Computational Atomic Physics in support of Solar and Fundamental Physics

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Collaborators

- Si Ran and Jon Grumer (now in Uppsala), Lund University
- Roger Hutton, Fudan University
- Wenxian Li and Per Jönsson, Malmö University
- Philip Judge, HAO and Cai Wang, Hebei University

- Second part: a collaboration between Lund, Tsinghua and Fudan Universities

Outline of todays talk

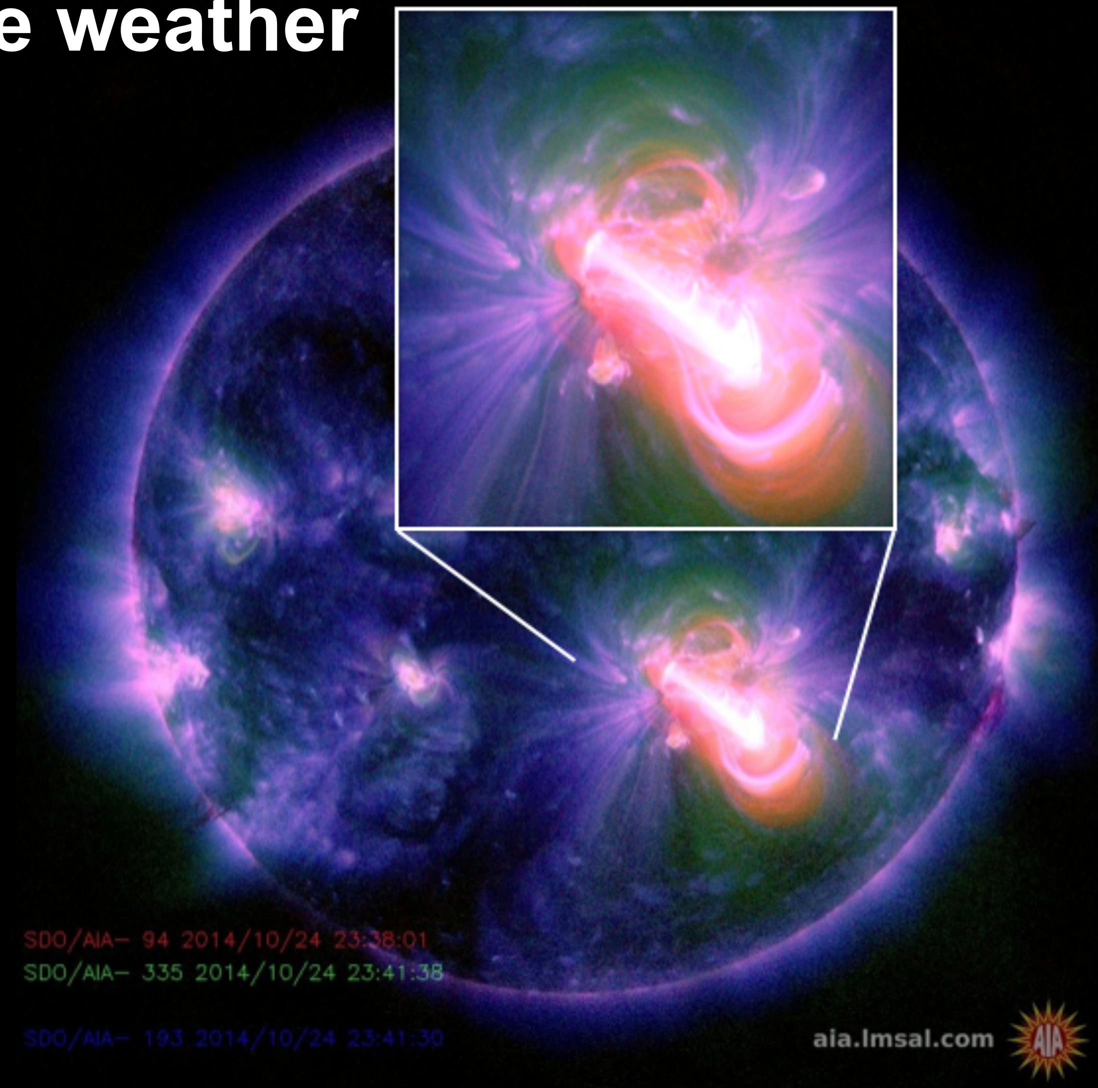
Part 1: A first direct measurement of the coronal magnetic field

- Why do want to know the field?
- A new line as a result of quantum interference in Fe^{9+}
- Recent result on this process

Part 2: A negative ion candidate for laser cooling

- Why is it interesting?
- Why so hard for negative ions?
- results

Part 1: The sun magnetic energy → thermal → heat corona and space weather



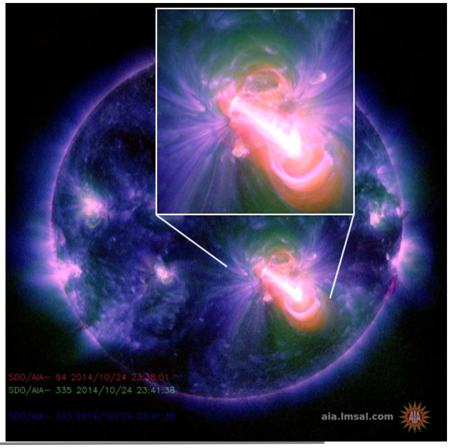
No measures of these field strengths!

There is no direct measurement of these fields

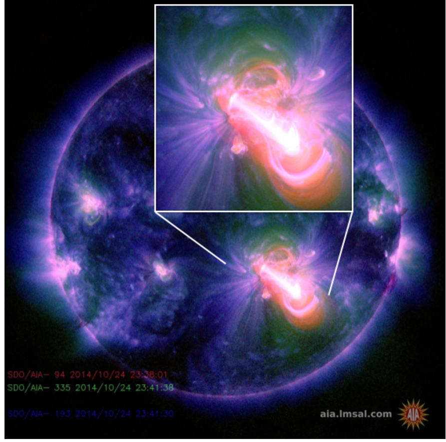
Zeeman effect requires higher fields

Hanle effect is very complex – but work in progress

We have recently proposed an ”exotic” method, by using detailed atomic structure, to determine these field strengths.



How to measure magnetic fields?



The temperature is high, so we have highly ionized atoms

Fast electrons, give strong internal magnetic field of the ions

Internal magnetic field in Tesla ≈ fine structure in cm^{-1}

Typical fine structure thousands of cm^{-1}

Internal magnetic field is thousands of Tesla

So we need to find an enhanced effect ...

Now a ”movie” from a Science Slam talk ...

Which we actually won...

Welcome to the world of quantum states!

Ions have specific energy states.

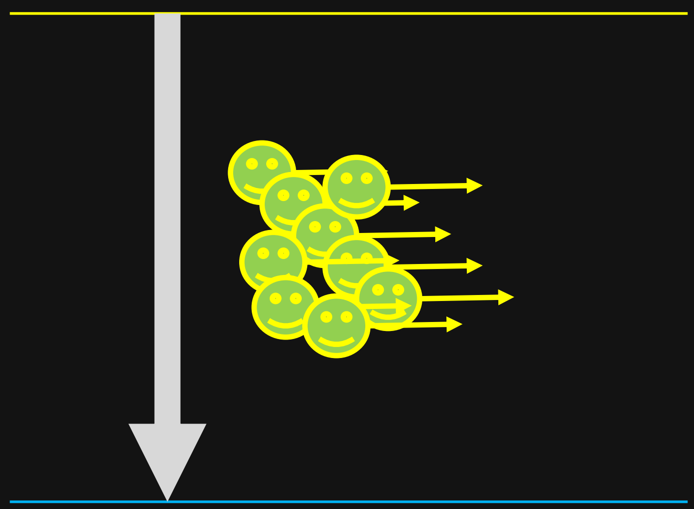
Most often, they are in their lowest – ground state.

Ions get excited to higher levels.

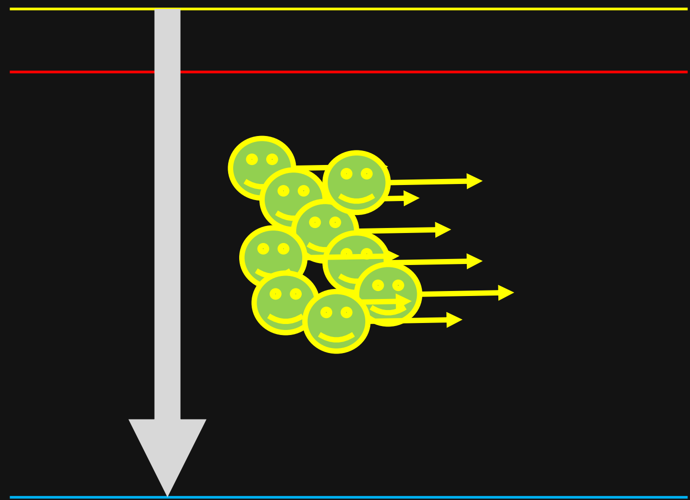
Ions get excited to higher levels.

Sometimes they can decay to lower states.

Ions get excited to higher levels.
Sometimes they can decay to lower states by emitting photons.

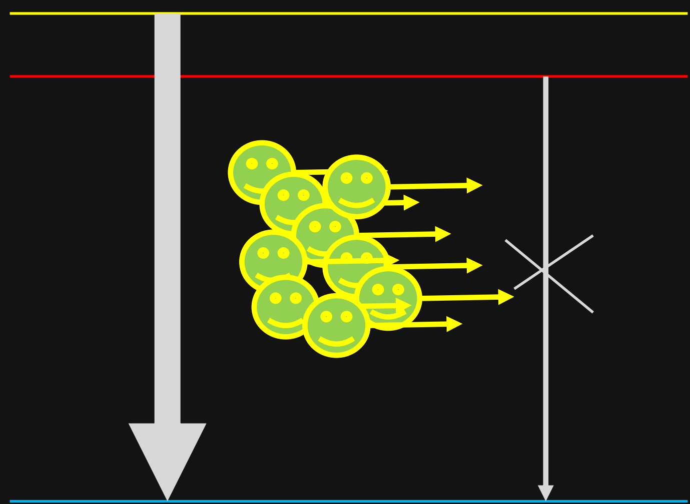


Other states have different properties



Other states have different properties

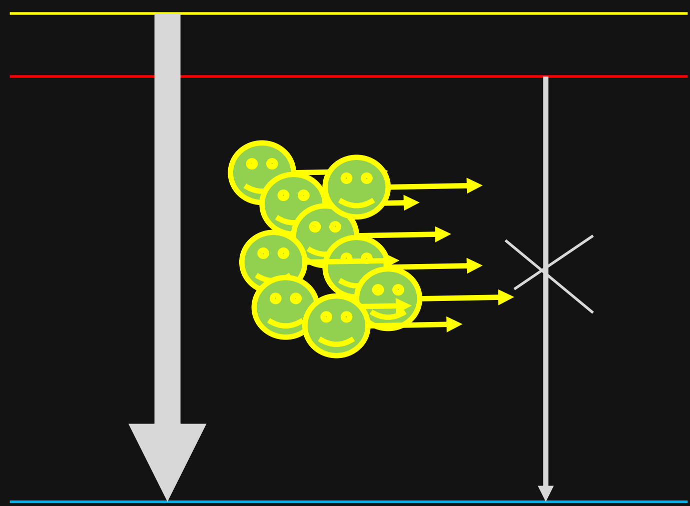
No decay is allowed – the atom get stuck!



Other states have different properties

No decay is allowed – the atom get stuck!

No photons sent out.



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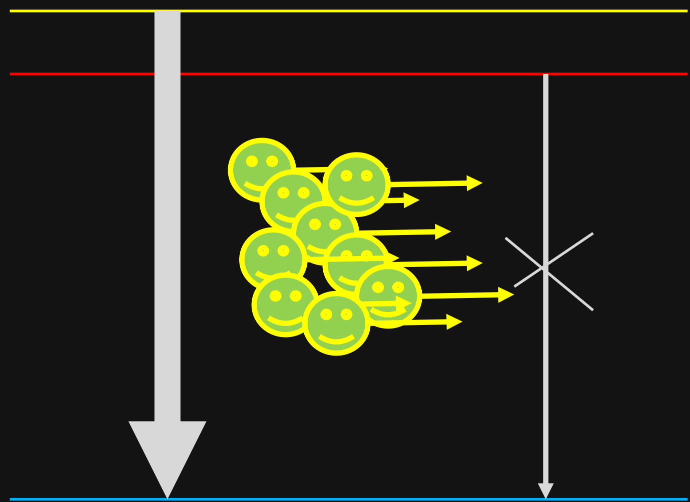
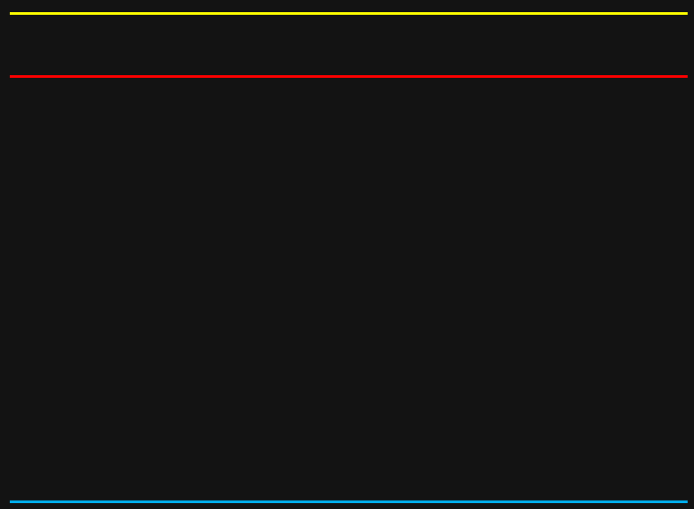


But a magnetic field can change the picture.



