Opacity Calculations for Stellar Astrophysics

Jean-Christophe Pain[1,2]

[1]CEA, DAM, DIF, F-91297 Arpajon, France
[2]Université Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes,
F-91680 Bruyères-le-Châtel Cedex, France

This work discusses results obtained through numerous collaborations, in particular with:

J. E. Bailey (SNL)
S. Bastiani (LULI)
C. Blancard (CEA)
J. Colgan (LANL)
Ph. Cossé (CEA)
M. Dozières (General Atomics)
G. Faussurier (CEA)
F. Gilleron (CEA)
D. Gilles (CEA)
S. B. Hansen (SNL)
R. M. More (Pleasanton, CA, USA)
T. Nagayama (SNL)
S. N. Nahar (Ohio State University)
A. K. Pradhan (Ohio State University)
F. Thais (CEA)
S. Turck-Chièze (CEA)

Outline of the talk

1. Opacities and stars
2. Computation of opacity: the SCO-RCG code
3. Opacity comparisons in conditions representative of stellar envelopes
4. Spectroscopy experiments
5. Boundary of the convective zone of the Sun: the enigmatic Z-pinch experiment on iron

Part 1

Opacities and stars

Historical remarks

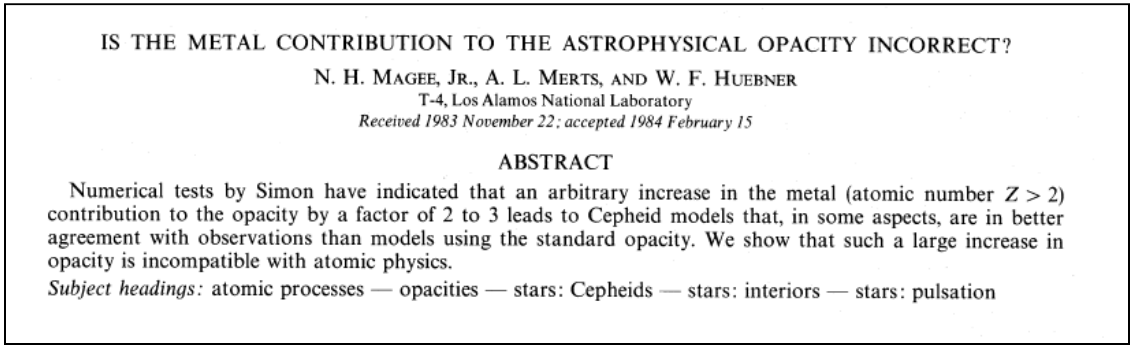
- In 1926, **Eddington** identifies opacity as a key parameter of stellar models.

- In 1929, **Russell** publishes the first quantitative analysis of the chemical composition of the solar atmosphere, first made by **Payne-Gaposchkin** in 1924.

- At such temperatures and densities, most of the elements are not fully ionized.

- In the early sixties, **Cox** and **Huebner** introduce photo-excitation and photo-ionization processes in the calculation of stellar opacities.

- **Simon** raises in 1982 the problem of the pulsation of Cepheids: opacity of « heavy » elements: C, N, O, …



IS THE METAL CONTRIBUTION TO THE ASTROPHYSICAL OPACITY INCORRECT?

N. H. MAGEE, JR., A. L. MERTS, AND W. F. HUEBNER
T-4, Los Alamos National Laboratory
Received 1983 November 22; accepted 1984 February 15

ABSTRACT

Numerical tests by Simon have indicated that an arbitrary increase in the metal (atomic number $Z > 2$) contribution to the opacity by a factor of 2 to 3 leads to Cepheid models that, in some aspects, are in better agreement with observations than models using the standard opacity. We show that such a large increase in opacity is incompatible with atomic physics.

Subject headings: atomic processes — opacities — stars: Cepheids — stars: interiors — stars: pulsation

- 1990's: OPAL (LLNL) and OP (Opacity Project = international academic collaboration): first stellar opacity tables.

N. H. Magee, Jr., A. L. Merts & W. F. Huebner, Astrophys. J. **283** , 264 (1984).

Simplified description of stellar structure

- Hydrostatic equilibrium:

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$$

- Mass:

$$\frac{dm}{dr} = 4\pi\rho r^2$$

- Luminosity:

$$L = -\frac{4\pi r^2}{3\boxed{\kappa_R}}\frac{ac}{\rho}\frac{dT^4}{dr}$$

Rosseland mean opacity

- Energy:

$$\frac{dL}{dr} = 4\pi\rho r^2\epsilon$$

P: pressure
T: temperature
ρ: density
M: mass
L: luminosity
ε: energy
r: radius
a: Stefan’s constant
c: speed of light

Part 2

Opacity calculation

The SCO-RCG code

Processes contributing to radiative opacity for local-thermodynamic-equilibrium plasmas

Opacity

Characterizes the interaction between electromagnetic radiation and matter by absorption and scattering processes at a frequency ν

$$K_\nu(\rho,T)=\frac{N_{\mathrm{Avo}}}{A}\sum_i \Theta_i(\rho,T)\left\{\sigma_{i,\nu}^{(\mathrm{abs})}(\rho,T)\times[1-\exp(-h\nu/k_{\mathrm{B}}\mathrm{T})]+\sigma_{i,\nu}^{(\mathrm{scat})}(\rho,T)\right\}$$

Occupation probability

Cross-section

- Photo-excitation (lines):

$$X_a^i(E_a)+\hbar\omega\rightarrow X_b^i(E_b)$$

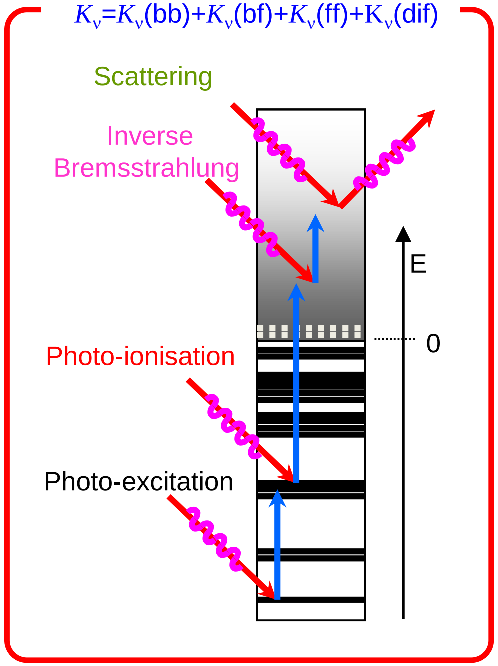
- Photo-ionization (edges):

$$X_a^i(E_a)+\hbar\omega\rightarrow X_b^{i-1}(E_b)+\epsilon_b \quad ; \quad \hbar\omega=E_b+\epsilon_b-E_a$$

- Inverse Bremsstrahlung:

$$X_a^i(E_a)+\epsilon_a+\hbar\omega\rightarrow X_b^i(E_b)+\epsilon_b \quad ; \quad \hbar\omega=E_b+\epsilon_b-(E_a+\epsilon_a)$$

- Scattering of a photon by free electrons (Compton) and by bound electrons (Rayleigh).



$K_\nu=K_\nu(\mathrm{bb})+K_\nu(\mathrm{bf})+K_\nu(\mathrm{ff})+K_\nu(\mathrm{dif})$

Radiative opacity

Planck mean

$$\kappa_P = \int_0^\infty W_P(u)\kappa(u)du$$

$$W_P(u) = \frac{15u^3e^{-u}}{\pi^4[1-e^{-u}]}$$

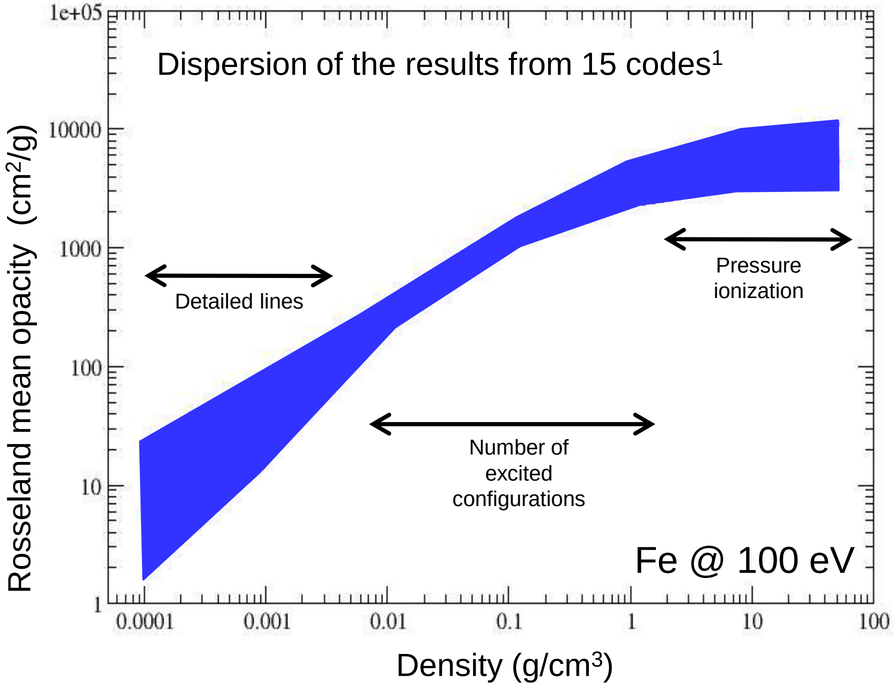
Rosseland mean

$$\frac{1}{\kappa_R} = \int_0^\infty \frac{W_R(u)}{\kappa(u)}du$$

$$W_R(u) = \frac{15u^4e^{-u}}{4\pi^4[1-e^{-u}]^2}$$

$$u = \frac{h\nu}{k_BT}$$

Issues for an accurate computation



---

[1] F. J. D. Serduke, E. Minguez, S. J. Davidson and C.A. Iglesias, JQSRT 65, 527 (2000).

The SCO-RCG code[1]: opacity of local-thermodynamic-equilibrium (LTE) plasmas

Atomic structure and « thermodynamics »: SCO (T. Blenski et al.[2])

- Generation of the list of configurations.
- Self-consistent computation of atomic structure.
- Includes plasma density effects[3] (pressure ionization, …).

Detailed Line Accounting (DLA) computations: RCG (R. D. Cowan[4])

- Source code developed for decades by spectroscopists.
- Well documented (731 pages book).
- « On the fly » calculation of levels and lines with wavefunctions from SCO.

No tabulated data

Max. number of lines per transition array: 800,000

Strengths : completeness (large number of excited states) and density effects on the wavefunctions.

Weakness: configuration interaction only inside non-relativistic configurations.

---

[1] J.-C Pain and F. Gilleron, High Energy Density Phys. **15**, 30 (2015).

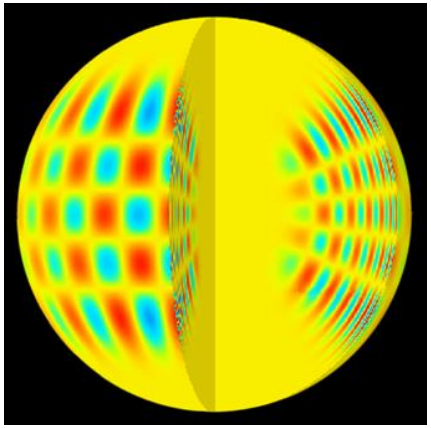
[2] T. Blenski, A. Grimaldi & F. Perrot, J. Quant. Spectrosc. Radiat. Transfer **65**, 91 (2000).

3J.-C Pain, G. Dejonghe and T. Blenski, J. Quant. Spectrosc. Radiat. Transfer **99**, 451 (2006).

[4] R. D. Cowan, The Theory of Atomic Structure and Spectra, 1981.

Part 3

Comparisons of opacities in conditions representative of stellar envelopes



Computed pattern of a p-mode solar acoustic oscillation of the Sun (*l*=20, *m*=16, and *n*=14.)
© CC

Envelopes of β Cephei-type stars

■ In 1902, Edwin Frost discovers the variability of the radial velocity of β Cephei (β Canis Majoris).

■ β Cephei type stars (8 to 18 $M_\odot$):

- Hot blue-white stars of spectral class B.
- Ex: ν Eridani, γ Pegasi, β Crucis, β Centauri…

β Cephei (Alfirk) (© Palomar Observatory)

Magnitude: +3.16 to +3.27.
Period: 4.57 hours.

■ Opacity of the « iron group » (Cr, Fe & Ni):

$T \approx$ 200-300,000 K and $\rho \approx 10^{-7}$-10^{-6} g/cm^3

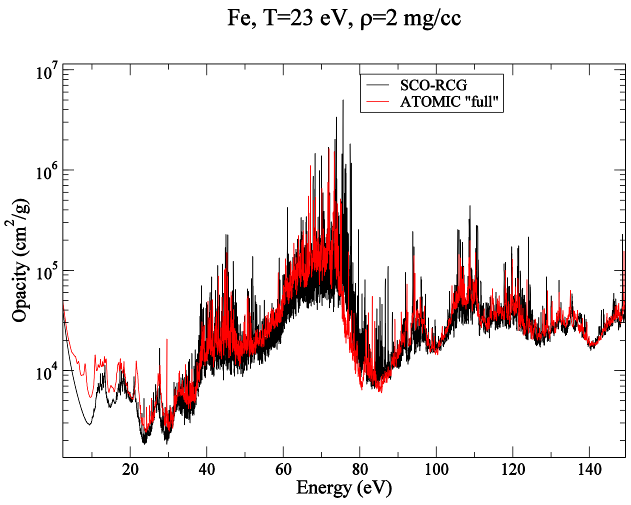
The iron-group opacity peak excites acoustic (p) modes through the "**kappa-mechanism**".

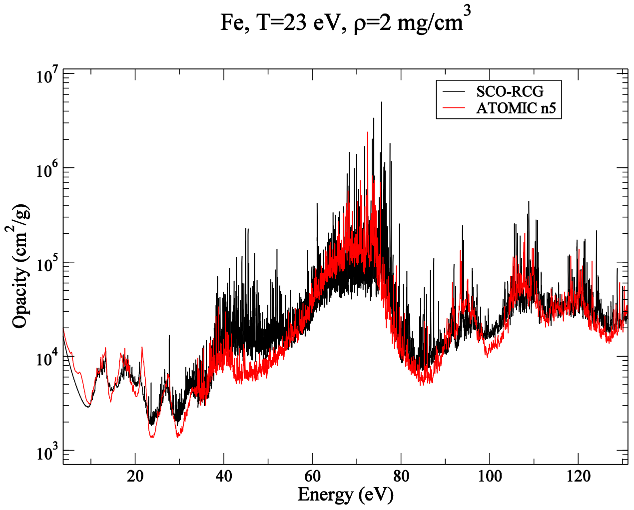
■ « Slowly Pulsating B » (SPB) stars are subject to gravity modes (« g » modes), also connected to iron opacity. Their mass is from 2 to 6 $M_\odot$.

E. B. Frost, "The Period of Beta Cephei", Astrophys. J., **24**, 259 (1906).

Comparison of spectral opacities

- Stellar envelopes of β Cephei type stars: $\rho \approx 10^{-6}$ g/cm^3 and $T \approx 30$ eV.
- **Equivalent conditions of mean ionization with higher density accessible to experiment.**


Fe, T=23 eV, ρ=2 mg/cc


Fe, T=23 eV, ρ=2 mg/cm³

Fe Rosseland mean opacities

ATOMIC « full »	ATOMIC n5	SCO-RCG
19508	15205	18510

ATOMIC code (OPLIB tables)[1]
(Los Alamos National Laboratory)

“n5”: limited to $n_{max}=5$ but includes configuration interaction.
“full”: large number of states but no configuration interaction.

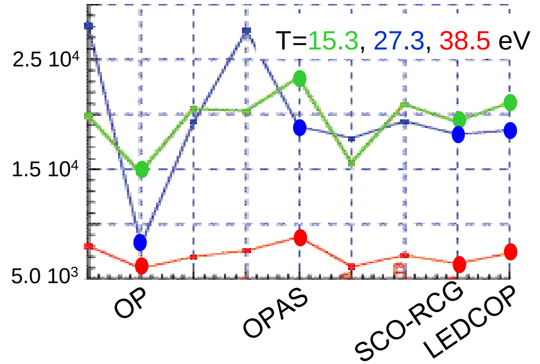
Dilemna: completeness or accuracy?

[1] J. Colgan et al., ApJ **817**, 116 (2016).
S. Turck-Chièze et al., ApJ **823**, 78 (2016).

