More Complex, \( W^{25+} \), which is In-like. There are now 41 fine structure levels belonging to the ground “state”.

A partial energy level diagram of In-like tungsten. The energy levels are taken from our RMBPT calculations. Highest levels are close to 28 eV. For convenience we show levels up to only 12 eV as the higher energy levels will not contribute to observable spectral lines.
Comparison of our results with other data

### W\(^{27+}\)

<table>
<thead>
<tr>
<th>Transition</th>
<th>(^{5}\text{d}^{10}\text{f})</th>
<th>(^{5}\text{d}^{10}\text{f})</th>
<th>(^{2}\text{F}_{5/2} \rightarrow ^{5}\text{d}^{10}\text{f})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed (SH-EBIT)</td>
<td>29599.81</td>
<td>(3377.43±0.26 \text{ Å})</td>
<td>29570</td>
</tr>
<tr>
<td>MCDF (SH-EBIT)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RMBPT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPTMP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MCDF(Ding)</td>
<td>29151</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADAS (arf40_ic#w27)</td>
<td>28823.4 (60951a)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### W\(^{26+}\)

| Transition          | \(^{5}\text{d}^{10}\text{f}\)  | \(^{5}\text{d}^{10}\text{f}\)  | \(^{2}\text{F}_{5/2} \rightarrow ^{2}\text{D}_{3/2} \rightarrow ^{2}\text{D}_{5/2} \rightarrow ^{1}\text{G}_{4}/^{2}\text{F}_{3} \rightarrow ^{2}\text{H}_{4} \rightarrow ^{2}\text{F}_{3} \rightarrow ^{2}\text{F}_{5} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} \rightarrow ^{2}\text{F}_{1} \rightarrow ^{2}\text{F}_{2} | |
|---------------------|-----------------|----------------|------------------------------------------------|
| Observed (SH-EBIT)  | 2632.61±0.12    | 2918.90±0.11*  | 3337.48±0.09*                                   |
| GRASP (SH-EBIT)     | 2578            | 2916           | 3339                                           |
| FAC (SH-EBIT)       | 2649.7          | 2923.2         | 3332.4                                         |
| Other works         | --              | --             | --                                             |
| ADAS (arf40\_ic#w26)| 2663.1 (60952a)| 2947.8 (60952a)| 3436.6 (60952a) (60952a)                        |

### W\(^{25+}\)

| Transition          | \(^{5}\text{d}^{10}\text{f}\)  | \(^{5}\text{d}^{10}\text{f}\)  | \(^{2}\text{I}_{11/2} \rightarrow ^{2}\text{I}_{9/2} \rightarrow ^{2}\text{I}_{3/2} \rightarrow ^{2}\text{I}_{11/2} | |
|---------------------|-----------------|----------------|------------------------------------------------|
| Observed (SH-EBIT)  | 4938.4±1.5      | 5878.3±2.0     | 5889.0                                         |
| GRASP (SH-EBIT)     | 5049.0          | 5881.3         | 5881.3                                         |
| RMBPT               | 4946.6          | 5881.3         | 5881.3                                         |
| ADAS (arf40\_ic#w25)| 5087.6 (60953a)| 5860.3 (60953a)| 5860.3 (60953a) (60953a)                       |
Future tungsten work

$W^{27+}$ has 1 f electron outside a closed shell, $W^{13+}$ is one f hole.

$W^{25+}$ has 3 f electrons, $W^{17+}$ has 3 holes in the 4f shell.

So, similar structure is expected between, for example, $W^{25+}$ and $W^{17+}$

Electron impact experiments needs to think about this.
Alkalilike Spectra in the Promethium Isoelectronic Sequence

L. J. Curtis and D. G. Ellis

Department of Physics and Astronomy, The University of Toledo, Toledo, Ohio 43606
(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 XV 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.

For high enough \( Z \), \( 5s \, ^2S_{1/2} - 5p \, ^2P_{1/2, 3/2} \) lines should be strong, but what is high enough \( Z \) ?

