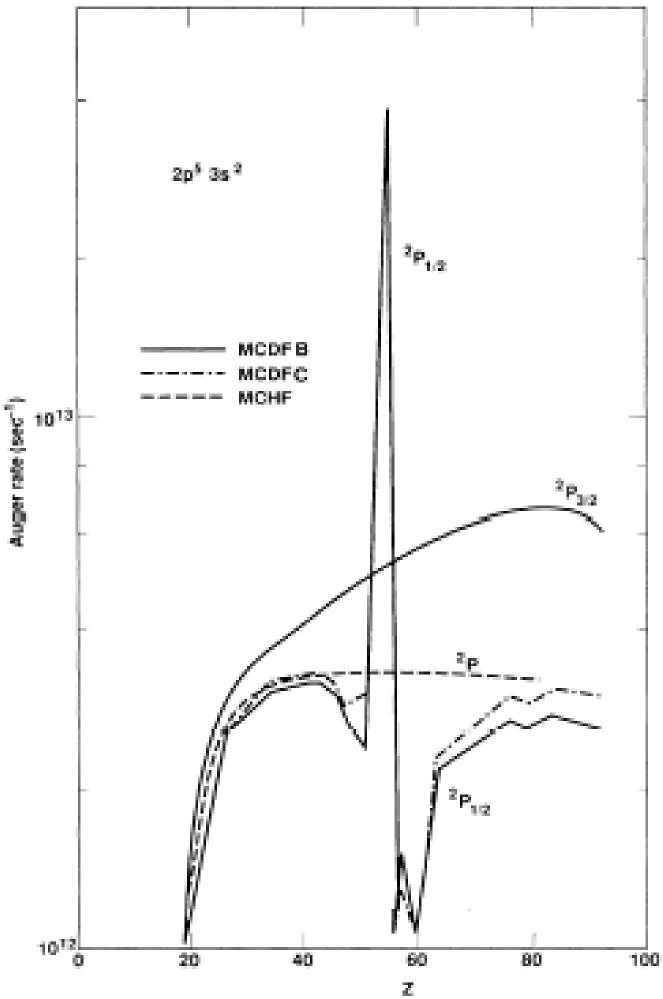


FIG. 2. Calculated Auger rates for the $2p^5 3s^2\,{}^2P$ states as functions of atomic number. The solid curves indicate the results from the MCDF calculations with the Coulomb and Breit interactions for the Auger operator. The dash-dotted curves represent the values from the MCDF calculations with the Coulomb operator only. The dashed curve displays the predictions from the nonrelativistic multiconfiguration Hartree-Fock model. The curves are labeled by the initial states of the transitions. For the $2p_{3/2}$ state, MCDFC coincides with MCDFB.

Auger rates for the $2p^5 3s^2\ {}^2P$ levels of Na-like ions, 1< Z < 92, from M.H, Chen

The $2p^5 3s^2\ {}^2P$ levels can also x ray decay.

b) Tungsten spectroscopy

i) Tungsten may be interesting for fusion diagnostics

Other speakers have/will mention this

ii) Also fits in the category of unsolved mysteries

Alkalilike Spectra in the Promethium Isoelectronic Sequence

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(Received 23 July 1980; revised manuscript received 10 November 1980)

Highly ionized members of the Pm sequence should produce strong resonance lines in the uv spectra of hot plasmas contaminated by heavy elements. These ions for $Z \geq 74$ have an alkali structure with ground configuration $4f^{14}5s$. Hartree-Fock calculations show that in W XIV through U XXXII the dominant resonance lines are the $5s$-$5p$ doublets in the range $\lambda = 100$–400 Å. Approximate predictions are given for the doublet wavelengths, line strengths, and mean lives.