Comparisons of Fe Rosseland mean opacities

T (eV)	n_e (cm^{-3})	ρ (g/cm^3)	OP (cm^2/g)	ATOMIC « full » (cm^2/g)	SCO-RCG (cm^2/g)
10.8	10^{17}	$1.35\ 10^{-6}$	24.7	64	62.6
15.3	$3.16\ 10^{17}$	$3.44\ 10^{-6}$	358	682.3	673.8
17.2	10^{17}	$9.52\ 10^{-7}$	354	486,2	499.2
21.6	10^{18}	$8.85\ 10^{-6}$	1270	1359	1313
25.5	$3.16\ 10^{17}$	$2.44\ 10^{-6}$	232	130.6	121.9

Rosseland mean (cm^2/g)

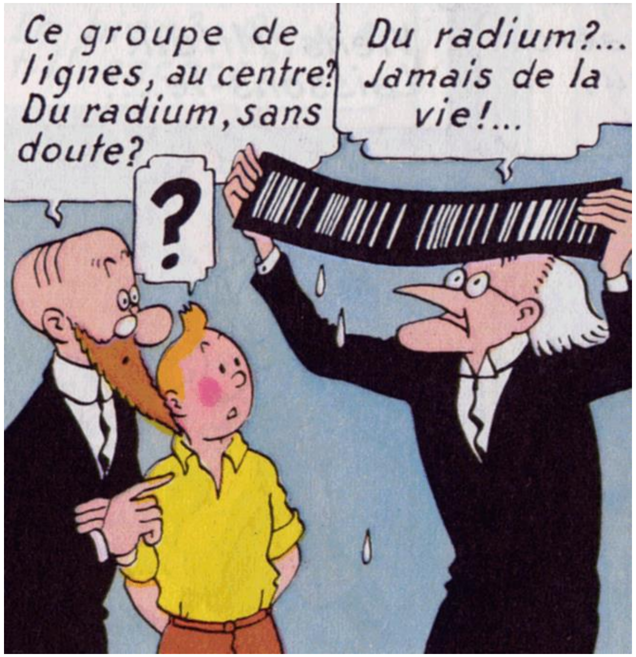


Max. difference ~10% (excluding OP)

S. Turck-Chièze et al., ApJ **823**, 78 (2016).

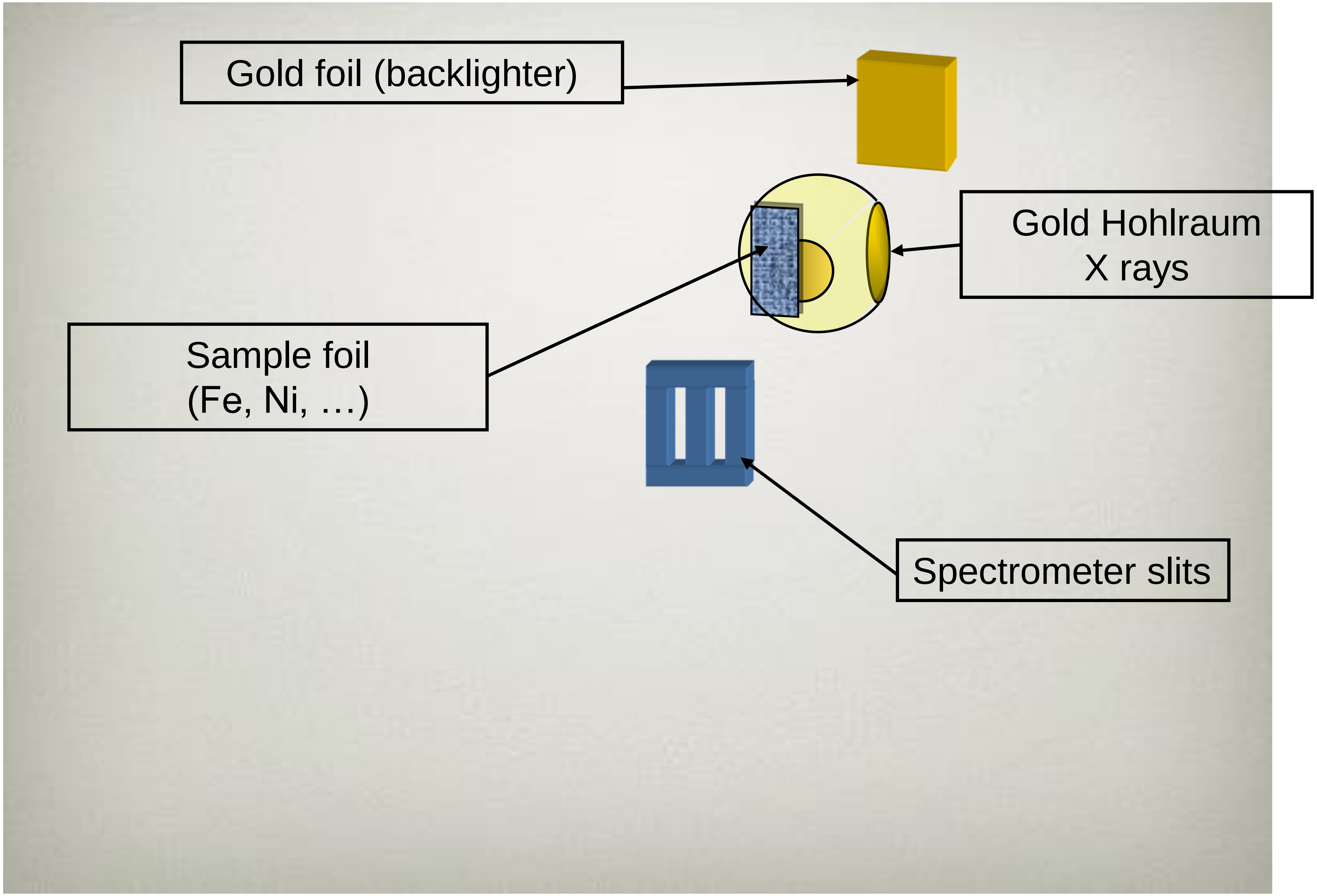
Part 4

Spectroscopy experiments



(*) - This group of lines, in the center: radium, isnt'it?...
- Radium? No way! …

Principle of a laser spectroscopy absorption experiment



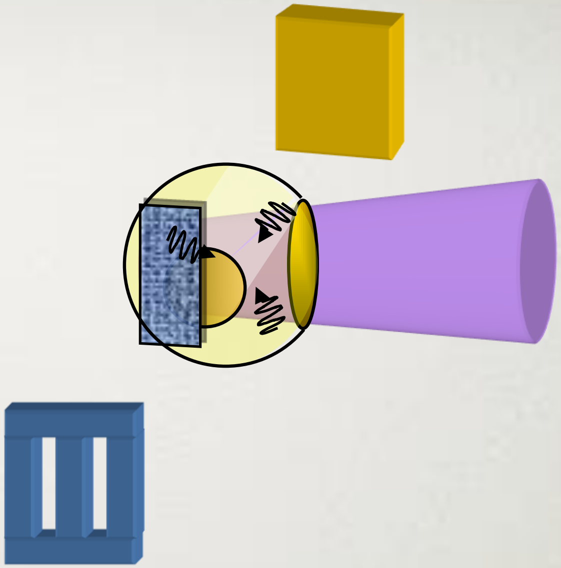
Gold foil (backlighter)

Gold Hohlraum
X rays

Sample foil
(Fe, Ni, …)

Spectrometer slits

Principle of a laser spectroscopy absorption experiment

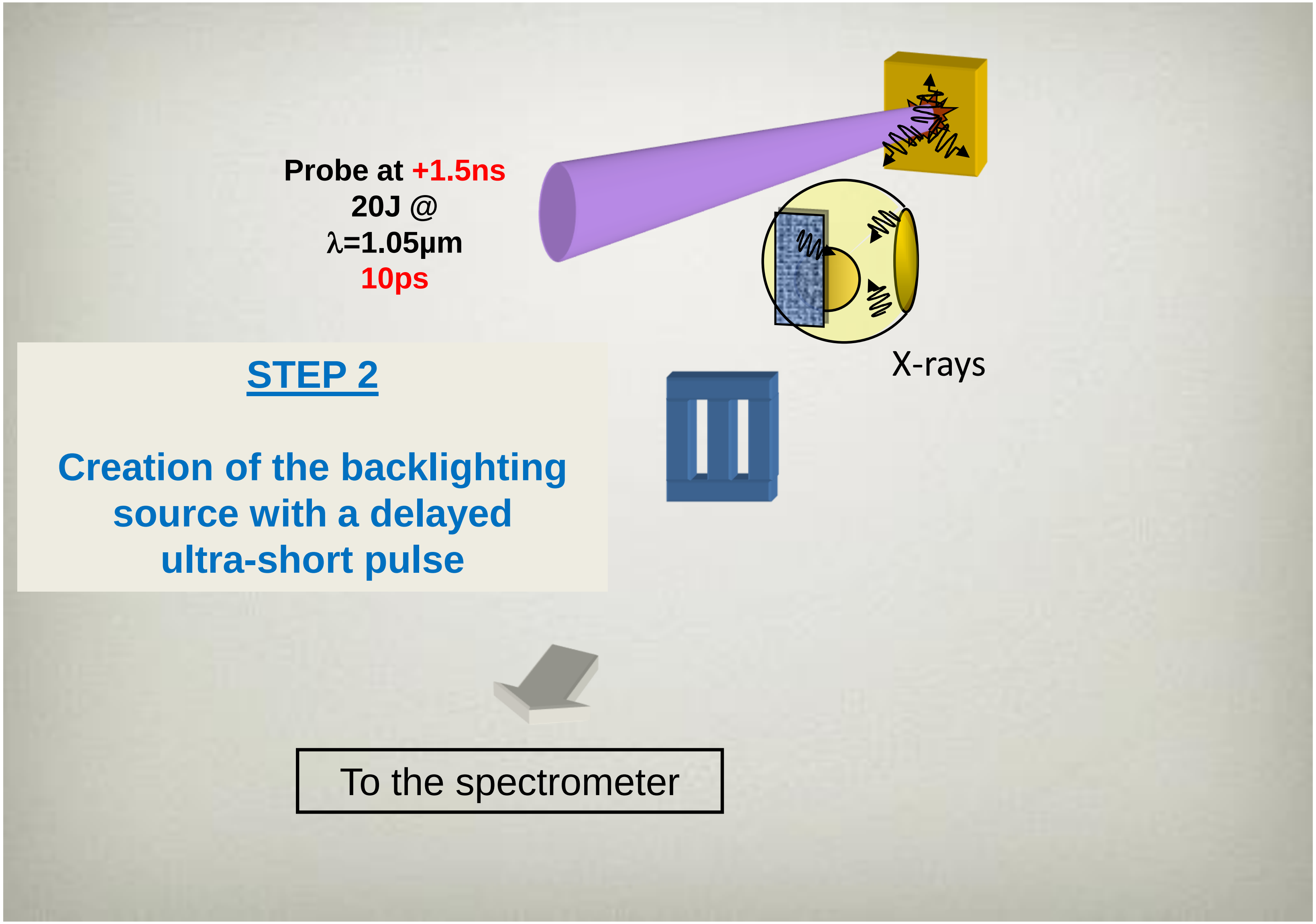


Heating:
150J @
λ=0.54µm
500ps

STEP 1

Heating of the foil by the laser-irradiated Hohlraum

Principle of a laser spectroscopy absorption experiment

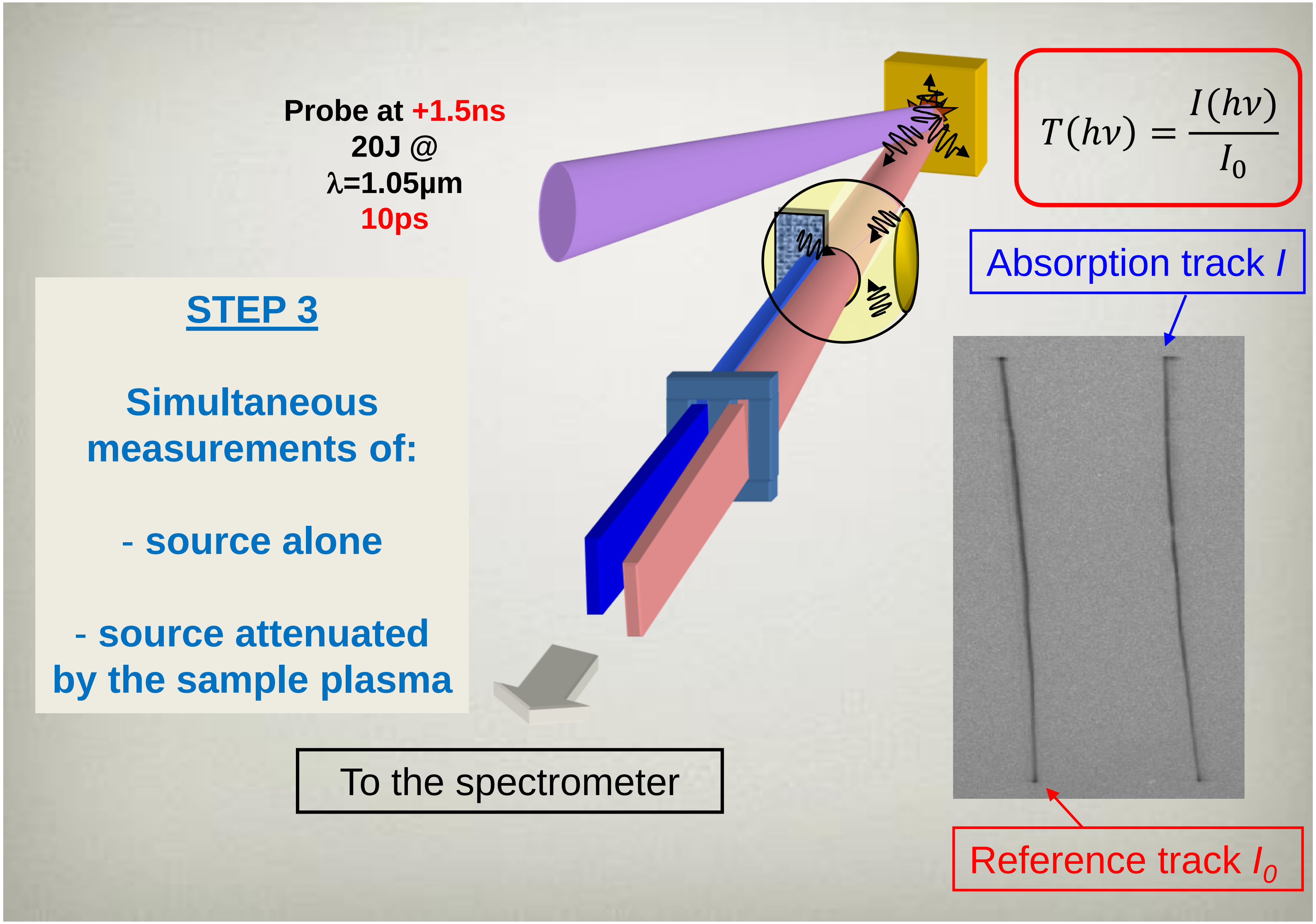


STEP 2

Creation of the backlighting source with a delayed ultra-short pulse

To the spectrometer

Principle of a laser spectroscopy absorption experiment



Probe at +1.5ns
20J @
λ=1.05µm
10ps

STEP 3

Simultaneous measurements of:

