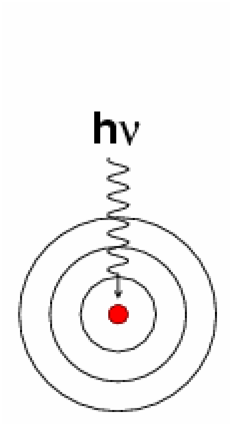
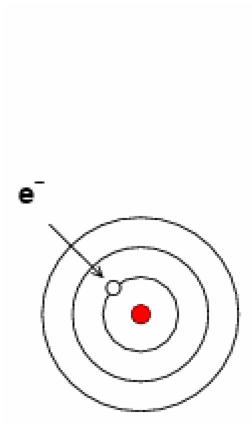
Nuclear Excitation in Plasmas

G. Gosselin, P. Morel, V. Méot
(CEA, France)

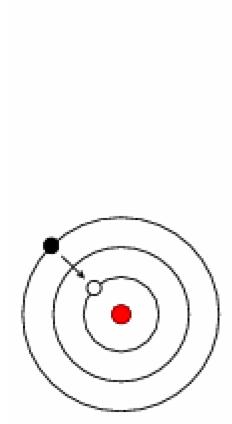
Nuclear Excitation Processes in Plasmas



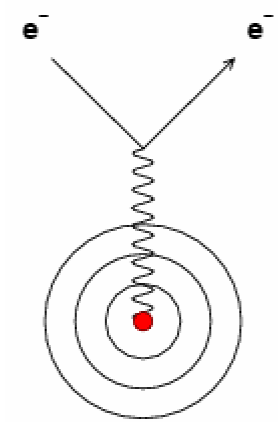
Photon Absorption



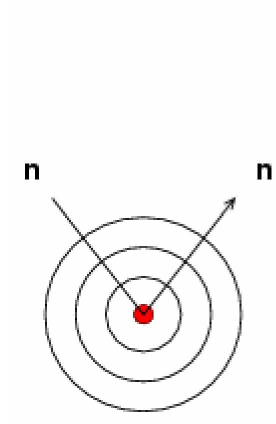
NEEC



NEET



Electron Inelastic Scattering



Neutron Inelastic Scattering

Thermodynamic Equilibrium

- Ions, electrons and photons are at thermodynamic equilibrium

$$T_i = T_e = T_r = T$$

- Nuclear populations are not Ł Boltzmann law does not apply

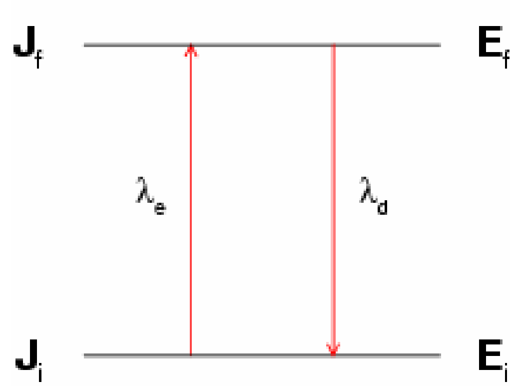
$$N_i \neq \frac{(2J_i + 1)e^{-\frac{E_i}{kT}}}{\sum_{j=1}^{n} (2J_j + 1)e^{-\frac{E_j}{kT}}}$$

- Equilibration time (under stationary conditions)

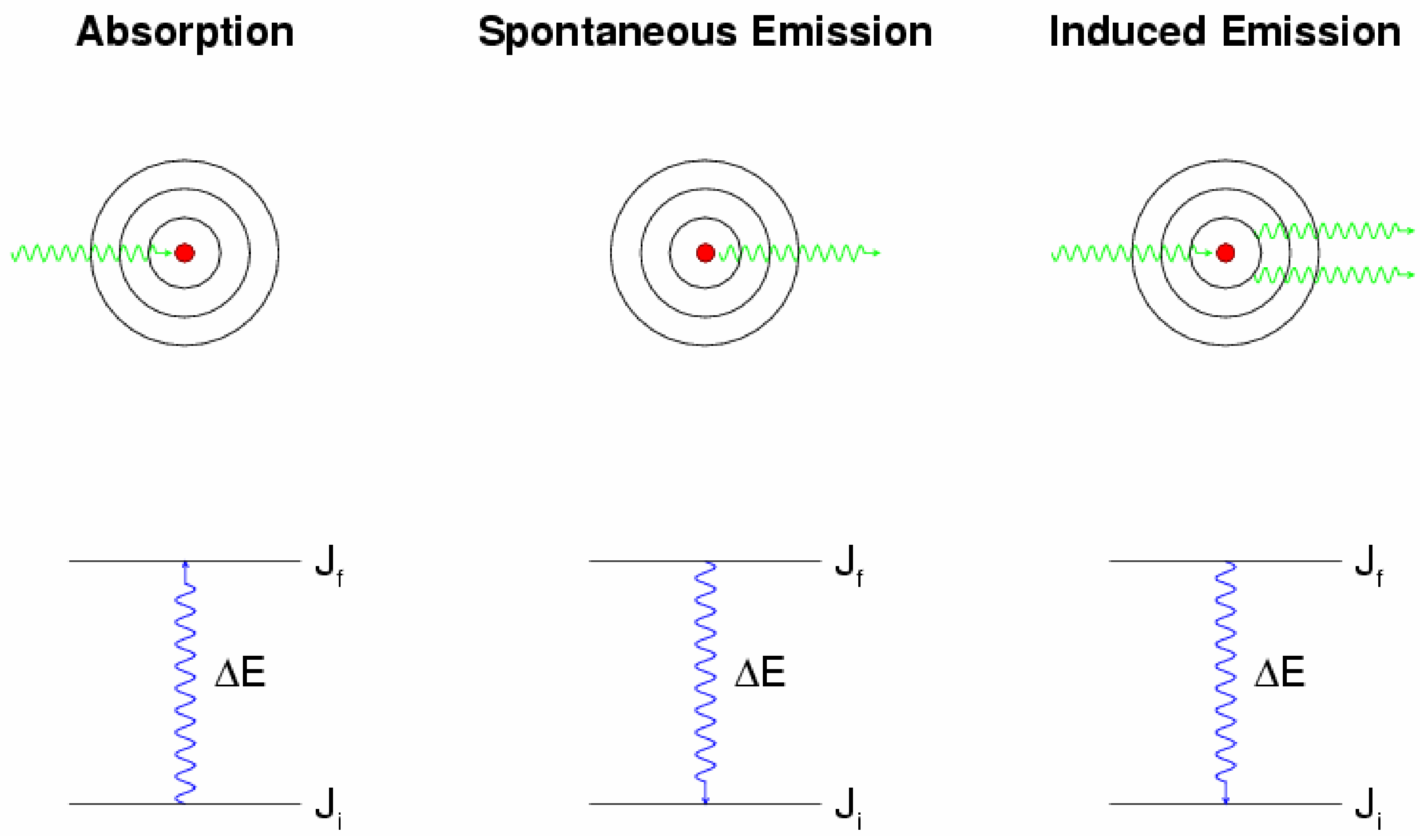
$$\tau = \frac{\ln\ 2}{\lambda_e + \lambda_d}$$