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The two states interchange properties.

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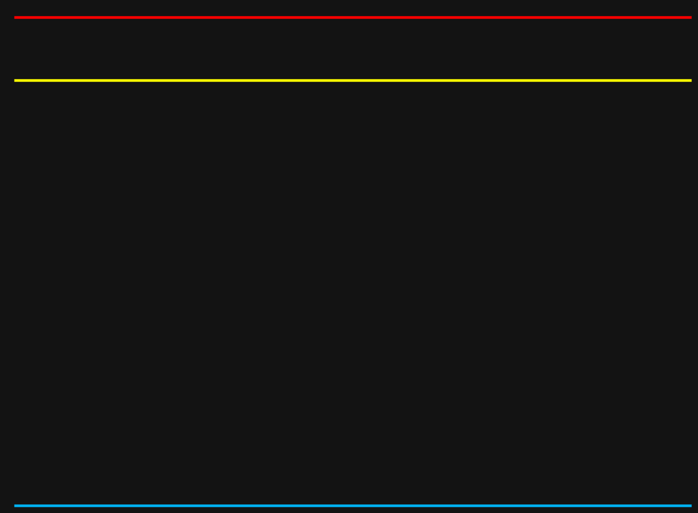

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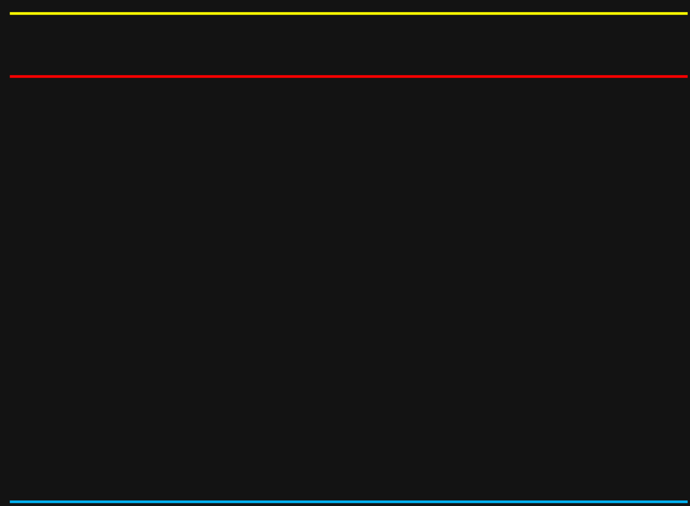

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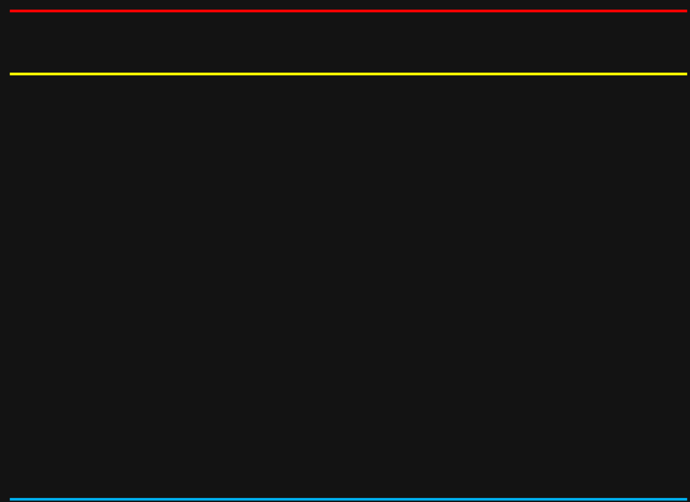

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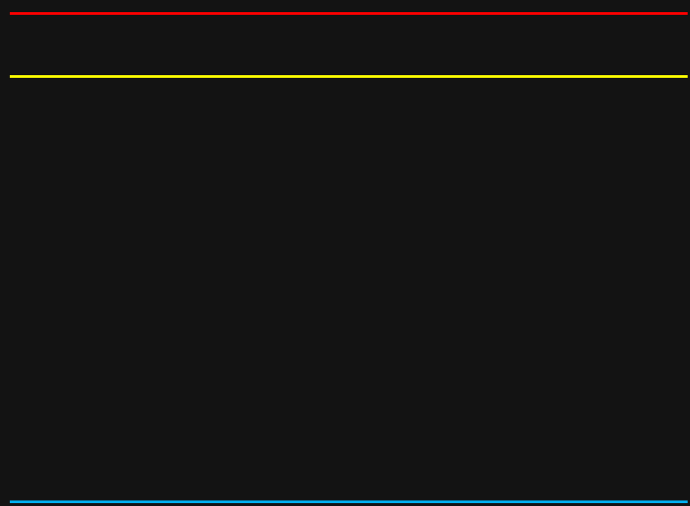


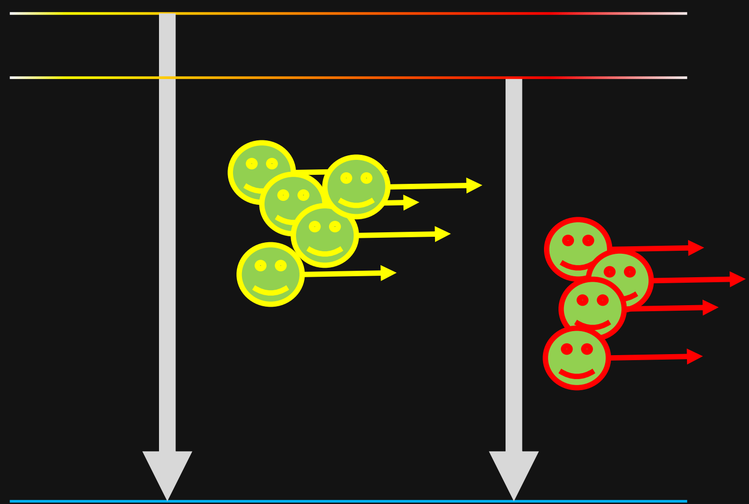
But a magnetic field can change the picture.
The two states interchange properties.

But a magnetic field can change the picture.

The two states interchange properties.

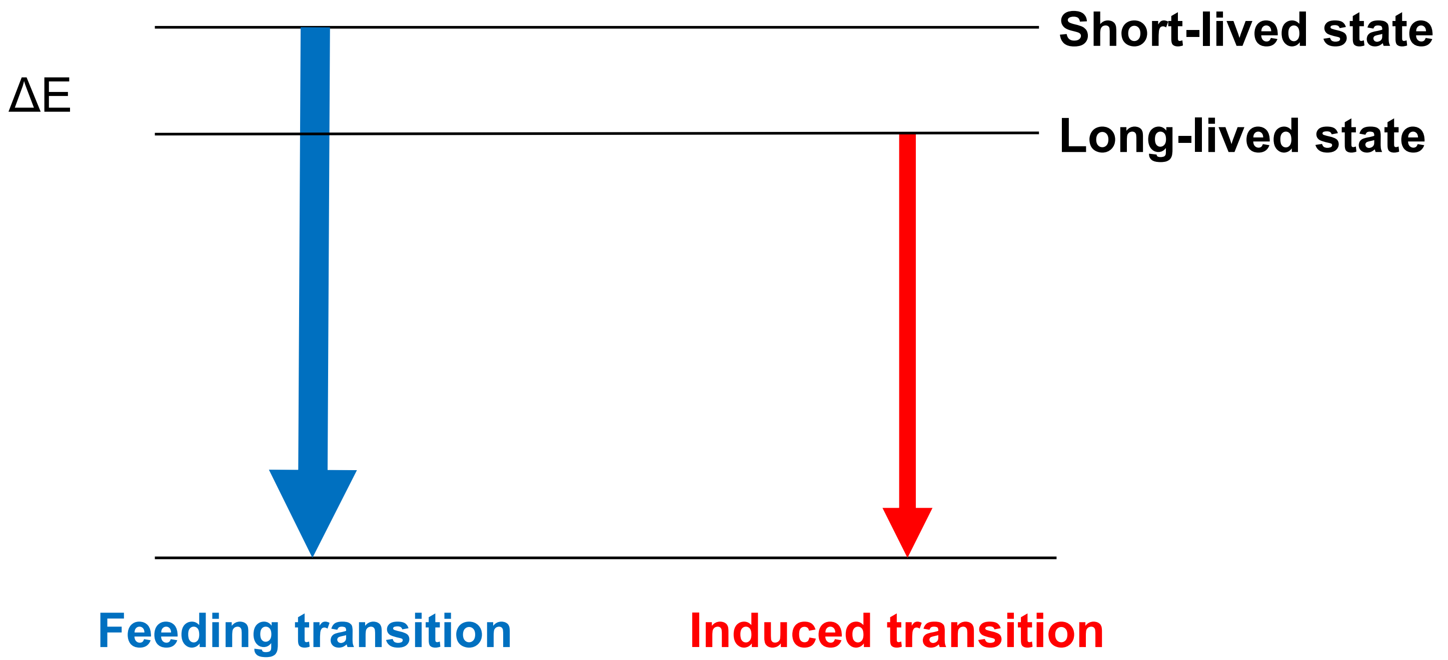
The atom is unstuck

But a magnetic field can change the picture.
The two states interchange properties.
The atom is unstuck
….. And photons are sent out from both states.

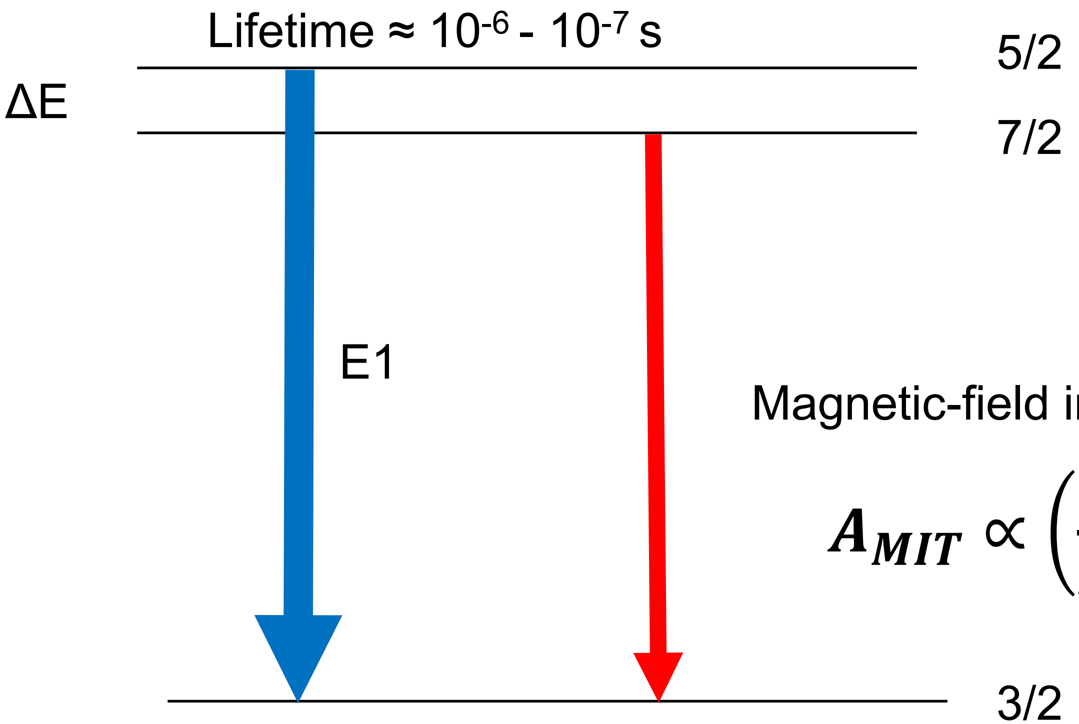


Clearly the number of red photons will depend on the strength of the magnetic field and on how close the degeneracy is

We need two excited levels



Candidate in Cl-like ions

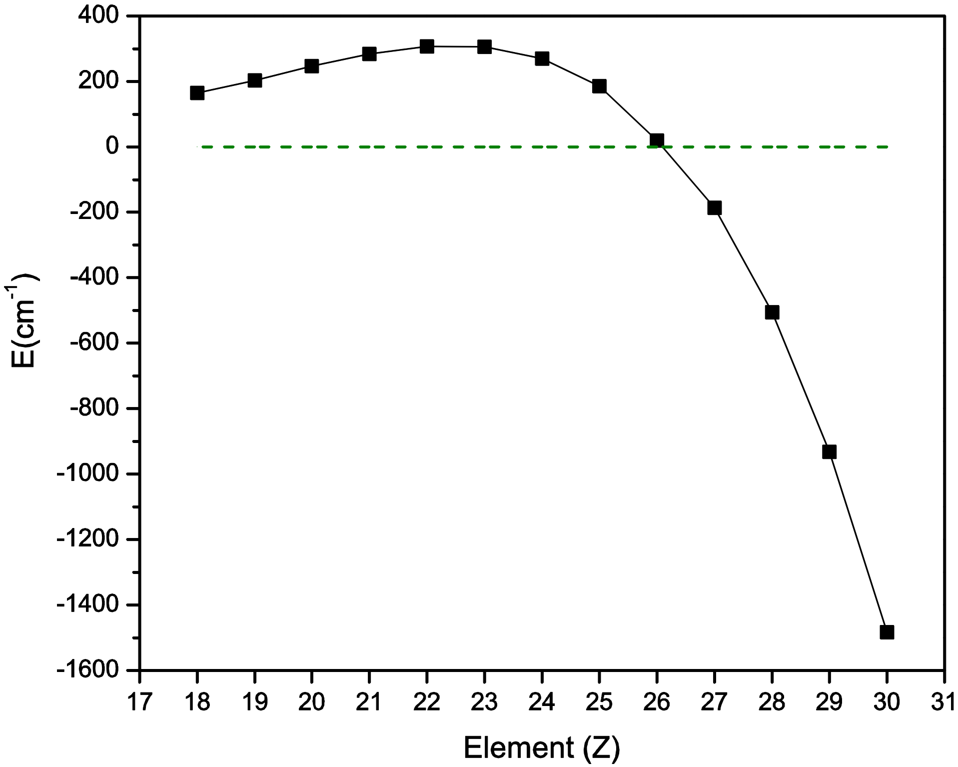


$$A_{MIT} \propto \left(\frac{B}{\Delta E}\right)^2$$

*Li Wenxian et al., Astrophysical Journal, **807**, 69, (2015)*

A lucky coincidence!