Phys. Rev. Lett. 45, 2099 (1980)

Pm is Z = 61

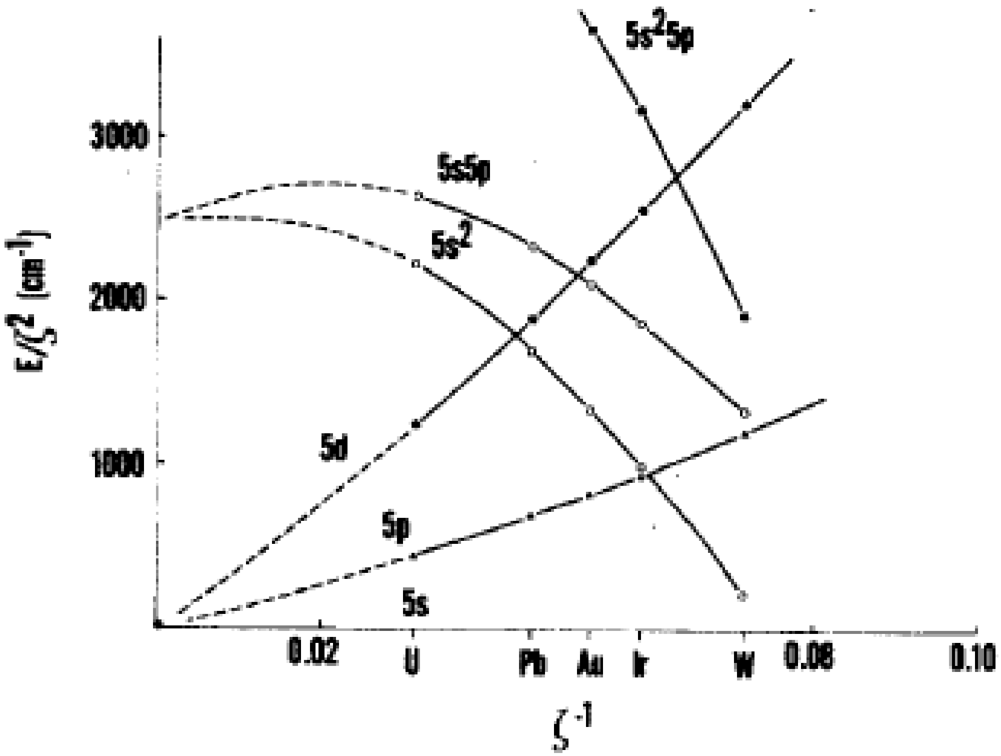


FIG. 1. Configuration energies in the promethium isoelectronic sequence. E/ζ^2 is plotted against $1/\zeta$, where $\zeta = Z - 60$ is the core charge and E is the average energy of the configuration above the ground-state configuration $4f^{14}5s$. These energies are the results of single-configuration Hartree-Fock calculations with no relativistic corrections. Triangles, $4f^{14}5p$; filled circles, $4f^{14}5d$; open squares, $4f^{13}5s^2$; open circles, $4f^{13}5s5p$; filled squares, $4f^{12}5s^25p$.

TABLE III. $5s\ ^2S$–$5p\ ^2P$ lines in Pm sequence.

Z	Spectrum	Line	λ (Å)	τ (ps)	S (a.u.)
74	W XIV	1/2–1/2	379	80	1.16
		1/2–3/2	277	31	
77	Ir XVII	1/2–1/2	325	63	0.96
		1/2–3/2	226	20	
79	Au XIX	1/2–1/2	297	56	0.86
		1/2–3/2	199	16	
82	Pb XXII	1/2–1/2	263	47	0.73
		1/2–3/2	166	11	
92	U XXXII	1/2–1/2	186	31	0.47
		1/2–3/2	96	4	

From Curtis and Ellis

Phys. Rev. Letts, 45 2099 (1980)

TABLE II. $5s\ ^2S-5p\ ^2P$ lines in the *Pm* sequence.