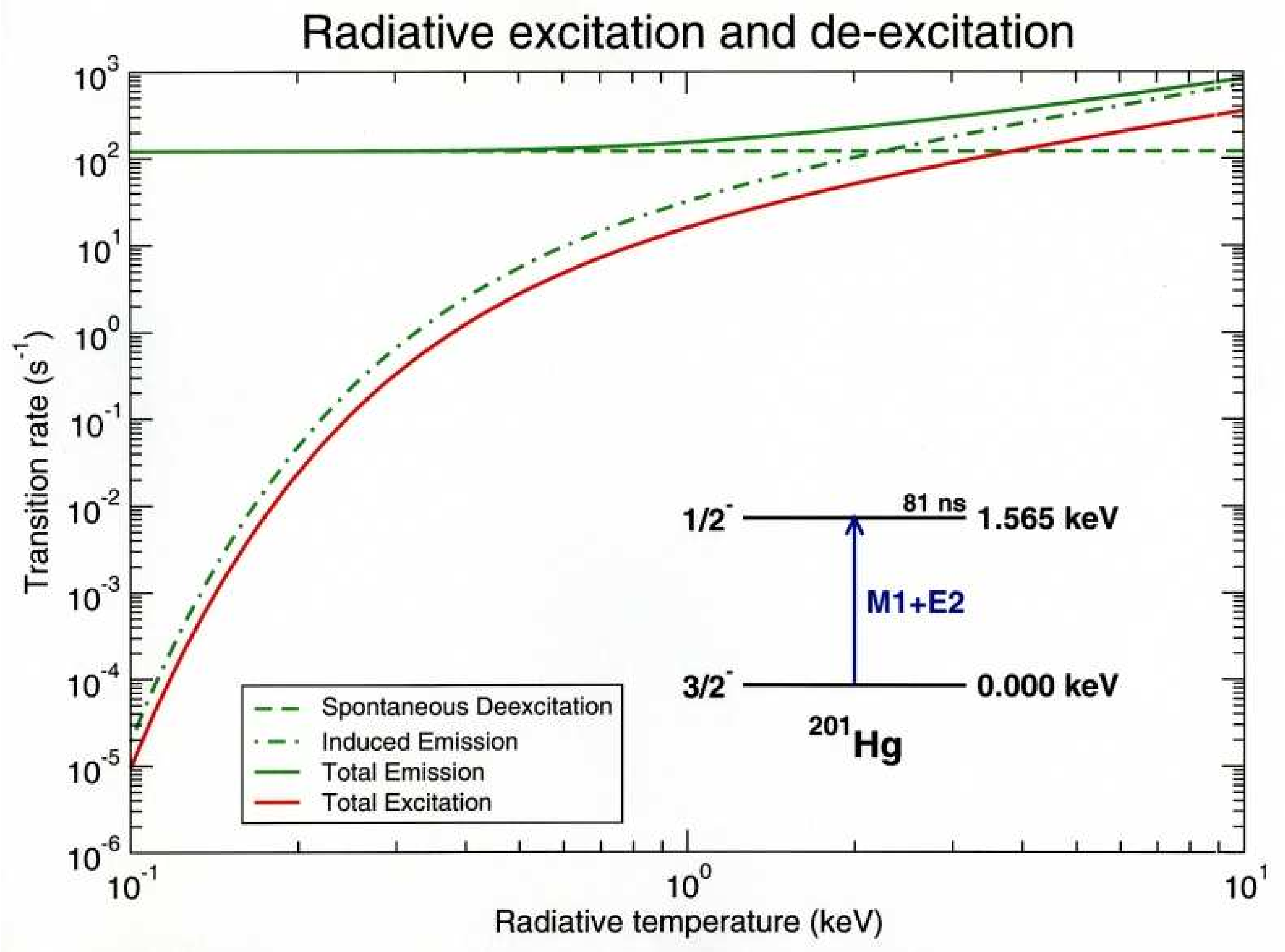
- Populations at equilibrium

$$\frac{N_f(\infty)}{N_i(\infty)} = \frac{\lambda_e}{\lambda_d}$$



Radiative excitation and de-excitation





G. Gosselin, P. Morel, Phys. Rev. **C70**, 064603 (2004)

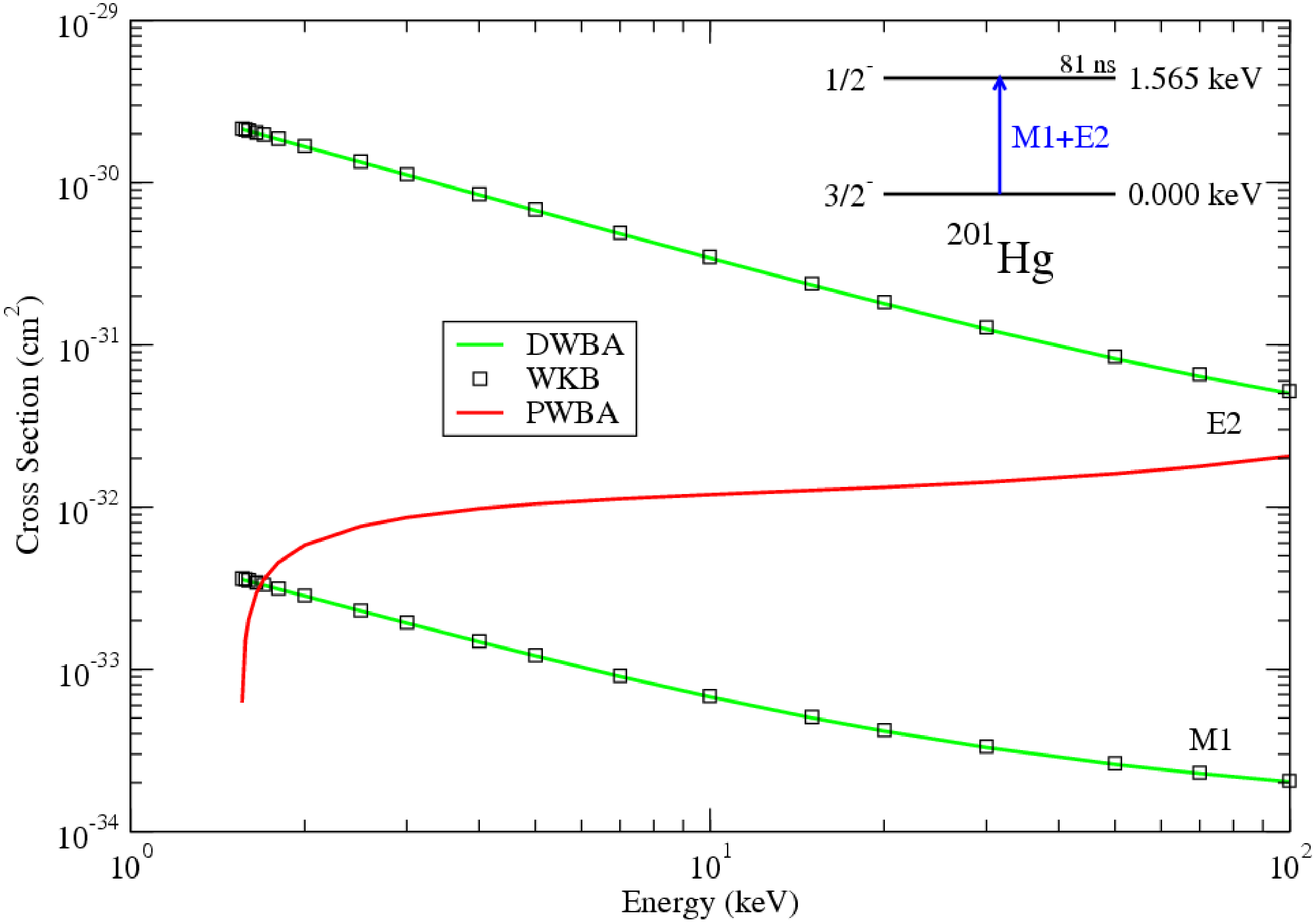
Quantum Coulomb Excitation

- PWBA Approximation
  - Plane wave : works well at high energy
- DWBA Approximation
  - Distorted wave function : works well over the whole energy domain
  - Radial equation can be solved by two methods
    - Exact solution (only with an unscreened potential)
    - WKB method
- Radial exact solution
  - Hypergeometric functions
  - Numerical evaluation very difficult for low energies

$$\frac{d^2\varphi_\ell}{dr^2}+\left[\frac{2m}{\hbar^2}E-\frac{2m}{\hbar^2}V(r)-\frac{\ell(\ell+1)}{r^2}\right]\varphi_\ell=0$$

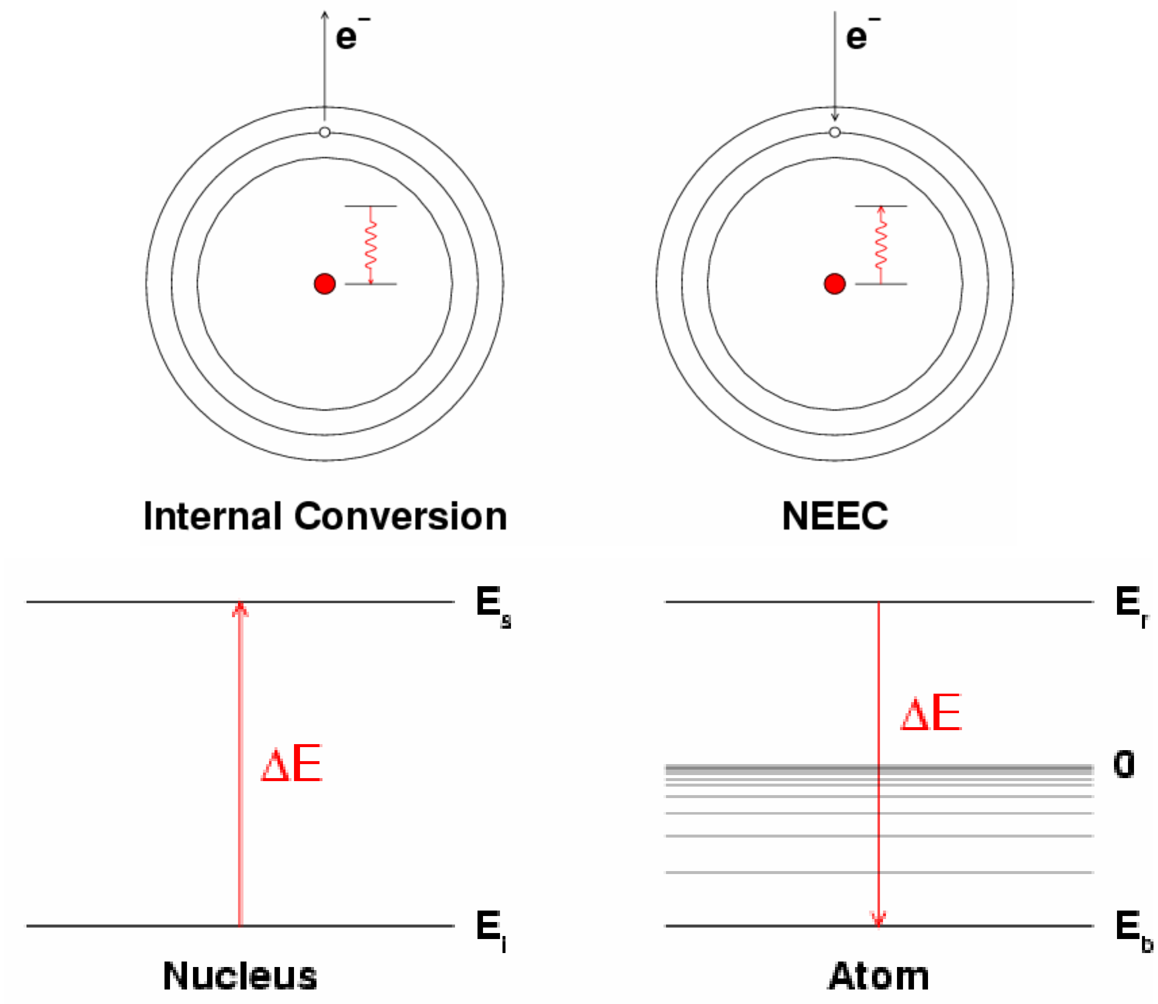
- WKB Method
  - Approximate radial equation resolution
  - Solution by Langer
    - Asymptotic solutions Bessel functions
    - No divergence at turning point

Inelastic Electron Scattering



G. Gosselin, N. Pillet, V. Méot, P. Morel, A. Dzyublik, Phys. Rev. C79, 014604 (2009)

Internal Conversion / Electronic Capture



Internal conversion / NEEC

- Internal conversion coefficient

$$\alpha = \frac{\lambda^{IC}_{J_f \to J_i}}{\lambda^{\gamma}_{J_f \to J_i}} = \frac{T^{\gamma}_{J_f \to J_i}}{T^{IC}_{J_f \to J_i}}$$

- Internal conversion rate in laboratory

$$\lambda^{nuc}_{IC} = \frac{\mathrm{Log}\,2}{T^{IC}_{J_f \to J_i}} = \frac{2\pi}{\hbar} \left| \left\langle \psi_i \varphi_r \right| H \left| \psi_f \varphi_b \right\rangle \right|^2 \rho_r(E_r)$$