ΔE as a function of nuclear charge in Cl-like ions (17 electrons)



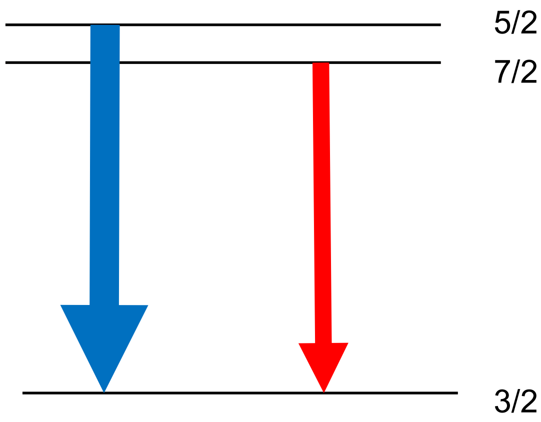
Minimum for Fe^{9+} with high abundance!

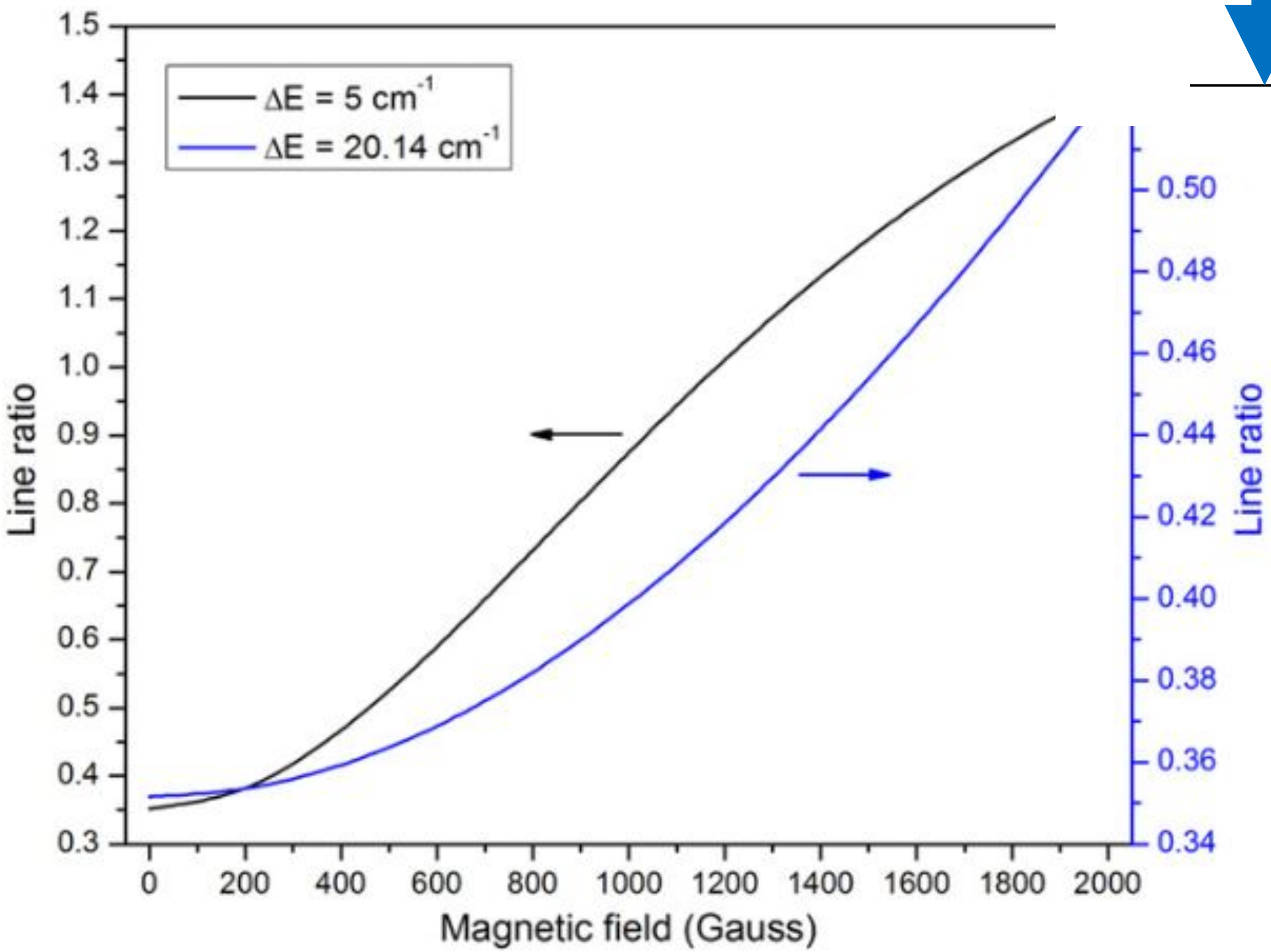
We need to determine ΔE

Table 1
Atomic Data for Fe x

	Method	λ	ΔE	A_{E1}
Observation	Solar (Thomas et al. 1994; Brosius et al. 1998)	257.25	0	···
	Solar (Sandlin 1979)	···	5	···
Theory	Present	257.7285	20.14	6.30[6]
	MCDF (Huang et al. 1983)	246.4924	78	1.63[6]
	MCDF (Dong et al. 1999)	256.674	108	6.27[6]
	MCDF (Aggarwal & Keenan 2004)	···	54.85	···
	MR-RMBPT (Ishikawa et al. 2010)	257.1924	18	···
	R-matrix (Del Zanna et al. 2012)	246.8890	109.74	···
	CI (Bhatia & Doschek 1995)	256.1974	−58	1.21[6]
	CI (Deb et al. 2002)	257.0846	21	2.42[5]

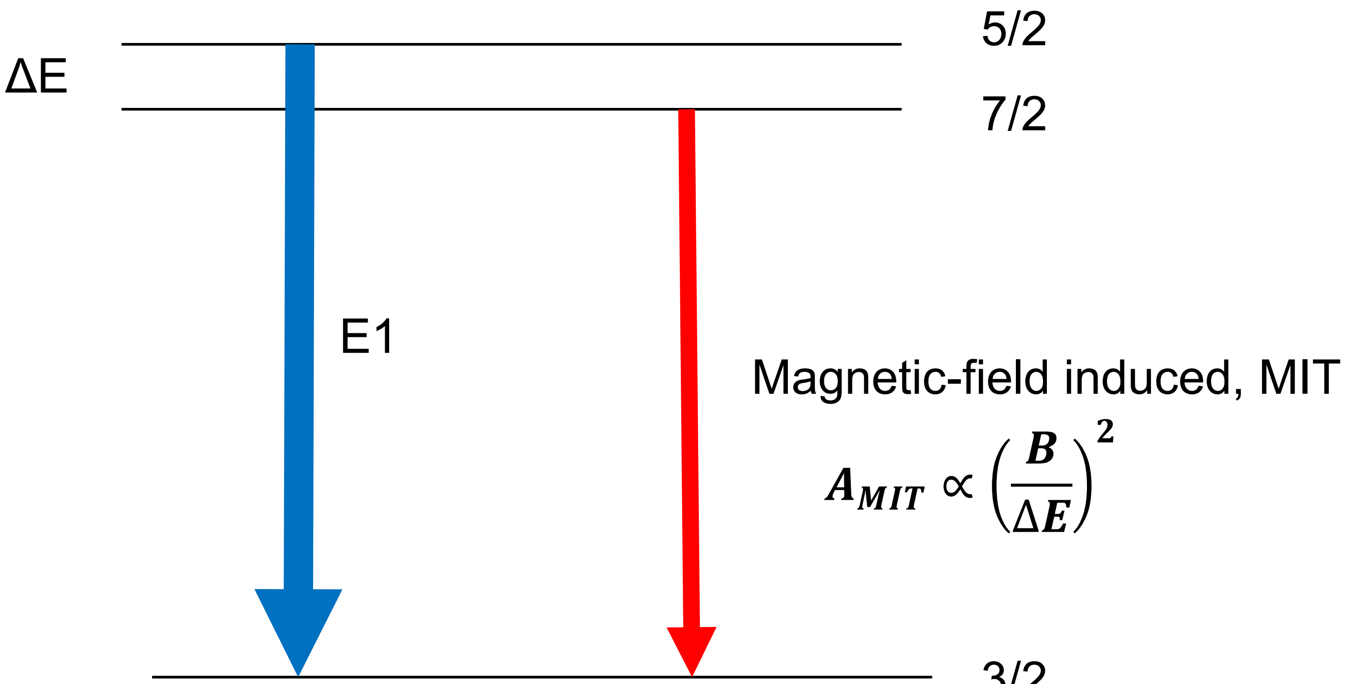
Relative intensity MIT/E1





Done, right?

- But, energy of transitions are about 390 000 cm^{-1}
- While ΔE is a few cm^{-1}
- We will not resolve them

