Identification of Auger electron heating irradiating solids with micrometer-focused XUV Free Electron Laser Radiation from FLASH

at intensities larger than 10^{16} W/cm^2

F.B. Rosmej[1,2]

[1]Sorbonne Universités, Pierre et Marie Curie, Paris, France
[2]Ecole Polytechnique, LULI-PAPD, Palaiseau, France

frank.rosmej@upmc.fr

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International Collaboration « Peak Brightness »

S.Bajt, L.F. Cao, J. Chalupsky, H. Chapman, J. Cihelka, H.-K. Chung, T. Döppner, S. Dusterer, T. Dzelzainis, M. Fajardo, C. Fortmann, E. Galtier, S.H. Glenzer, G. Gregori, P.V. Hajkova, P.A. Heimann, L. Juha, M. Jurek, R. Fäustlin, F. Khattak, M. Kozlova, J. Krzywinski, T. Laarmann, H.J. Lee, R. W. Lee, R. Levesque, P. Mercere, B. Nagler, A. Nelson, A. Przystawik, P. Radcliffe, H. Reinholz, D. Riley, G. Ropke, F.B. Rosmej, J. K. Seksl, R. Sobierajski, R. Thiele, T. Tiggesbaumker, S. Toleikis, N.X. Truong, T. Tschentscher, I. Uschmann, S. Vinko, J. Wark, T. Whitcher, A. Wierling, E. Forster, R. Redmer, U. Zastrau

DESY (FLASH), UPMC, LULI, LLNL, SLAC, Berkeley, QUB, Oxford, Jena, Rostock…….

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I. Introduction & Motivation

Matter and Energy

solid → heating → liquid → heating → gas

destruction of cristaline structure

structureless particles

phase transitions = key physics

gas → heating → **PLASMA**

considerable number of charged particles

↓

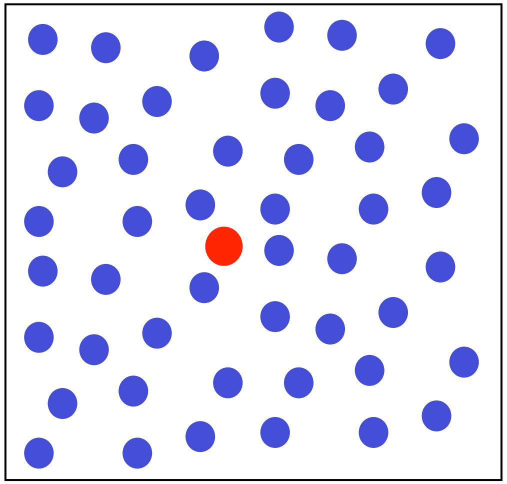
electric microfield

destruction of atomic structure

Matter under extreme conditions

PLASMA — high pressure → **Warm Dense Matter**
WDM: $T \approx T_F$

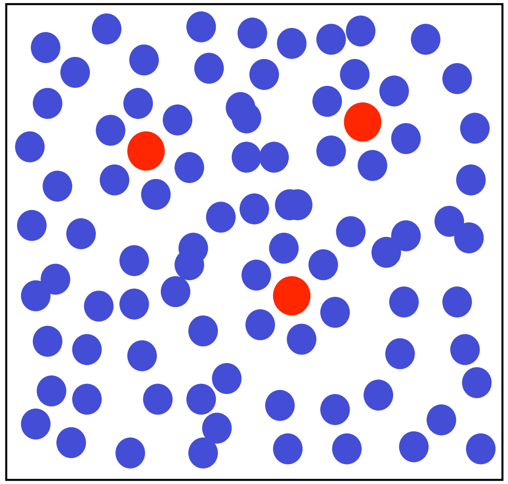
return of a certain cristaline structure



$$\frac{V_{Coulomb}}{V_{thermal}} = \Gamma \propto \frac{1}{rT} \propto \frac{\rho^{1/3}}{T}$$

decrease of temperature T

increase of density n



Partition function ?

Interesting experiment to encounter high Γ

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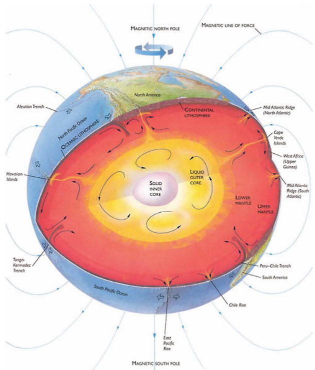
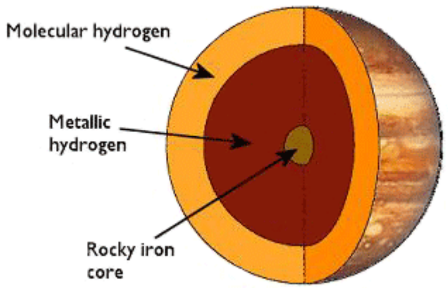
Importance of Warm Dense Matter

I. In the univers

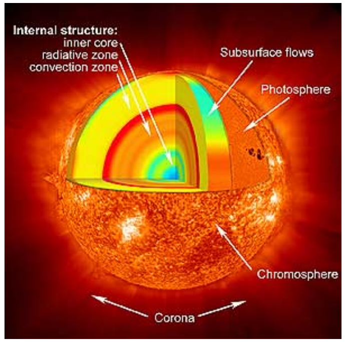
Earth:
magnetic field



Jupiter:
metallic hydrogen

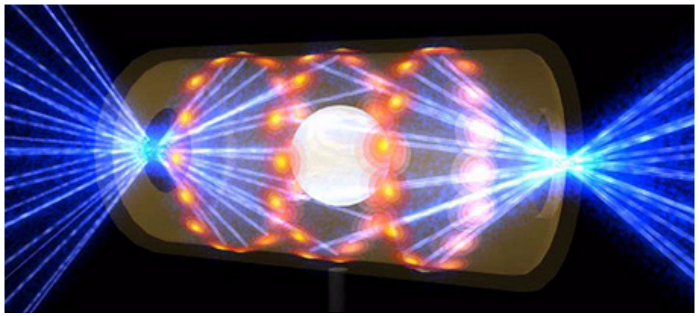


Sun:
thermonuclear fusion

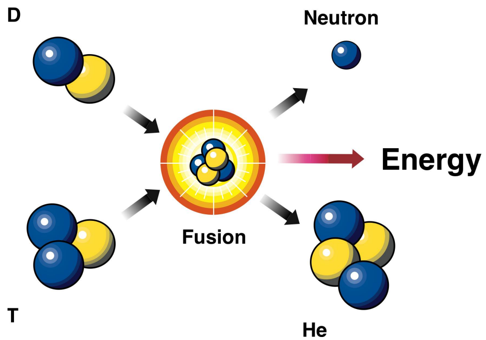


II. Heating of matter

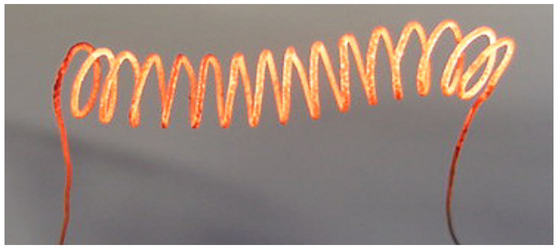
Laser/Heavy ion beams



Inertial fusion



Electric heating



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II. Matter under extreme conditions:

-Atomic physics studies-

Atomic physics and derived quantities

Atomic Structure

Particle statistics

Atomic kinetics

Atomic physics in dense plasmas

Atoms/Ions/Molecule/ Cluster/….