- NEEC cross section in laboratory

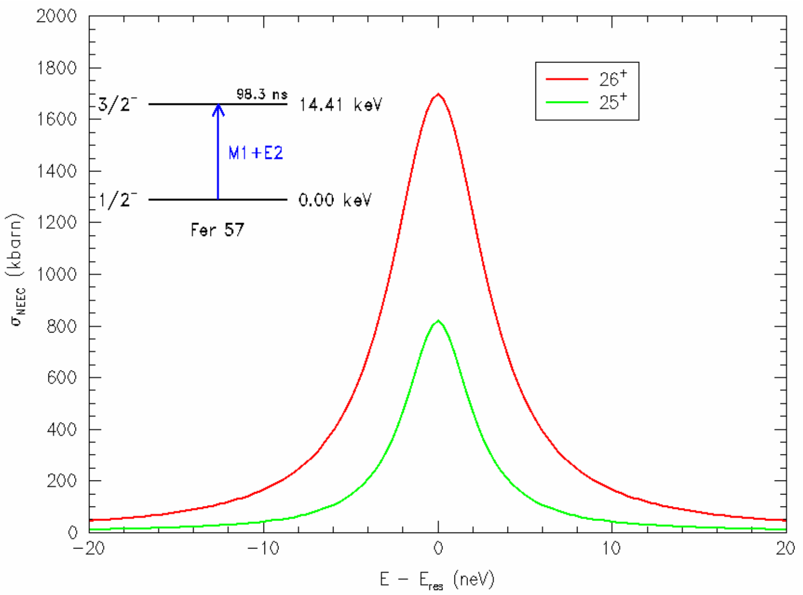
$$\sigma_{NEEC}(E) = \frac{2\pi}{\hbar\, v_e} \left| \left\langle \psi_f \varphi_b \right| H \left| \psi_i \varphi_r \right\rangle \right|^2 \rho_b(E)$$

NEEC cross section

$$\sigma_{NEEC}(E) = \frac{\pi\hbar^2}{2m_e E}\,\frac{2J_f+1}{2J_i+1}\,\frac{\hbar\alpha \mathrm{Log}2}{T^{\gamma}_{J_f \to J_i}}\,\frac{\Gamma}{(E-E_r)^2+\left(\frac{\Gamma}{2}\right)^2}$$

$$\sigma_{NEEC} = \frac{\pi^2\hbar^2}{m_e E}\,\frac{2J_f+1}{2J_i+1}\,\frac{\hbar\alpha \mathrm{Log}2}{T^{\gamma}_{J_f \to J_i}}\,\delta(E-E_r)$$

- Laboratory conditions
  - Non excited atom
  - Natural level widths
  - Internal conversion coefficient α



Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

Relativistic Average Atom

- Thomas-Fermi-Dirac model
  - The atom lies in a spherical box whose radius is dictated by density
  - Average atom : mean value of binding energies and occupation numbers
  - Relativistic : necessary for heavy nuclei internal conversion calculations

B. F. Rozsnyai, Phys. Rev. A5 (1972) 1137

Macroscopic transition rates

- Excitation rate : NEEC

$$\lambda_e = \int_0^{\Delta E} \sigma_{NEEC}(E) v_e f(E) P(E - \Delta E) dE$$

$$\lambda_e = \frac{2J_f + 1}{2J_i + 1} \frac{\alpha(T_e) \mathrm{Log}\, 2}{T^{\gamma}_{J_f \to J_i}} g(E_b) f_{FD}(E_r)[1 - f_{FD}(E_b)] \left[\mathrm{erf}\left(\frac{E_r}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{E_b}{\sigma\sqrt{2}}\right) \right]$$

- De-excitation rate : Internal conversion

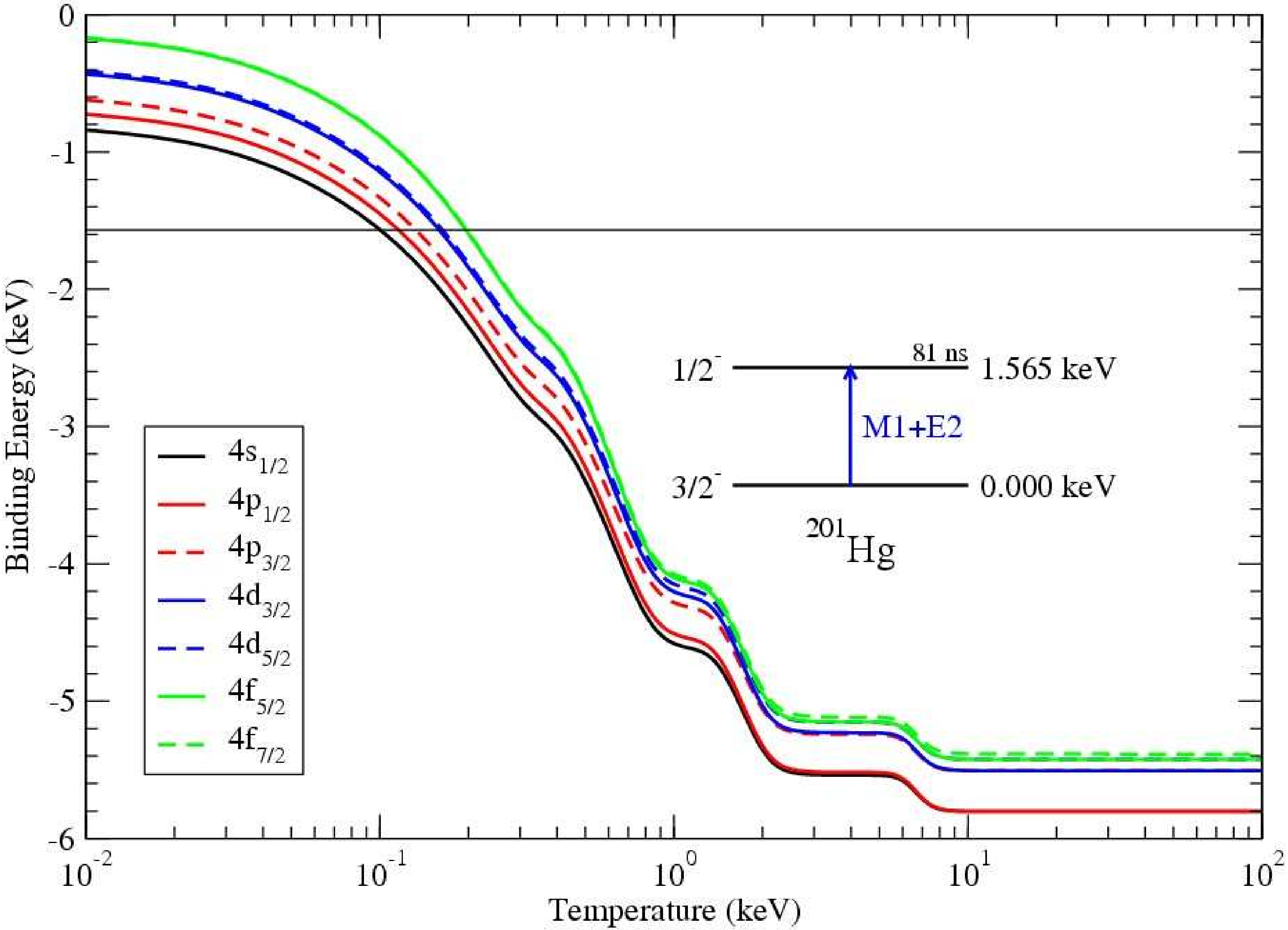
Calculated with Average Atom wavefunctions

$$\lambda_d = \int_{-\Delta E} \lambda_{IC} f(E) P(E + \Delta E) dE$$

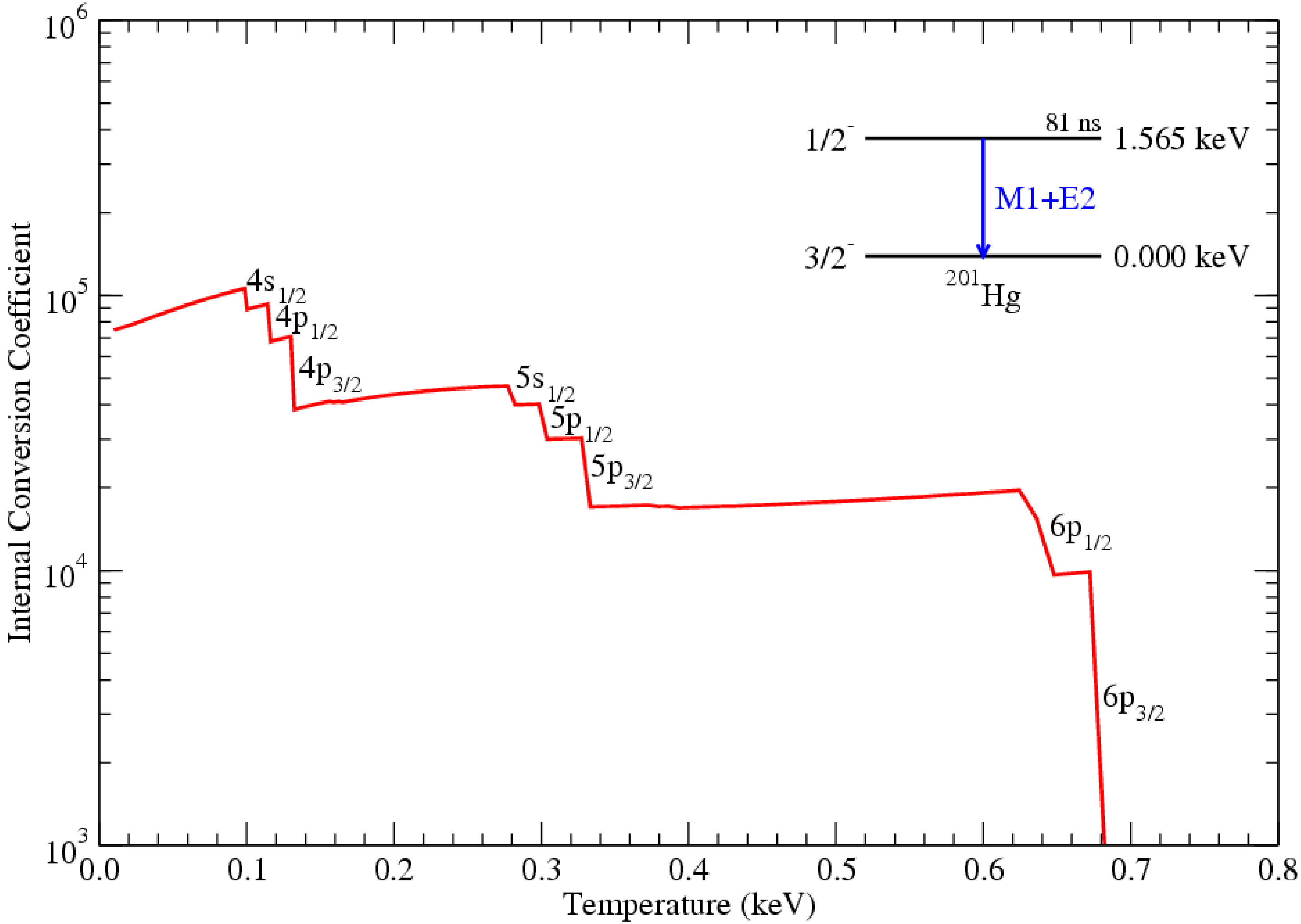
$$\lambda_d = \frac{\alpha(T_e) \mathrm{Log}\, 2}{T^{\gamma}_{J_f \to J_i}} g(E_b) f_{FD}(E_b)[1 - f_{FD}(E_r)] \left[\mathrm{erf}\left(\frac{E_r}{\sigma\sqrt{2}}\right) - \mathrm{erf}\left(\frac{E_b}{\sigma\sqrt{2}}\right) \right]$$