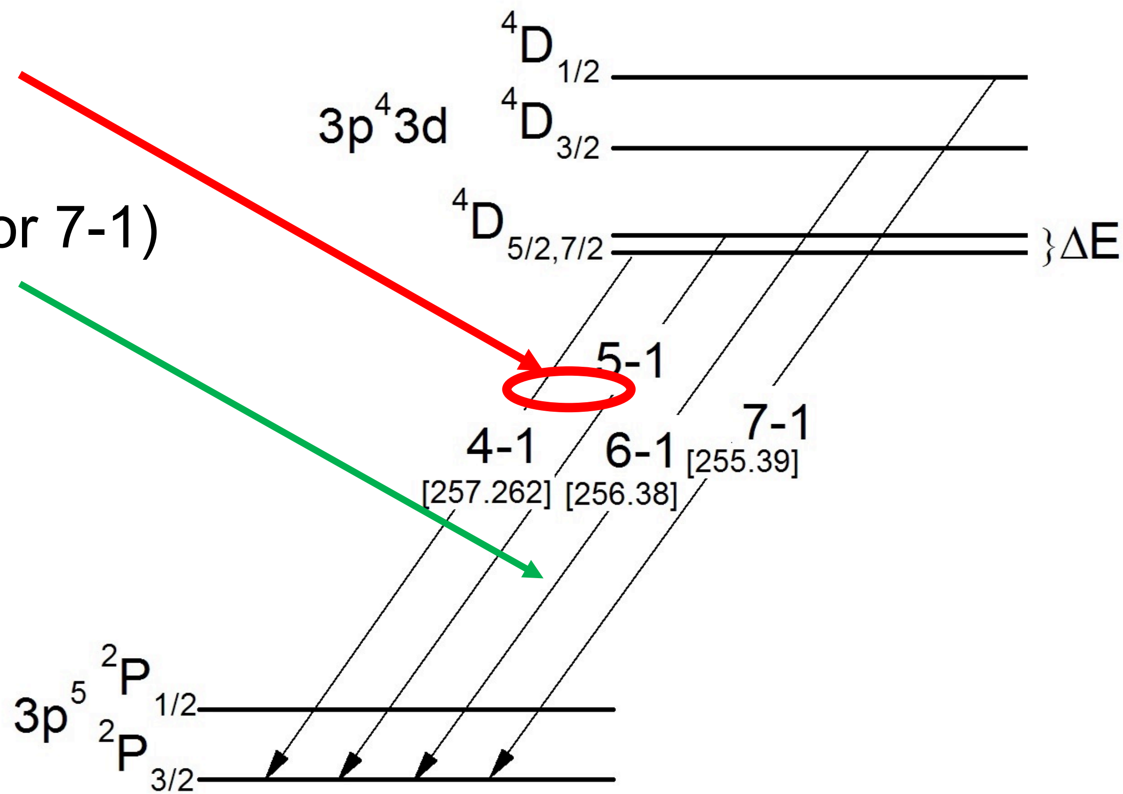


$$A_{MIT} \propto \left(\frac{B}{\Delta E}\right)^2$$

But the blended lines intensity will depend on B

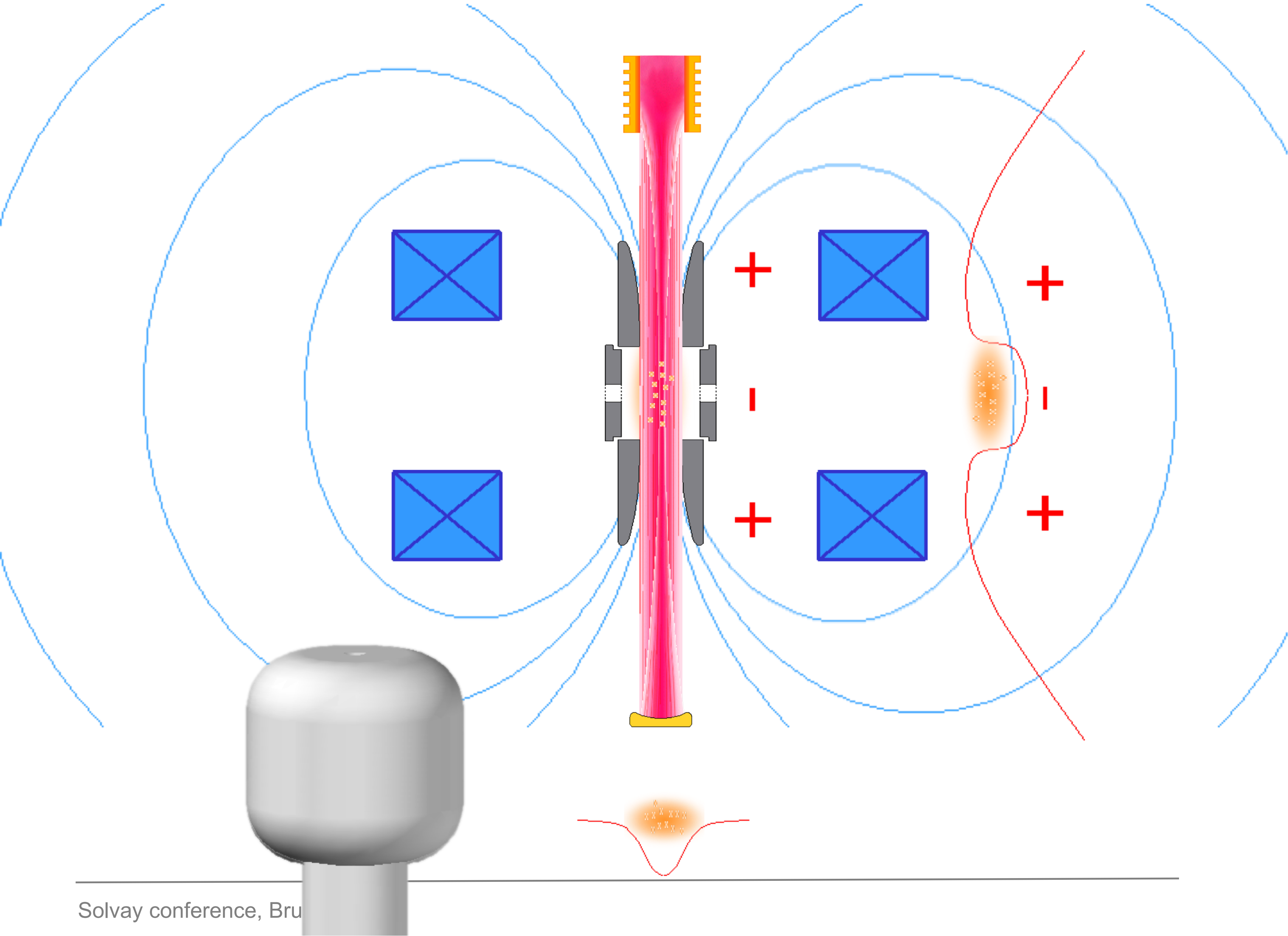
So we need an indirect method

- 4-1 and 5-1 blended
- Lines close by 6-1 (or 7-1)
- Independent of B
- Normalising lines

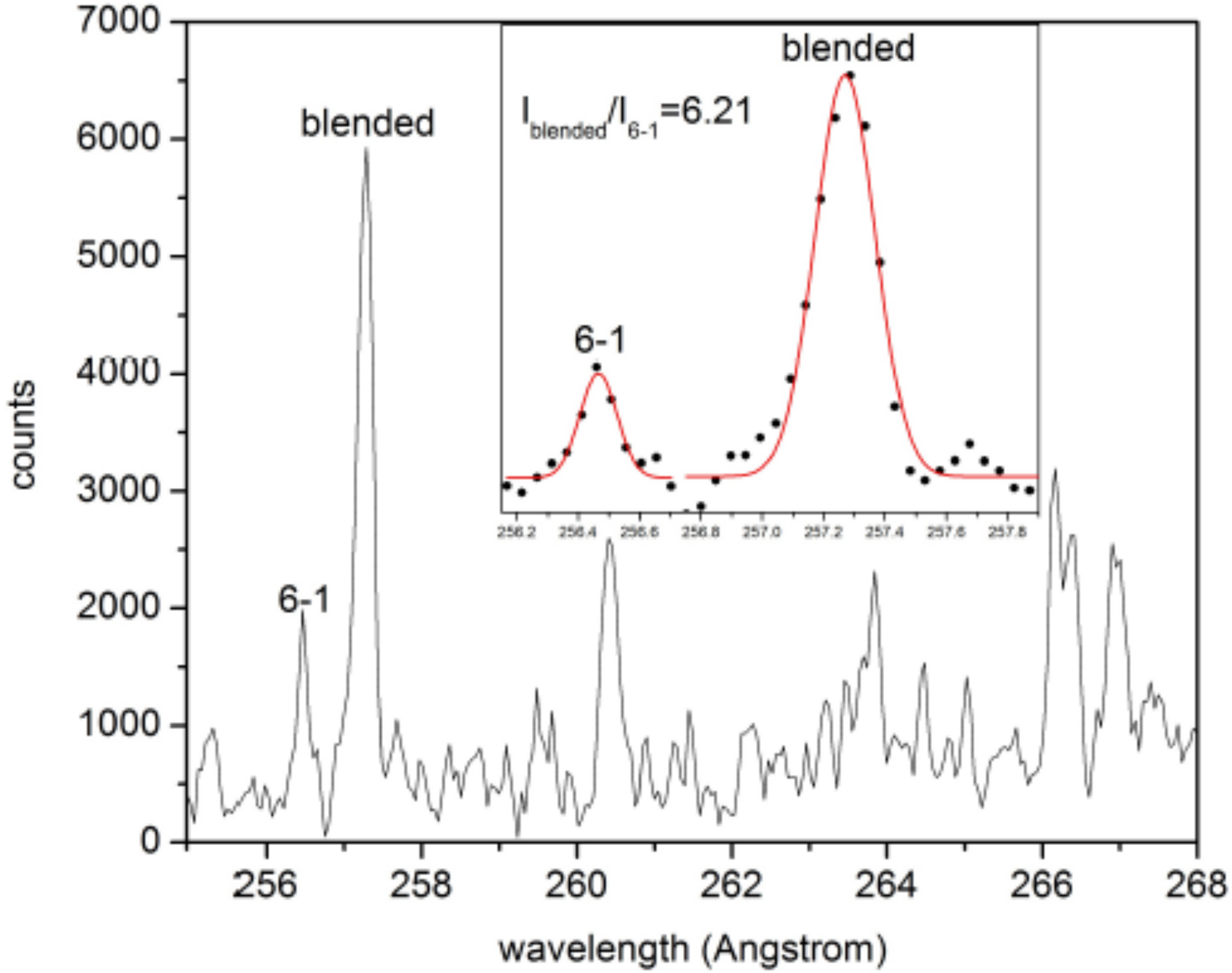


But we need to determine ΔE!

- Before we continue designing the measurement in the sun
- We need to know ΔE
- So we can move to a plasma with known B
- Our choice is an Electron Beam Ion Trap (EBIT)