For reference, Pm I has the structure \([Xe]4f^{5}6s^{2}6H_{5/2}\)

Old tungsten mystery

W^{13+}, Pm-like W

Bottom spectra are experimental from the Berlin EBIT (2000)
Top spectra are calculated (2013)

Note He II has lines at 256.32 Å and 243.03 Å
More calculations for Pm-like ions

PHYSICAL REVIEW A 88, 032512 (2013)

Contribution of the $4f$-core-excited states in determination of atomic properties in the promethium isoelectronic sequence

U. I. Safronova and A. S. Safronova
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P. Beiersdorfer
Physics Division, Lawrence Livermore National Laboratory, Livermore, California 94550, USA
FIG. 4. (Color online) Synthetic spectra (red) for the $[4f^{14}5s + 4f^{13}5s\,5p + 4f^{12}5s\,5p^2] \leftrightarrow [4f^{14}5p + 4f^{13}5s^2 + 4f^{12}5s\,5p]$ transitions in Pm-like W$^{13+}$ (top) and Pm-like Au$^{18+}$ (bottom). A resolving power $R = E/\Delta E = 400$ is assumed to produce a Gaussian profile (blue).

These atomic data are particularly important for fusion research where tungsten is produced in low ionization stages.
What does Kramida say?

This does not mean that the 5s–5p transition cannot be observed.

However, according to our calculations, this transition should be weaker than multiple lines of the $4f^{13}5s^2$–$4f^{13}5s5p$ and $4f^{12}5s^25p$–$4f^{12}5s5p^2$ transitions dominating the spectrum in this region.

Therefore, the identifications of Hutton et al. should be considered as tentative at this time.
The effect of magnetic fields on atomic structure

Not only Zeeman splitting and hence broadening!

P. Beiersdorfer et al., PRL. 90, 235003 (2003)

Figure 8: Spectrum of the $\text{Ar}^+\,2p \rightarrow 3s$ emission at an electron density of $n \approx 1.25 \times 10^{10}$ cm$^{-3}$ measured on EBIT-I. The lines are labeled using the notation defined in Fig. 7.
Our work on this subject:

Theoretical results for $2p^53s\,^3P_{0,2}$-$2p^6\,^1S_0$ E1 transitions in Ne-like ions (zero nuclear spin) between Mg III and Zn XXI, also Ne I.

Both “perturbing” states $2p^53s\,^1P_1$ and $2p^53s\,^3P_1$ in order to produce reliable transition rates.

For $2p^53s\,^3P_0$ the magnetic-field-induced transition is the dominant decay for the light elements, even in a relatively weak magnetic field.

Magnetic field effect on the lifetimes of $2p^53s\,^3P_{0,2}$ states of neutral $^{20}$Ne. Lifetimes are drastically reduced by a magnetic field. May be reason for the discrepancies in the lifetime of the $2p^53s\,^3P_2$ state between experiment [14.73(14) s] and theory (17.63 s).

More effects of magnetic induced transitions

Heavy ion storage rings confine the ions to the ring using magnetic fields

Recently E1M1 two photon decay measurements were proposed at GSI for the 2s2p $^3P_0$ level in Be-like ions.

Magnetic field will induce an E1 transition to the ground state and the transition rate needs to be considered.
Magnetic induced transitions in Cl-like ions
Summary

EBITS have important uses in assisting plasma diagnostics

Providing Atomic Data

Looking for Magnetic Sensitive Lines
Thank you for attention!
5th International Workshop on the Physics at EBITS and Advanced Research Light sources, PEARL 2014

May 2nd – 5th, Fudan University, Shanghai, China

Organizers: Baoren Wei, Yunqing Fu, Chongyang Chen, Roger Hutton and Yaming Zou

Contact: Baoren Wei at brwei@fudan.edu.cn

Speakers: Gordon Berry etc
Our first spectroscopic investigation using the permanent magnet EBIT was $\text{W}^{27+}$

The $\text{W}^{27+}$ ion has a relatively simple $^2F$ ground state and an M1 line connecting the lowest $^2F_{5/2}$ with the $^2F_{7/2}$ has already been the subject of some theoretical investigations.