Principle of detailed balance fulfilled (Boltzmann)

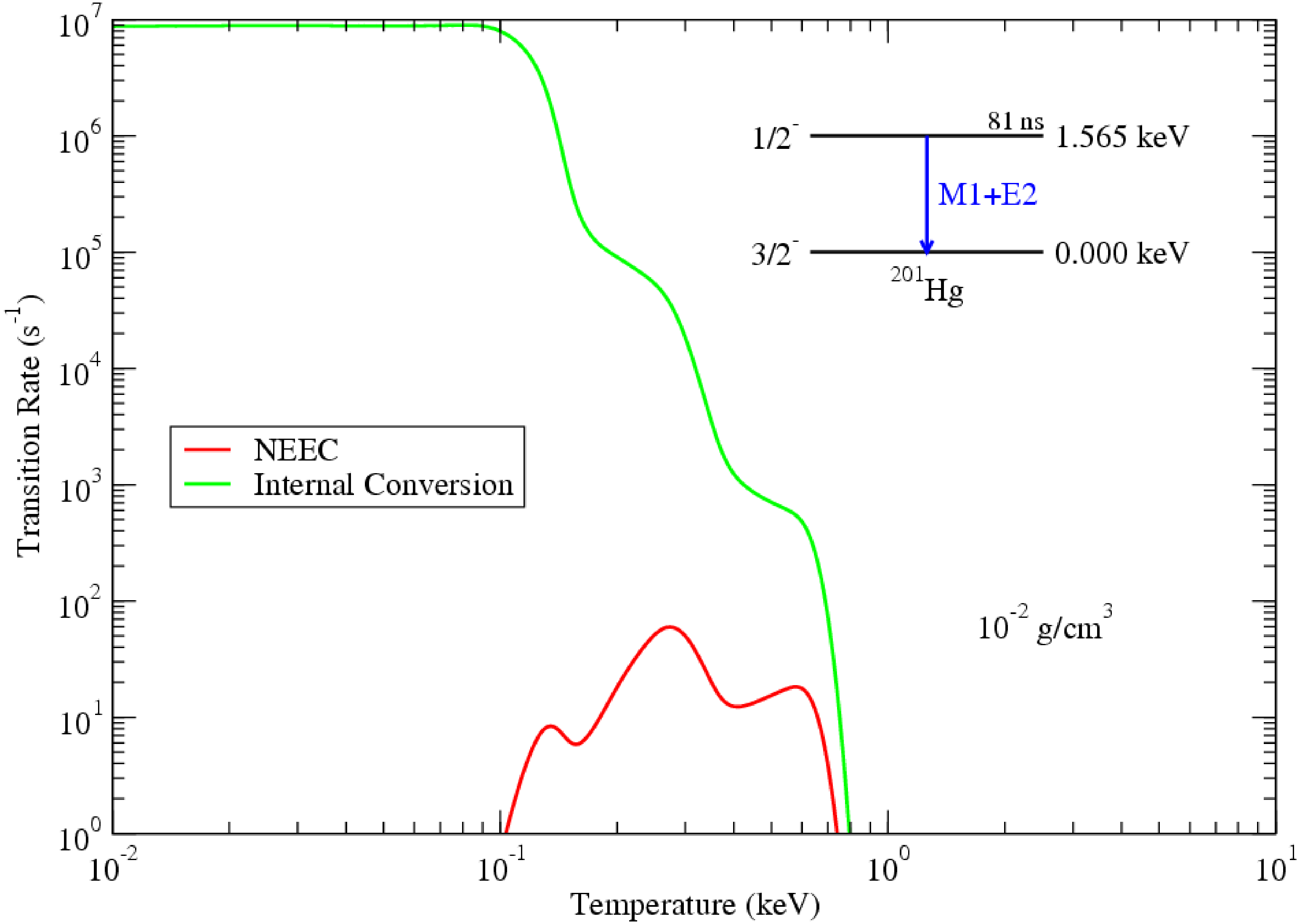
G. D. Doolen, Phys. Rev. C18 (1978) 2547



Binding Energy (keV)
Temperature (keV)
$4s_{1/2}$
$4p_{1/2}$
$4p_{3/2}$
$4d_{3/2}$
$4d_{5/2}$
$4f_{5/2}$
$4f_{7/2}$
81 ns
$1/2^-$
1.565 keV
M1+E2
$3/2^-$
0.000 keV
^{201}Hg

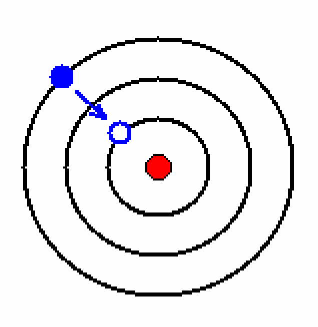


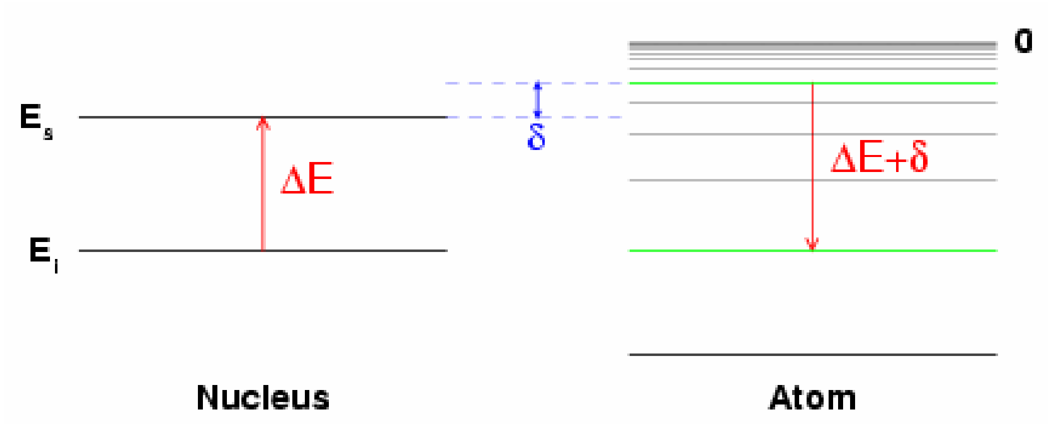
Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France



G. Gosselin and P. Morel, Phys. Rev. **C70** (2004) 064603

NEET in plasma





- Resonant phenomenon
  - Energy mismatch : δ
  - Quantum selection rules (spin, parity)

M. Harston, J. F. Chemin, Phys. Rev. **C59** (1999) 2462

Coupling Matrix Element

$$|R_{12}(\delta)|^2 = 4\pi\alpha\omega_N^2\left(\omega_N + \frac{\delta}{2}\right)^{2L}\frac{2J_2+1}{L^2[(2L+1)!!]^2}\begin{pmatrix} J_1 & J_2 & L \\ \frac{1}{2} & -\frac{1}{2} & 0 \end{pmatrix}^2 |R_{n_1\kappa_1 n_2\kappa_2}|^2 B(EL)$$

Nuclear Transition Energy

Atomic Matrix Element

Nuclear Matrix Element

Expression nearly identical to Internal Conversion matrix element

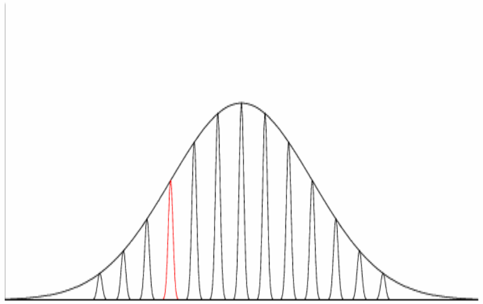
NEET Transition Rate

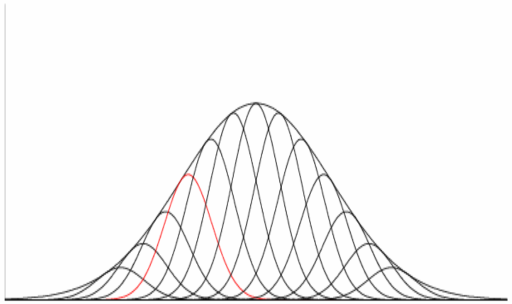
- Summation over every configuration

$$\lambda_{NEET}(\rho, T_e) = \sum_{\alpha,\beta} P_\alpha(\rho, T_e)\lambda_\alpha P^\infty(\delta_{\alpha\beta})$$