Distribution of different ionisation stages

Distribution of ground and excited states

Emission

Scattering

Absorption/ Opacity

Transmission

Conductivity

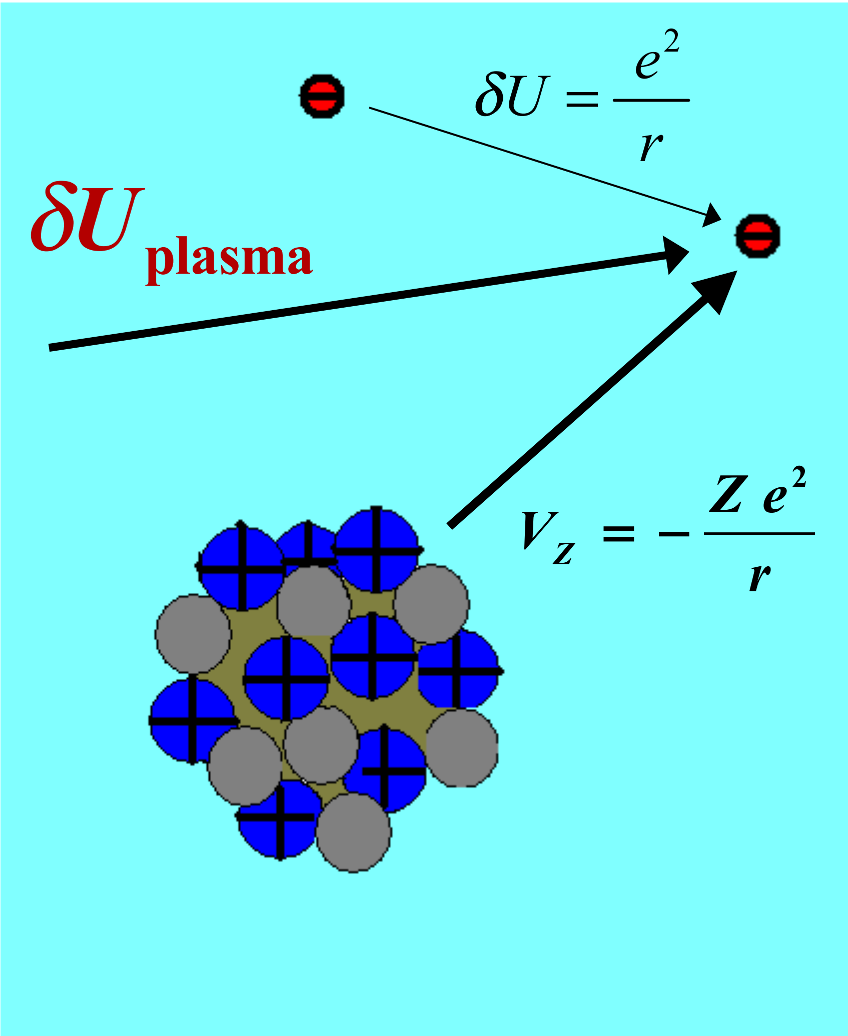
Compressibility

Phase transitions

•
•
•

Equation of state

Atomic physics in dense plasmas



$$(L_r - \delta U_{\mathrm{Plasma}} + E)(R^0 + \delta R) = 0$$

$$\delta R_{nl}(r) = \int_0^\infty dr'\, r'^2\, g_{nl}(r, r')\, \delta U_{\mathrm{Plasma}}(r')\, R^0_{nl}(r')$$

General expression
for arbitrary plasma potential

F.B. Rosmej, K. Bennadji, V.S. Lisitsa, PRA 2011

- Arbitrary temperature
- Scaling laws
- Comparison with experiments

LULI: e-e exchange energy shift in dense plasmas

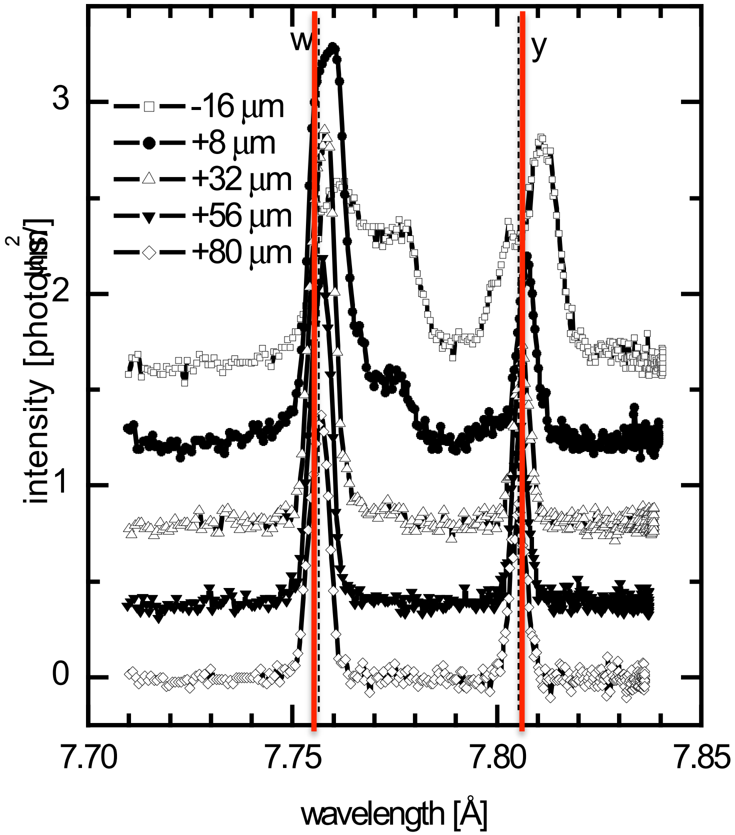
There exist one pair of suitable transitions in He-like ions:

Resonance line: $1s^2\ {}^1S_0 - 1s2p\ {}^1P_1$

Intercombination line: $1s^2\ {}^1S_0 - 1s2p\ {}^3P_1$

"A spin in a dense plasma"

$$\Delta E_x = \left(E\left({}^1P_1\right) - E\left({}^3P_1\right)\right)_{vaccum} - \left(E\left({}^1P_1\right) - E\left({}^3P_1\right)\right)_{plasma}$$



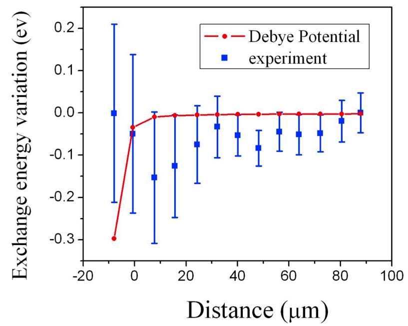
O. Renner, P. Adámek, P. Angelo, E. Dalimier, E. Förster, E. Krousky, F.B. Rosmej, R. Schott, JQSRT **99**, 523 (2006).

Finite temperature ion sphere model:

$$\Delta E_x \propto n_e \left(\frac{23}{Z^3} + \frac{11.6}{Z^2 \sqrt{T(eV)/2Ry}} \right)$$

Debye model:

$$\Delta E_x \propto \frac{n_e Z_{eff}}{Z\,T}$$

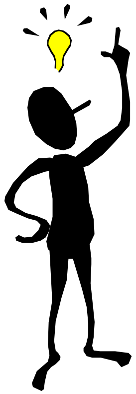


F.B. Rosmej, K. Bennadji (EMMI-fellow), V.S. Lisitsa, PRA 2011

Exp. Trend $\Delta E_x\left({}^1P_1\right) > \Delta E_x\left({}^3P_1\right)$ ok

Opacity measurements

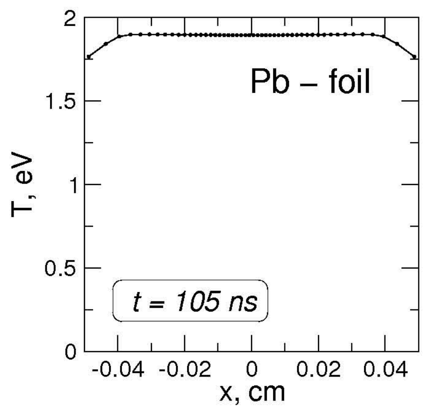
If T is too small for self-emission studies: $$\frac{V_{Coulomb}}{V_{thermal}} = \Gamma \propto \frac{1}{rT} \propto \frac{\rho^{1/3}}{T}$$