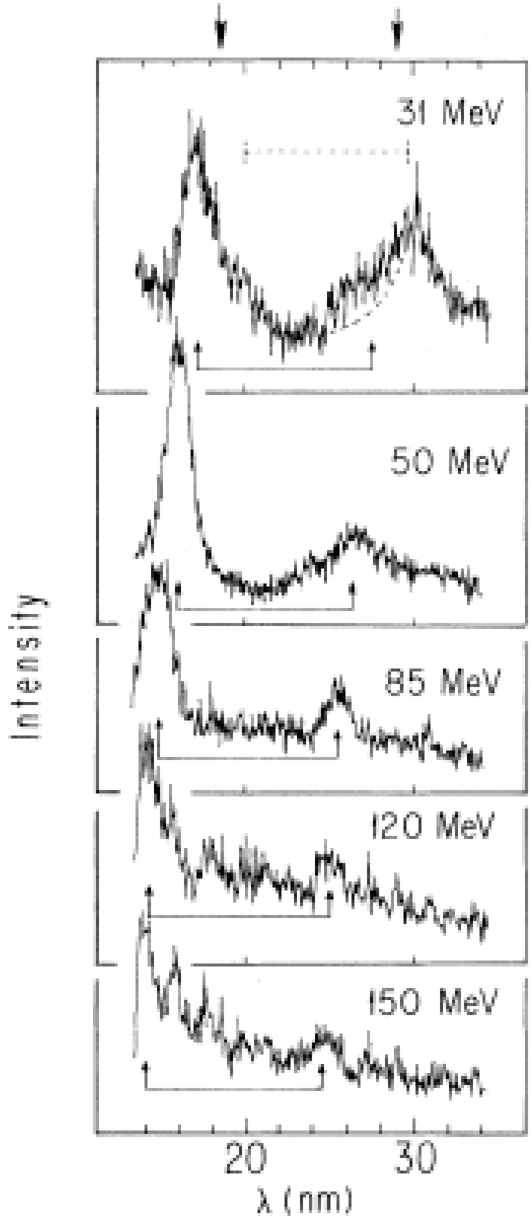
Z	Spectrum	Line	λ (Å) HF	HFP[a]	DF
74	W XIV	$\frac{1}{2}$-$\frac{1}{2}$	376.49	379	370.79
		$\frac{1}{2}$-$\frac{3}{2}$	284.26	277	262.42

Theodosiou and Raftopoulos

Phys. Rev. **A28**, 1186 (1983)

Theodousiou's predictions

1188



Experimental work

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

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Nuclear Instruments and Methods 202 (1982) 53–58

FIG. 3. Experimental spectra obtained by colliding 31- to 150-MeV gold ions on carbon foils (adapted from Ref. 5). The two large arrows at the top of the figure indicate the $5s\,^2S - 5p\,^2P$ line wavelengths predicted by the DF approximation. The dotted line indicates the HFP predictions (from Ref. 1). The solid lines ending in the two arrows give the predicted DF line separation *shifted* to overlap with the experimental lines. The energy *splittings* are seen to agree very well.

Another Experiment, also Beam-Foil

Tentative Identification of the $5s-5p$ Transitions in Pm I-Like Au XIX

Z. Phys. D1, 381 (1986)

E. Träbert and P.H. Heckmann

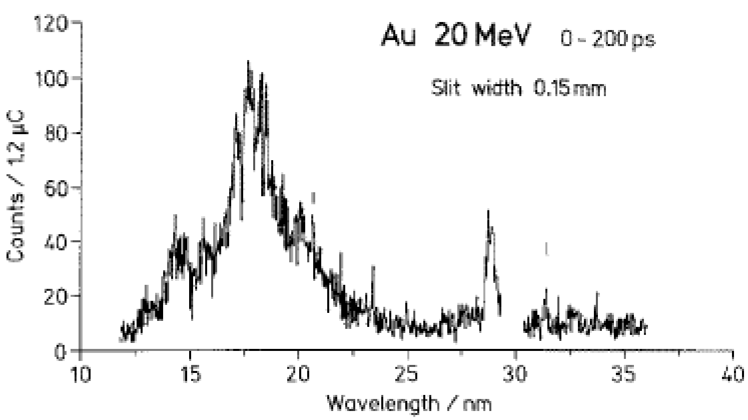


Fig. 1. Spectrum of Au at 20 MeV ion energy with the spectrometer viewing at the foil and at the first about 200 ps of the decay. Line width (FWHM) 0.12 nm. The gap near 30 nm is due to a foil breakage detected too late