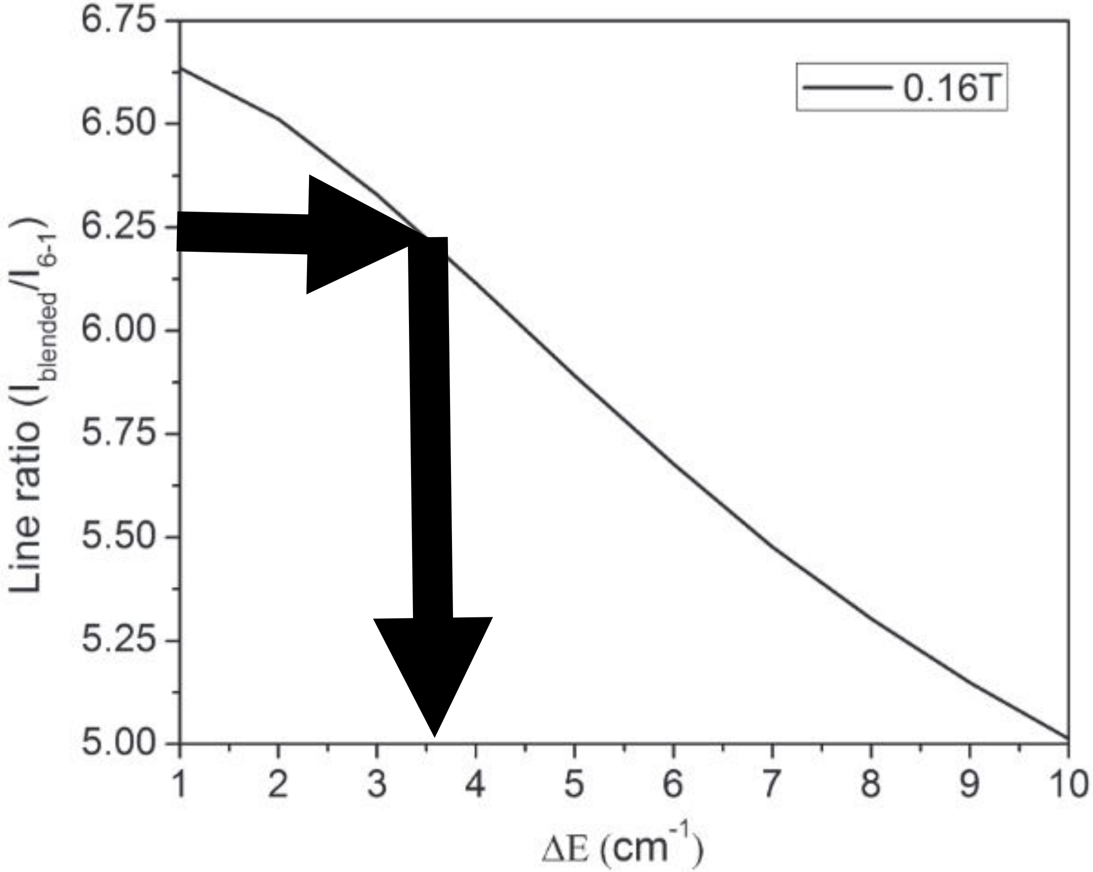


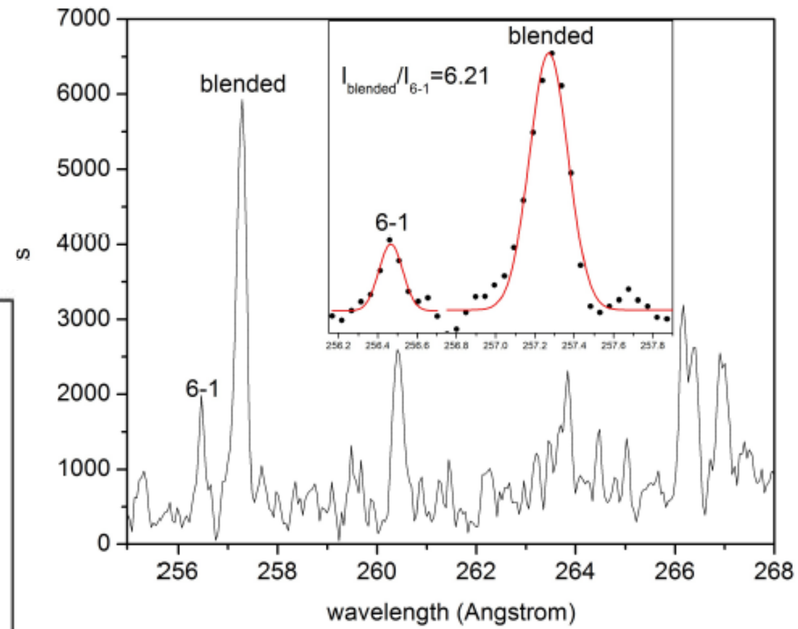
Resulting spectra from EBIT



*W. Li et al., The Astrophysical Journal, **826**, 219, (2016).*

Modelling to determine ΔE



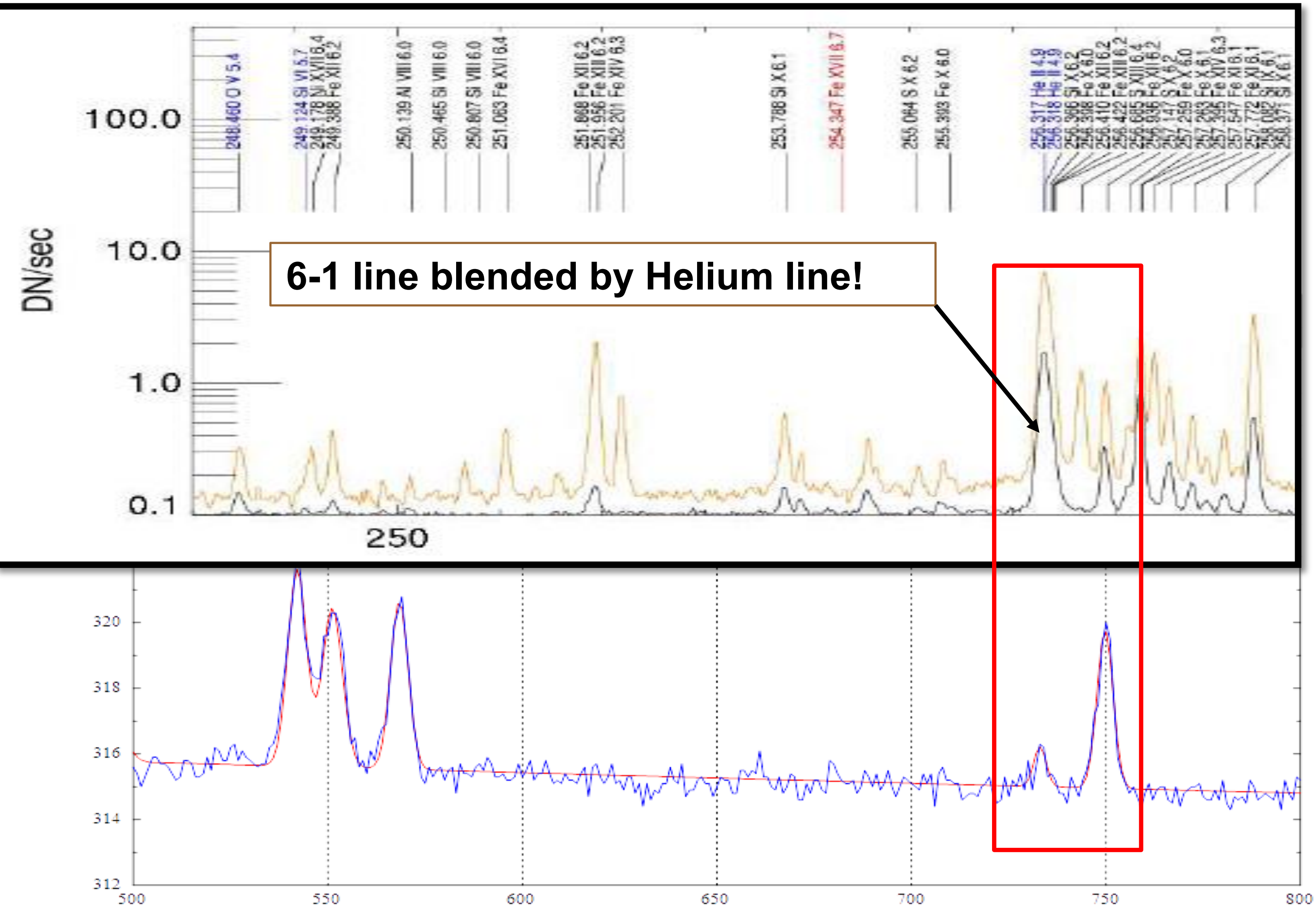


Results:
ΔE ≈ 3.5 cm^{-1}

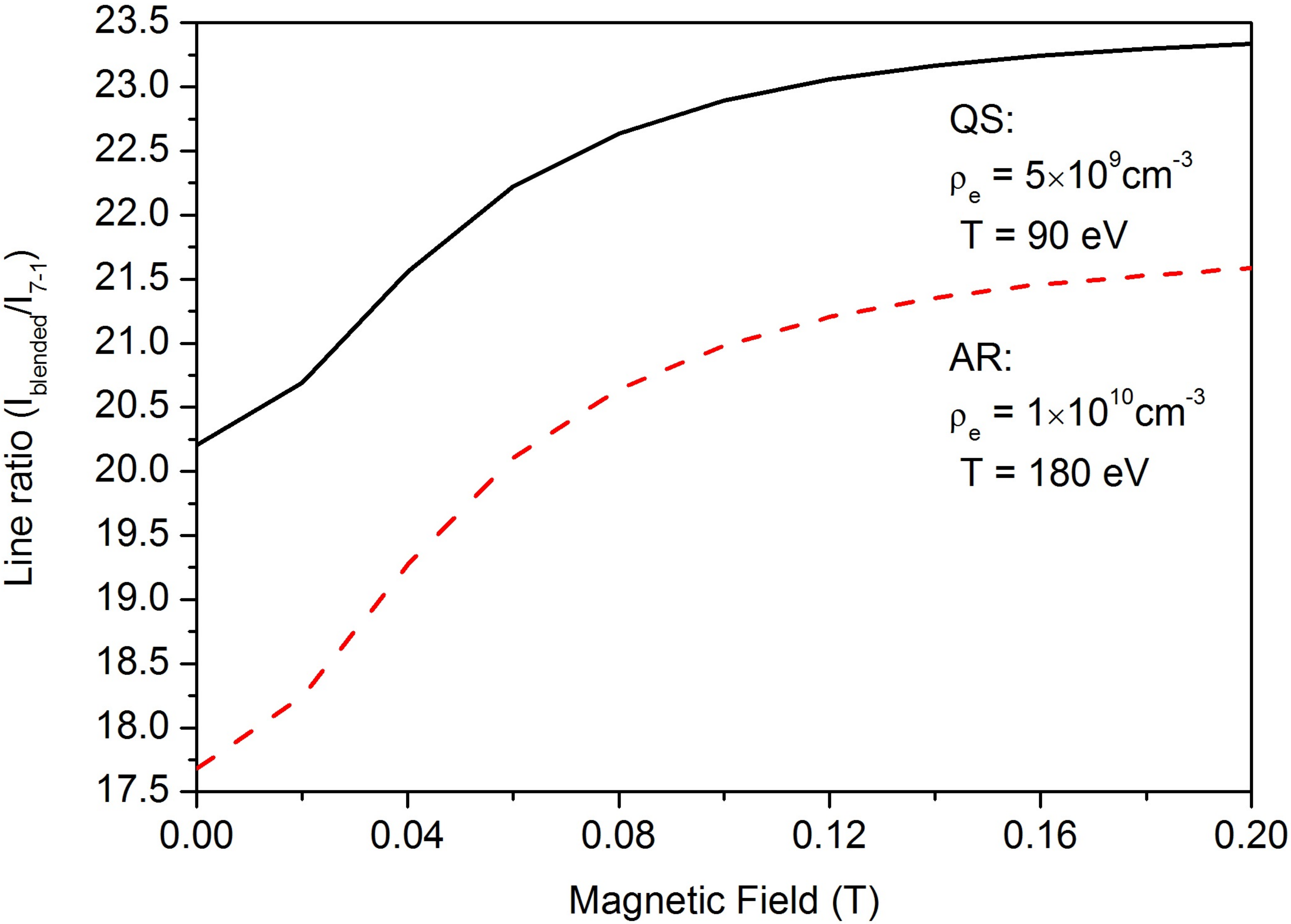
with large errors (14% in ratio)

W. Li et al., The Astrophysical Journal, ***826****, 219, (2016).*

Back to the sun – HINODE spectra

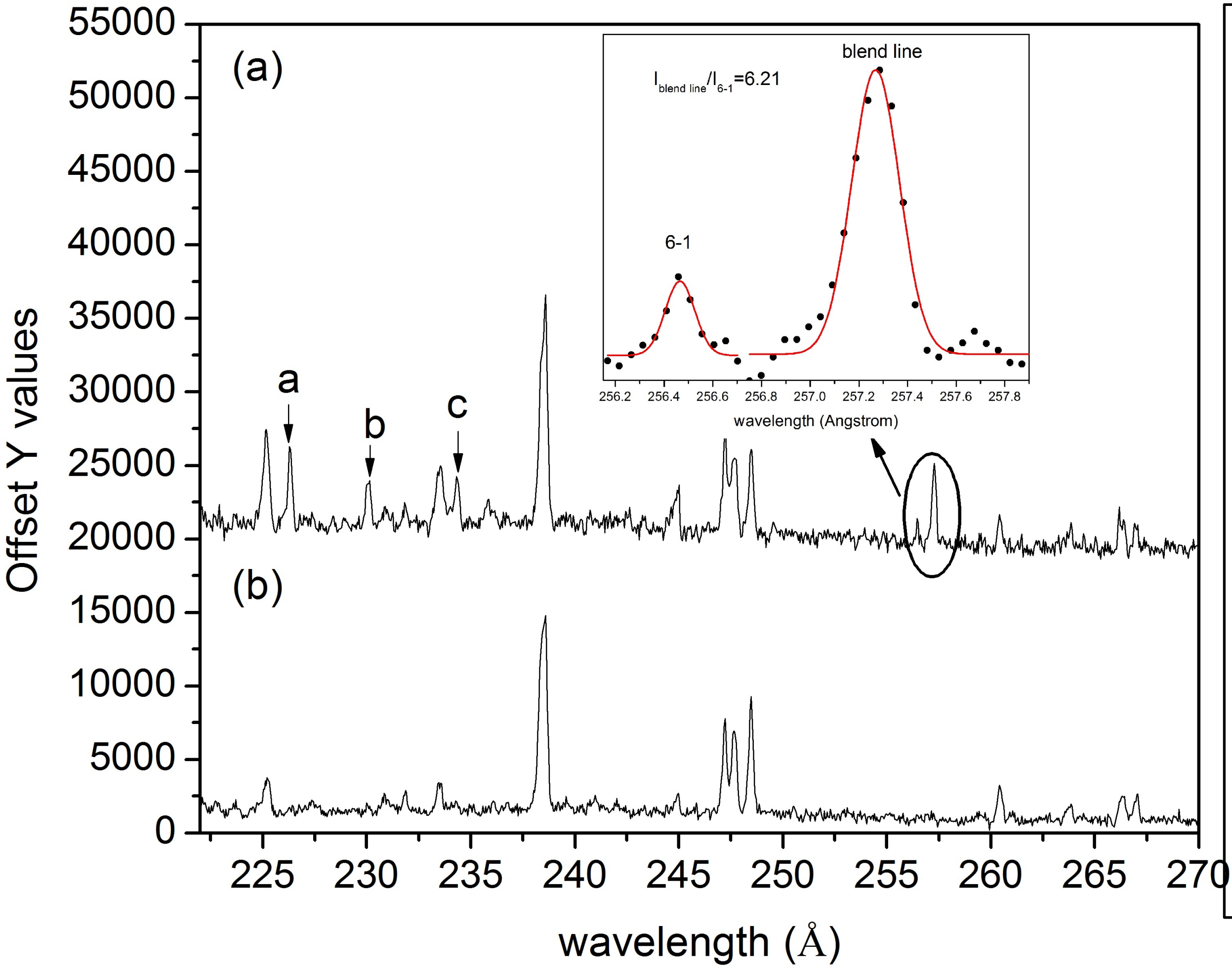


Possible to measure blended relative to 7-1



But 7-1 is very weak

Further work on ΔE – in EBIT



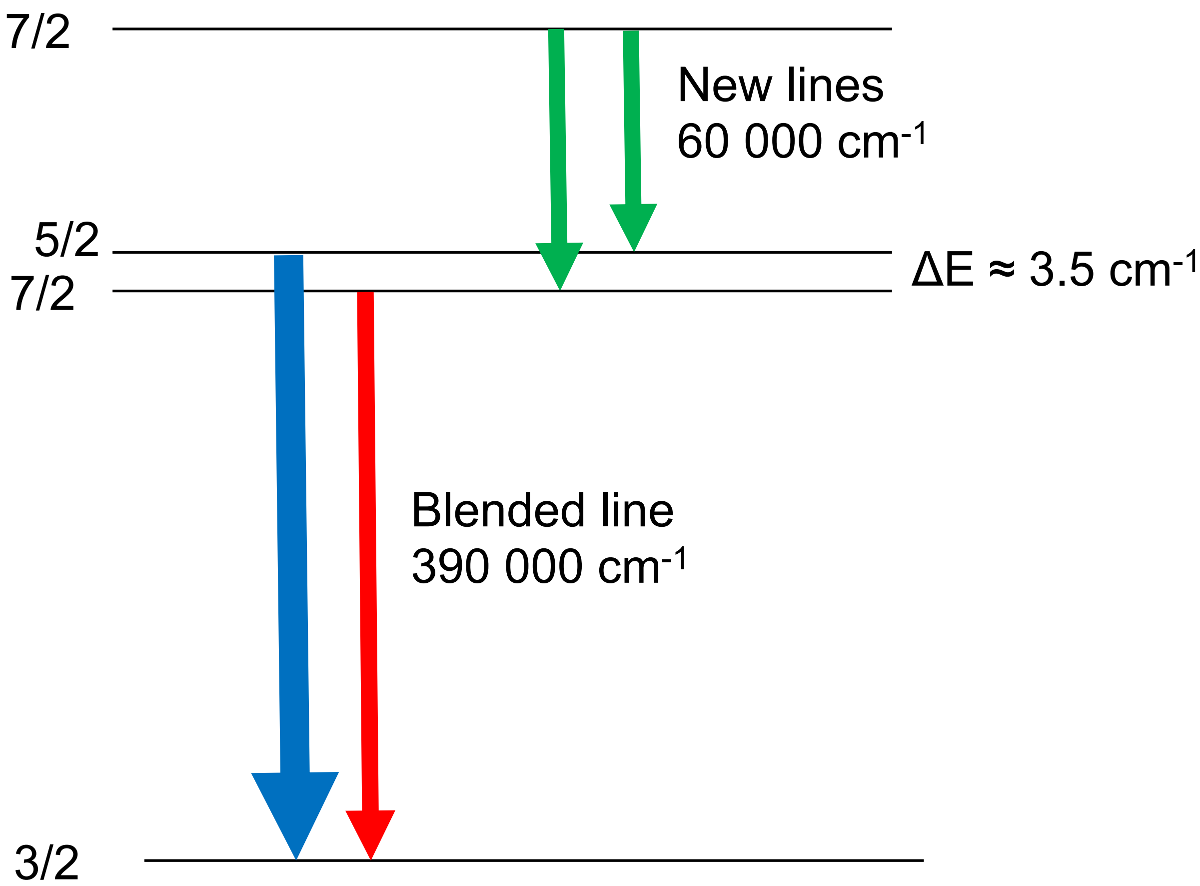
- a, b and c are Fe^{9+} lines
- Can be used as normalisation lines
- Give values consistent with 3.5 cm^{-1}
- Complex