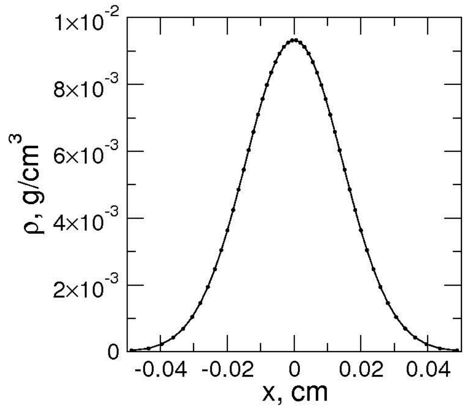


Opacity measurements with heavy ion beams:

homogenous,
macroscopic samples,
known energy deposition

Talk: Andreas Tauschwitz

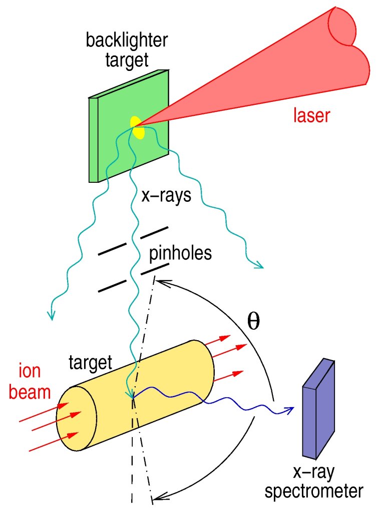




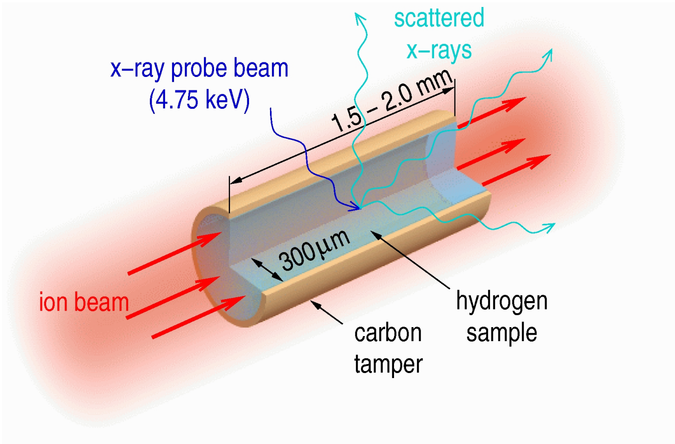
An. Tauschwitz, V.G. Novikov, A. Tauschwitz, F.B. Rosmej, J. Abdallah, E. Onkels, J. Jacoby, J.A. Maruhn: *"Intense ion beams as a tool for opacity measurements in warm dense matter"*, Rapid Comm. Appl. Physics B **95**, 13 (2009).

Absorption spectra – versus – At. Phys. simulations

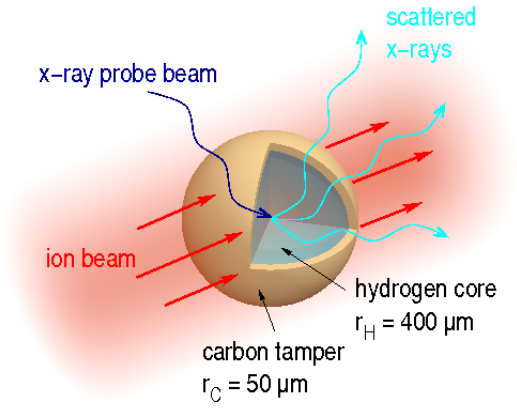
WDM created that it can be **well** diagnosed



D. Riley & F.B. Rosmej 2003,
GSI Annual report



An. Tauschwitz et al.,
PRE **68**, 056406 (2003)



An. Tauschwitz et al.,
HEDP **3**, 371 (2007)

Talk: Paul Neumeyer – Backlighter/Scatter source developments

WDM

« Radiative properties of Warm Dense Matter produced by intense heavy ion beams »

www.gsi.de/forschung/phelix/Experiments/FAIR/WDM/index.html

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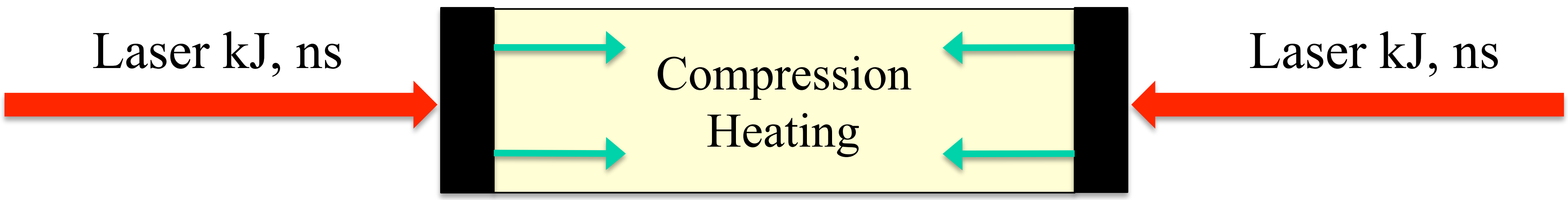
III. Free Electron Lasers - FLASH

-Atomic physics studies-

Drawbacks of standard experimental approaches

Creation of Warm Dense Matter



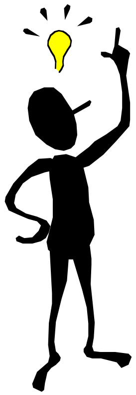
X-ray radiation (diagnostic) necessary to **escape solid matter**, but creation impossible at small temperature

Creation of X-rays => high temperature $kT \approx E_X \approx keV$

=> $V_{coulomb} << V_{therm}$ => Γ <<1: the interesting regime is lost

ns-time scale: the direct access of transitions of phases is difficult

Free Electron X-ray Lasers - XFEL



...... creation of K-, L-hole states

Photo Ionization: $K^2L^NM^X + h\nu_{keV} \rightarrow K^1L^NM^X + e$

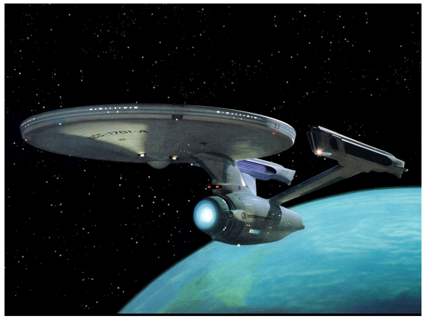
X-rays: $K^1L^NM^X \rightarrow K^2L^{N-1}M^X + h\nu_{keV,\mathbf{target}}$

No temperature needed to excite X-rays !

Synchrotron radiation creates K-holes but does not heat the solid because of very low photon intensity (10^{12} photons/sec)

XUV/X-ray Free Electron Lasers have a brilliance about 10 orders of magnitude higher to allow **photoionisation and heating**