This fine structure interval is also given in the comprehensive review of available tungsten data by Kramida and Shirai, however as will be discussed here, there are reasons to doubt the value quoted, which is a little problematic.
Energy levels and spectral lines of tungsten, W III through W LXXIV

A.E. Kramida\textsuperscript{a,}\textsuperscript{*}, T. Shirai\textsuperscript{b,1}

\textsuperscript{a}Atomic Physics Division, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8422, Gaithersburg, MD 20899-8422, USA
\textsuperscript{b}Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, 801-01 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan
The W III spectra in the region of 600–2680 Å were observed by Iglesias et al. [5] with a sliding-spark light source. They identified a total of 2636 lines as the transitions among 71 levels of the inter-

erly described by the $L_S$ term label. It has 39% of the $^2P^o$ character and 34% of $^4S^o$.

2.9. W XI

Gd I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{15}5s^25p^2$ $^3P_0$ 3
Ionization energy $1685000 \pm 10000$ cm$^{-1}$ (208.9 ± 1.2 eV) [4]
According to our calculations, the lowest excited levels belong to the $4f^{15}5s^5p^3$ configuration and are located approximately 46000 cm$^{-1}$ above the ground state.

2.10. W XII

Eu I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{15}5s^25p^2$ $^4P^{7/2}$
Ionization energy $1868000 \pm 10000$ cm$^{-1}$ (231.6 ± 1.2 eV) [4]
According to our calculations, although the average energy of the $4f^{15}5s^5p^3$ configuration is lower than that of $4f^{15}5s^5p^2$, the latter configuration has a much larger spread of the energy levels. Therefore, the ground state appears to be $4f^{15}5s^5p^2$ $^4P^{7/2}$, while the first excited state, $4f^{15}5s^5p^3$ $^5P^{1/2}$, is located approximately 11000 cm$^{-1}$ above it. Considering the large uncertainty of the calculations, the ground state of W XII is uncertain. The term label is also only tentative, as the coupling scheme of the $4f^{15}5s^5p^3$ configuration is very far from pure $L_S$. Our calculations yield 24% of $4f^{15}5s^5p^3$ $^5P^{1/2}$ and 24% of $4f^{15}5s^5p^3$ $^5P^{3/2}$ as the leading components of the composition of the ground state.

2.11. W XIII

Sm I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{14}5s^2$ $^3S_0$
Ionization energy $2083000 \pm 10000$ cm$^{-1}$ (258.2 ± 1.2 eV) [4]
The first excited levels, according to our calculations, belong to the $4f^{14}5s^25p$ configuration and are located approximately 16000 cm$^{-1}$ above the ground state. Considering the large uncertainty of the calculations, this level ordering is uncertain.

2.13. W XV

Nd I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{12}5s^2$ $^3H_6$
Ionization energy $2624000 \pm 12000$ cm$^{-1}$ (325.3 ± 1.5 eV) [4]
No experimental data are available on this spectrum.

2.14. W XVI

Pr I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{11}5s^2$ $^4I_{15/2}$
Ionization energy $2919000 \pm 12000$ cm$^{-1}$ (361.9 ± 1.5 eV) [4]
No experimental data are available on this spectrum.

2.15. W XVII

Ce I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{11}5s^2$ $^4I_{15/2}$
Ionization energy $3129000 \pm 10000$ cm$^{-1}$ (387.9 ± 1.2 eV) [4]
As follows from our calculations, the first excited state, $4f^{10}5s^2$ $^4I_{15/2}$, is located approximately 19000 cm$^{-1}$ above the ground state.

2.16. W XVIII

La I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}4f^{11}5s^2$ $^4I_{15/2}$
Ionization energy $3393000 \pm 11000$ cm$^{-1}$ (420.7 ± 1.4 eV) [4]
As follows from our calculations, the first excited state, $4f^{10}5s^2$ $^4I_{15/2}$, is located approximately 30000 cm$^{-1}$ above the ground state.

2.17. W XIX

Ba I isoelectronic sequence
Ground state $1s^22s^22p^63s^23p^63d^{10}4s^24p^64d^{10}5s^2$ $^4I_{15/2}$
Ionization energy $3727000 \pm 11000$ cm$^{-1}$ (462.1 ± 1.4 eV) [4]
As follows from our calculations, the first excited state, $4f^{10}5s^2$ $^4I_{15/2}$, is located approximately 120000 cm$^{-1}$ above the ground state.
An Experimental and Theoretical Study of the Ground State M1 Transition in Ag-like Tungsten.