- **source alone**
- **source attenuated by the sample plasma**

To the spectrometer

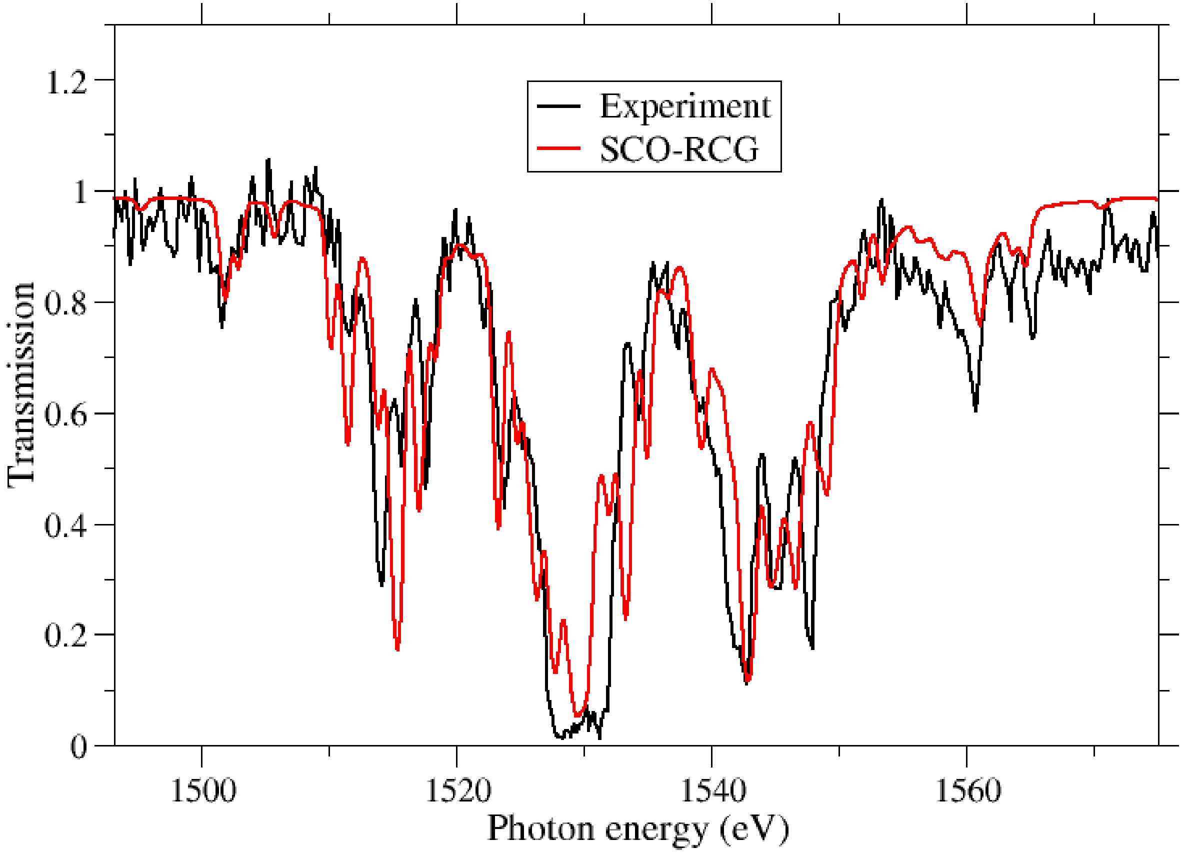
$$T(h\nu) = \frac{I(h\nu)}{I_0}$$

Absorption track *I*

Reference track I_0

Laser HELEN (AWE, UK): transmission of aluminum

Aluminium (37 eV, 0.01 g/cm^3),
S. J. Davidson et al., AWE (UK), 1988



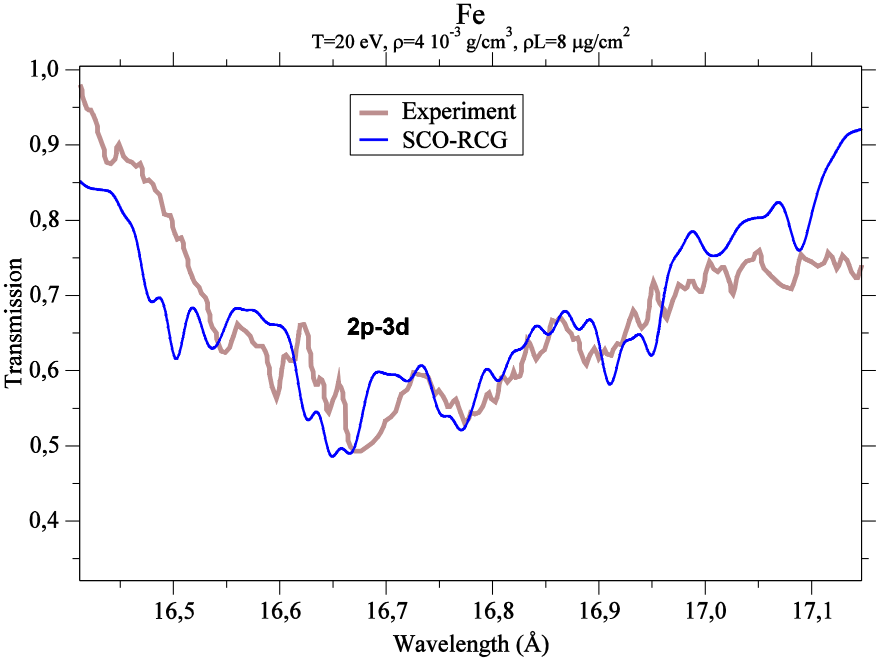
Beer-Lambert's law

$$T(h\nu) = e^{-\rho L \kappa(h\nu)}$$

S. J. Davidson et al., App. Phys. Lett. **52,** 847(1988).

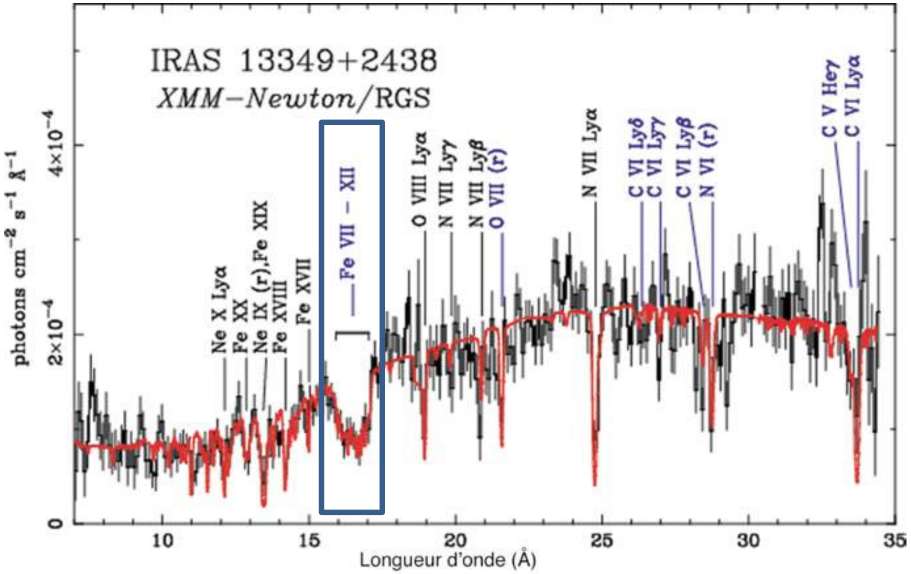
Laser ASTERIX IV (Germany): transmission of iron

2p-3d transitions of ions Fe VII to Fe XII



T=20 eV, ρ=4 10^{-3} g/cm^3

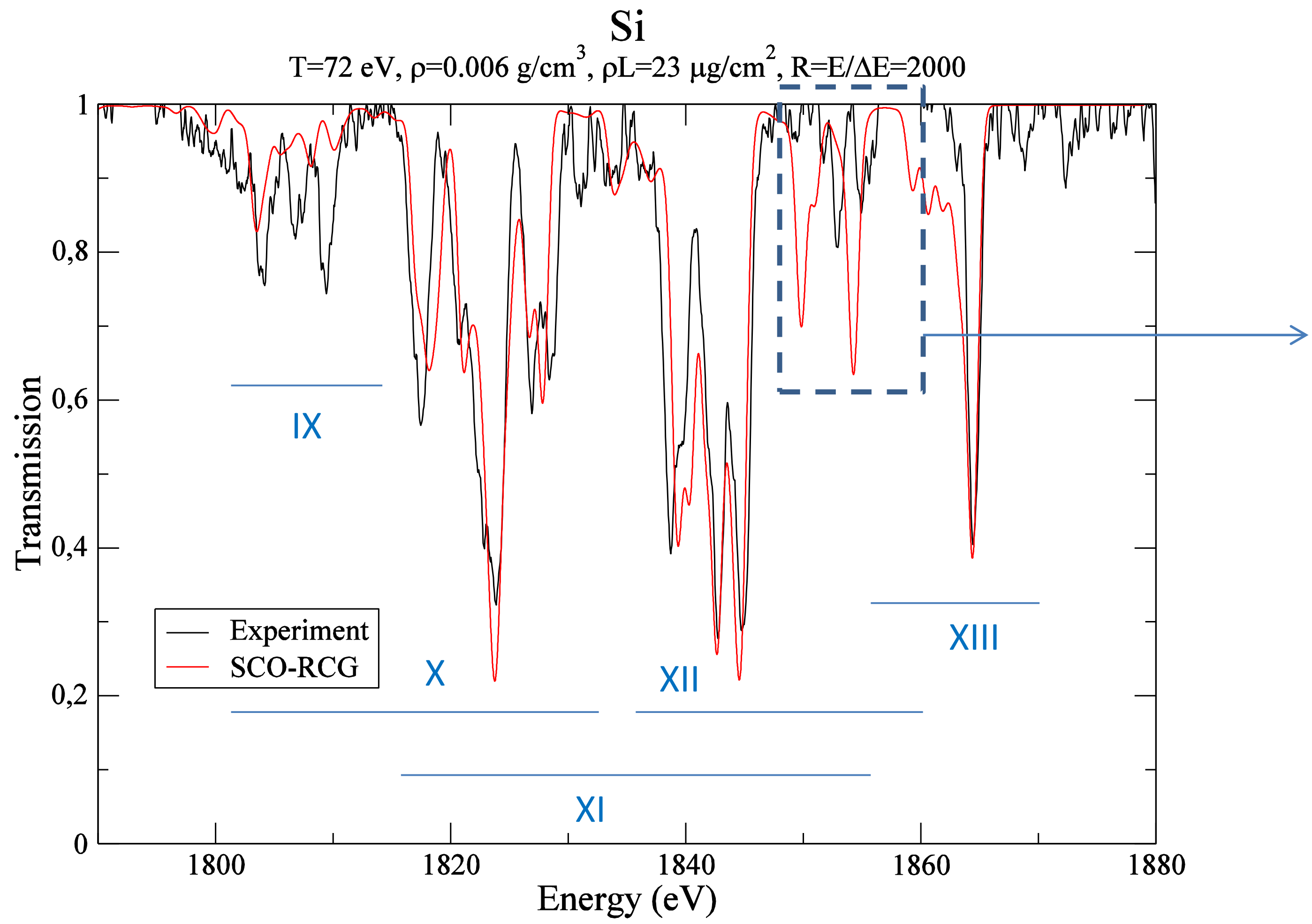
Spectrum of the quasar IRAS 13349 + 2438 measured by XMM-Newton



C. Chenais et al., Astrophys. J. **127**, 275 (2000).
C. Chenais-Popovics, Laser Part. Beams **20**, 291 (2002).
M. Sako et al., A&A **365**, L368 (2001).

Transmission of silicon (Shenguang II laser, China, 2009)

1s-2p Transitions of ions Si IX to Si XIII

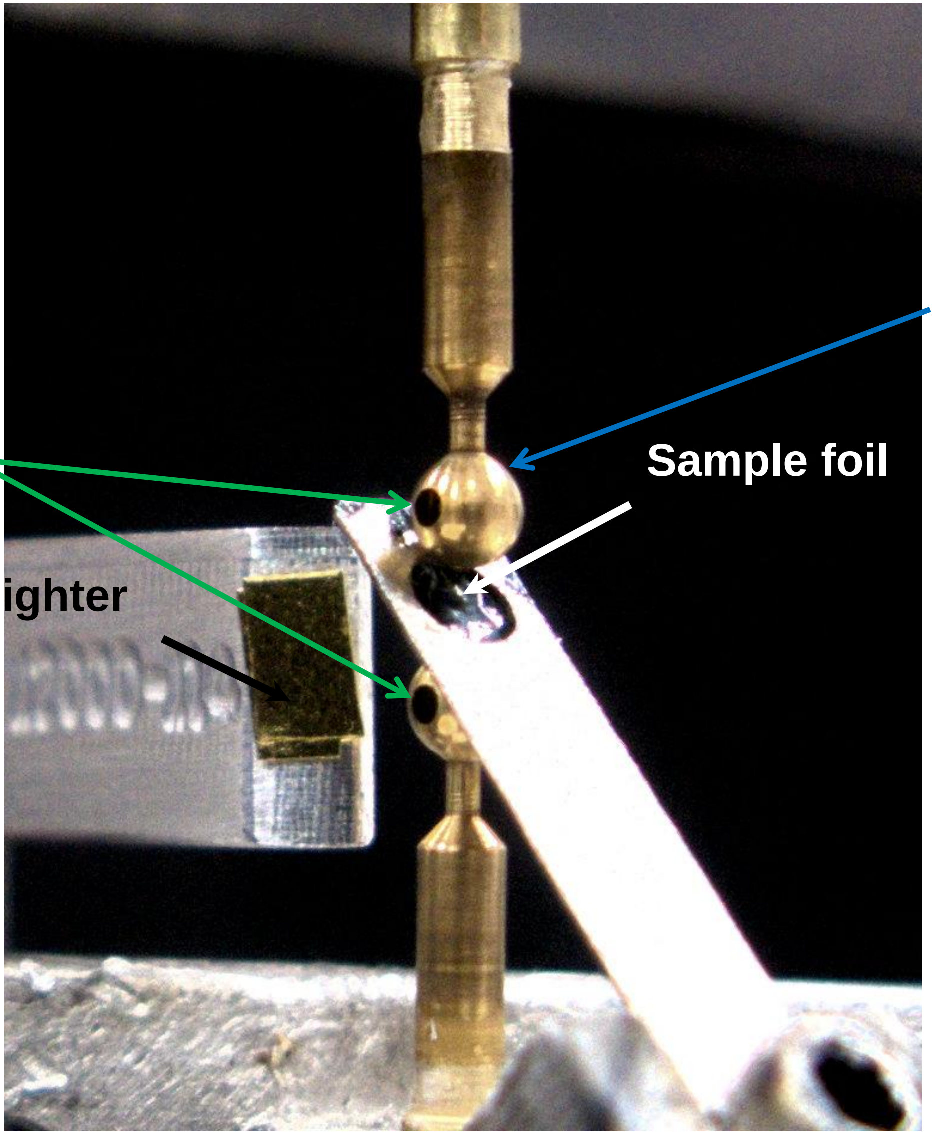


Configuration interaction?

G. Xiong et al., Astrophys. J. **816**, 36 (2016).
J.-C. Pain, F. Gilleron and M. Comet, Atoms **5**, 22 (2017).

Silicates: - around AGB stars and in disks around Ae/Be stars.
- processed in the diffuse interstellar medium.

Laser experiment at LULI laser facility (Ecole Polytechnique, France): double-Hohlraum design



Hohlraum
φ=3 mm

2 ns beams
400 J, 1.5 ns

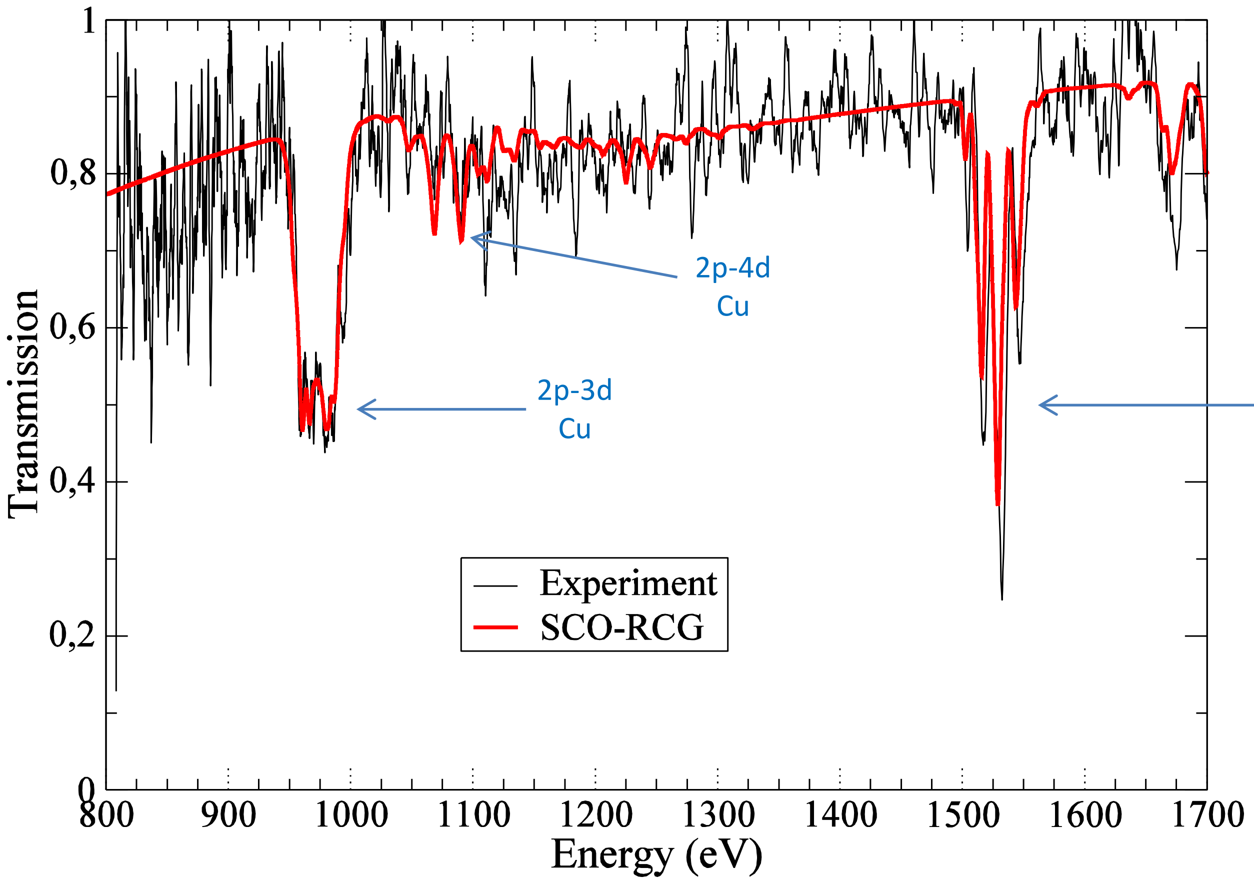
Sample foil

Backlighter

Transmission of copper (LULI, 2013)