Problems with these lines

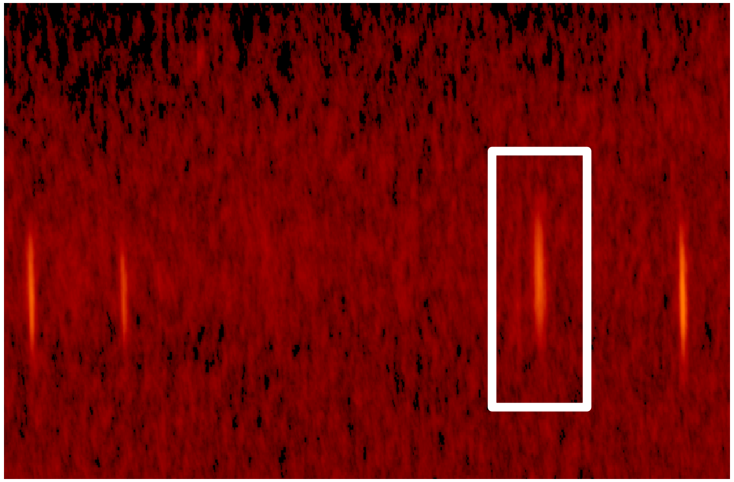
Normalisation lines far from blended line, requires correction for

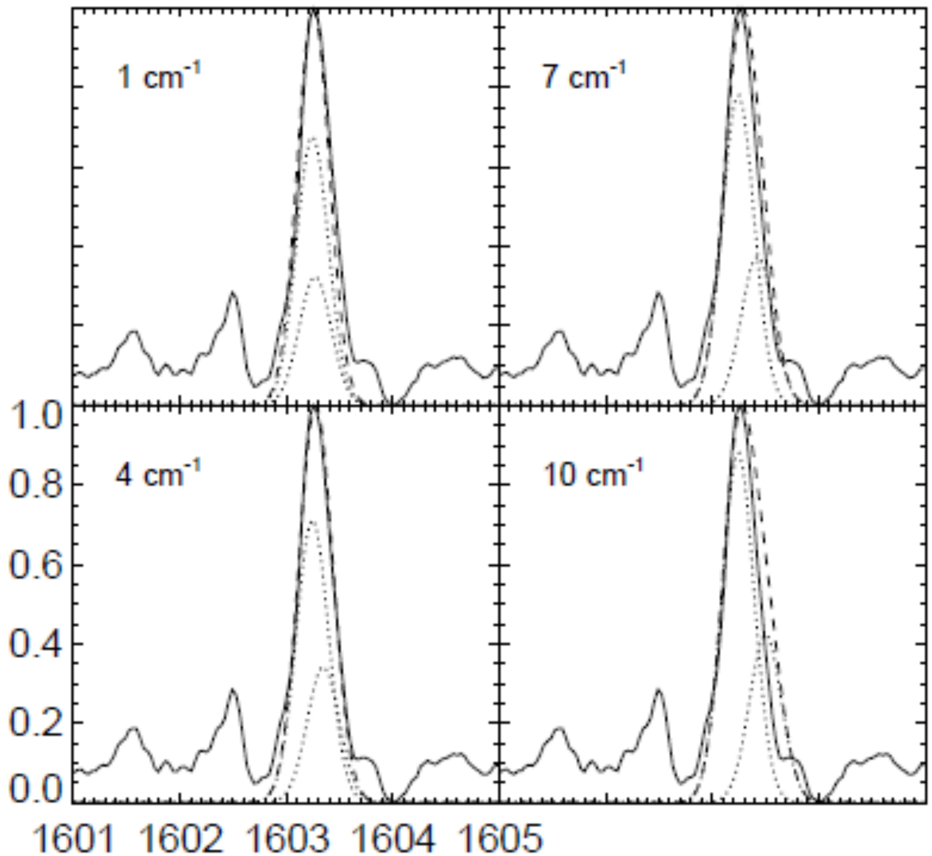
- Grating efficiency, measured using a synchrotron
- CCD efficiency, data from ANDOR
- Soft x ray filter, calculated using LBL soft ware

Possible direct measurement from above



Skylab spectra from solar limb





Resulting $\Delta E = 3.6 \pm 2.7\ \text{cm}^{-1}$

*P. Judge et al., The Astrophysical Journal **833**,185 (2016).*

Now back to determine coronal fields

- We have a value for ΔE
- There are HINODE data for two regions:
  - 240 – 270 Å
  - 170 – 200 Å (many lines in Fe^{9+})
- We use low wavelength region lines (174 and 175 Å) for density determination (10^9 cm^{-1})
- … and normalization.
- B-field only parameter left to fit intensity of blended line.

Consistent result for B-field in active region

B = 250 Gauss

(with large error bars – order of magnitude)

First direct determination of this field!

R. Si et al., to be submitted for publication. (2019)

Many remaining questions

- The uncertainty of ΔE is still 70%
- Electron density and magnetic fields?
- Location of Fe^{9+} in the corona?
- There is a competing M2 transition, to the MIT – for small B-field it is not negligible.

Part II: Cooling of ions

Why cooling ions?

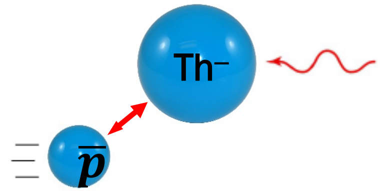
- To minimise Doppler broadening
- and increase observation time

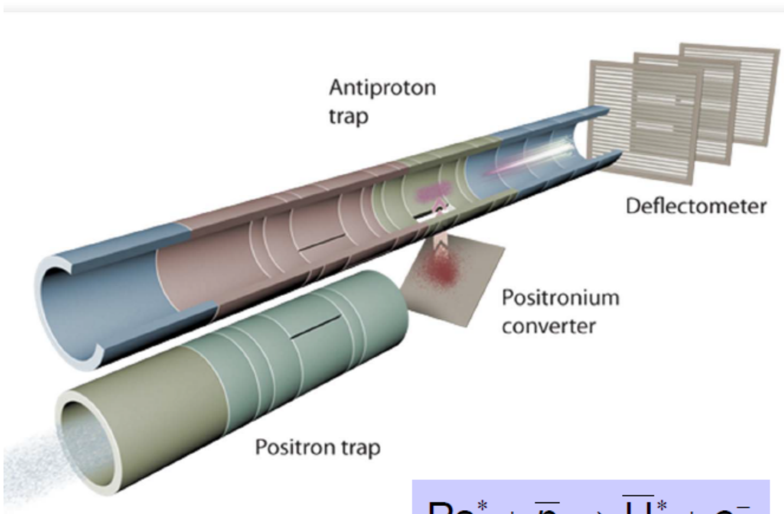
Applications

- Fundamental tests
- Atomic clocks
- Bose-Einstein condensation
- etc

Why cool negative ions?

- Application: Creating anti-Hydrogen
- Need cool anti-protons, which are negative
- Can use negative ions to sympathetically cool them in a trap
- See AEGIS experiment at CERN

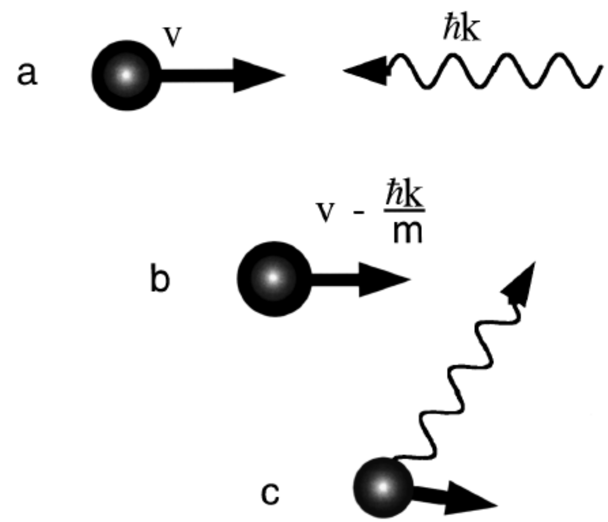




$$\mathrm{Ps}^* + \bar{p} \rightarrow \overline{\mathrm{H}}^* + e^-$$

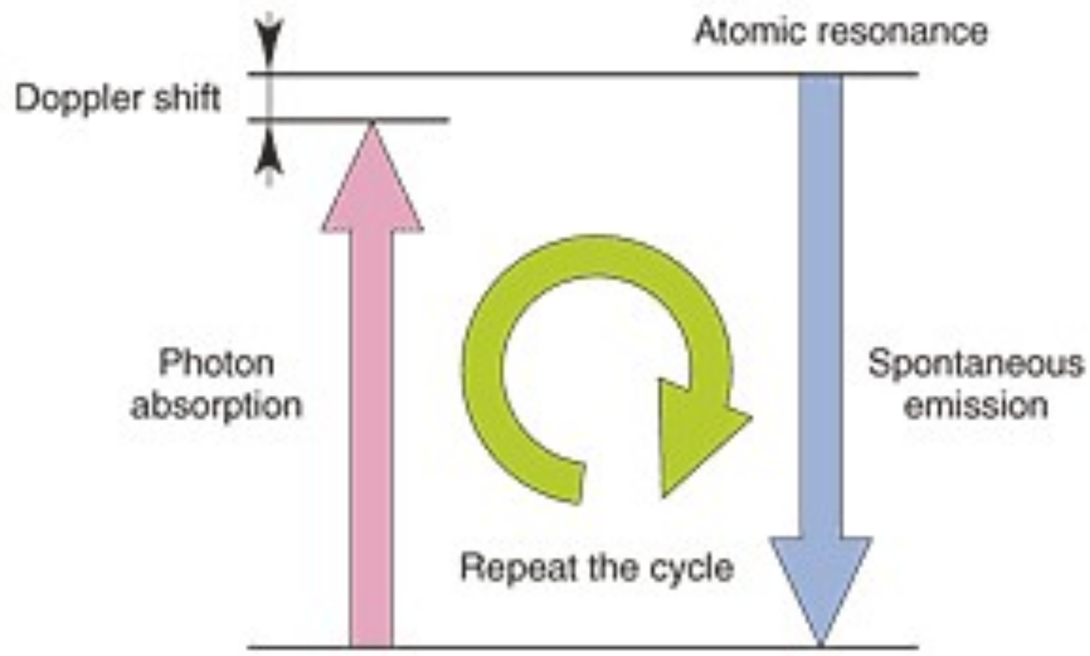
Laser-cooling of ions (Doppler cooling)

- Tune laser-frequency below resonance
- Can be absorbed by ions meeting the light (a)
- Slows down the ion (b)
- Re-emission isotropic leads to net slowing down – cooling (c)



Conditions

Need a strong transition, since many absorptions are needed to slow down the ion – E1 transitions!