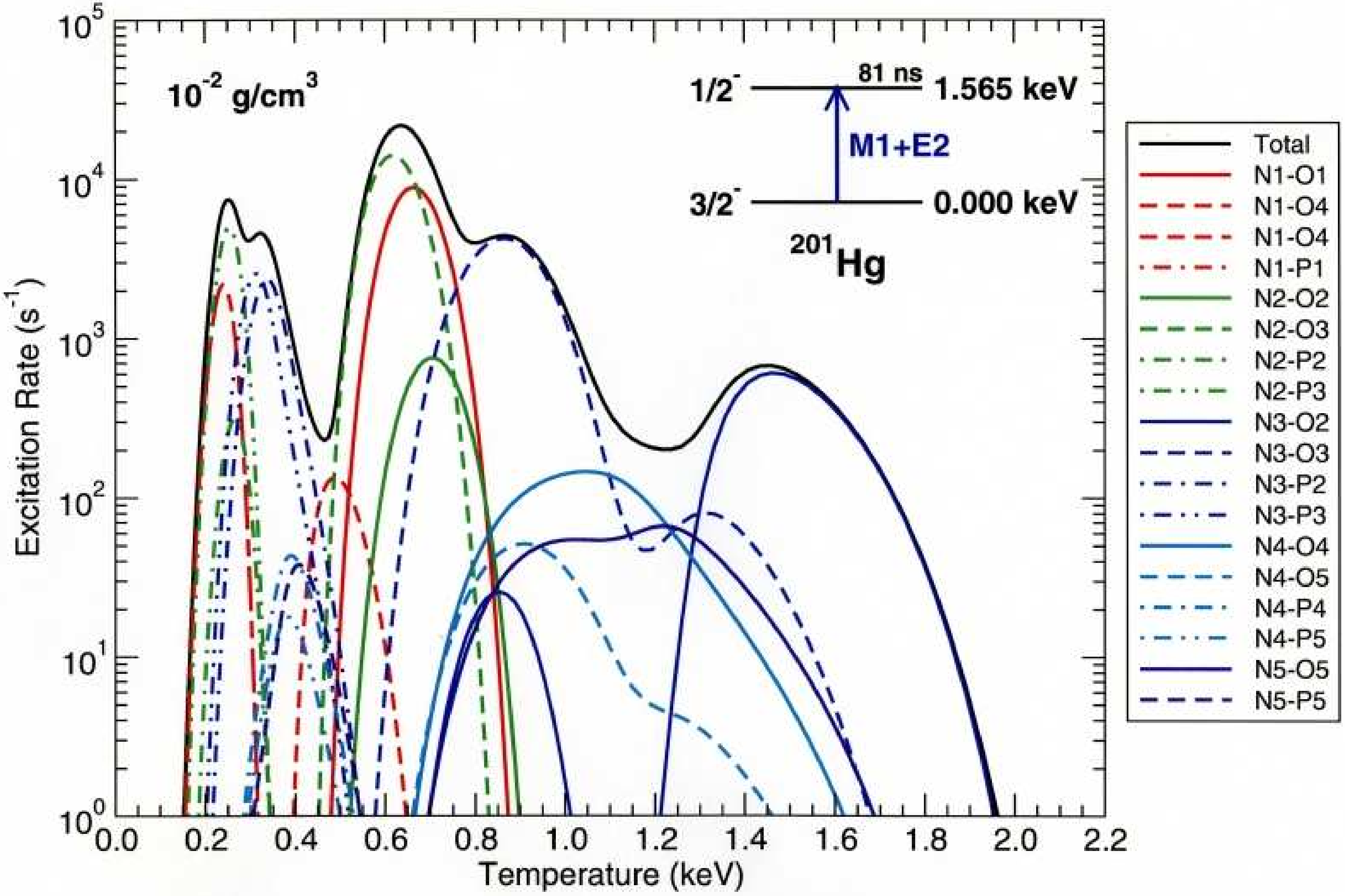
- Statistical envelope

$$\lambda_{NEET}(\rho, T_e) = \frac{2\pi}{\hbar} D_1 p_1 (1 - p_2) \left| R_{12}(\bar{\delta}) \right|^2 \frac{e^{-\frac{\bar{\delta}^2}{2\sigma^2}}}{\sqrt{2\pi}\sigma}$$



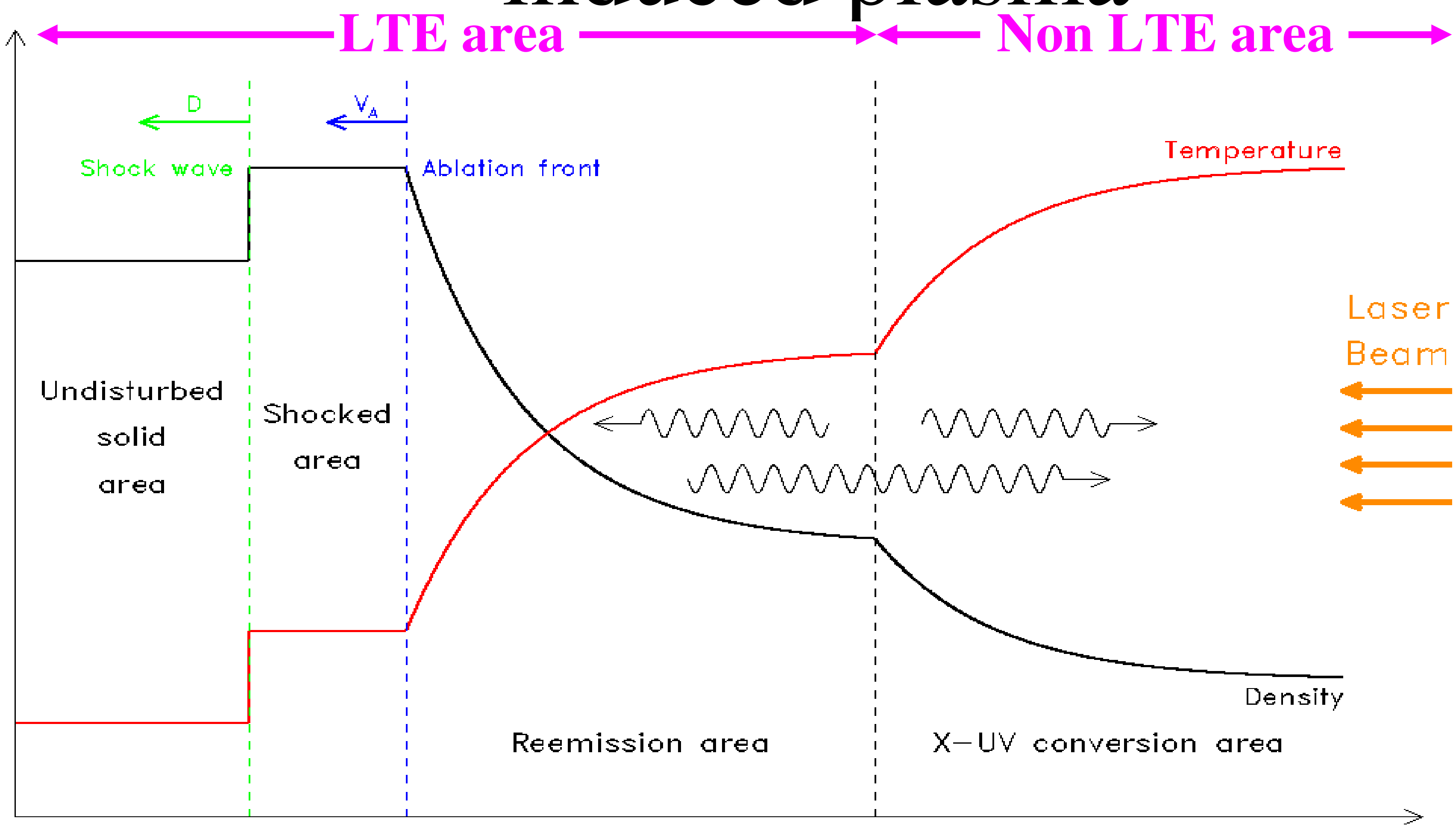


P. Morel, V. Méot, G. Gosselin, D. Gogny, W. Younes, Phys. Rev. A60, 063414 (2004)



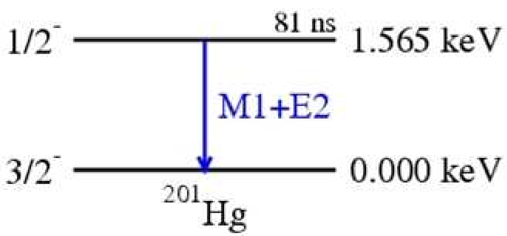
10^5
10^4
10^3
10^2
10^1
10^0
Excitation Rate (s^-1)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
Temperature (keV)
10^-2 g/cm^3
1/2^-
81 ns
1.565 keV
M1+E2
3/2^-
0.000 keV
201Hg
Total
N1-O1
N1-O4
N1-O4
N1-P1
N2-O2
N2-O3
N2-P2
N2-P3
N3-O2
N3-O3
N3-P2
N3-P3
N4-O4
N4-O5
N4-P4
N4-P5
N5-O5
N5-P5

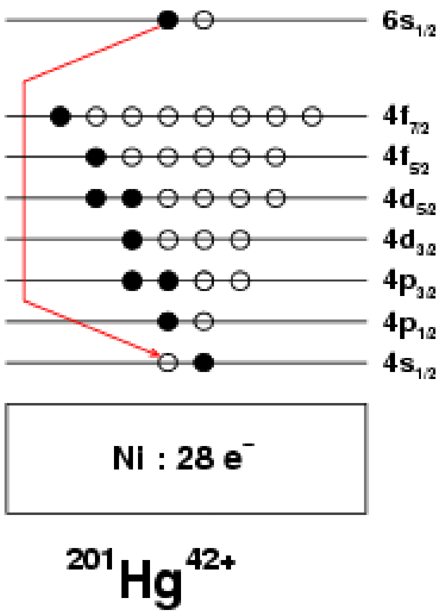
Thermodynamic profile of a laser induced plasma



Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

Non LTE NEET rate : ^{201}Hg





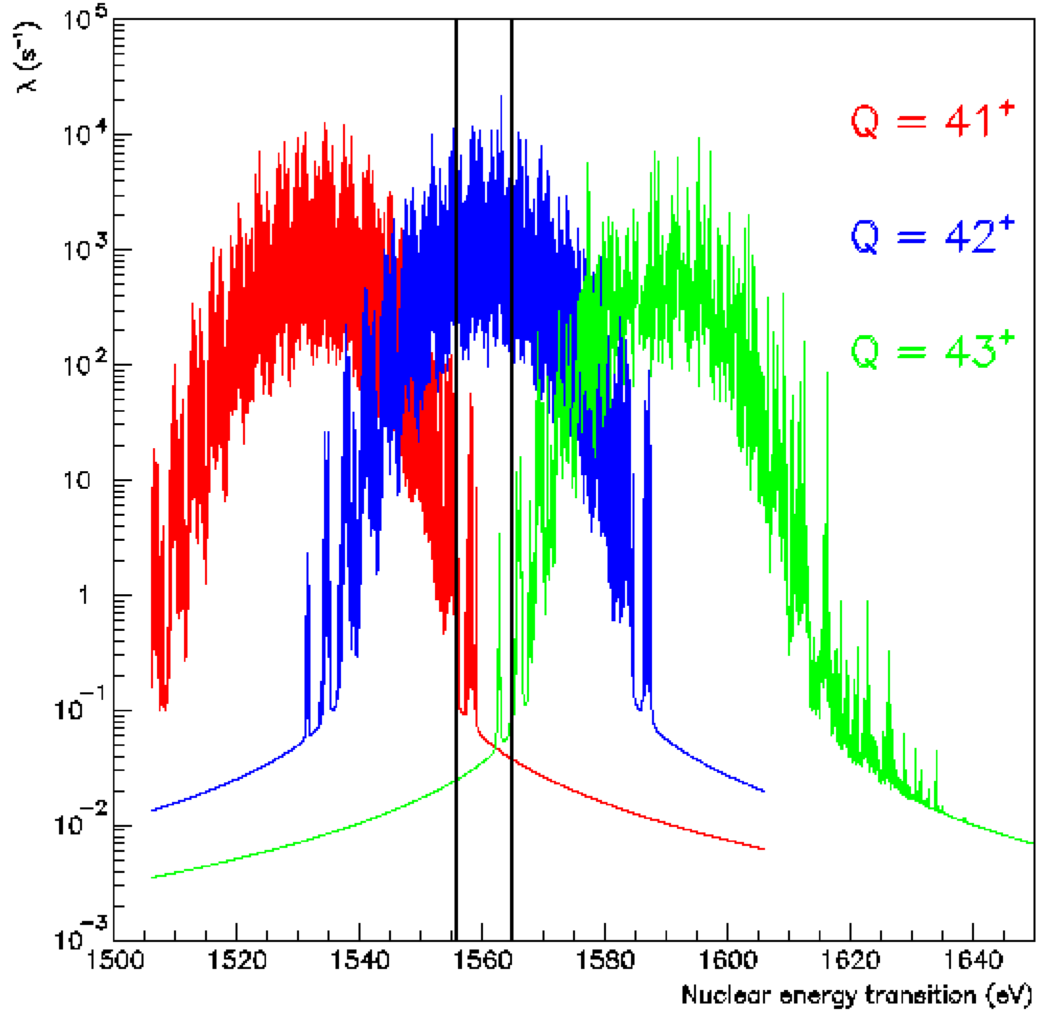
- Dirac-Fock model
  - Detailed configurations

3705 NEET-allowing distributions

- For each configuration :
  - Total energy by DF calculations
  - Probability by Bernouilli distribution

$$P(N=k)=C_n^k p^k (1-p)^{n-k}$$

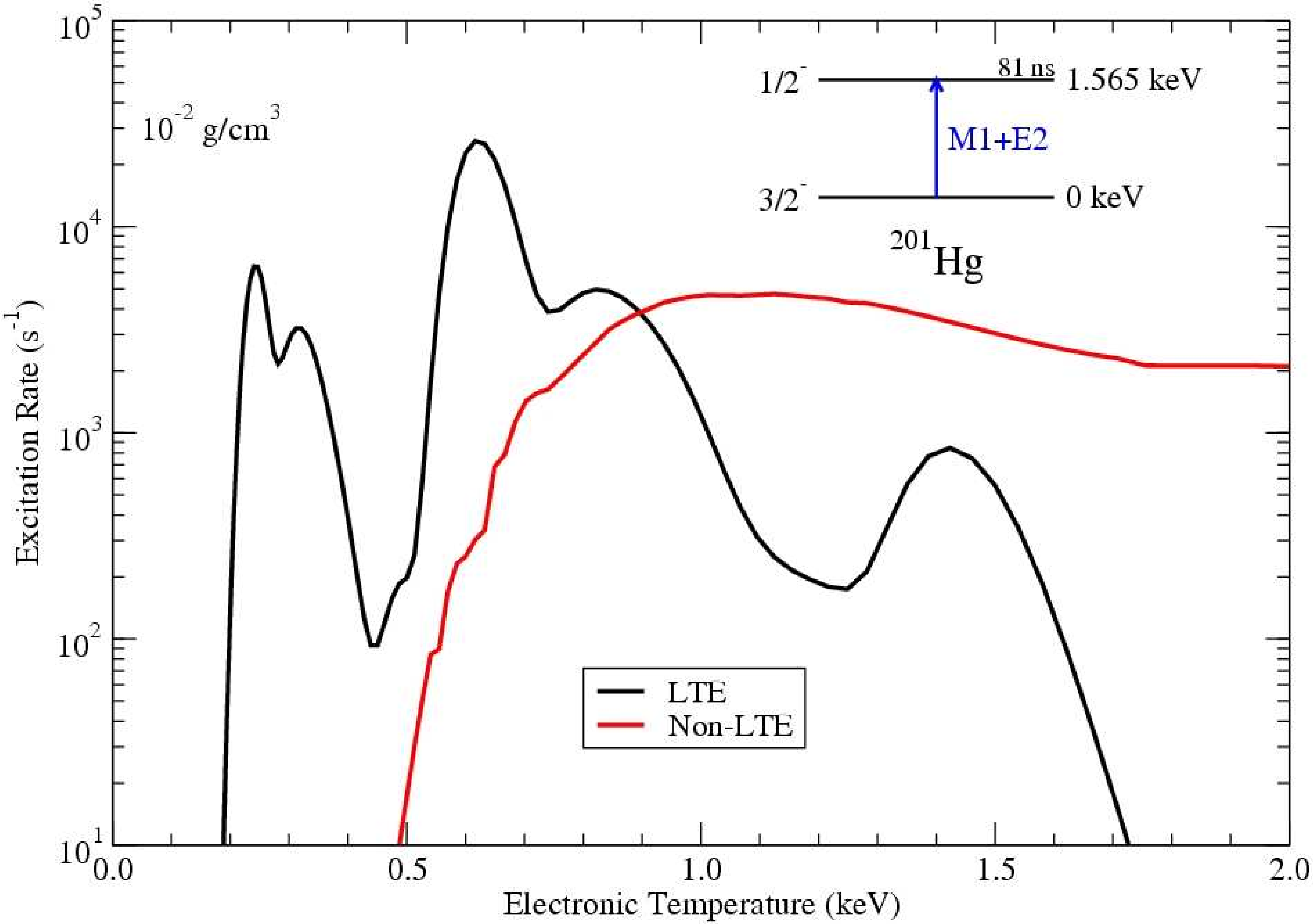
^{201}Hg NEET rate for N1-P1 transition



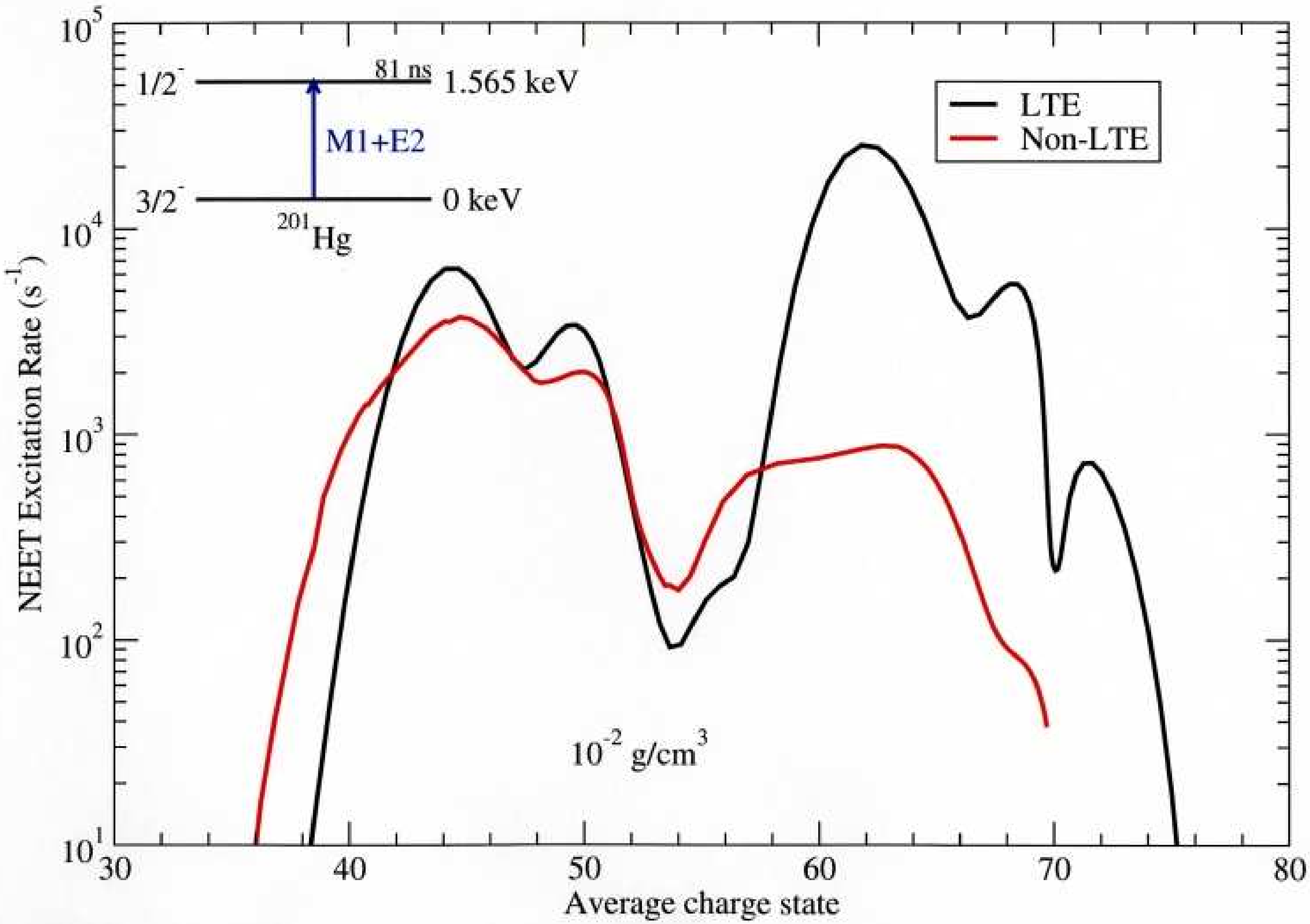
Self consistent average atom model SHAAM

$$\lambda^{NEET}(\rho, T_e) = \frac{2\pi}{\hbar} D_1 p_1 (1 - p_2) \left| R_{1,2} \right|^2 \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\langle\delta\rangle^2}{2\sigma^2}}$$