$$\boxed{T(h\nu) = e^{-\rho L \kappa(h\nu)}}$$

Laser, Cu, T=27 eV, ρ=0.01 g/cm^3, ρL=15 μg/cm^2



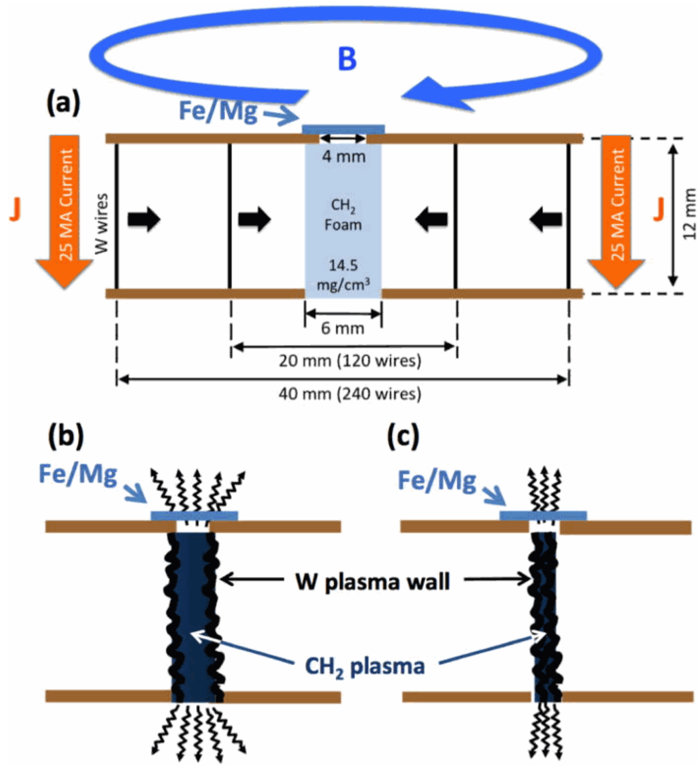
2p-4d
Cu

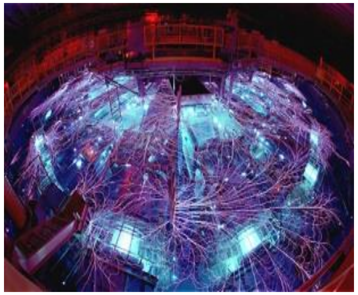
2p-3d
Cu

1s-2p
Transitions
Al

M. Dozières et al., High Energy Density Phys. **17**, 231 (2015).

Z-pinch experiment at Sandia National Laboratory (SNL): transmission of iron





© SNL

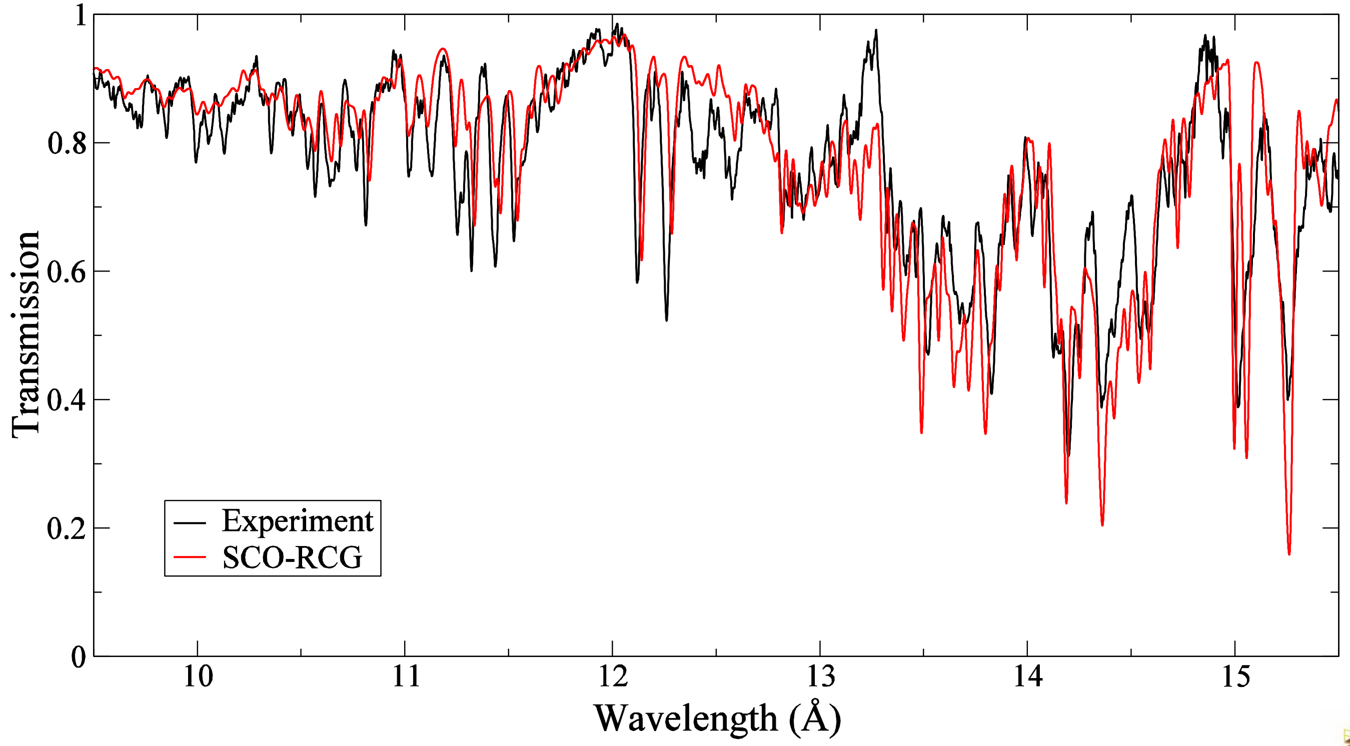
Figure: Experimental setup (©Sandia National Laboratory).

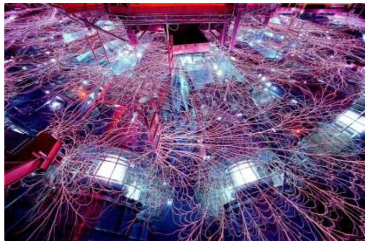
(a) The two concentric tungsten cages and the central plastic foam (CH_2).

(b) When the tungsten plasma collides with the CH_2 foam, the shock-generated radiation is trapped in the tungsten cages and heats the sample.

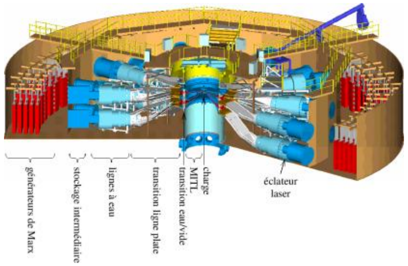
(c) At stagnation, an intense radiation (backlighter) is created, used to probe the sample (radiography).

Z-pinch experiment at Sandia National Laboratory (SNL): transmission of iron


Z-pinch, Fe, T=150 eV, ρ=0.058 g/cm^3, ρL=54 μg/cm^2


© SNL

instr. width=1.8 eV

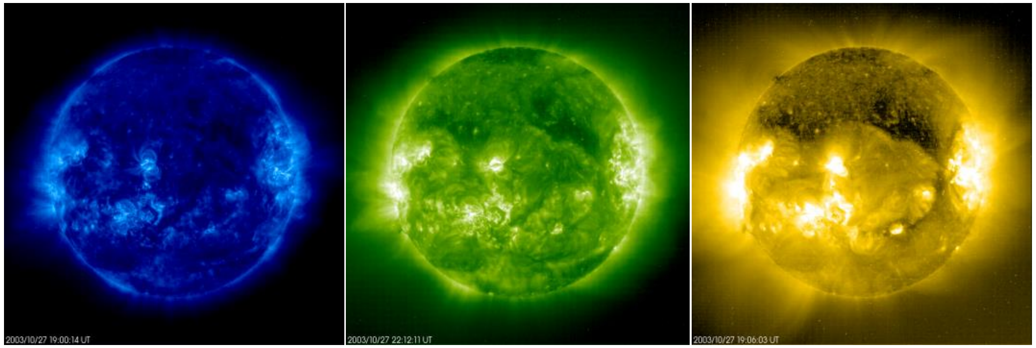


J. E. Bailey et al., Phys. Rev. Lett. **99**, 265002 (2007).

Part 5

Base of the solar convective zone

The enigmatic iron experiment



© EIT/SOHO

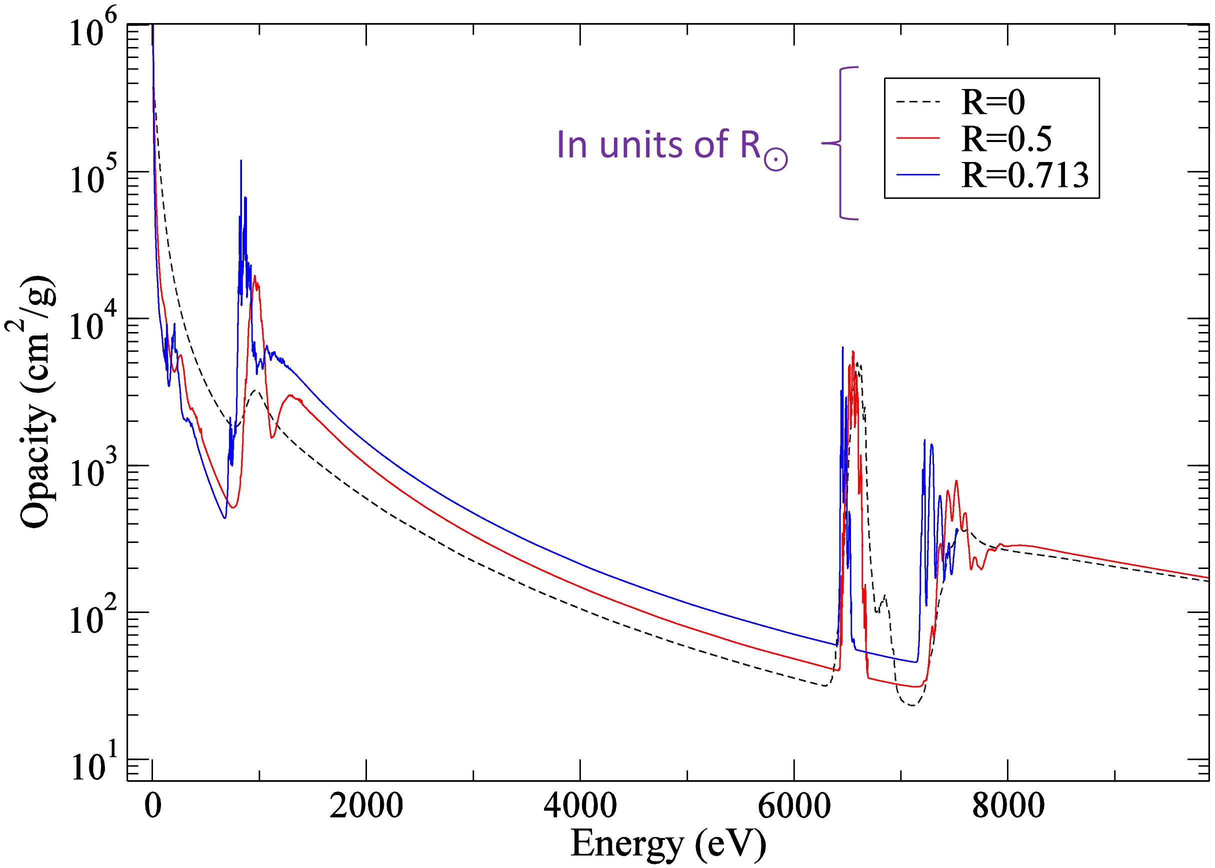
Fe IX 171 Å, T=7 10^5 K ; Fe XII 195 Å, T=1.4 10^6 K ; Fe XV 284 Å, T=2 10^6 K

Iron opacity at different distances from the Sun center

T (eV)	ρ (g/cm^3)	$R/R_\odot$
1345.78	152.055	0
340.701	1.29718	0.5
188.18	0.188062	0.713

Fe
Z^*=15.088
T=188.18 eV
ρ=1,13 g/cc

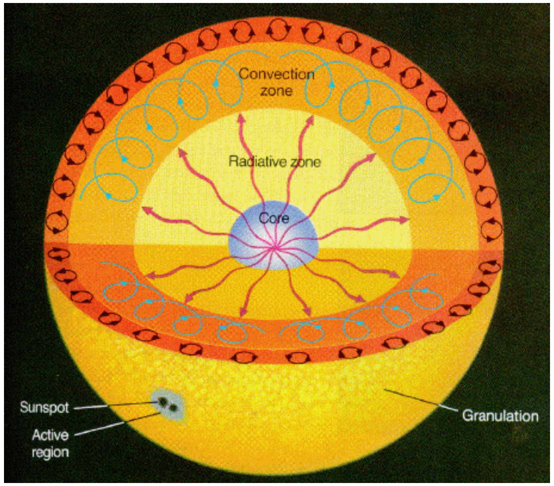
Ion charge	Fraction
13	0.0188
14	0.127
15	0.290
16	0.338
17	0.180
18	0.0421
19	0.00385
20	0.000132

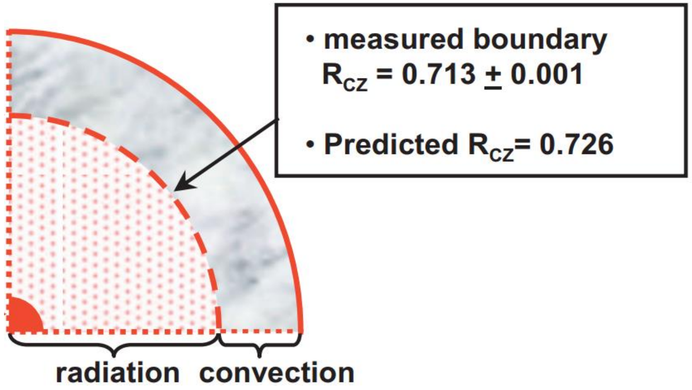


In units of $R_\odot$

From the radiative zone to the convective zone: the BCZ

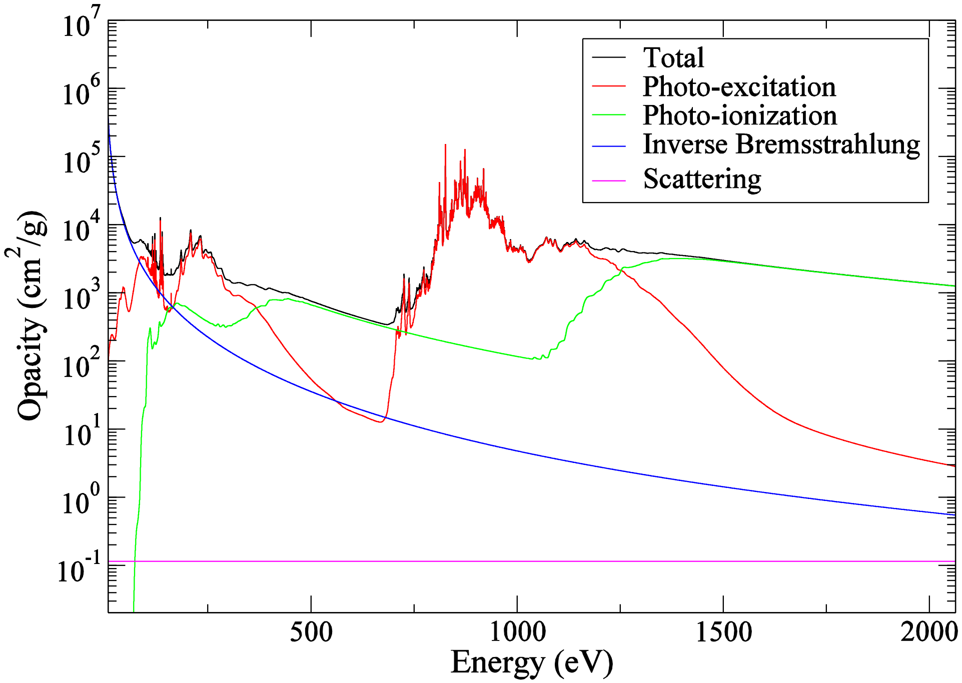
- Iron contributes for 25 % of the total opacity at the BCZ (boundary of the convective zone) of the Sun.




- **measured boundary $R_{CZ} = 0.713 \pm 0.001$**
- **Predicted $R_{CZ} = 0.726$**

© J. Bailey

Fe, T=192.91 eV, $n_e = 10^{23}$ cm^{-3}



From the radiative zone to the convective zone: the BCZ

- Recent reevaluation of the abundances of C, N and O in the solar mixture enhanced the disagreement between heliosismic measurements and predictions of the SSM (Standard Solar Model).

In order to reconcile observations and modeling, a 5 to 20 % increase would be necessary.