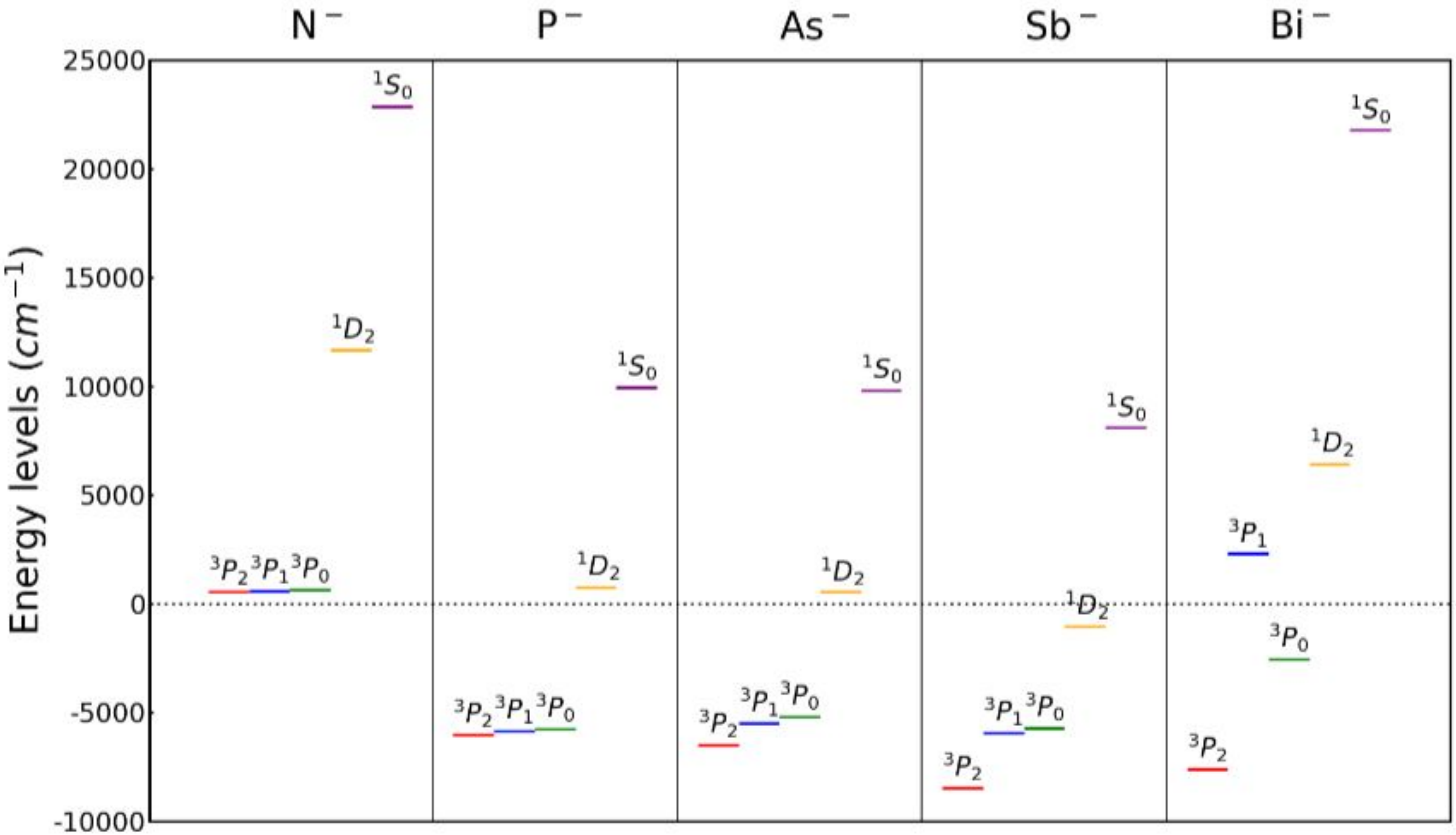


Why hard for negative ions?

- Atoms and positive ions have many cycles – ”easy” to cool
- Negative ions often only have one bound state
- And if more than one, usually of the same parity
- So often no E1-transitions

Example: negative ions in Nitrogen group

Ground configuration: np^4



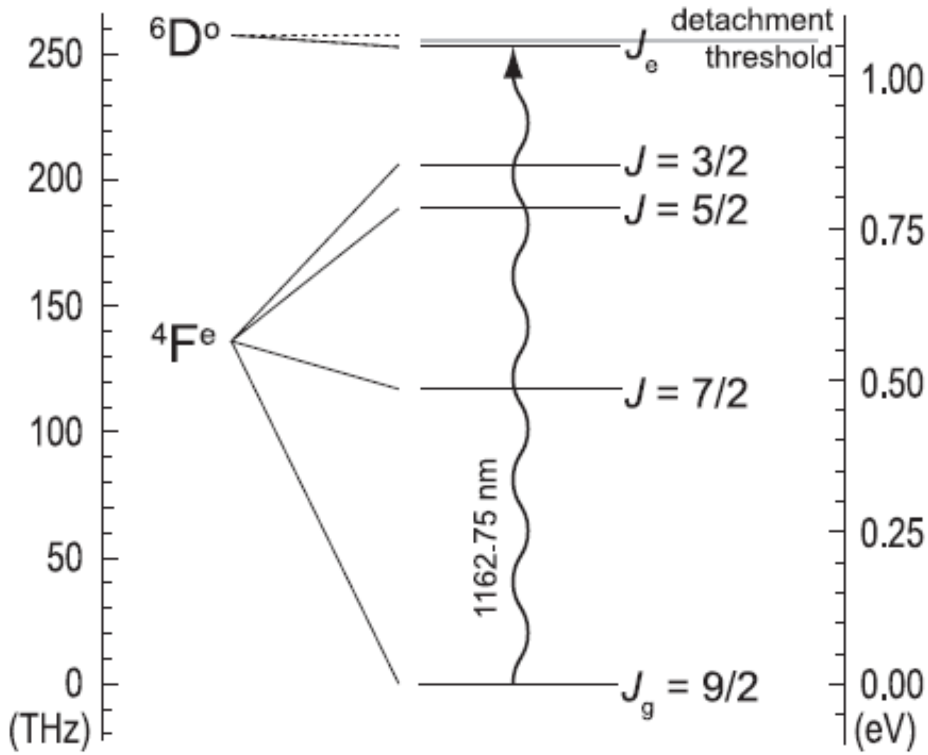
Y. Su et al., J. Phys. B ***52*** *(2019)*

Three cases of E1-transitions in anions

Case 1: Os^- (Z=76)

But transition very slow with rate of 50 s^{-1}

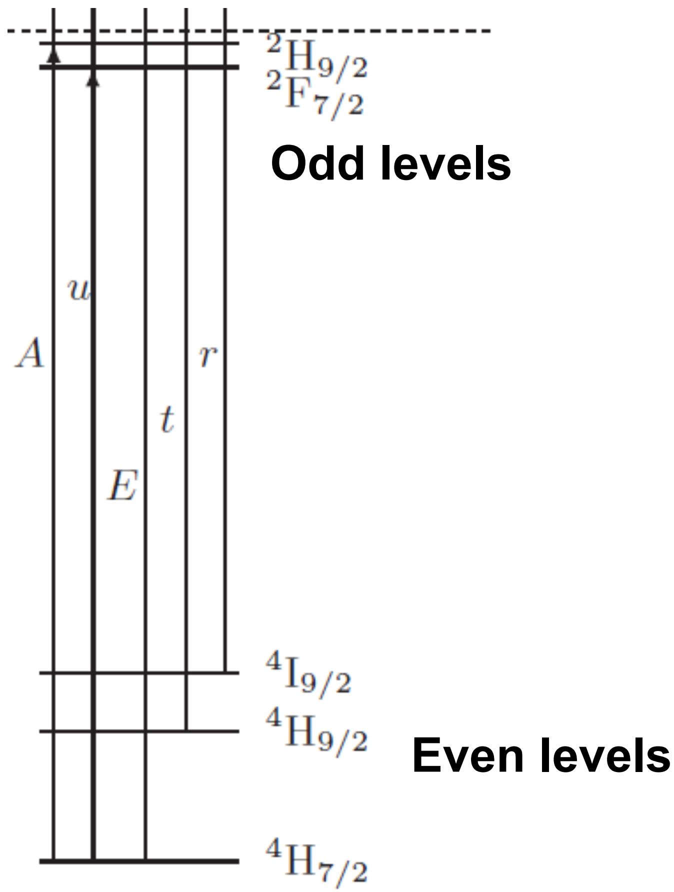
Not suitable for cooling!



Three cases of E1-transitions in anions

Case 2: Ce^- (Z=58)

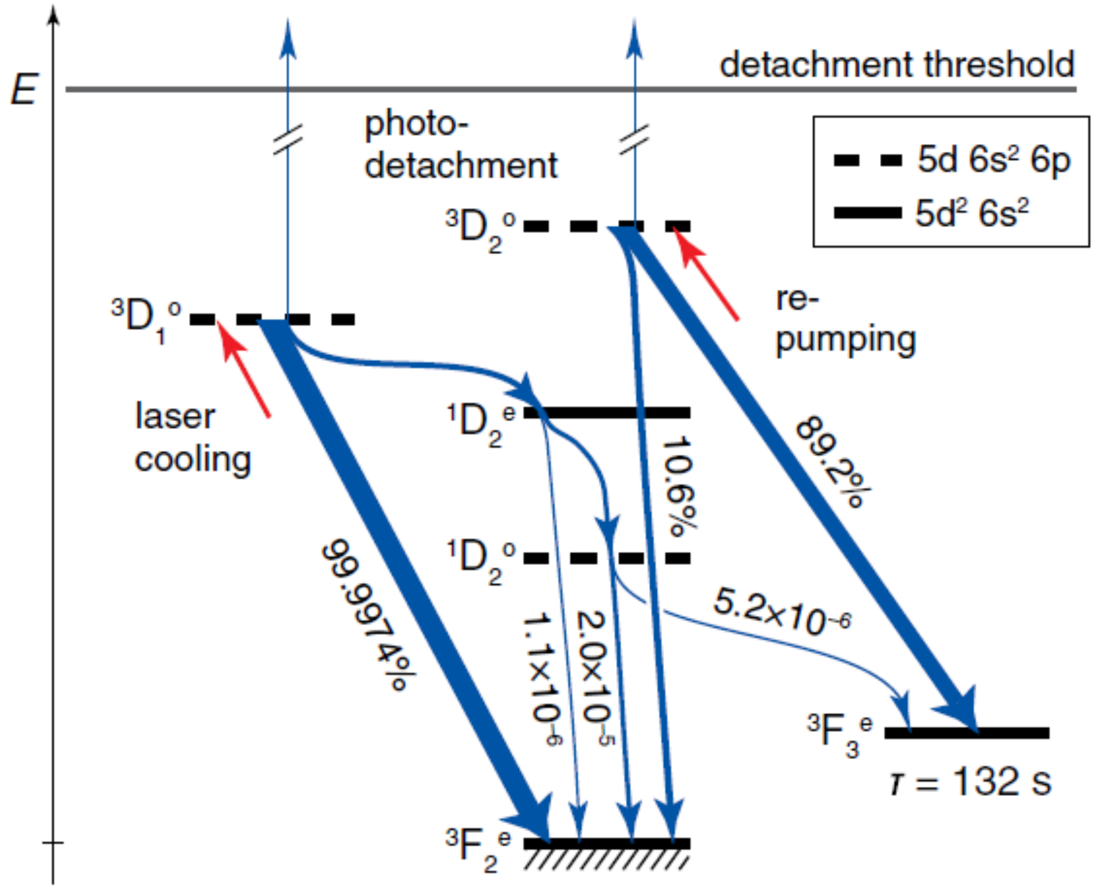
- After absorption to odd levels
- Many decay nodes to even levels
- Dark states
- Breaks cycle



Three cases of E1-transitions in anions

Case 3: La^- (Z=57)

- Promising candidate
- But, has nuclear spin I = 7/2
- Every level split up in hyperfine structure
- Dark states!



New candidate proposed

Th^- (Z= 90)

- Discussed by O'Malley and Beck
  - correlation only in valence shells
- New GRASP-calculations by R. Si
  - Correlation also with and within core

Property	O'Malley and Beck	Present
Electron affinity	0368 eV	0.599 eV
Ground state	Odd	Even

Results for neutral Th

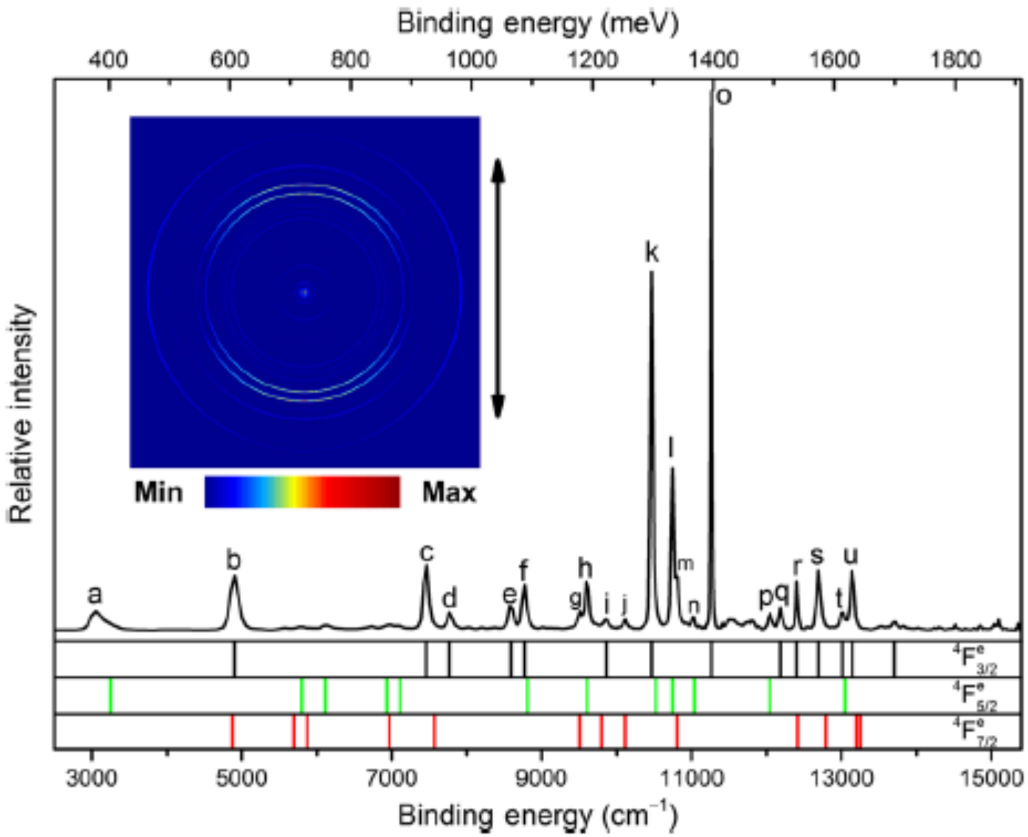
	Our calculation (cm^{-1})	Expt from NIST ASD (cm^{-1})
$6d^2 7s^2\ ^3F_2$	0	0
$6d^2 7s^2\ ^3P_0$	2684 (125)	2558
$6d^2 7s^2\ ^3F_3$	2705 (-163)	2869
$6d^2 7s^2\ ^3P_2$	3691 (3)	3688
$6d^2 7s^2\ ^3P_1$	3788 (-77)	3865
$6d^2 7s^2\ ^3F_4$	4889 (-72)	4961