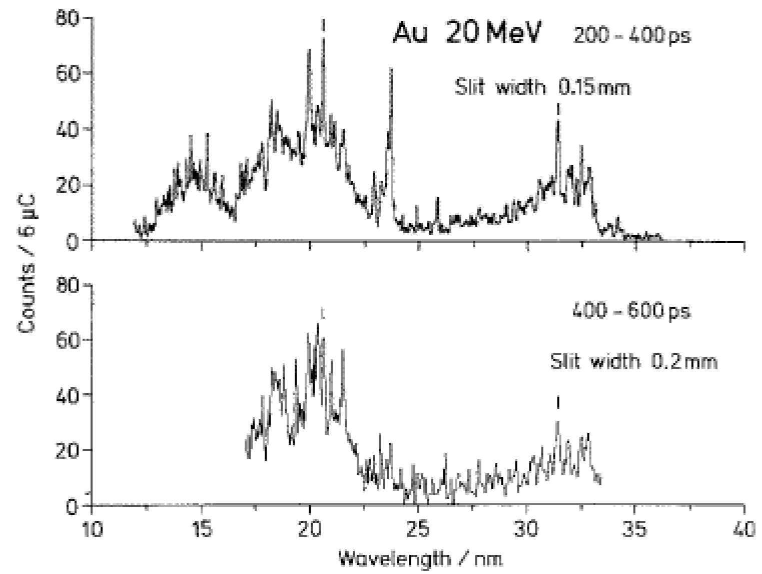


Fig. 2a, b. Spectrum as in Fig. 1. **a** Flight time interval 200–400ps. Line width 0.12 nm. **b** Flight time interval 400–600 ps. Line width 0.15 nm (wider spectrometer slits)

Results from the work by Trabert and Heckmann

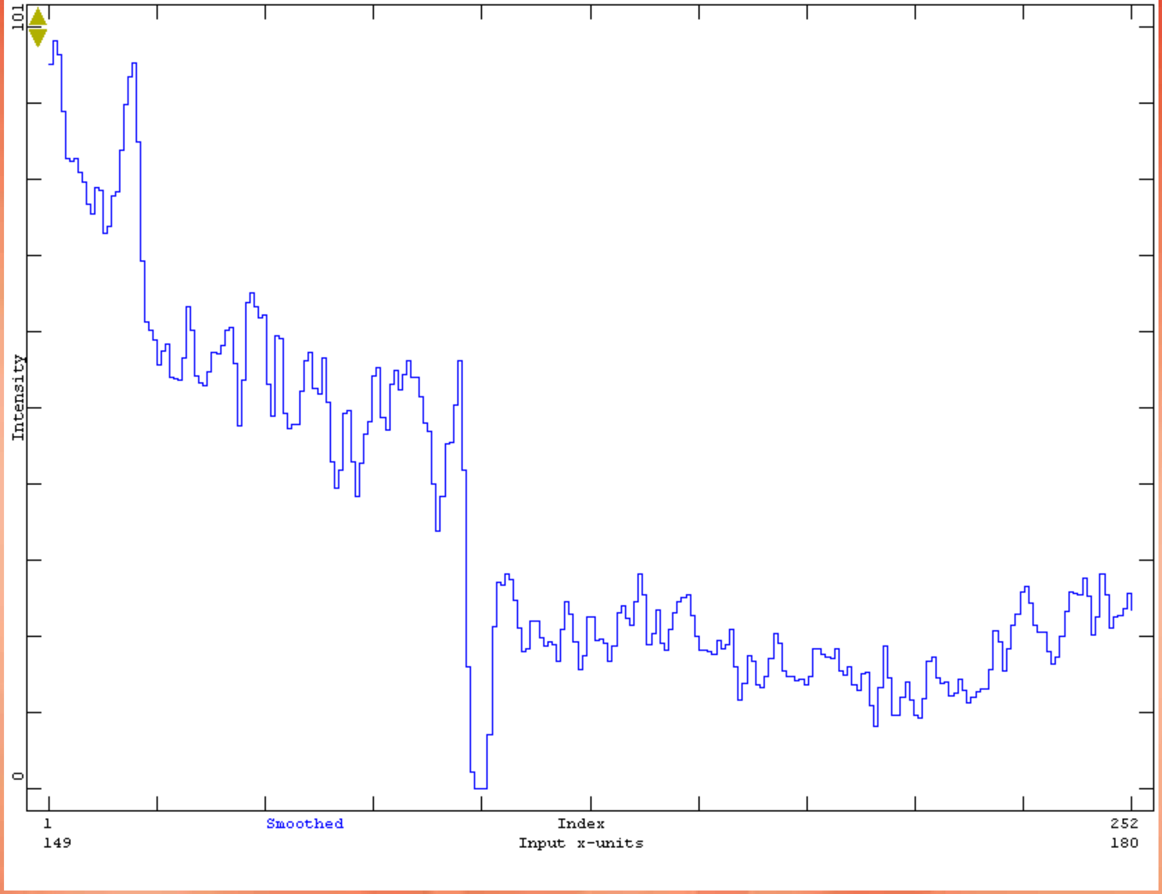
Rel. intensity	Wavelength (nm)		Tentative identification
	This work	Theory	
60	19.88		
65	19.97		
45	20.32		
67	20.58	19.9 [1] 18.643 [5]	Au XIX $5s$-$5p_{3/2}$
40	20.93		
38	21.12		
25	21.39		
30	21.50		
30	23.56		
50	23.72		
37	31.37	29.7 [1] 29.033 [5]	Au XIX $5s$-$5p_{1/2}$
25	31.86		
25	32.00		
32	32.47		
20	32.82		