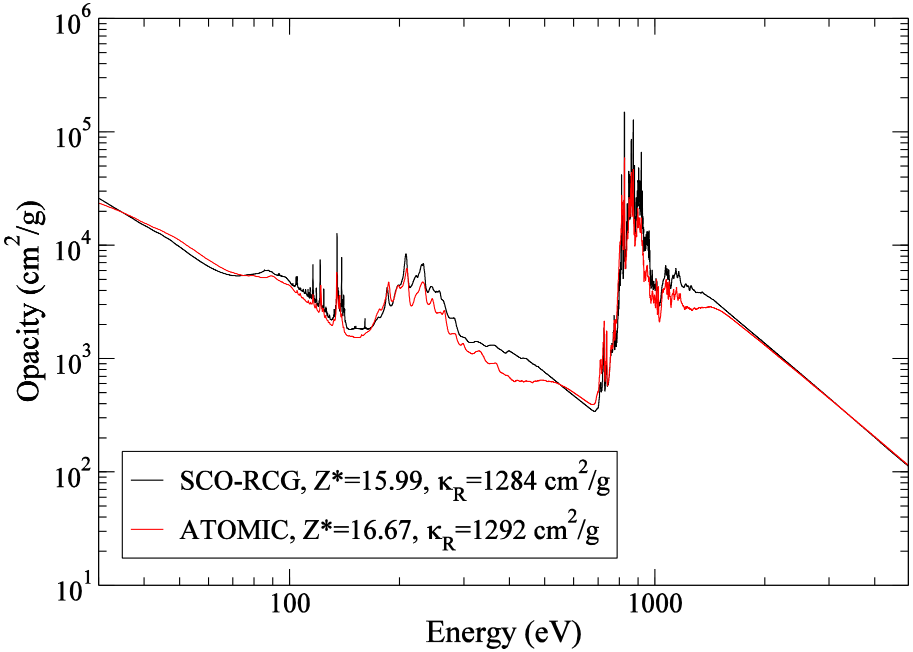
Fe, T=192 eV, n_e=3.1 10^{23} cm^{-3}

code	OP	ATOMIC	SCO-RCG
κ_R (cm^2/g)	854	1292	1284

Analysis of 3D convective atmospheres

Element	Previous abundances [1]	New abundances[2]
H	12	12
He	10,93	10,93
C	8,52	8,43
N	7,92	7,83
O	8,83	8,69
Fe	7,50	7,50

Table: $A_x = Log_{10}(N_x/N_H)+12$, where N_X is the number of atoms of element X (H, He, C, N, O et Fe).

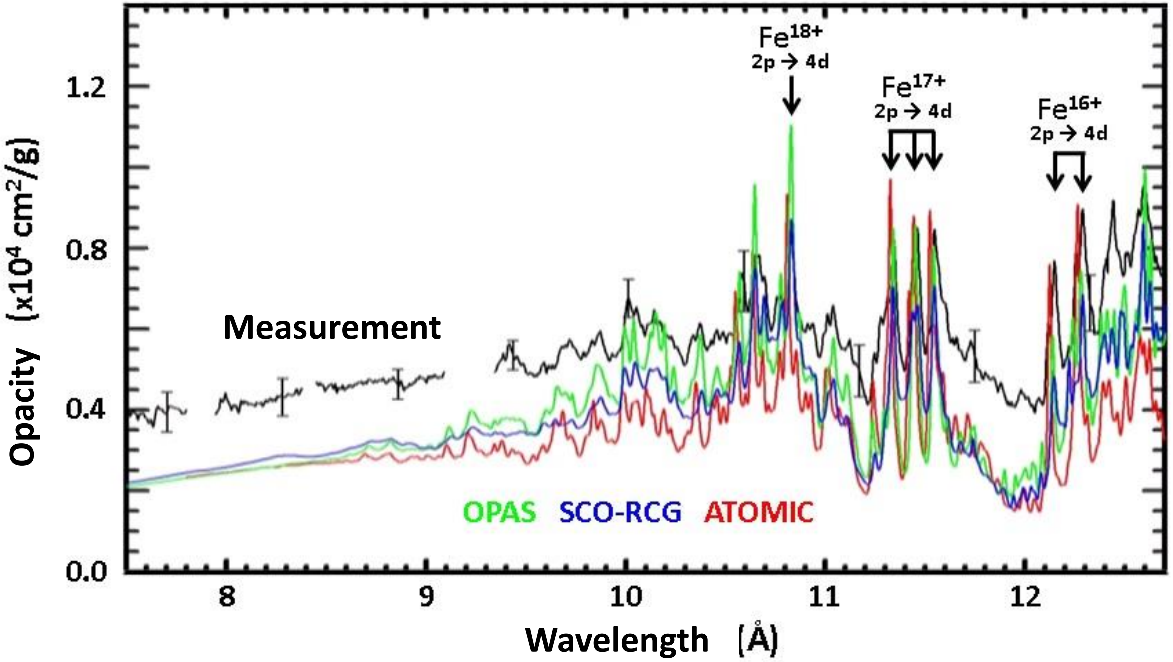


[1] N. Grevesse & A. J. Sauval, Space Sci. Rev. **85**, 161 (1998).
[2] M. Asplund and N. Grevesse, A. J. Sauval & P. Scott, A&A **47**, 481 (2009).

J. Colgan et al., ApJ **817**, 116 (2016).

Iron transmission measurement on the Z machine (SNL)

- Purpose: measuring iron transmission in conditions close to the ones of the BCZ.



Fe
T=182 eV
ρ=0.17 g.cm^{-3}
(n_e=3.1 10^{22} cm^{-3})

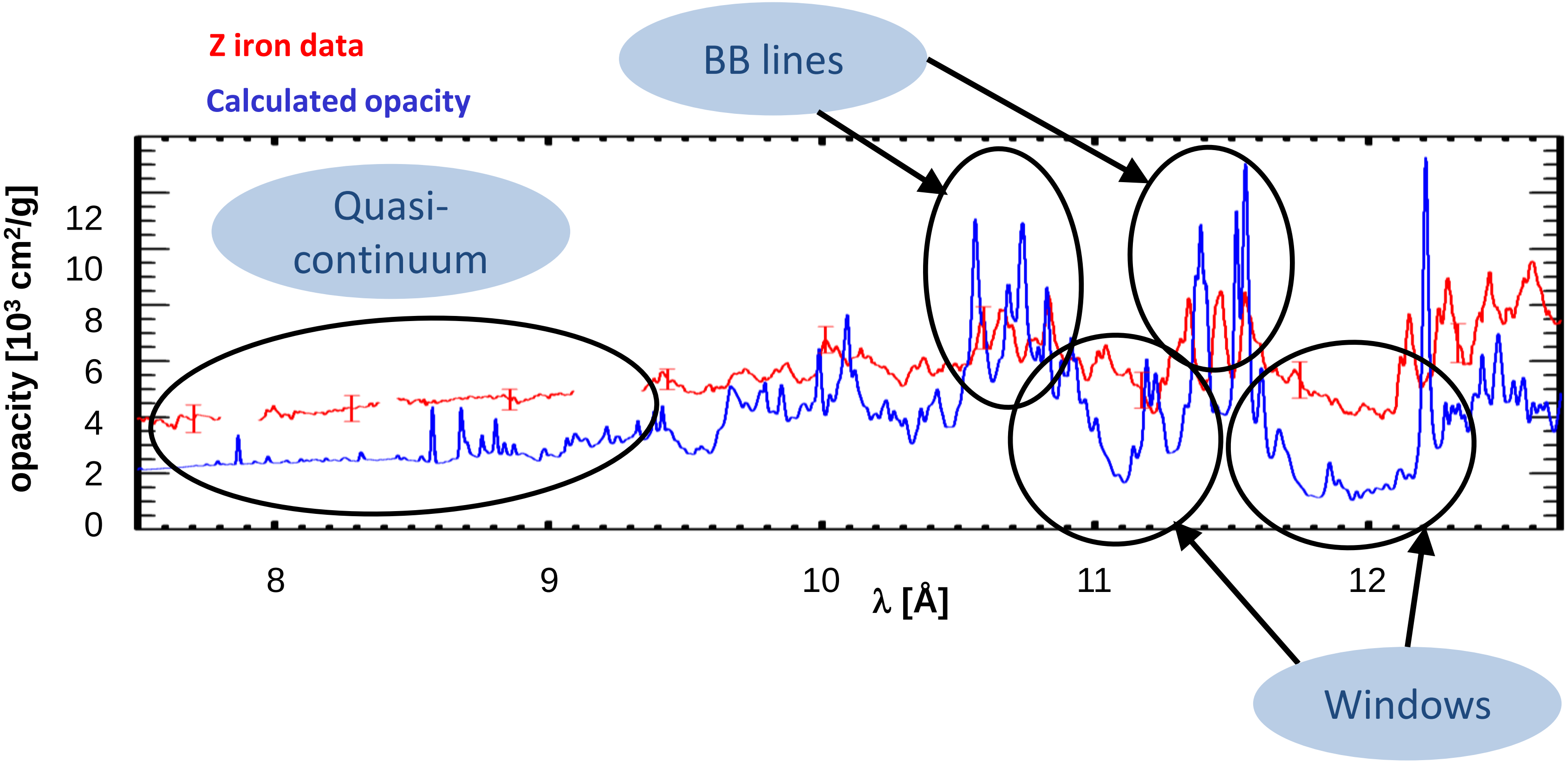
Figure: Iron opacity at T≈2.11 MK and n_e= 3.1x10^{22} e-/cm^3. The experimental spectrum (black) is compared to three calculations: ATOMIC (USA), SCO-RCG and OPAS (CEA, France).

- **Inclusion the measured spectrum in a Rosseland average for a solar mixture → 7 % increase.**

J. E. Bailey et al., Nature **517,** 56 (2015).

Reported opacity discrepancy is complex and deserves further scrutiny

Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen



Quasi-continuum

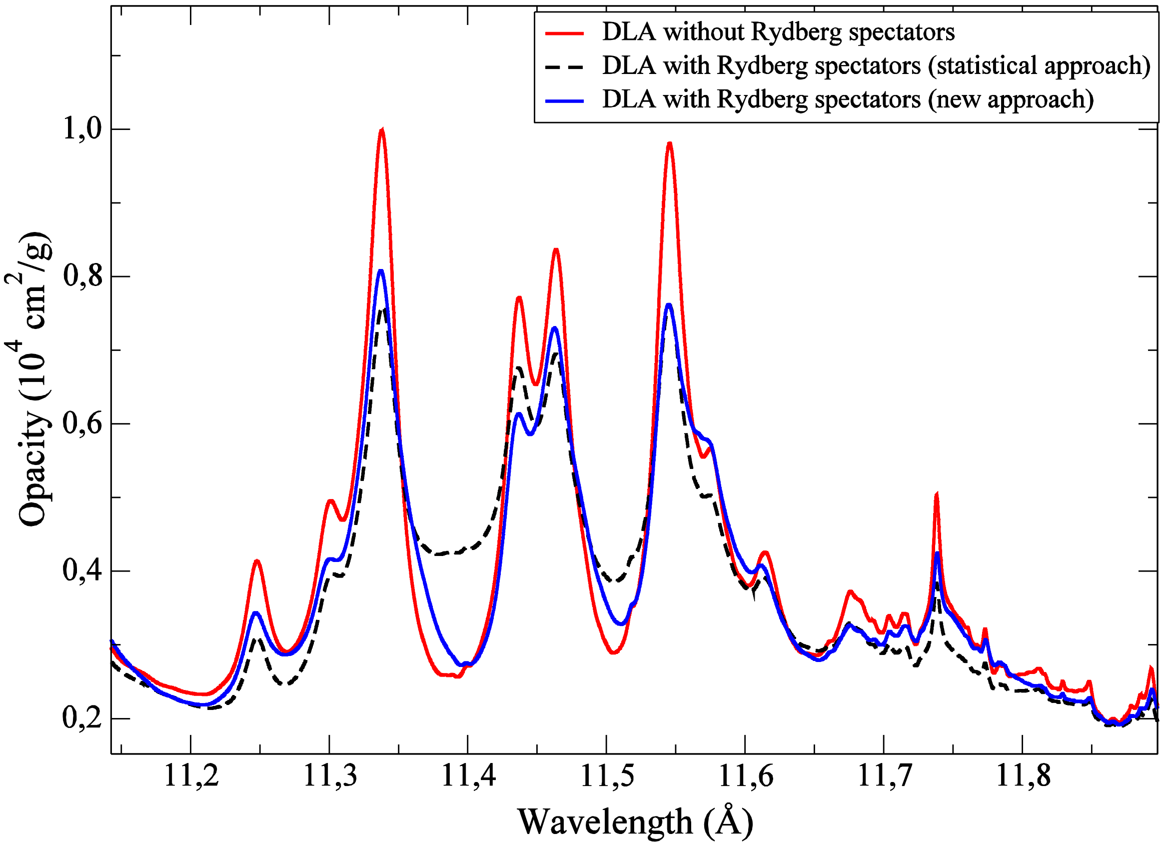
BB lines

Windows

Is opacity theory inaccurate?
Is opacity experiment flawed?

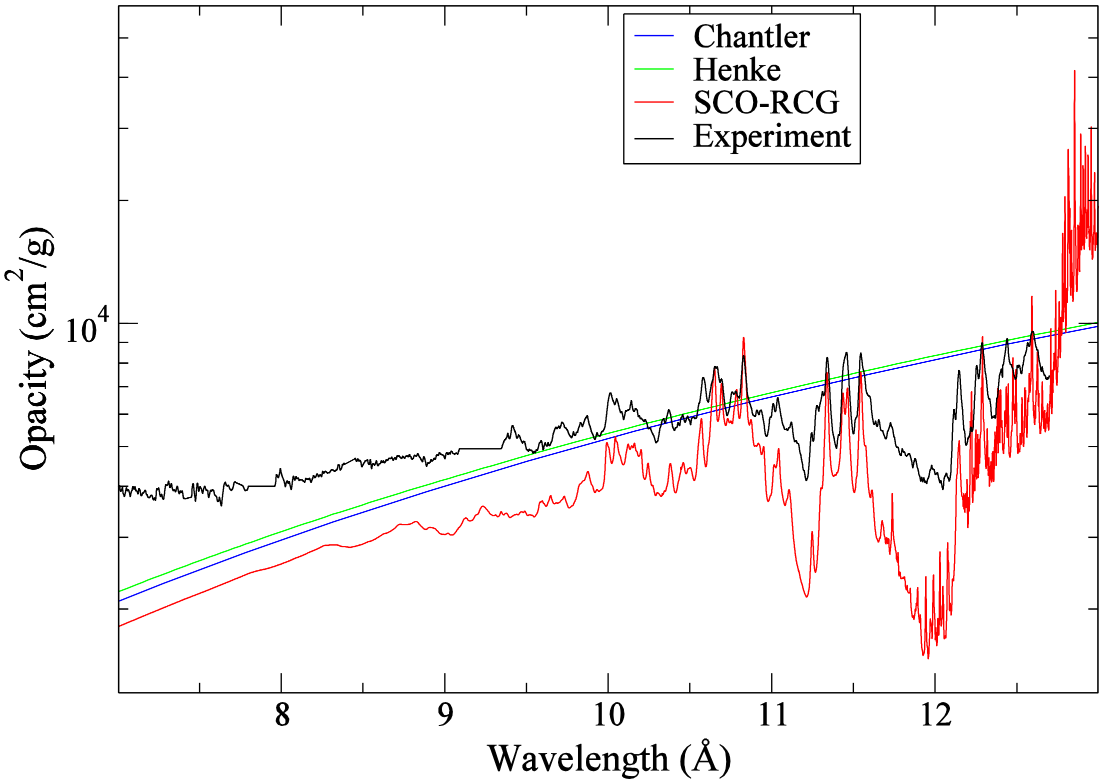
Modeling of highly excited states

SCO-RCG, T=182 eV, ρ=0.17 g.cm^{-3}, n$_e$=3.1 10^{22} cm^{-3}.



J.-C. Pain and F. Gilleron, High Energy Density Phys. **15**, 30 (2015).

Comparison with « cold » opacity



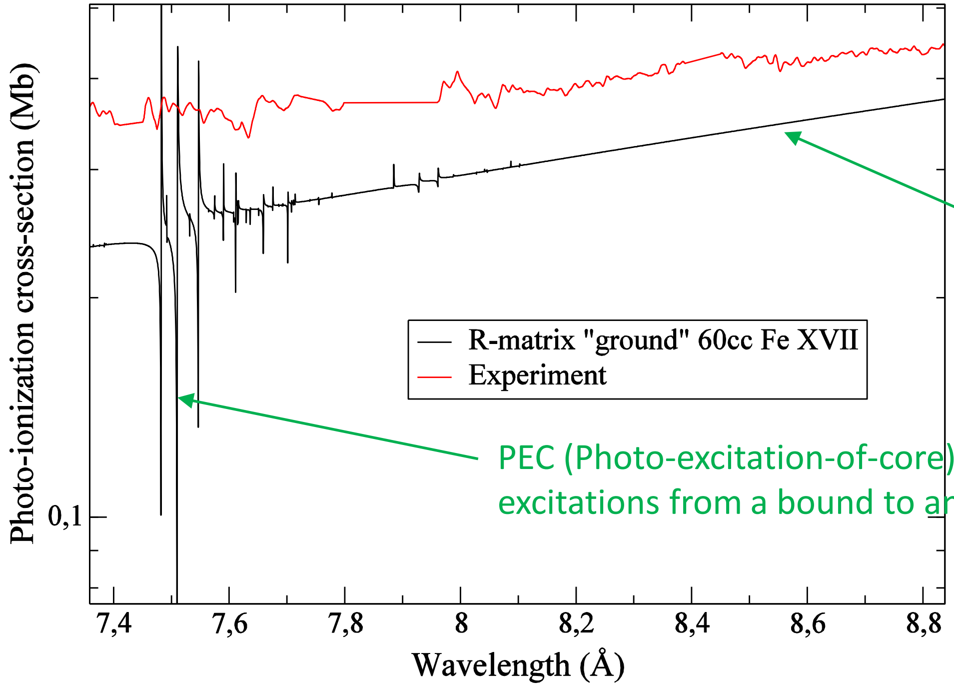
Fe

SCO-RCG conditions:
T=182 eV
ρ=0.17 g.cm^{-3}
(n_e=3.1 10^{22} cm^{-3})

C. T. Chantler, J. Phys. Chem. Ref. Data **24**, 71 (1995).
B. L. Henke et al., At. Data Nucl. Data Tables **54**, 181 (1993).
C. A. Iglesias, High Energy Density Phys. **15**, 4 (2015).