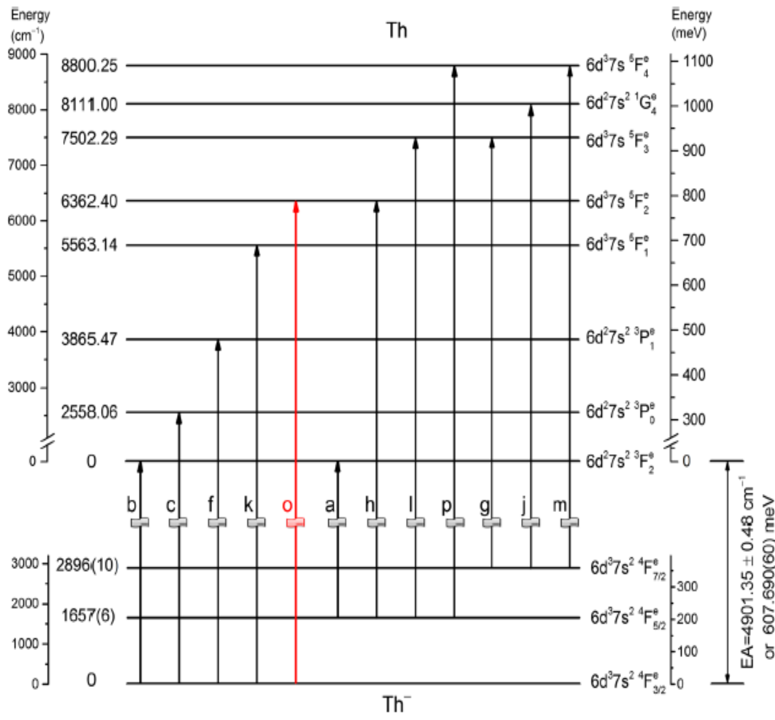
Results for Th$^-$

TABLE I. Measured and calculated excitation energies of Th$^-$ states, and the electron affinity of Th.

	Measured		Calculated	
State	cm^{-1}	meV	cm^{-1}	meV
$6d^3 7s^2\,{}^4F^e_{3/2}$			0	0
$6d^2 7s^2 7p\ {}^4G^o_{5/2}$			401	50
$6d^3 7s^2\,{}^4F_{5/2}$	1657(6)	205.4(7)	1377	171
$6d^3 7s^2\,{}^4F_{7/2}$	2896(10)	359.1(12)	2642	328
$6d^2 7s^2 7p\ {}^4F^o_{3/2}$			3033	376
$6d^3 7s^2\,{}^4F_{9/2}$			3637	451
$6d^2 7s^2 7p\ {}^2S^o_{1/2}$			3904	484
$6d^2 7s^2 7p\ {}^4F^o_{7/2}$			3974	493
$6d^2 7s^2 7p\ {}^4F^o_{5/2}$			3992	495
Electron affinity of Th	4901.35(48)	607.690(60)	4832	599

Photoelectron imaging experiment





Results for Th$^-$

Requirement: strong lines and no dark states

Upper level	Lower level	Energy cm^{-1}	Energy meV	$A\,(s^{-1})$	τ
$6d^2 7s^2 7p\ {}^4G^o_{5/2}$	$6d^3 7s^2 {}^4F^e_{3/2}$	401	50	1.95[+1]	51.3 ms
$6d^3 7s^2 {}^4F^e_{5/2}$	$6d^2 7s^2 7p\ {}^4G^o_{5/2}$	976	121	2.08[+0]	0.480 s
$6d^3 7s^2 {}^4F^e_{7/2}$	$6d^2 7s^2 7p\ {}^4G^0_{5/2}$	2241	278	1.24[+2]	8.08 ms
$6d^2 7s^2 7p\ {}^4F^o_{3/2}$	$6d^3 7s^2 {}^4F^e_{3/2}$	3033	376	6.26[+4]	15.9 μs
	$6d^3 7s^2\ {}^4F_{5/2}$	1656	205	2.01[+2]	
$6d^2 7s^2 7p\ {}^2S^o_{1/2}$	$6d^3 7s^2 {}^4F^e_{3/2}$	3904	484	1.17[+4]	85.5 μs
$6d^2 7s^2 7p\ {}^4F^o_{7/2}$	$6d^3 7s^2 {}^4F_{5/2}$	2597	322	6.86[+3]	138 μs
	$6d^3 7s^2 {}^4F_{7/2}$	1332	165	4.01[+2]	
$6d^2 7s^2 7p\ {}^4F^o_{5/2}$	$6d^3 7s^2 {}^4F^e_{3/2}$	3992	495	1.40[+4]	42.4 μs
	$6d^3 7s^2 {}^4F_{5/2}$	2615	324	9.57[+3]	
	$6d^3 7s^2 {}^4F_{7/2}$	1350	167	5.82[+1]	

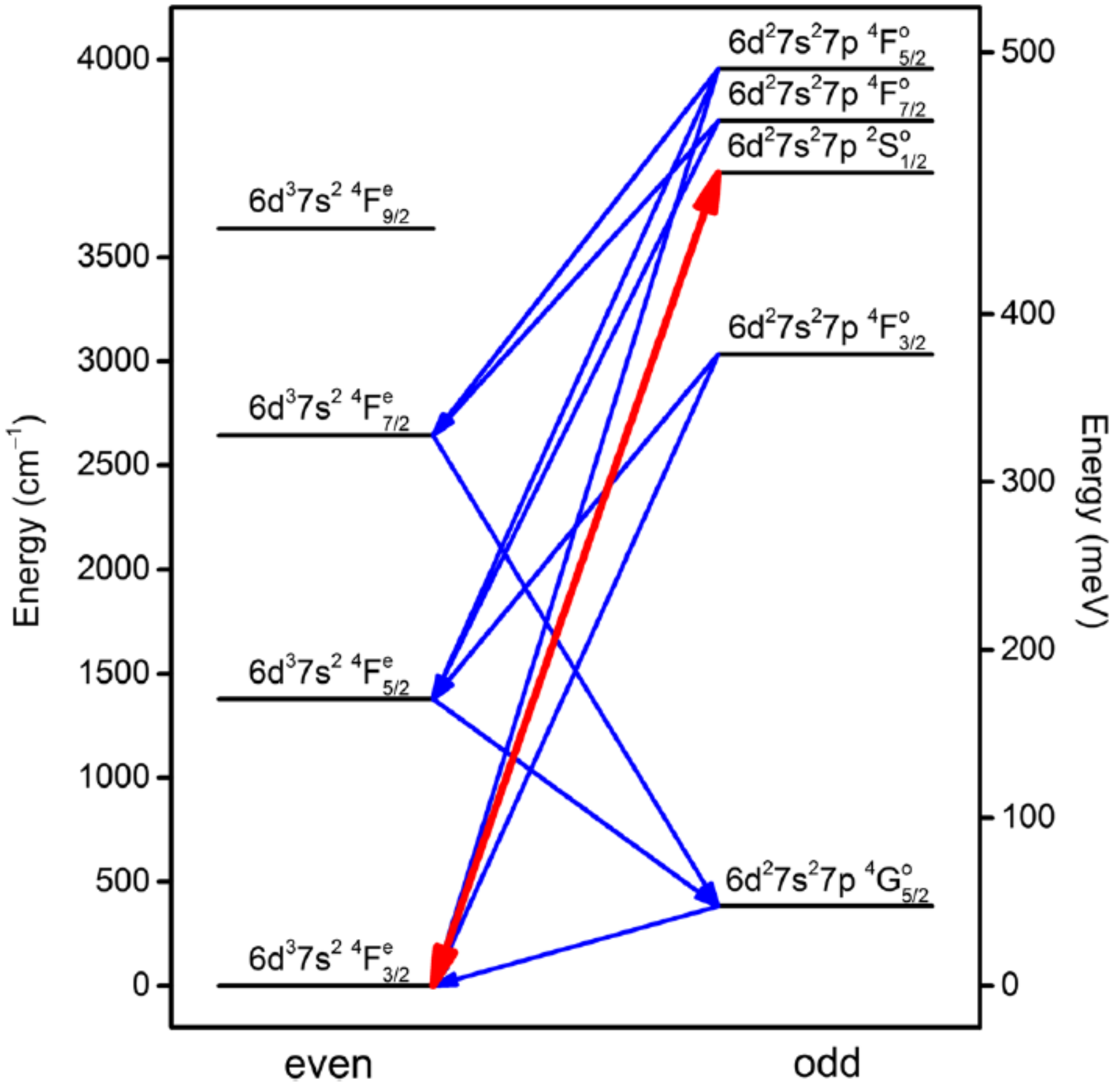
To weak

Dark states

candidate

Dark states

Candidate in Th⁻



Tang, R., Si, R. et al. Phys. Rev. Lett. ***123*** *203002 (2019) (editor's choice)*

Conclusions

Presented two examples where detailed structure calculations are essential.

1. First direct determination of coronal magnetic field strengths.

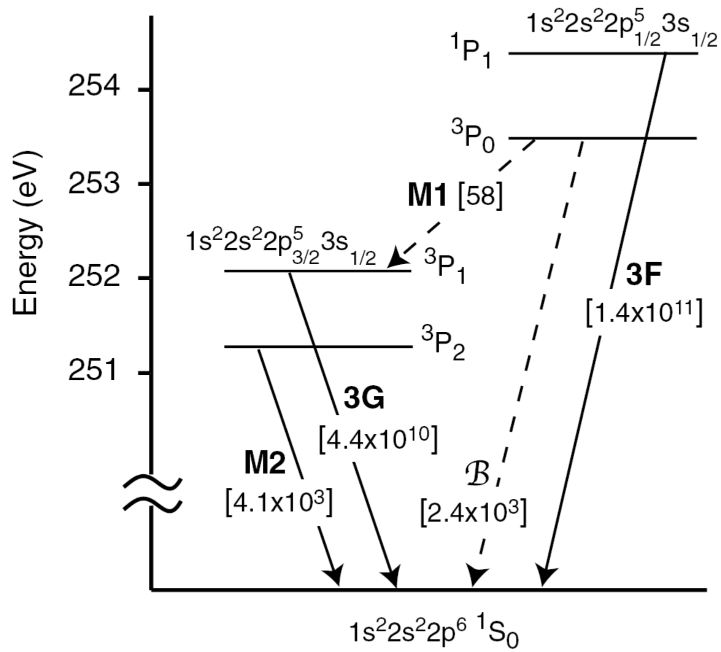
2. New (and better) proposal of laser cooling of negative ions and thereby supporting measurements of gravitational symmetry between matter and anti-matter.

Thank you for your attention!

The effect of magnetic fields on atomic structure

Not only Zeeman splitting BUT an entirley new line !

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



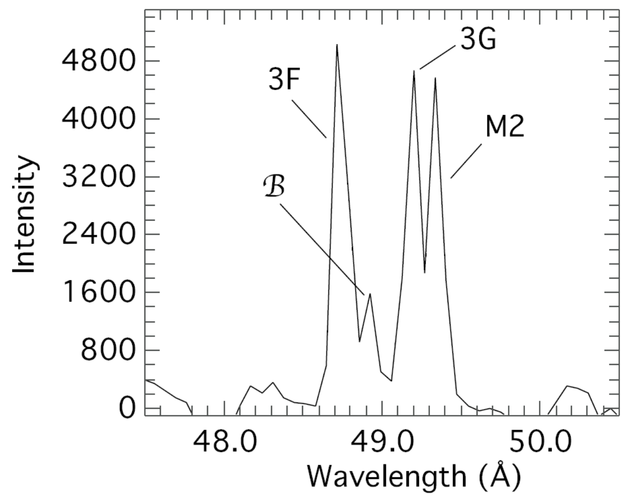


Figure 8: Spectrum of the Ar^{8+} $2p-3s$ emission at an electron density of $n \approx 1.25 \times 10^{10}$ cm^{-3} measured on EBIT-I. The lines are labeled using the notation defined in Fig. 7.