Of course, if Pm-like ions show such interesting behavior, it is likely that systems close to Pm-like, such as Sm-like, may also show such properties, e.g. for highly ionized members we may expect Mg-like characteristics, i.e $5s^2\ {}^1S_0 - 5s5p\ {}^{1,3}P_1$ transitions..

At least one search for this has been undertaken (Kaufman et al, Physica Scripta 42, 75 (1990))

"Search for intercombination lines in few-electron spectra of rare-earth sequence ions of Os through Au"

Other experiments to verify this interesting collapse



wavelength

Unpublished beam-foil spectrum of 30 MeV Lead from RIKEN

Experiments other than beam-foil ?

There was one interesting attempt to find these lines using electron capture from He atoms to Pb^{22+} and Pb^{23+} ions.

These experiments were done using the ECR facility in Grenoble, unfortunately the results were negative.

The experimental set up was verified using an oxygen beam, but no lines from the lead beams were seen.

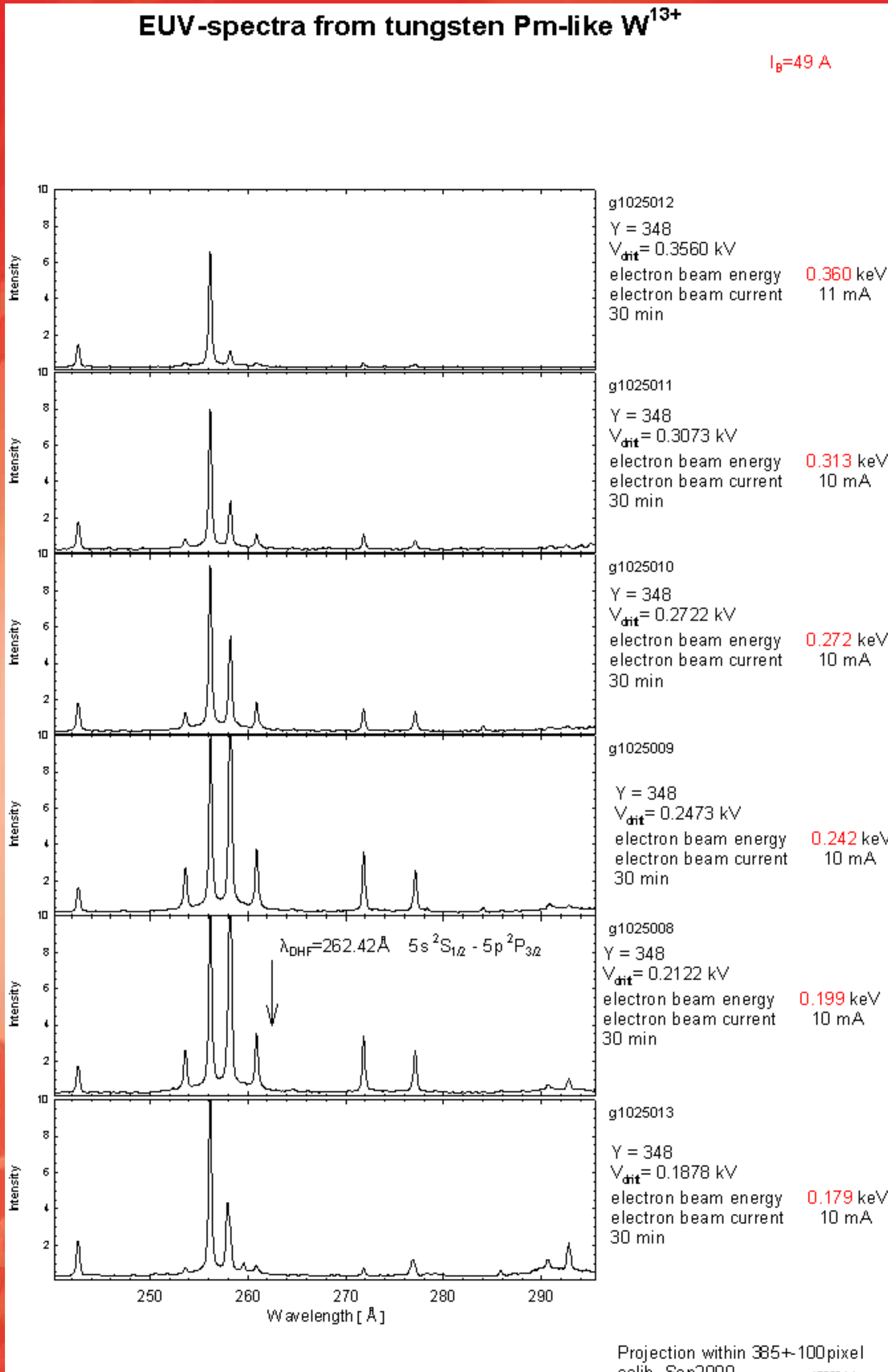
So, the situation surrounding these interesting lines remained unclear.