10 orders of magnitude in velocity



Not just more quick ...but completely different

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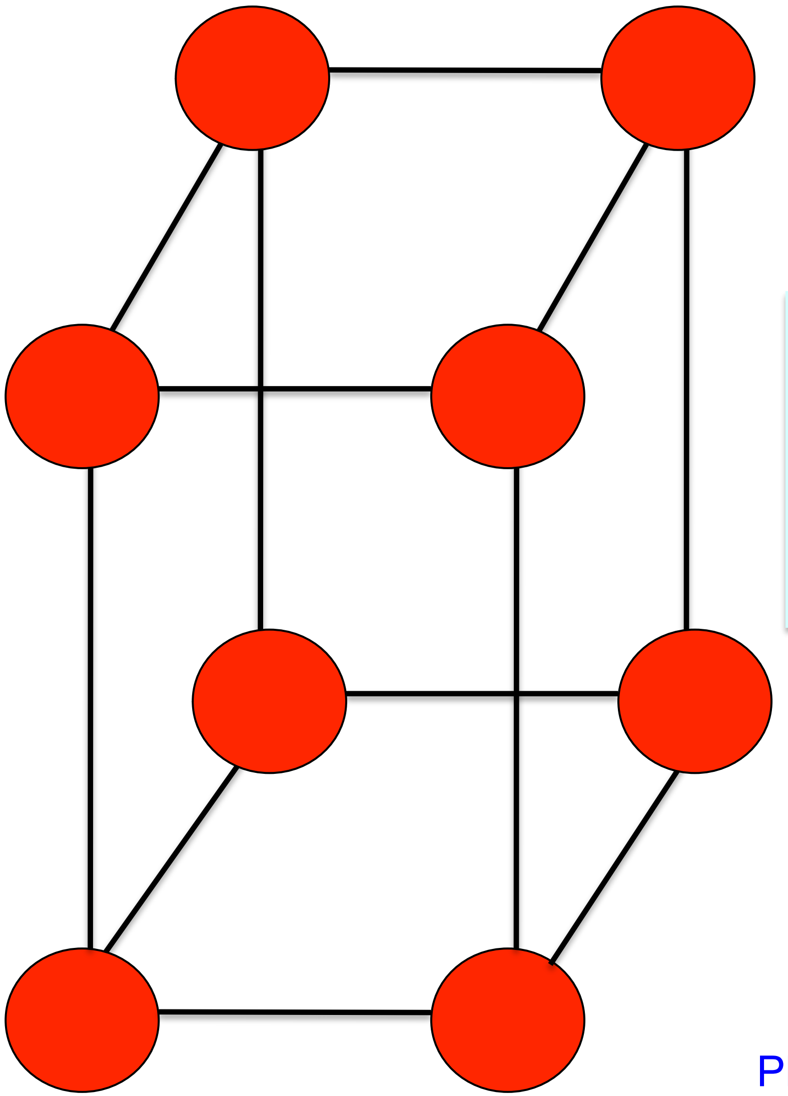
What is so different ?



XFEL

photoionisation
of internal shells

crystal
10 fs
hollow
I > 10^{16} W/cm^2

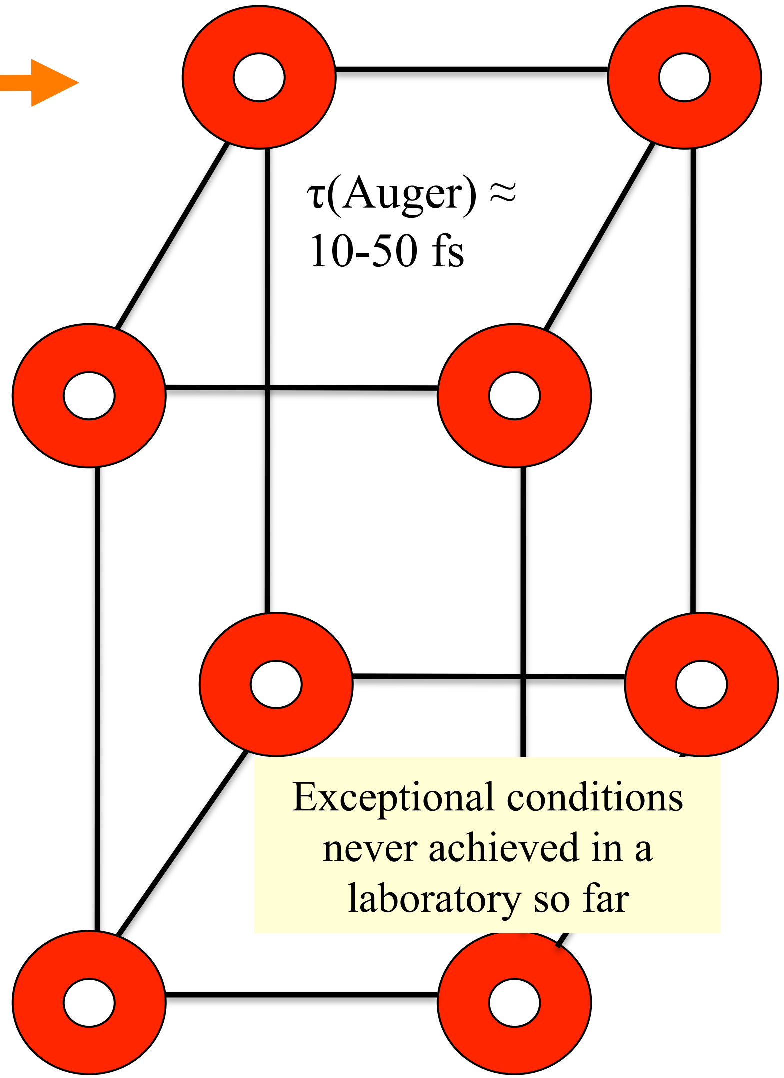
Exotic Matter

Conduction band

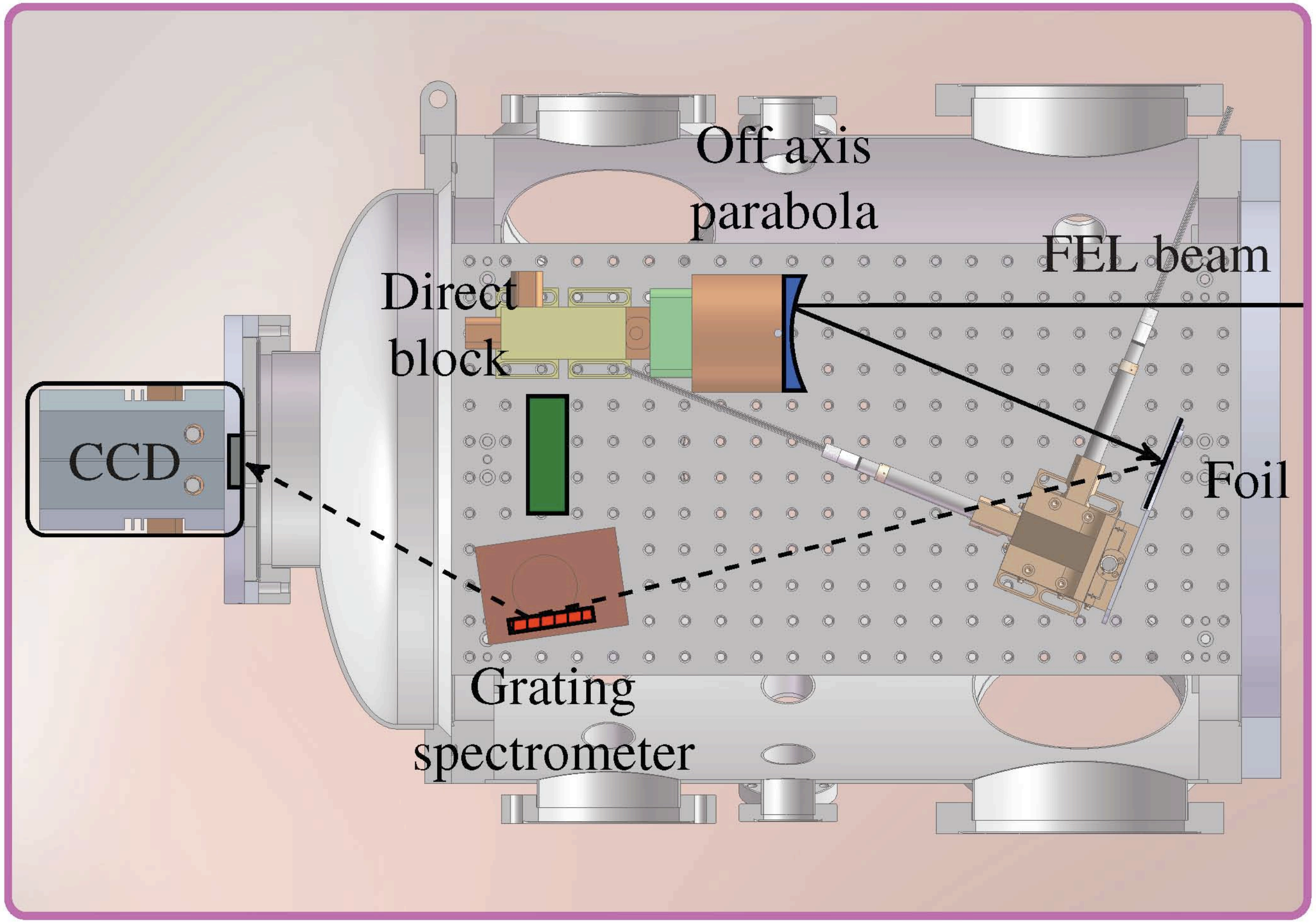
heating (Auger)