- Screened Hydrogenic Average Atom Model
  - LTE / non-LTE atomic physics calculation (ρ, T_e, T_r)
  - Charge state distribution
  - Mismatch variance σ
  - Average electronic shell populations
- Relativistic Average Atom Model
  - Relativistic but only LTE
  - Wave functions
  - Binding energies



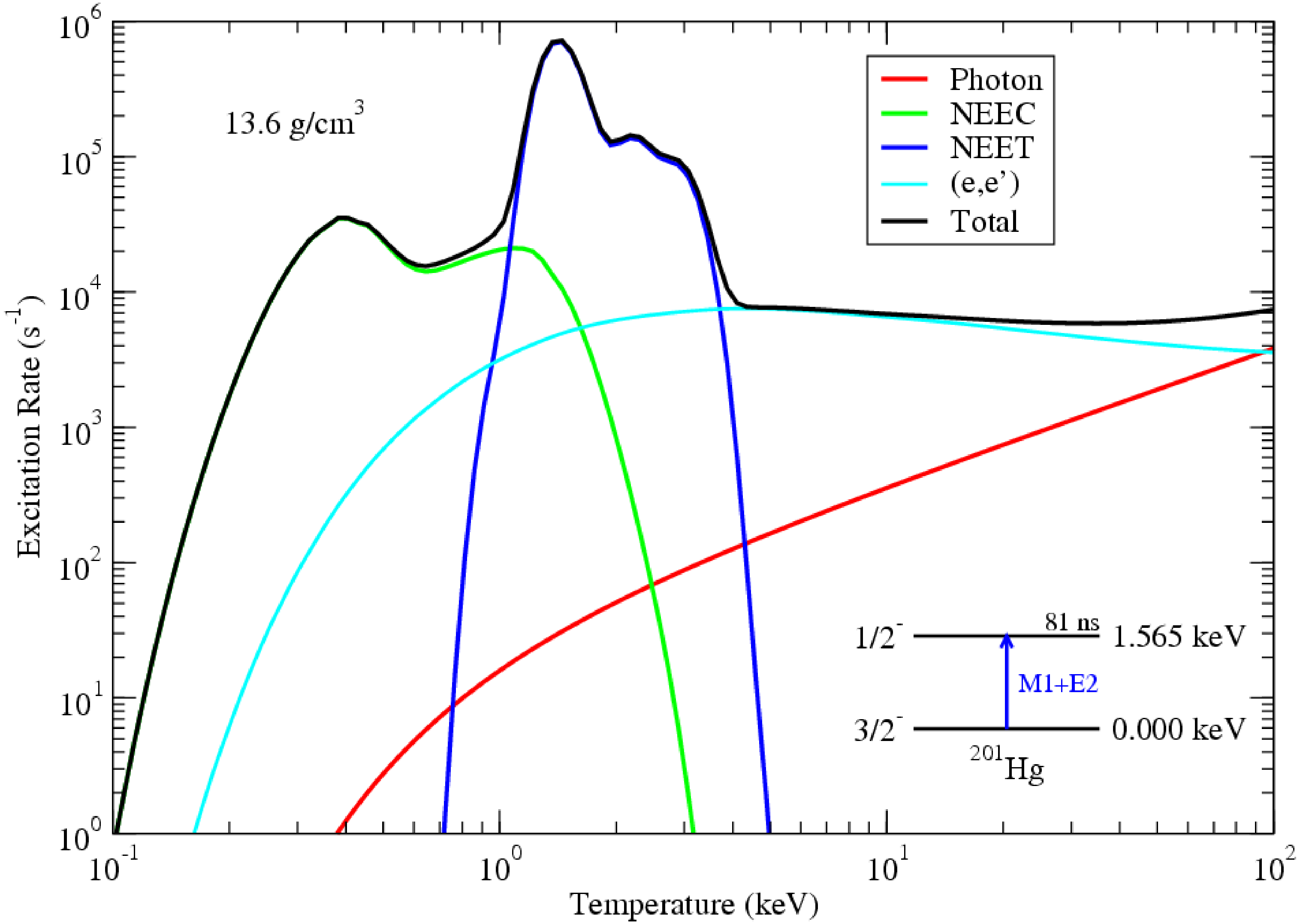
P. Morel, V. Méot, G. Gosselin, G. Faussurier, Ch. Blancard, Phys. Rev. **C81**, 034609 (2010)



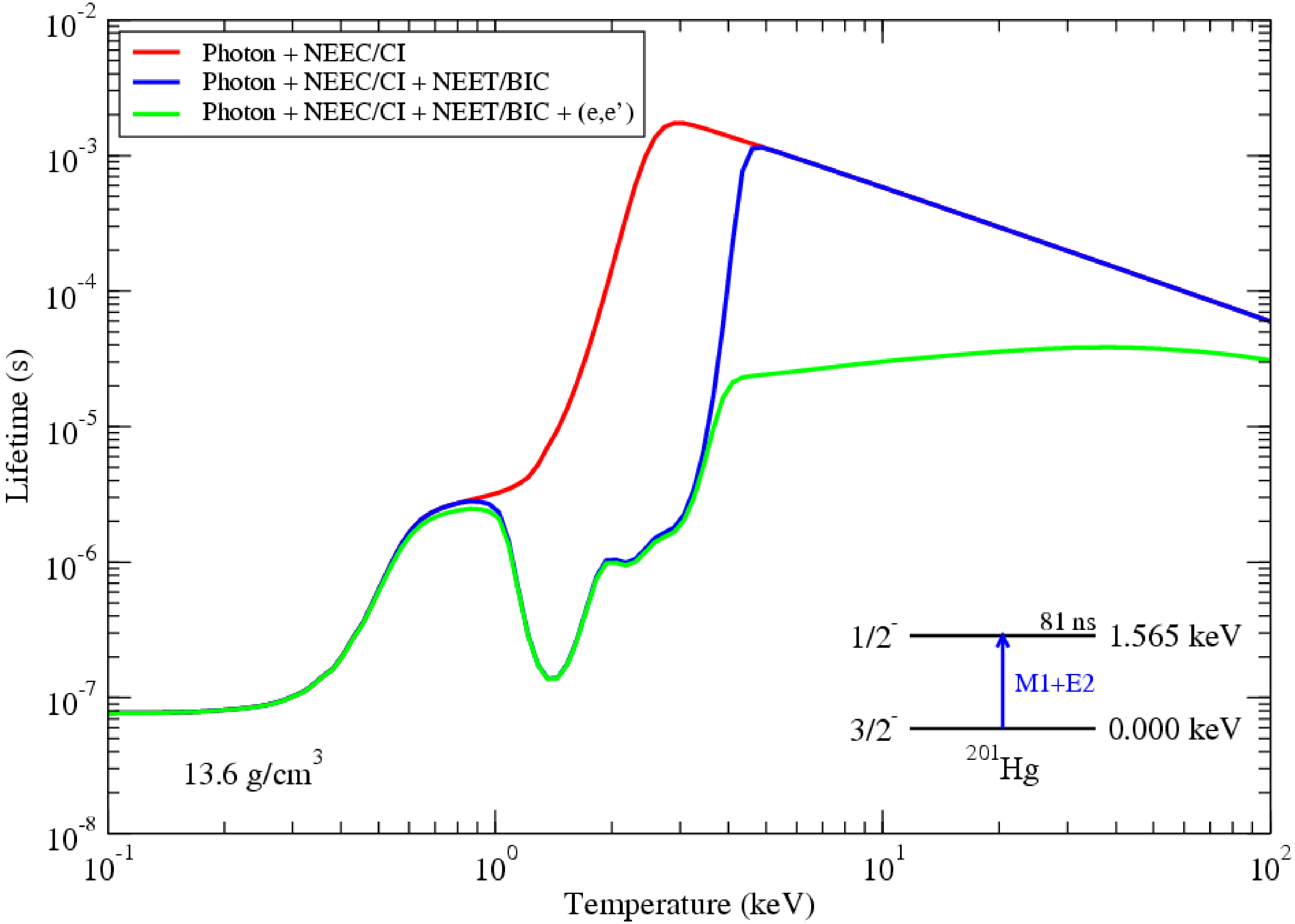
Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

Total Excitation Rate

ETL Excitation Rates

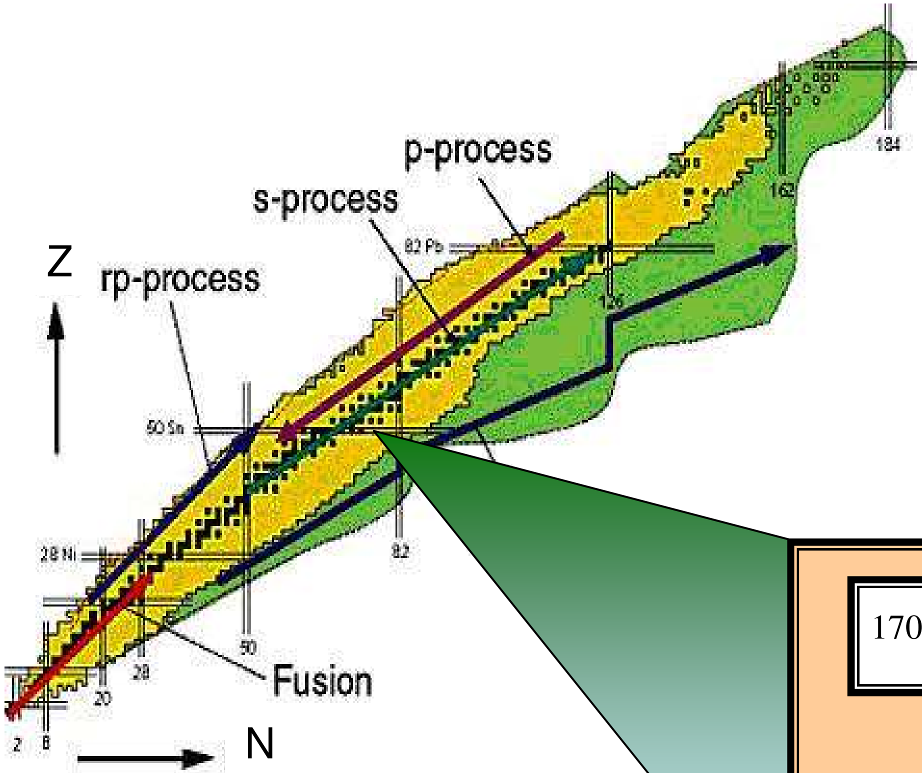


Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France



G. Gosselin, V. Méot, P. Morel, Phys. Rev. C76, 044611 (2007)

The s-process (slow neutron capture) makes most nuclei with A>56 via (n,γ) is massive stars