Distorted Wave vs R-matrix computation of photo-ionization

- Nahar and Pradhan reported extensive R-matrix calculations of unprecedented complexity for ion Fe XVII and found large enhancement in photo-ionization cross-sections, in addition to strongly peaked photo-excitation-of-core resonances.



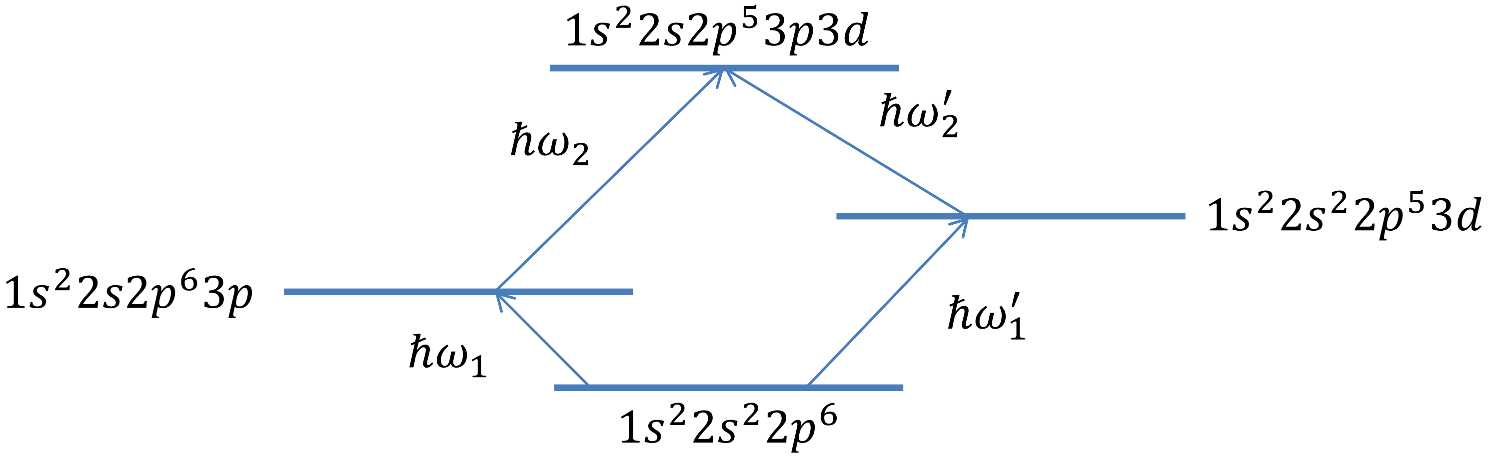
Direct photo-ionization

PEC (Photo-excitation-of-core) resonances = excitations from a bound to an auto-ionizing state.

S. N. Nahar et al., Phys. Rev. A **83**, 053417 (2011). [60 LS core states]. http://cdsweb.u-strasbg.fr/topbase/topbase.html
S. N. Nahar and A. K. Pradhan, Phys. Rev. Lett. **116**, 235003 (2016). [99 LS core states].
C. Blancard et al., Phys. Rev. Lett. **117**, 249501 (2016).
S. N. Nahar and A. K. Pradhan, Phys. Rev. Lett. **117**, 249502 (2016).

Two-photon absorption

- **We are performing calculations to figure out whether there is a strong two-photon opacity effect**.



The mystery arises in a context of uncertainty in modeling the Solar interior.

- Quantum theory of two-photon emission/absorption published by Goeppert-Mayer[1] in 1931 and applied to emission from metastable hydrogen in interstellar space by Breit and Teller[2].

Two-photon cross-sections are obtained using Fermi's "Golden Rules" for quantum perturbation theory.

[1] M. Goeppert-Mayer, Ann Phys 9, 273 (1931).
[2] G. Breit and E. Teller, ApJ **91**, 215 (1940).

Two-color two-photon absorption (collaboration R. M. More)

- One should consider **two photons of different energies** $\hbar\omega_1, \hbar\omega_2 \rightarrow \sigma(\omega_1, \omega_2)$.

$\omega_1 = \omega_2$ occurs only by accident and makes a tiny contribution.

- I made a one-color calculation[2] and found $\sigma(\omega_1, \omega_1)$ was too small... So did M. Kruse ans C. Iglesias[3]...

Everybody agree it's too small, but it's not the right process!

- Photon ω_1 is from the backlighter, the other photon is from the plasma or from the backlighter.

Total photon energy is constrained : $\hbar\omega_1 + \hbar\omega_2 = \Delta E = E_{\text{final}} - E_{\text{initial}}$.

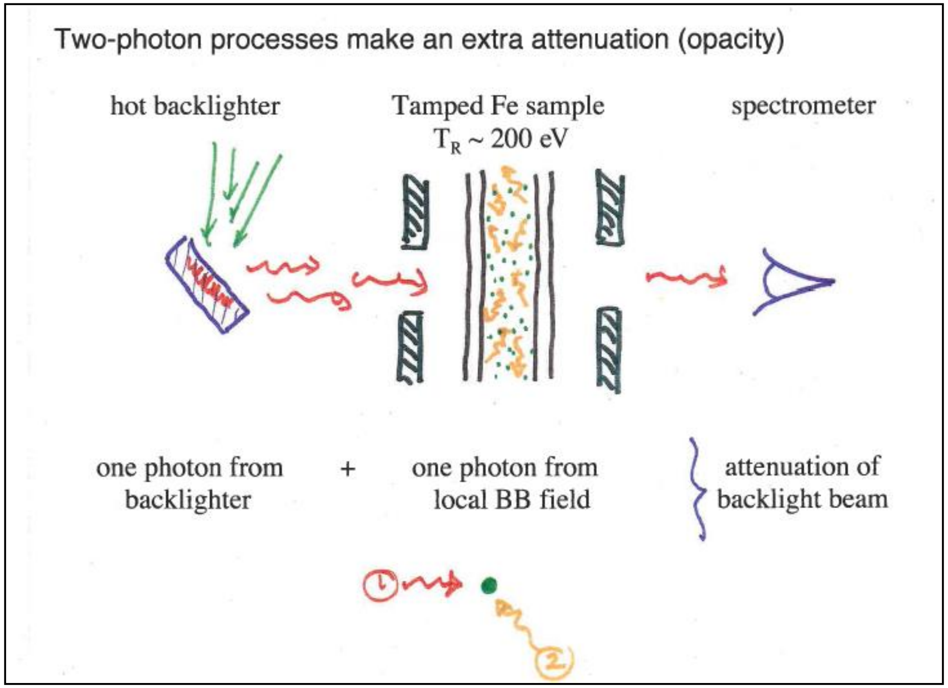
- For any $\hbar\omega_1$ ($< \Delta E$), there can be a second photon that has the right energy $\hbar\omega_2 = \Delta E - \hbar\omega_1$.
- It is a continuous absorption, even for bound-bound transitions.
- It should be compared to the low-opacity gaps between one-photon lines.

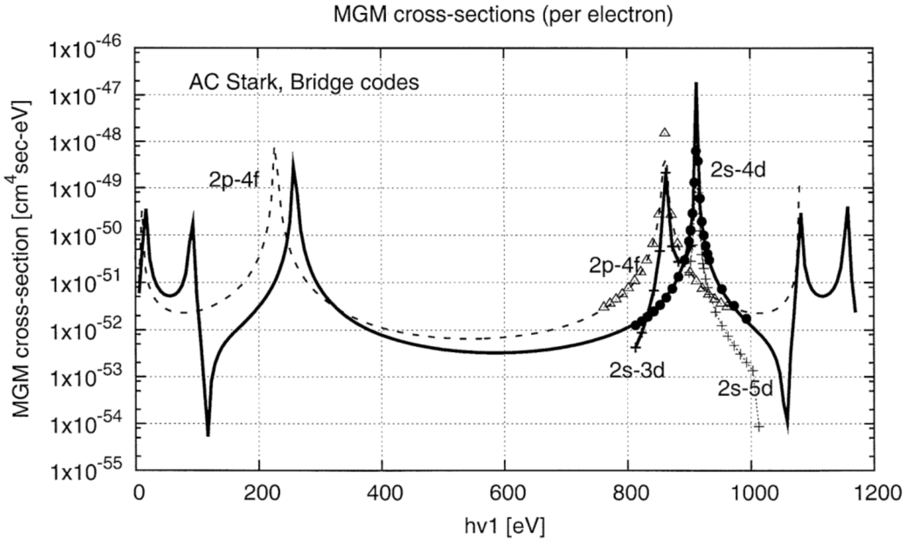
The integral is much larger than the cross-section for two identical photons.

---

[1] R. M. More, S. B. Hansen and T. Nagayama, High Energy Density Phys. **24**, 44 (2017).
[2] J.-C. Pain, High Energy Density Phys. **26**, 23 (2018).
[3] M. Kruse and C. Iglesias, High Energy Density Phys. **31**, 38 (2019).
[4] R. M. More, J.-C. Pain, S. B. Hansen, T. Nagayama and J. Bailey, High Energy Density Phys., in press (2019).

Two-photon perturbation theory (collaboration R. M. More)





Two-photon processes: divergent views

■ **Kruse-Iglesias** calculations include two-photon ionization cross-sections for ground as well as singly and doubly excited configurations of different charge states of Fe. Similar calculations were done for Cr and Ni.

Conclusions of the authors:

(i) All the two-photon ionization cross-sections were found to be more than 3 orders magnitude smaller than the corresponding single-photon one[1].

(ii) The ratio of two- to one-photon ionization cross-sections displays a weak dependence on nuclear charge along an isoelectronic sequence.

(iii) Furthermore, earlier work[2] showed two-photon ionization increasing with decreasing temperature. Such behavior cannot the discrepancies between experimental and theoretical results at the higher energies only for Fe at high temperature (Anchor 2).

■ **Work is in progress to include more ions / states in the calculation[3].**

[1] M.K.G. Kruse & C.A. Iglesias , HEDP **41**, 100976 (2021).
[2] M.K.G. Kruse & C.A. Iglesias, HEDP **31**, 38 (2019).
[3] R. M. More, J. E. Bailey and J.-C. Pain, work in progress.

Raman and Rayleigh scatterings

■ **Photon scattering** is also a two-photon process.

It is often included in opacity models assuming the Thomson cross-section.

As in two-photon absorption, however, scattering displays resonances whenever one of the photon energies coincides with the energy differences between bound states involved.
That is, the resonances occur at the same photon energies as single photon spectral lines.

■ **Kruse-Iglesias:** Away from the resonances, Rayleigh (elastic) and Raman (inelastic) scattering are comparable or smaller than the Thomson scattering cross-section[1], and thus unlikely to contribute much.

■ Resonant inelastic X-ray scattering (RIXS), which can be described as a Raman effect, was observed in recent experiments on the large free-electron X-ray laser LCLS. As Compton scattering reduces x-ray transmission, so does the RIXS scattering.
Work is in progress to quantify its impact[2].

■ Baggott, Rose and Mangles suggest an additional process in which a non-resonant photon is absorbed and **the intermediate state is stabilized by an electron collision[3]**.

[1] K. McNamara, D.V. Fursa & I. Bray, Phys. Rev. A **98**, 043435(2018).
[2] R. M. More, J. E. Bailey and J.-C. Pain, work in progress.
[3] R. A. Baggott , S. J. Rose and S. P. D. Mangles, Phys. Rev. Lett. **125**, 145002 (2020).

Transient localization effect

■ Liu et al. developed a formalism to study the wavefunctions of the continuum electrons that takes into account the quantum de-coherence caused by coupling with the plasma environment[1].

■ They find that the photoionization cross section of Fe^{16+} is considerably enhanced, which partly explains the big difference between the measured opacity and the models.

Novelty to account for plasma effects = replacement of the final continuum energy eigenstate with a wave packet, which energy is conserved in the photon ionization.

Iglesias' criticisms:

(i) First, the wave packet is assumed a stationary state (to apply the Golden Rule) even though it does not have a specific energy eigenvalue.

(ii) A second *ansatz* for the wave packet density of states ensures the formulas reduce to the distorted wave result in the absence of the plasma.

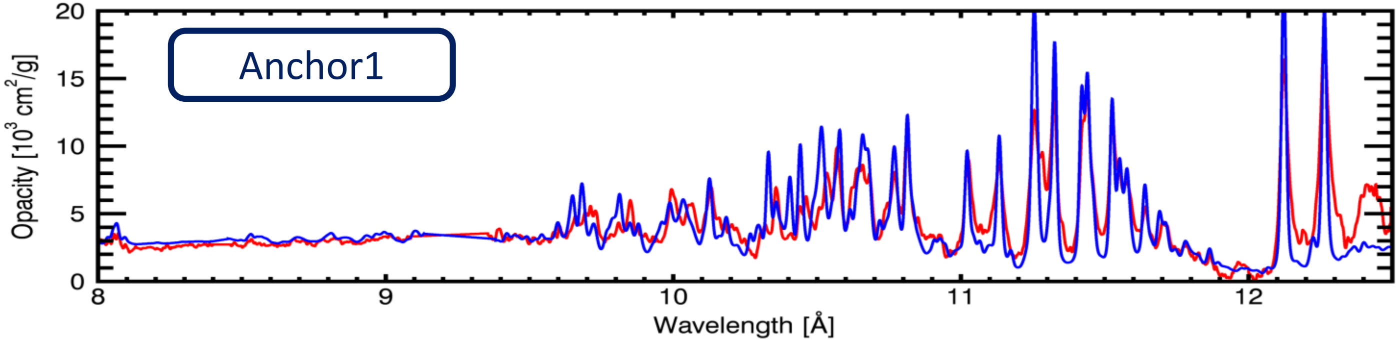
(iii) Finally, the velocity form of the photon-electron interaction is replaced with an approximate length form = reasonable for the Sandia experiments but may fail for more strongly coupled plasmas or high photon energies[2].

[1] P. Liu, C. Gao, Y. Hou, J. Zeng, *et al.*, Commun. Phys., 95 1 (2018)
[2] C. A. Iglesias, HEDP **47**, 101043 (2023).

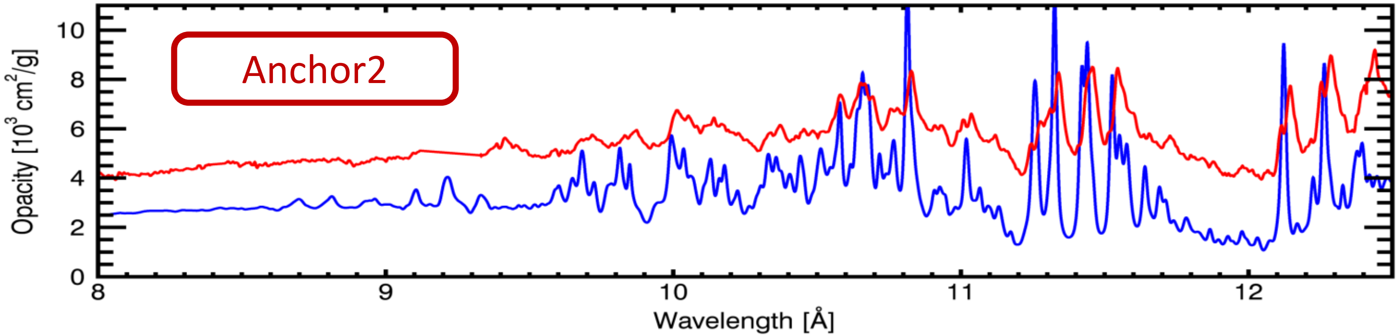
Summary for Fe

Convection Zone Base: T_e=185 eV, n_e = 90e21 e/cc

Data at T_e=156 eV, n_e= 7e21 e/cc
Calculated opacity*



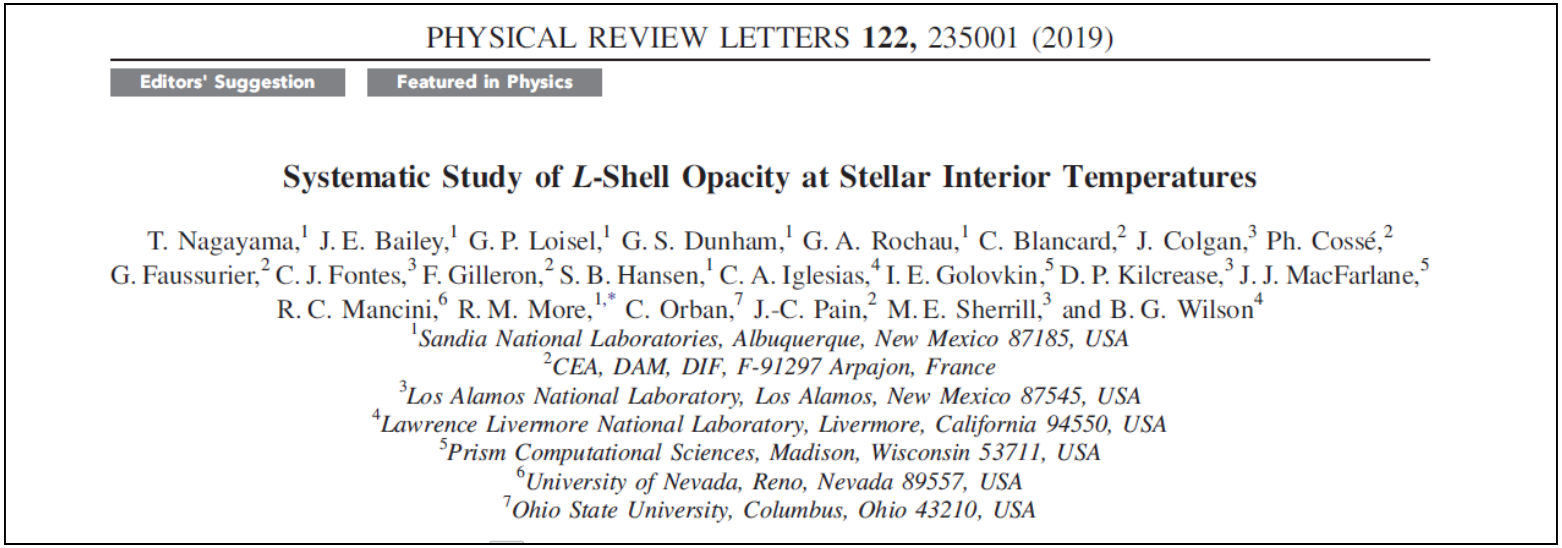
Data at T_e=182 eV, n_e= 38e21 e/cc
Calculated opacity



***SCRAM model (S. B. Hansen)**

Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen

What about Cr and Ni?