Phase transitions

X-ray emission from exotic matter



Experimental setup



µm-focussing: $\phi < 1$ µm
Intensities > 10^{16} W/cm^2

λ=13.5 nm (92 eV), τ = 15 fs
E= 50 µJ, N = 10^{12} photons/pulse

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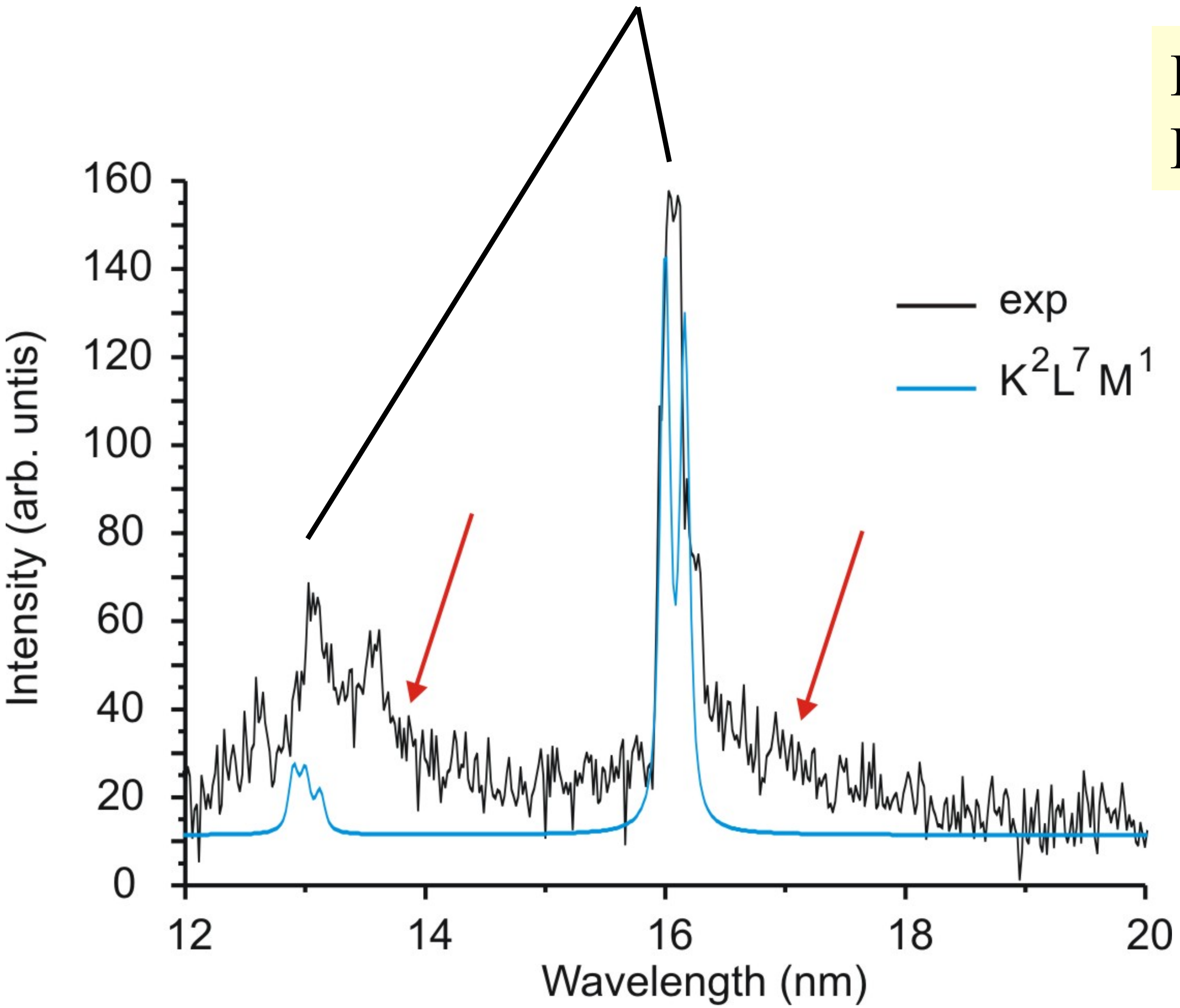
Al-case: Resonance lines do not explain the observations

Dominant spectral features: Al IV

Line emission:
$K^2L^7M^1 \rightarrow K^2L^8 + h\nu_{IV}$



What is missing ?

Resonance line emission (13-16 nm):

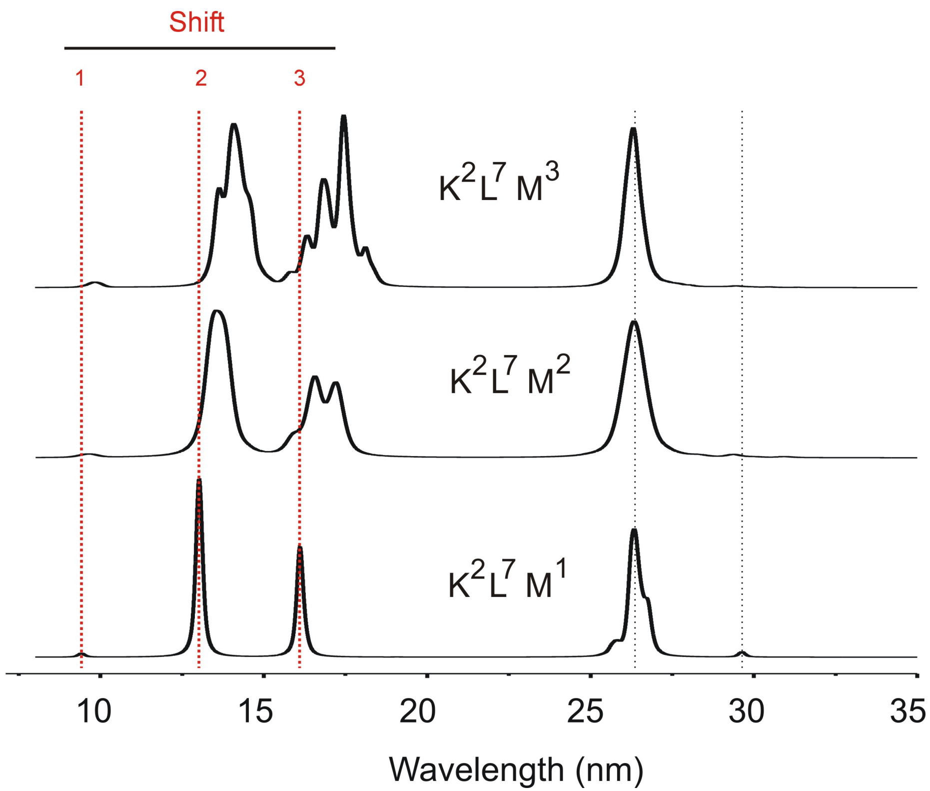
$K^2L^7M^1 \rightarrow K^2L^8 + hc/\lambda$

Screened resonance transitions:

$K^2L^7M^2 \rightarrow K^2L^8M^1 + hc/(\lambda+\delta\lambda)$

$K^2L^7M^3 \rightarrow K^2L^8M^2 + hc/(\lambda+\delta\lambda')$

$\delta\lambda$ = red line wings



F.B. Rosmej et al., J. Phys. Conf. Series ***244****, 042028 (2010)*

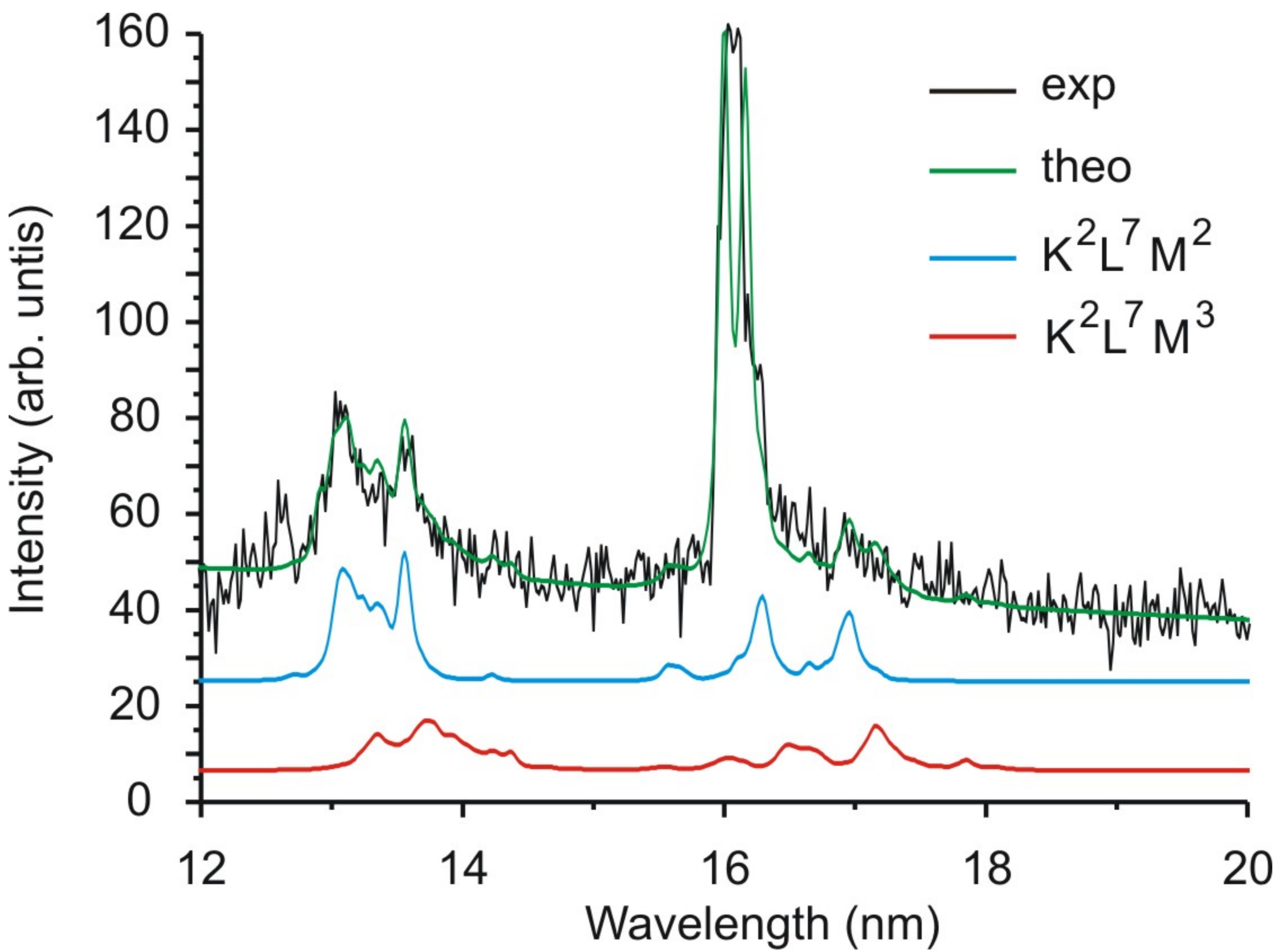
Screened resonance transitions = Emission from hole states

Hole states induced by photoionïation (FLASH: 92 eV):

$K^2L^8M^3 + h\nu_{FLASH} \rightarrow K^2L^7M^3 + e$

$K^2L^8M^2 + h\nu_{FLASH} \rightarrow K^2K^7M^2 + e$

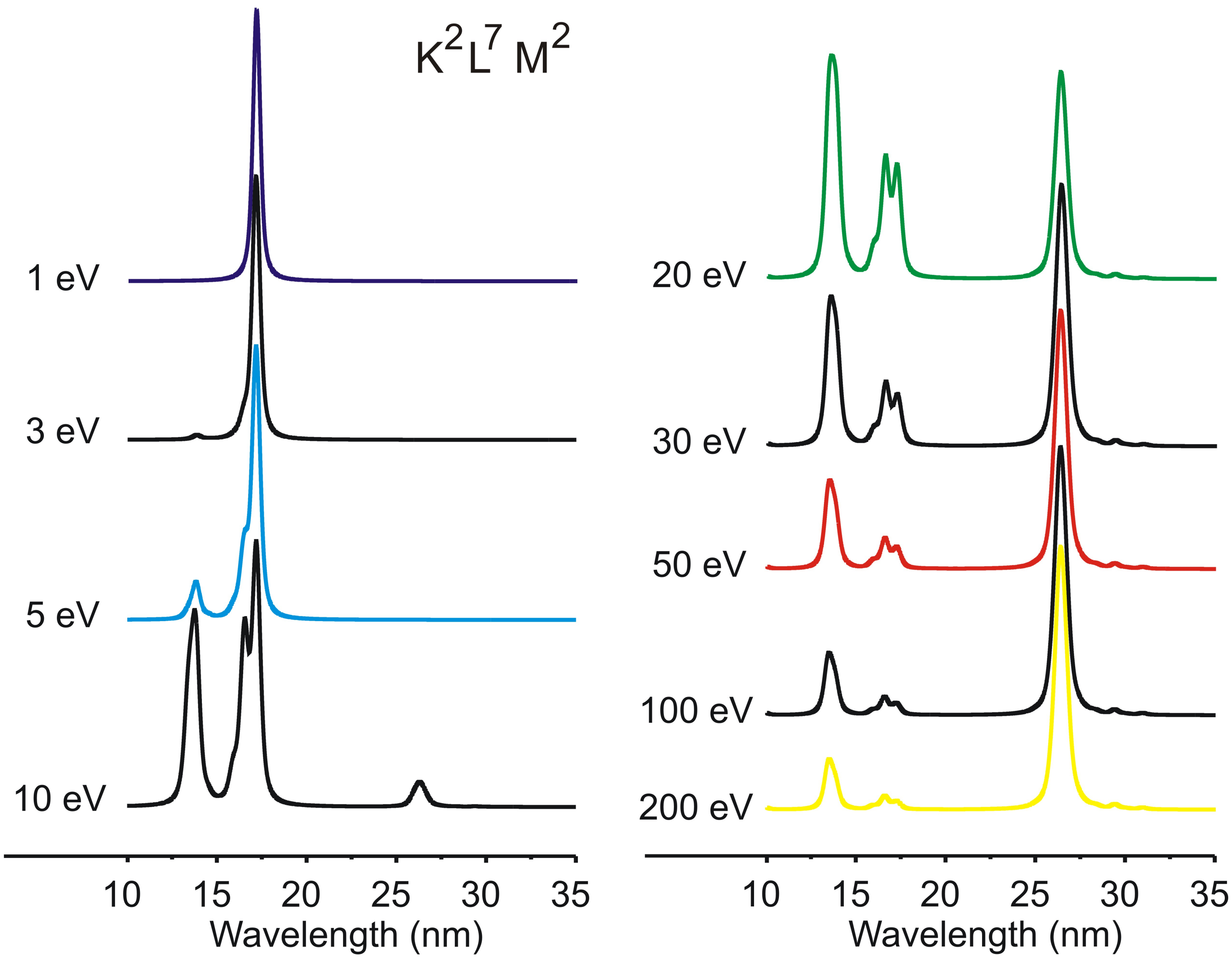
Inclusion of screened hole states matches the experiment