EBIT experiments

The idea was that, as most excitation in EBITs goes via electron impact, that EBIT spectra of such possibly complex systems could be simpler.

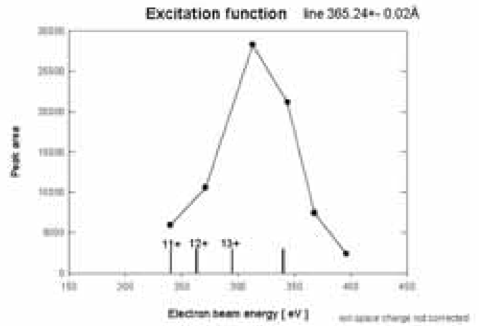
The experiment used W, as that is inherent in most EBITs, and required a rather low electron beam energy, which in turn means also a low beam current, but it turned out that the experiment was indeed possible.

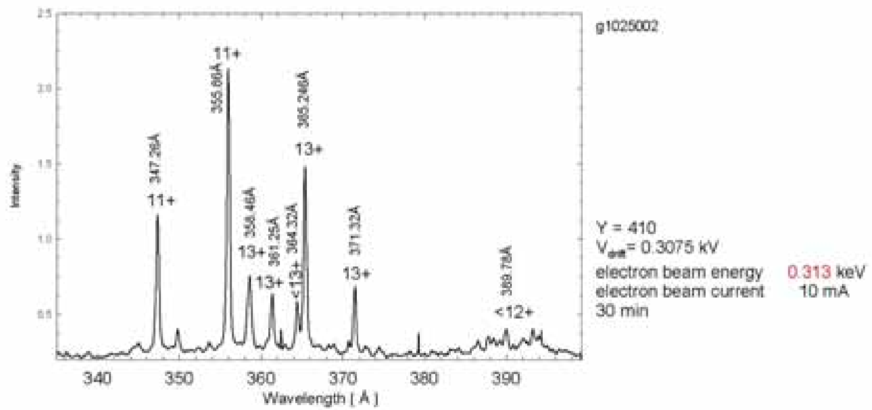
Lower charge states have higher electron impact cross sections, so the lower current is compensated