PHYSICAL REVIEW LETTERS **122,** 235001 (2019)

Editors' Suggestion

Featured in Physics

Systematic Study of *L*-Shell Opacity at Stellar Interior Temperatures

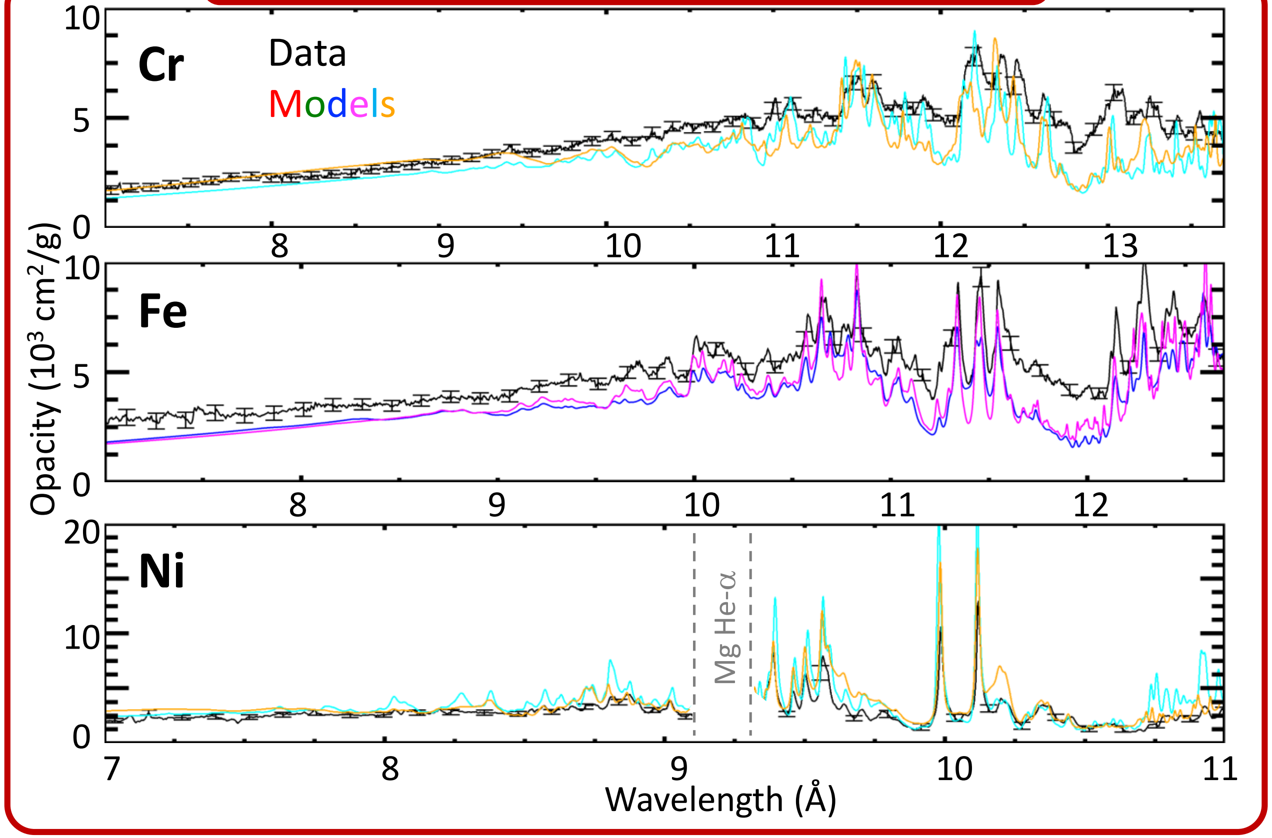
T. Nagayama,[1] J. E. Bailey,[1] G. P. Loisel,[1] G. S. Dunham,[1] G. A. Rochau,[1] C. Blancard,[2] J. Colgan,[3] Ph. Cossé,[2] G. Faussurier,[2] C. J. Fontes,[3] F. Gilleron,[2] S. B. Hansen,[1] C. A. Iglesias,[4] I. E. Golovkin,[5] D. P. Kilcrease,[3] J. J. MacFarlane,[5] R. C. Mancini,[6] R. M. More,[1,*] C. Orban,[7] J.-C. Pain,[2] M. E. Sherrill,[3] and B. G. Wilson[4]

[1]*Sandia National Laboratories, Albuquerque, New Mexico 87185, USA*
[2]*CEA, DAM, DIF, F-91297 Arpajon, France*
[3]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[4]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[5]*Prism Computational Sciences, Madison, Wisconsin 53711, USA*
[6]*University of Nevada, Reno, Nevada 89557, USA*
[7]*Ohio State University, Columbus, Ohio 43210, USA*

Why is there an anomaly for Fe but not for Ni?

Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen

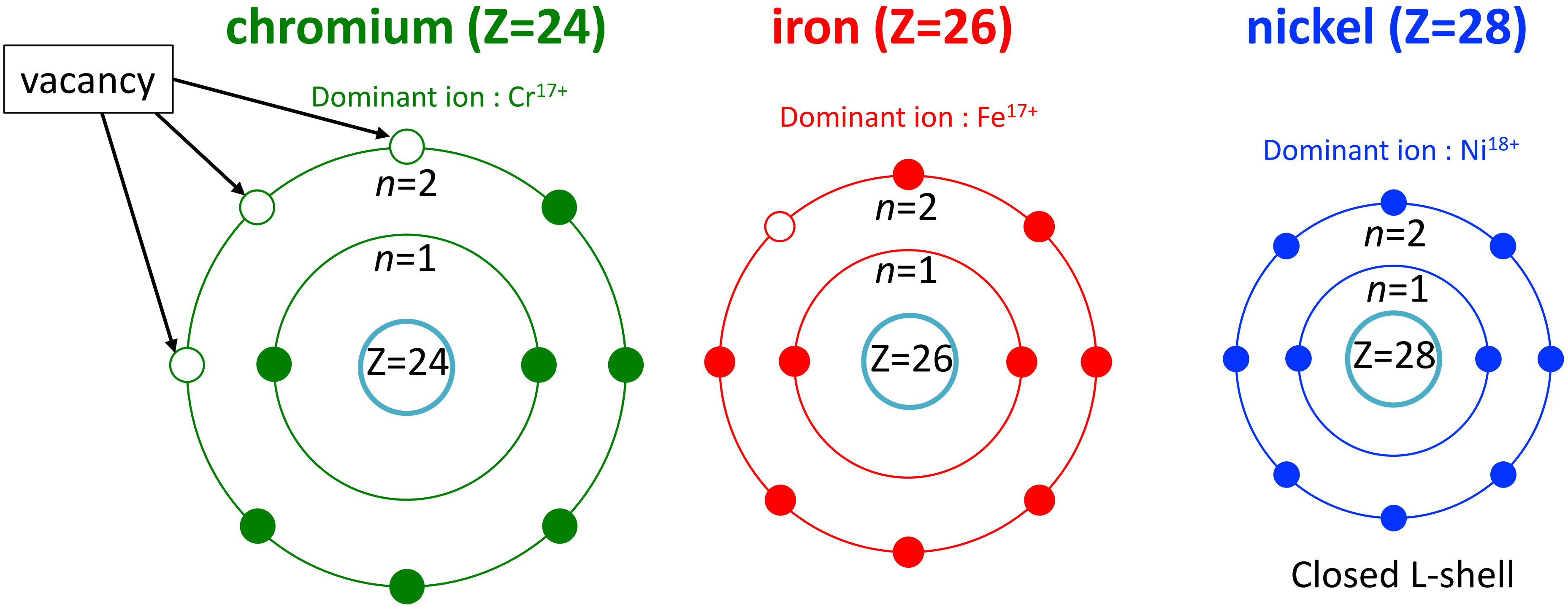
Anchor2: $T_e \sim 180$ eV, $n_e \sim 30 \times 10^{21}$ cm^{-3}



- T_e and n_e are diagnosed independently
- Reproducibility is confirmed

Why is there an anomaly for Fe but not for Ni?

Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen



More ← Less

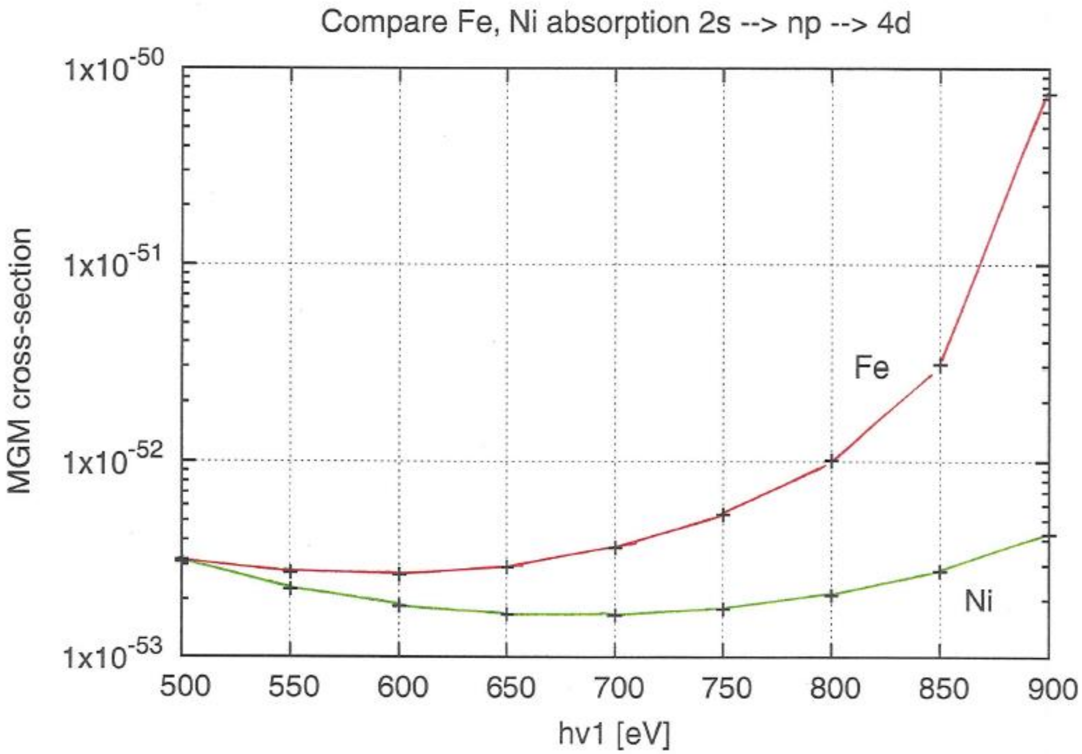
L-shell vacancies

# of excited states

Density effects

Why is two-photon absorption significant for Fe but not for Ni?

- Since the energies are ~200 eV larger for Ni than for Fe, the cross-section and the population from the Bose-Einstein factor are smaller. **The 2-photon process in Ni is 10 times smaller than for Fe**. That helps to understand why it is not visible in the experiments. **At a higher temperature, it might be visible**.

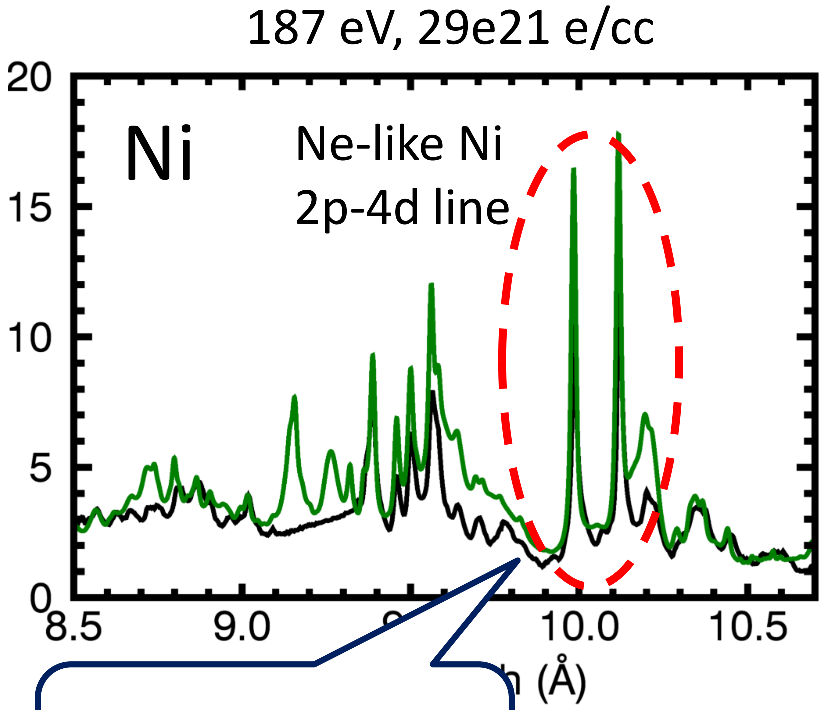


collaboration
R. M. More, J. E. Bailey,
J.-C. Pain

$$\sigma^{MGM} = 8\pi^3\left(\frac{e^2}{\hbar c}\right)^2 \frac{\hbar}{(\hbar\omega_1)(\hbar\omega_2)} \left| \sum_n \frac{\delta E_{in} R_{in}\ \delta E_{nf} R_{nf}}{E_i - E_n} \right|^2 \Gamma_{ang}\ I(\hbar\omega_1 + \hbar\omega_2)$$

Can we check accuracy of modeled line shapes?