Hole states

E. Galtier, F.B. Rosmej et al., Physical Review Letters **106**, 164801 (2011)

Temperature dependence: $K^2L^7M^2$-configurations

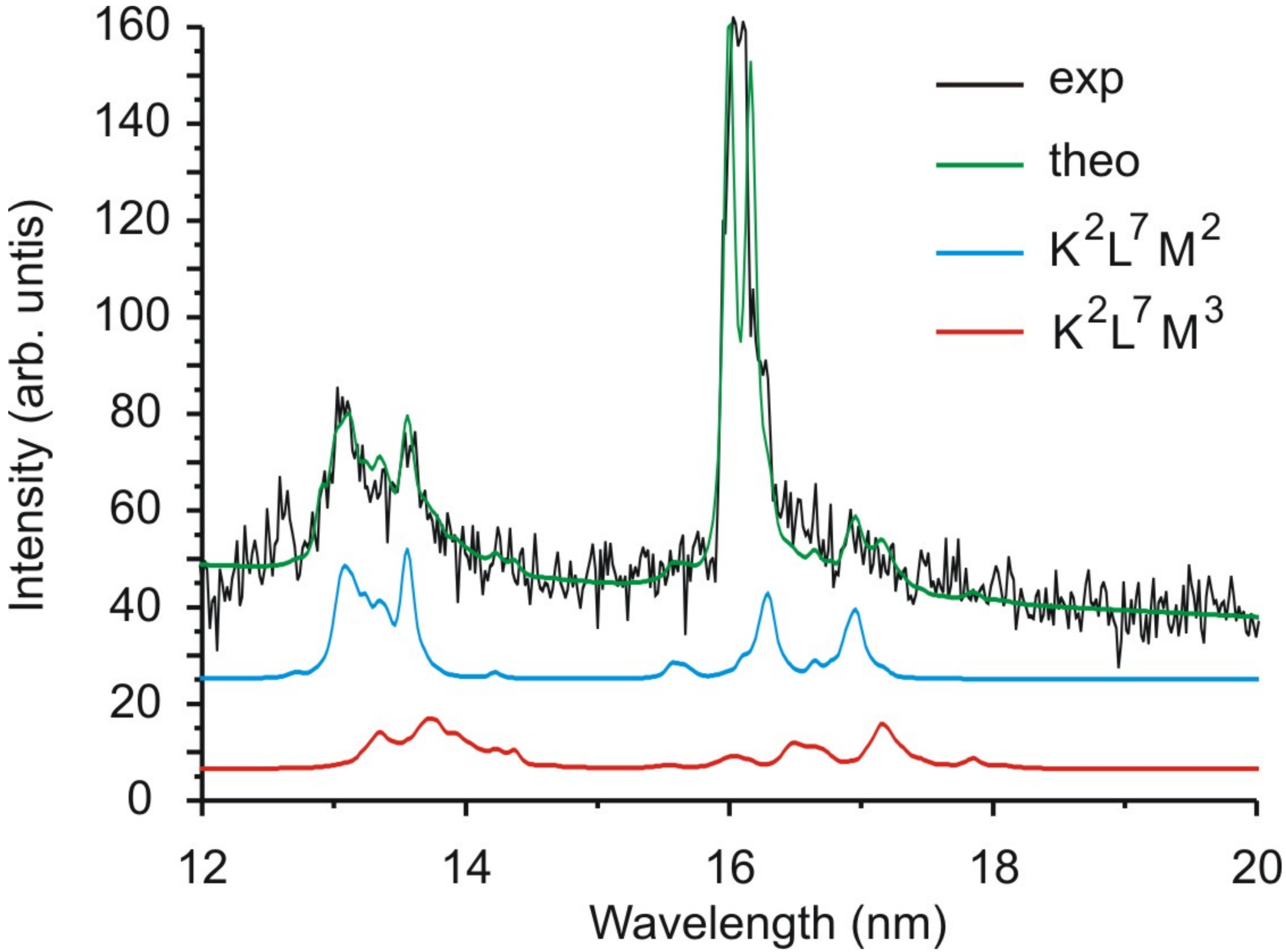


MARIA-simulations

*MARIA-code (F.B. Rosmej):
J. Phys. B Lett. **30**, L819 (1997)
EPL **55**, 472 (2001);
EPL **76**, 1081 (2006)

F.B. Rosmej/UPMC/LULI

Emission from hole states and temperature sensitivity



Hole states ($K^2L^7M^2$, $K^2L^7M^3$) → $kT_e \cong 25\pm10$ eV

E. Galtier, F.B. Rosmej et al., Physical Review Letters **106**, 164801 (2011)

Do we understand a so high temperature ?

$K^2L^8M^3 + h\nu(92\ \text{eV}) \Rightarrow K^2L^7M^{\mathbf{3}} + \mathbf{e}_{\text{Photoionisation}}(32\ \text{eV})$

Distribution among **4** electrons in the M-shell: $T \approx 8$ eV

=> much lower than spectroscopic results (25 eV) !

Relaxation of internal energy of « Hollow crystals »

Autoionization rate ≈ Radiadive decay rate x $(10^2\text{-}10^5)$

Relaxation by autoionisation: $K^2L^7M^4 \Rightarrow K^2L^8M^{\mathbf{2}} + \mathbf{e}_{\text{Auger}}(70\ \text{eV})$

Equilibration in M-shell: **2** x 8eV + **1**x70 eV => about 30 eV/electron

Is the high T = 30 eV consistent with other observations ?

Principle of Microreversibility: inverse process must exist

Time evolution !

$$Rate\ of\ inverse\ Auger\ effect \propto \Gamma_{Auger} \frac{\exp\left(-E_{res}/kT_e\right)}{\left(kT_e\right)^{3/2}}$$

Observation of inverse Auger: $K^2L^8M^2 + e \rightarrow K^2L^7M^3 \rightarrow K^2L^8M^2 + \mathbf{h\nu_{target}}$

XUV-FEL : $K^2L^8M^3 + h\nu \rightarrow K^2L^7M^3 \rightarrow K^2L^8M^2 + \mathbf{h\nu_{target}}$

That is the **same emission** and can hardly be distinguished

F.B. Rosmej/UPMC/LULI

What else to observe ?

Detailed atomic physics of the L-shell: **L^8** = $2s^2 2p^6$

Photoionisation: K^2**$2s^2 2p^6$**M^3 + hν(92eV) ➔ K^2**$2s^2 2p^5$**M^2 + e

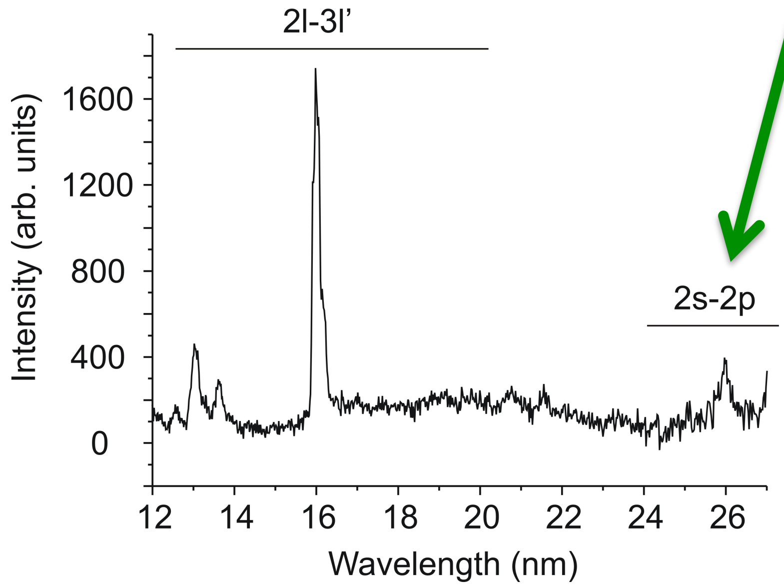
K^2**$2s^2 2p^6$**M^2 + hν(92eV) ➔ K^2**$2s^1 2p^6$**M^2 + **e(-20 eV)**

Inverse Auger: K^2**$2s^2 2p^6$**M^2 + e ➔ K^2**$2s^2 2p^5$**M^3

K^2**$2s^2 2p^6$**M^2 + e ➔ K^2**$2s^1 2p^6$**M^3 ➔ K^2**$2s^2 2p^5$**M^3 + $h\nu_{2p\text{-}2s}$

=> The 2s-hole is from "Inverse Auger"

=> 2p-2s intra-shell line comes from "kT_e"



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Density estimate

Spectral distribution :

$$I(\omega) \approx \sum_k f_k \sum_{i,j} \frac{\hbar\omega_{k,ji}}{4\pi} g_{k,j} A_{k,ji} \exp\left(-\Delta E_{k,ji}/kT_e\right) \Phi_{k,ji}\left(\omega_{k,ji},\omega\right)$$

$$\frac{\sum_{i,j\in M^2} \frac{\hbar\omega_{M^2,ji}}{4\pi} g_{M^2,j} A_{M^2,ji} \exp\left(-\Delta E_{M^2,ji}/kT_e\right)}{\sum_{i,j\in M^3} \frac{\hbar\omega_{M^3,ji}}{4\pi} g_{M^3,j} A_{M^3,ji} \exp\left(-\Delta E_{M^3,ji}/kT_e\right)} \approx const.$$

Fitted f_k parameters provide population ratio $n(K^2L^7M^2)/n(K^2L^7M^3)$:

Saha-Boltzmann

$n_e \approx 3 \times 10^{22}\ cm^{-3}$

This is consistent : $n_e C > A + \Gamma$

E. Galtier, F.B. Rosmej et al., Physical Review Letters **106**, 164801 (2011)

X-FEL induced Hollow Ion Emission: One or two photons?