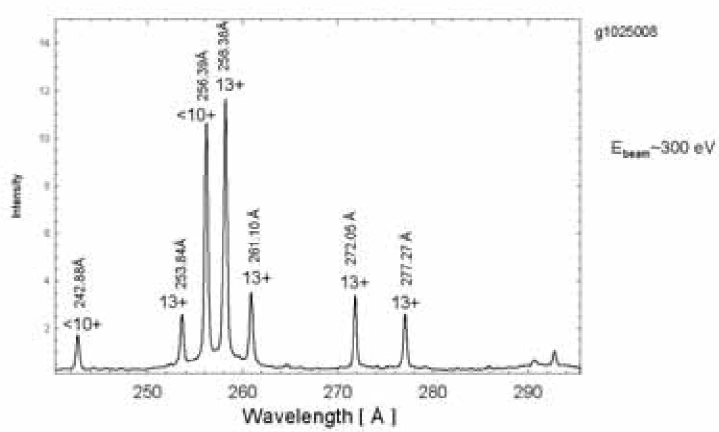


Spectra of Tungsten taken at the Berlin EBIT as a function of the electron beam energy

Spectra recorded using a Schwob 2 meter grazing incidence instrument and a multi-channel detector







Spectra for the wavelength regions of both the $^2P_{1/2}$ and $^2P_{3/2}$ transitions

And an excitation function, i.e. line intensity vrs electron beam energy

One other thing that is fairly well know and can be used, the fine structure separation.

The current situation

Table 1
A comparison of wavelengths for the 5s ^2S–5p ^2P doublet transitions for a number of Pr-like lines (a; 1/2–1/2, b; 1/2–3/2)

	Ion	DF wavelength	Present calculation	Experimental wavelength
W	a	370.79	366.2	365.3
	b	262.42	263.7	258.2
Ir	a	319.21	313.8	
	b	212.38	213.4	
Au	a	290.33	285.9	313.7
	b	186.43	186.8	205.8
Pb	a	255.70	251.5	
	b	154.98	154.5	153.0
U	a	179.63	175.1	175.4
	b	87.25	86.2	

The DF results are from [18]. The present calculated results are single configuration calculations done using the Cowan code [16]. The experimental wavelengths agree quite reasonably with both calculations for the case studied here, namely Pm-like W. Wavelengths are in Å, with an uncertainty of around 0.2 Å. The Au wavelengths are from [2], where the wavelength uncertainly is around 0.3 Å. The Pb wavelength for the 1/2–3/2 transition is from an unpublished beam-foil study [22]. Unfortunately it was not possible to accurately calibrate the spectrometer in this Pb experiment and therefore a conservative error of 1 Å is given. The U wavelength for the 1/2–1/2 transition is from [4] where the line identifications were given as tentative. The work here supports the identification for U in [4].

Following the good agreement between the EBIT spectra and the calculated wavelengths for the Pm-like resonance lines, an attempt to find these lines in ASDEX Upgrade tokamak spectra was undertaken. Spectra were recorded using a 2.2 m-grazing incidence spectrometer centered at the predicted wavelengths with similar line dispersions as in the EBIT spectra. These spectra are still under investigation, however there are interesting coincidences between the EBIT and the tokamak spectra, unfortunately there are some line blending problems which make identification in the tokamak more troublesome.

A little optimistic …

Basically these lines, if we could really find them, may not be of interest in fusion diagnostics.

Such relatively low charges states of high Z elements exist only in a very thin shell of the plasma, under normal operating conditions, and hence produce very weak spectral lines.

Although these Pm-like lines are interesting from an atomic structure point of view, they may be of limited value in plasma diagnostics.

Summary:

We have discussed:

(a) some early EBIT experiments on the spectroscopy of multi-electron Barium, and seen a few similarities with work done using other methods

(b) Discussed the interesting atomic structure of 61 electron tungsten

Physics at EBIT and Advanced Research Light sources

Pearl2007 in Shanghai, China, 8th-12th March 2007

Tentative speaker list

Klaus Bartschat

Klaus Blaum

Henrik Cederquist

Siegbert Hagmann

Takako Kato

Eva Lindroth

Rudolf Neu

Nobuyuki Nakamura

Reinhold Schuch

Thomas Stoehlker

Christoph Biedermann

Joachim Burgdoerfer

Fred Currell

Paul Indelicato

Leonti Labzowski

Robert Moshammer

Masaki Oura

Joachim Ullrich

Joshua Silver

Yasunori Yamazaki

Organiserse

Prof. Yaming Zou, Fudan University

Prof. Roger Hutton, Fudan University

Dr. Tomas Brage, Lund University

Pearl2007 website

www.pearl2007.fudan.edu.cn

Thank you !