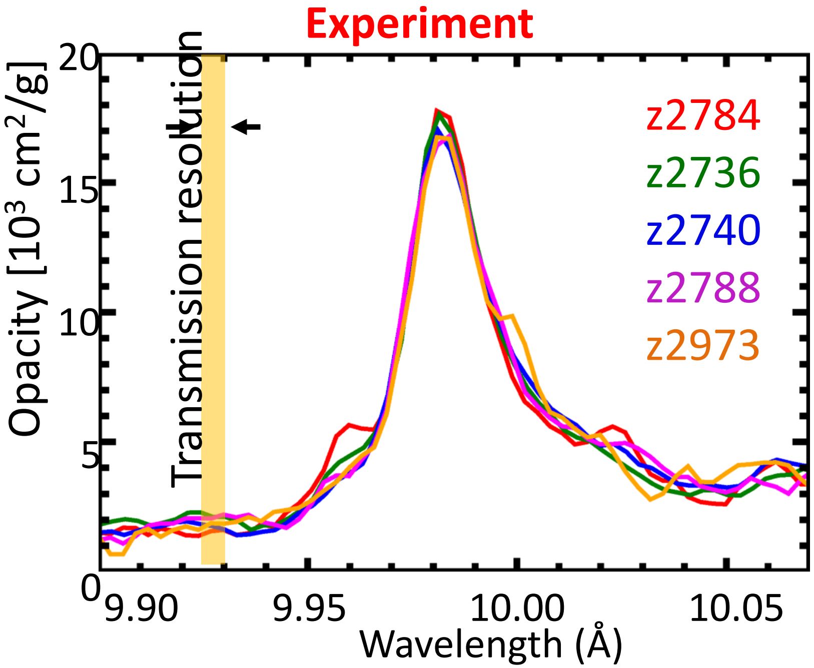
Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen

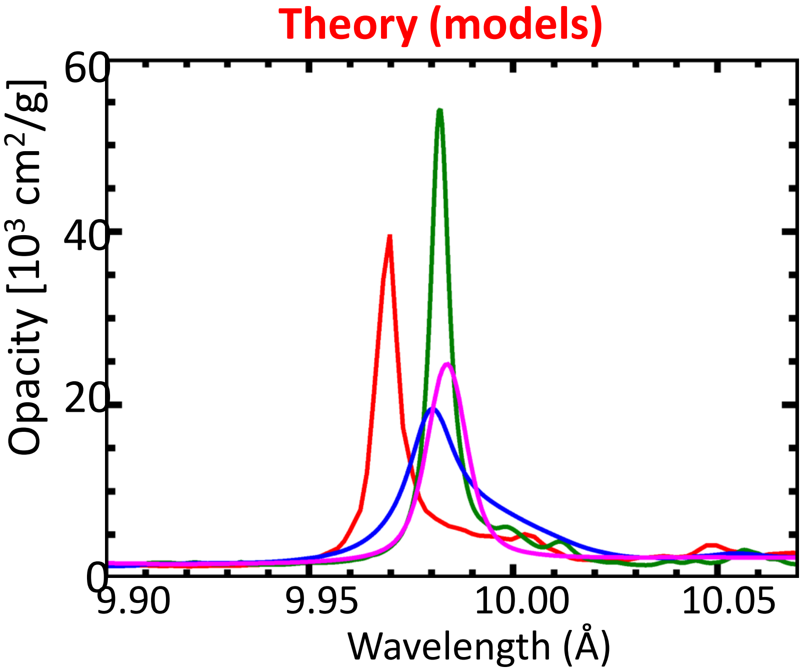


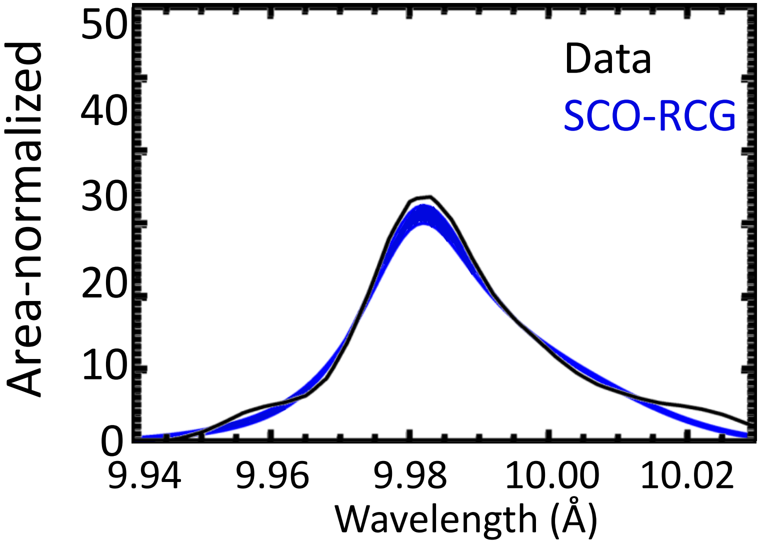
- Isolated
- Low continuum

We use n=2 → 4 lines from Ne-like Ni to assess the accuracy of calculated line shape

Line-shape of Ne-like Ni 2p-4d is accurately measured and appropriate to test approximations


Experiment

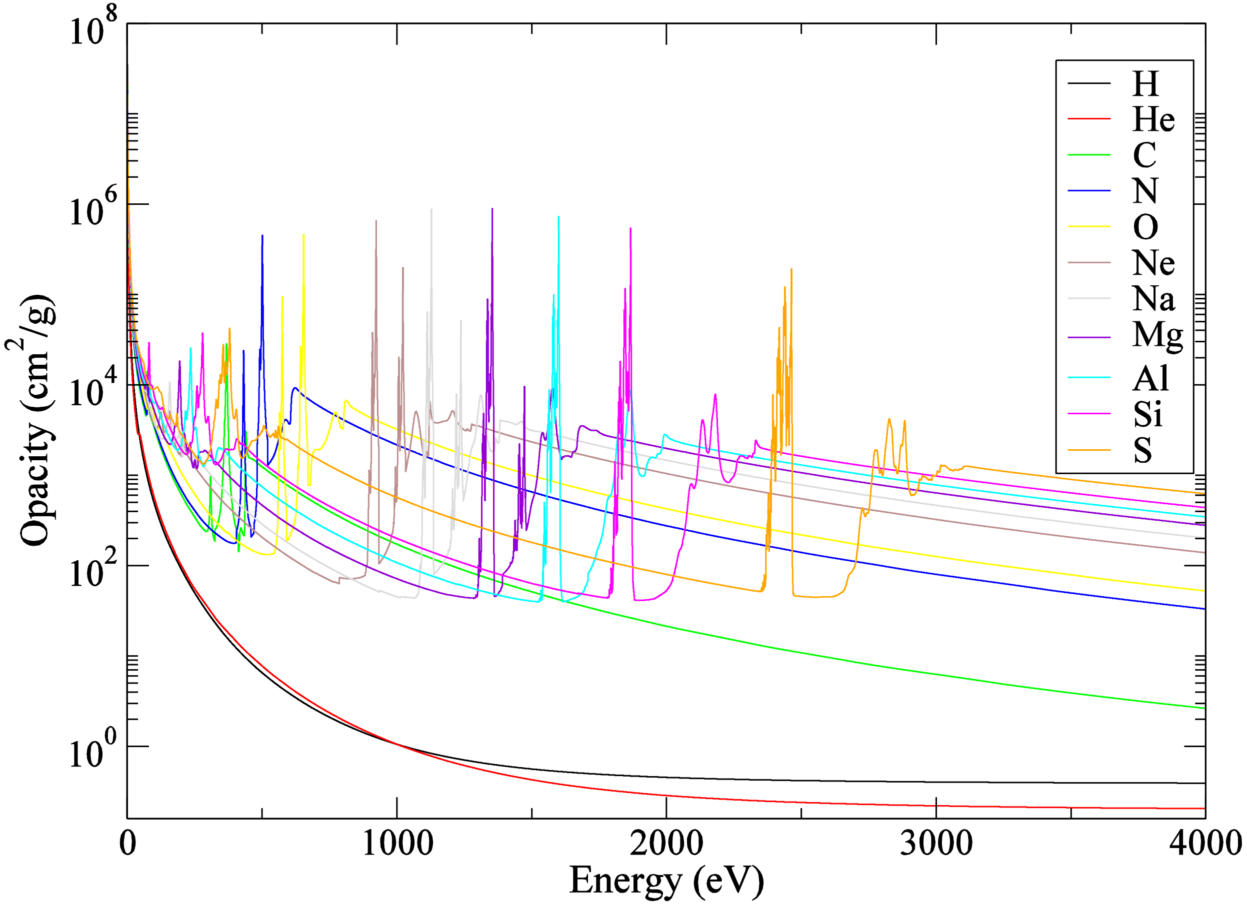

Theory (models)



Courtesy G. Loisel, J. E. Bailey, T. Nagayama, S. B. Hansen

Opacity of lighter elements at the BCZ

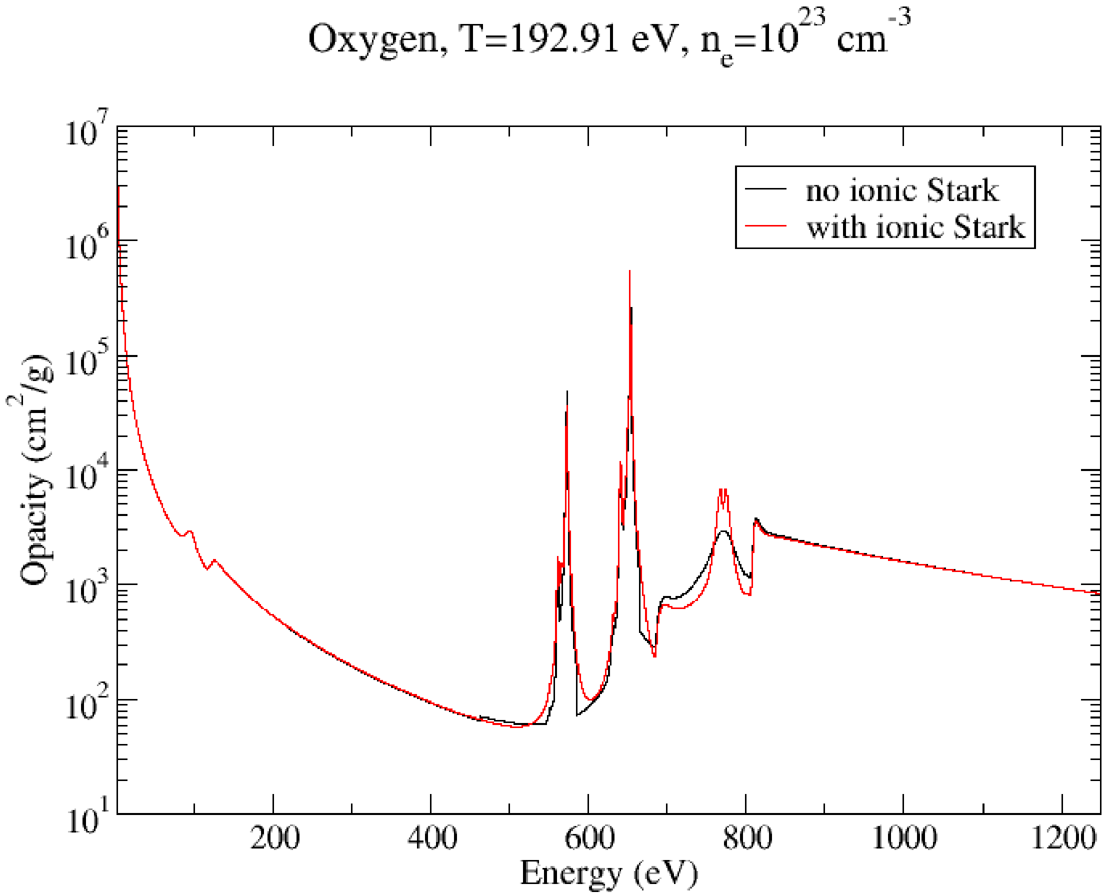
Solar mixture @ T=188.18 eV & $n_e=10^{23}$ cm^{-3}



M. Asplund and N. Grevesse, A. J. Sauval & P. Scott, A&A **47**, 481 (2009).

Particular case of oxygen: importance of Stark effect

	κ_P (cm2/g)	κ_R (cm2/g)
No ionic Stark	1685	273.5
With ionic Stark	1719	285.3



Magg et al. new abundances

- New observational material for the Sun, new updated atomic data, and up-to-date NLTE models to re-analyse the detailed chemical composition of the solar photosphere.

- Two families of **3D radiation-hydrodynamics simulations of solar convection**, to quantify the differences between the abundances inferred with both models.

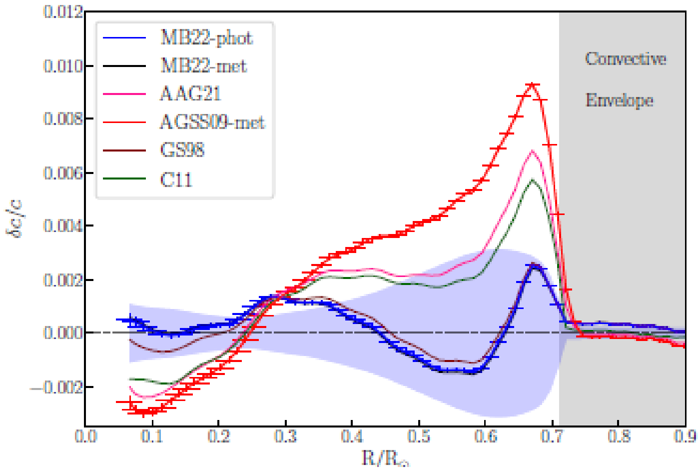
- New estimates of chemical abundances for C, N, O, Mg, Si, Ca, Fe, and Ni.

- Solar photospheric Z/X ratio = 0.0225, when calculated using the photospheric abundances only, and 0.0226, when meteoritic abundances used for most species, except C, N, and O, for which the photospheric values are used.

- Magg et al.'s estimates are 26% higher compared to those determined by Asplund et al. (2021), but in a much better agreement with Caffau et al. (2011) and Grevesse & Sauval (1998), the difference being 10% and 1%, respectively.

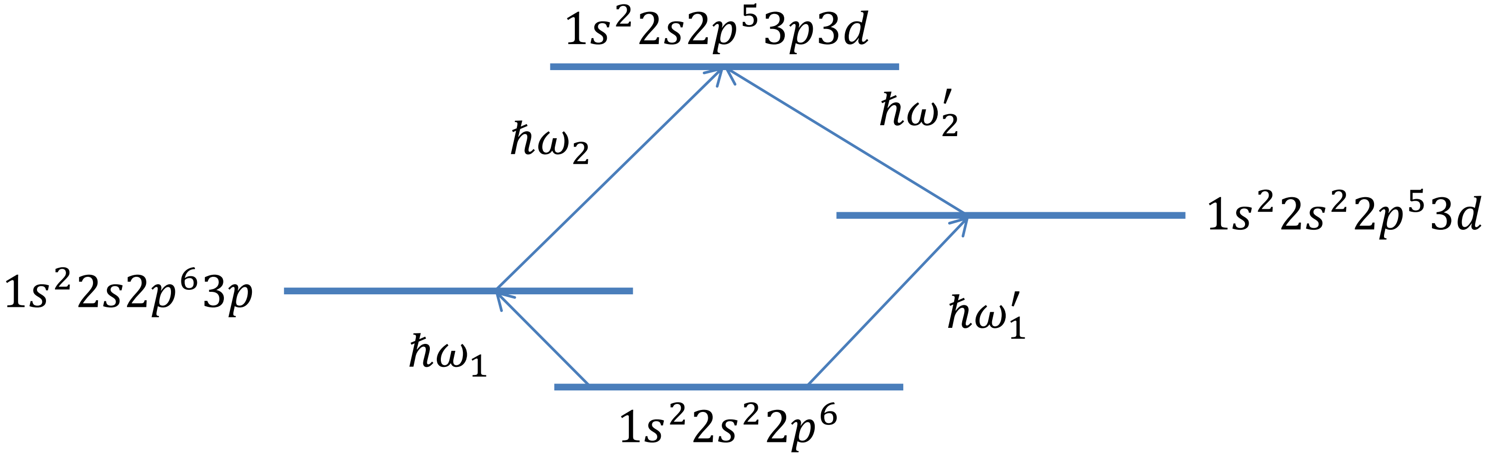
- Very close numerical agreement of Z/X with Grevesse & Sauval (1998) is, however, fortuitous, as abundances of individual elements are different in their study.

Magg. et al., A&A 661, A140 (2022).



Effect of two-photon processes

- **We are performing calculations to figure out whether there is a strong two-photon opacity effect**.



- To our knowledge, the problem of **acceleration (diffusion) induced by two-photon radiation** was never studied before. Astrophysicists usually take opacity tables (mostly OP and OPAL) as an input of their radiative-acceleration calculations.

- A phenomenon might be affected: the so-called **“saturation effect”.** When matter density increases, the number of ions per volume unit getting higher, the number of available photons likely to yield the acceleration decreases.

S. Turcotte, J. Richer, G. Michaud, C. A. Iglesias and F. J. Rogers , ApJ **504**, 539 (1998).
G. Alecian and F. LeBlanc, MNRAS **319**, 677 (2000).
G. Vauclair and S. Vauclair, « Competition between diffusion processes and hydrodynamical instabilities in stellar envelopes », *Edith A. Muller (ed.), Highlights of Astronomy, Vol.* 4, *Part II,* 193-203 (1977).

Conclusion and perspectives

■ Opacity computation requires to take into account **a huge number of levels** and **spectral lines**.

■ Some effects, such as **configuration interaction**, are still difficult to take into account properly.

■ Some **laser** or **Z-pinch** experiments are performed in order to test the models.

■ The **unexplained iron experiment** on Z stimulates new developments in the codes (photo-ionization, highly-excited states, two-photon processes[1,2], etc.).

■ In the same conditions, **the Ni spectrum is in good agreement with SCO-RCG**[3].

■ **An experiment is ongoing on NIF (National Ignition Facility) laser facility** in order to measure iron opacity in the same conditions as the Z experiment.

[1] R. M. More, S. B. Hansen and T. Nagayama, High Energy Density Phys. **24**, 44 (2017).

[2] J.-C. Pain, High Energy Density Phys. **26**, 23 (2018).

[3] J. E. Bailey et al., to be published.

Important issues for improvement of opacity calculations

- Need for detailed **accurate and complete** energy levels, line energies, f-values and cross-sections for atoms/ions/anions/molecules and transient ion dipoles formed in collisions[1].

- The steady increase in computing power should ease the **accuracy / completeness compromise**.

- **Plasma density effects:** pressure ionization (quasi-bound states), realistic microfield distributions for reliable line broadening.

- Quantum-mechanical calculation of **continuum absorption**: bound-free and free-free. **Continuity of oscillator strength** must be ensured.

- Proper accouting for **plasma oscillations** on the dielectric constant[2]: electron degeneracy and screening.

- Continue helioseismological work.

[1] A. E. Lynas-Gray et al. « Current State of Astrophysical Opacities: A White Paper », arXiv:1804.06804v1.
[2] B. M. Sarfraz et al., Phys. of Plasmas **25**, 032106 (2018).