Inner-shell photoionization:

$$E_{X\text{-}FEL} = 3.1\ \text{keV} > E_i(1s^1)$$

I. $K^2\ L^N + h\nu_{X\text{-}FEL} \rightarrow K^1\ L^N + e$

Relaxation time:
τ(autoionization) ➔ some 10 fs

II. $K^1\ L^N + h\nu_{X\text{-}FEL} \rightarrow K^{\mathbf{0}}\ L^N + e$

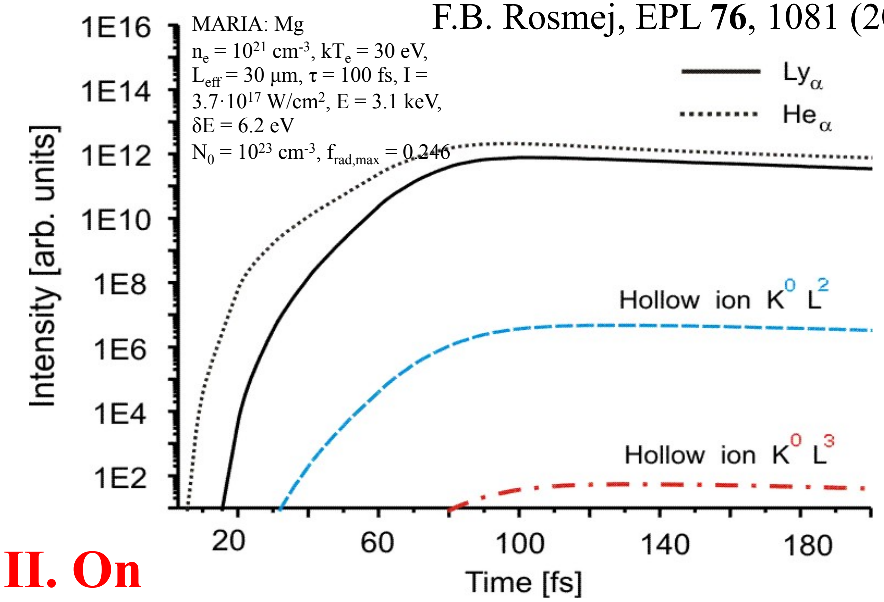
III. $K^{\mathbf{0}}\ L^N \rightarrow K^{\mathbf{1}}\ L^N + h\nu_{\text{Hollow Ion}}$

F.B. Rosmej, R.W. Lee, EPL **77**, 24001 (2007)
F.B. Rosmej et al., HEDP **3**, 218 (2007)

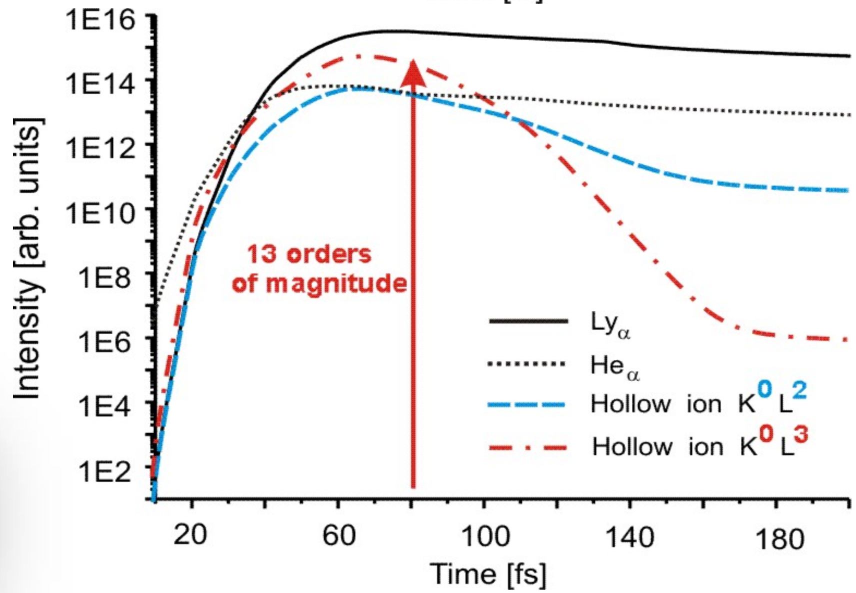
10 orders of magnitude will open up a new field of research

II. Off

MARIA-code:
F.B. Rosmej, EPL **76**, 1081 (2006)



II. On



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The temporal evolution

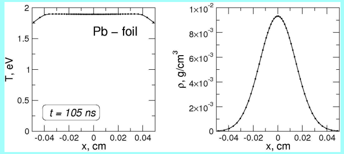
XUV-spectroscopy of hole states provides proof of :

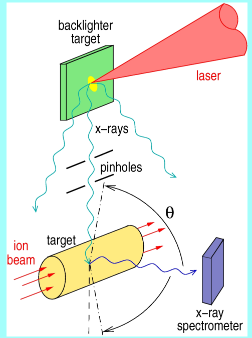
- near solid density, high temperature
- **time evolution and heating mechanisms (Auger)**

10 fs	Interaction FLASH-solid
fs	Photoionisation $K^2L^8M^3 + h\nu - K^2L^7M^3 + e$
	Equilibration of photo-electrons in the conduction band: $kT_e \approx 8$ eV
50 fs	Relaxation (potential energy) of hole states: $K^2L^7M^3$-$K^2L^8M^1$+ $\mathbf{e}_{\mathbf{Auger}}$
fs	Auger electron energy is redistributed in the conduction band
ps	Begin of crystal destruction and inverse Auger effect
ps	XUV target emission from hole states

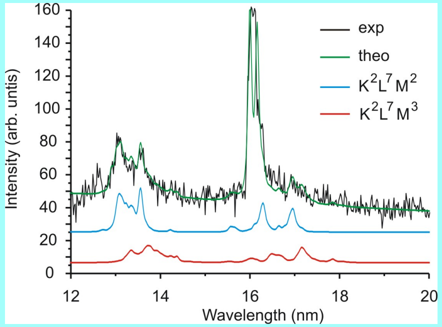
F.B. Rosmej/UPMC/LULI

IV. Conclusion and outlook





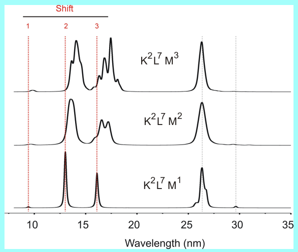
- XUV/X-ray FEL studies complementary to WDM produced by intense heavy ion beams:
  - opacity
  - radiative properties: scattering/emission



- L-shell spectroscopy and atomic physics identifies hole states:
  - Identification of Auger Effect
  - Signature of Auger heating

E. Galtier, F.B. Rosmej et al., PRL **106**, 164801 (2011)

- Time resolution via "atomic physics": Radiation time scale is driven by Auger time scale (some 10 fs)



- Hollow ion X-ray emission:
  - 10 fs time scales
  - no opacity/transparency

F.B. Rosmej, R.W. Lee: *"Hollow ion emission driven by pulsed x-ray radiation fields"*, EPL **77**, 24001 (2007)

Spectroscopy is a non-interfering matter probe

F.B. Rosmej/UPMC/LULI