Z. Fei$^{1,2}$, R. Zhao$^{1,2}$, Z. Shi$^{1,2}$, J. Xiao$^{1,2}$, M. Qiu$^{1,2}$, J. Grumer$^{3}$, M. Andersson$^{1,2}$, T. Brage$^{3}$, R. Hutton$^{1,2}$ and Y. Zou$^{1,2}$

$^1$The Key lab of Applied Ion Beam Physics, Ministry of Education, China
$^2$Shanghai EBIT laboratory, Modern physics institute, Fudan University, Shanghai, China
$^3$Division of Mathematical Physics, Department of Physics, Lund University, Sweden

Spectra were taken at a number of electron beam energies from 770 to 1200 eV.

Tungsten was injected into the EBIT via the volatile compound W\((\text{CO})_6\).

The spectra were recorded using an Andor 0.3 meter Czerny-Turner spectrometer.

In this respect, we can call this desk top physics!
<table>
<thead>
<tr>
<th>Source</th>
<th>Energy [cm(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>30 750</td>
</tr>
<tr>
<td>DF + Breit</td>
<td>29 239</td>
</tr>
<tr>
<td>DF + Breit + QED</td>
<td>29 261</td>
</tr>
<tr>
<td>FCV AS1</td>
<td>29 451</td>
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<td>AS2</td>
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<td>AS3</td>
<td>29 574</td>
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<td>AS4</td>
<td>29 593</td>
</tr>
<tr>
<td>AS5</td>
<td>29 603</td>
</tr>
<tr>
<td>AS5 + intra-CC</td>
<td>29 570</td>
</tr>
<tr>
<td>Experiment (this work)</td>
<td>29 599.81 ±2.28</td>
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<tr>
<td>Other theoretical work</td>
<td></td>
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<tr>
<td>Safronova&amp;Safronova (RMBT)</td>
<td>29 550</td>
</tr>
<tr>
<td>Ivanova (RPTMP)</td>
<td>31 769</td>
</tr>
<tr>
<td>Ding et al. (MCDF)</td>
<td>29 151</td>
</tr>
</tbody>
</table>

The Tungsten compilation by Kramida and Shirai gives an “experimentally determined” fine structure energy of 33000±800 cm\(^{-1}\).
Convergence of the calculations
In the Tungsten compilation by Kramida and Shirai an experimentally determined fine structure energy of $33000\pm800$ cm$^{-1}$ for the ground state is given. This is based on the identification of a line at 47.94 Å and by making a non-relativistic calculation using the Cowan code.

We find this all very puzzling for two reasons. First because Sugar and Kaufmann argue that the 47.94 Å line was not from Tungsten and second because large scale relativistic calculations do not predict the fine structure splitting to be around $33000$ cm$^{-1}$ but $29500$ cm$^{-1}$.
It would appear from the comparison between our measured and calculated wavelength for the $W^{27+}$ M1 transition, and from the above discussion, that the fine structure energy given in the Tungsten review paper is in error and should be revised.

Also, it would be useful if other ions in the Ag I iso-electronic sequence could be studied to confirm our findings.
Other tungsten lines
Old tungsten mystery

$W^{13+}$, Pm-like W

Bottom spectra are experimental from the Berlin EBIT (2000)
Top spectra are calculated (2013)

Note He II has lines at 256.32 Å and 243.03 Å
Concluding remarks

The Shanghai EBIT lab has successfully evolved from basically nothing in the year 2002 to a working lab with a range of EBITs in 2012.

In this talk I discussed the first real spectroscopic results from the lab, although we have published a number of papers on di-electronic recombination and on simulation and modeling of the EBIT charge state distribution.
Thank You for your attention!

2010 edition of our group
5th International Workshop on the Physics at EBITs and Advanced Research Light sources, PEARL 2014

May 2nd – 5th, Fudan University, Shanghai, China

Organizers: Baoren Wei, Yunqing Fu, Chongyang Chen, Roger Hutton and Yaming Zou

Contact: Kaifeng Zhao at brwei@fudan.edu.cn

Speakers: Gordon Berry etc et al
W^{26+} has been submitted to PRA and under review

W^{25+} is finished and ready to be submitted, also to PRA.