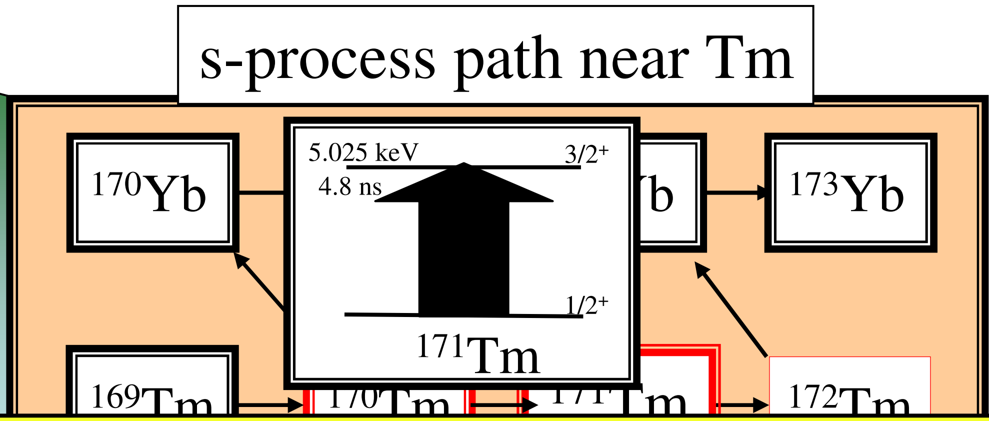
S-process conditions

$k_B T \approx 8, 30$ keV

$\Phi_\nu \approx 10^7$ /cm²•s

$\rho \approx 50\text{-}100$ g/cm³

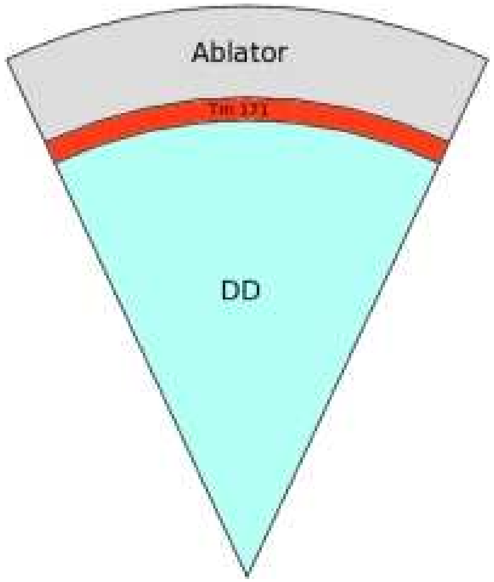
Lee Bernstein, LLNL

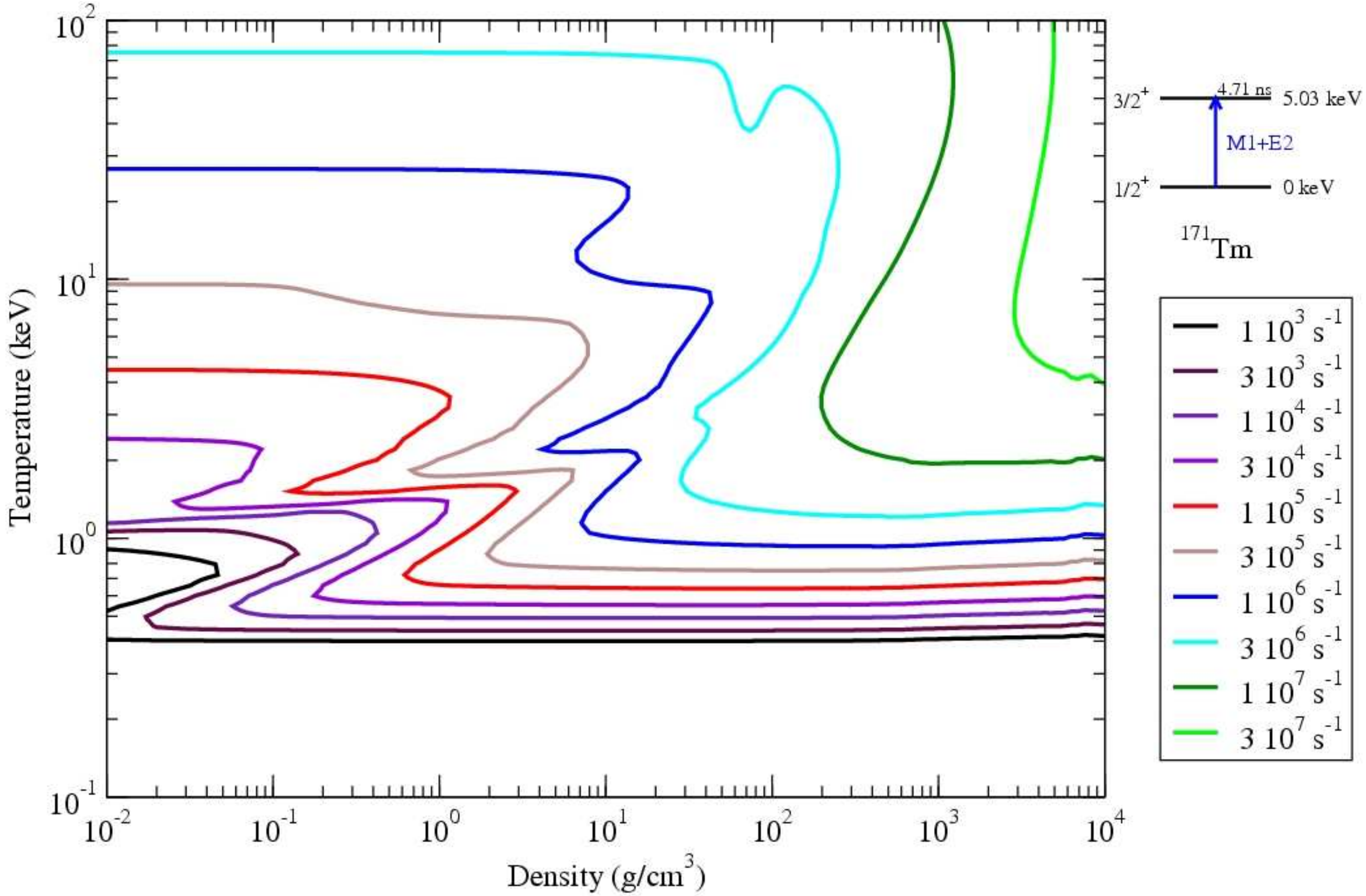


S-process branching provides a sensitive measure of stellar conditions

Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

NIF Experiment

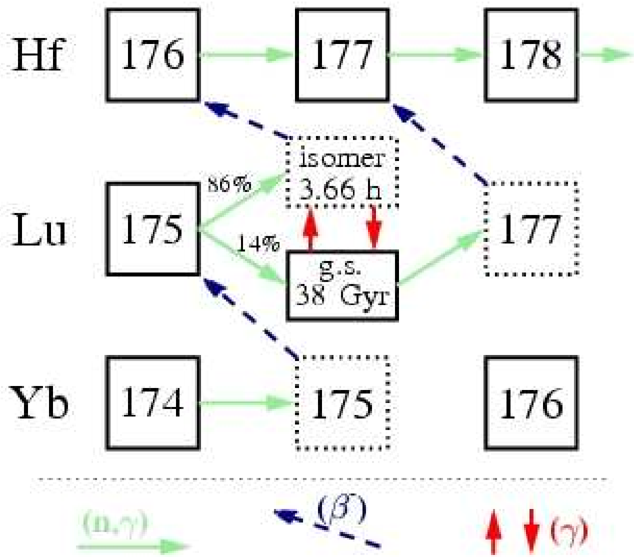


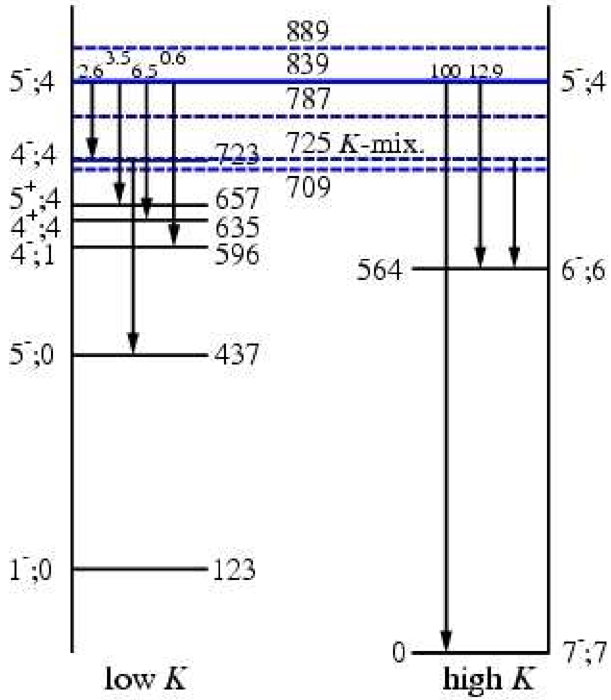


Requires hydrodynamic path optimization

Astrophysics Application

- S-process : ^{176}Lu
  - Low-K and High-K bands





In collaboration with P. Mohr, Diakonie-Klinikum, Schwabish-Hall

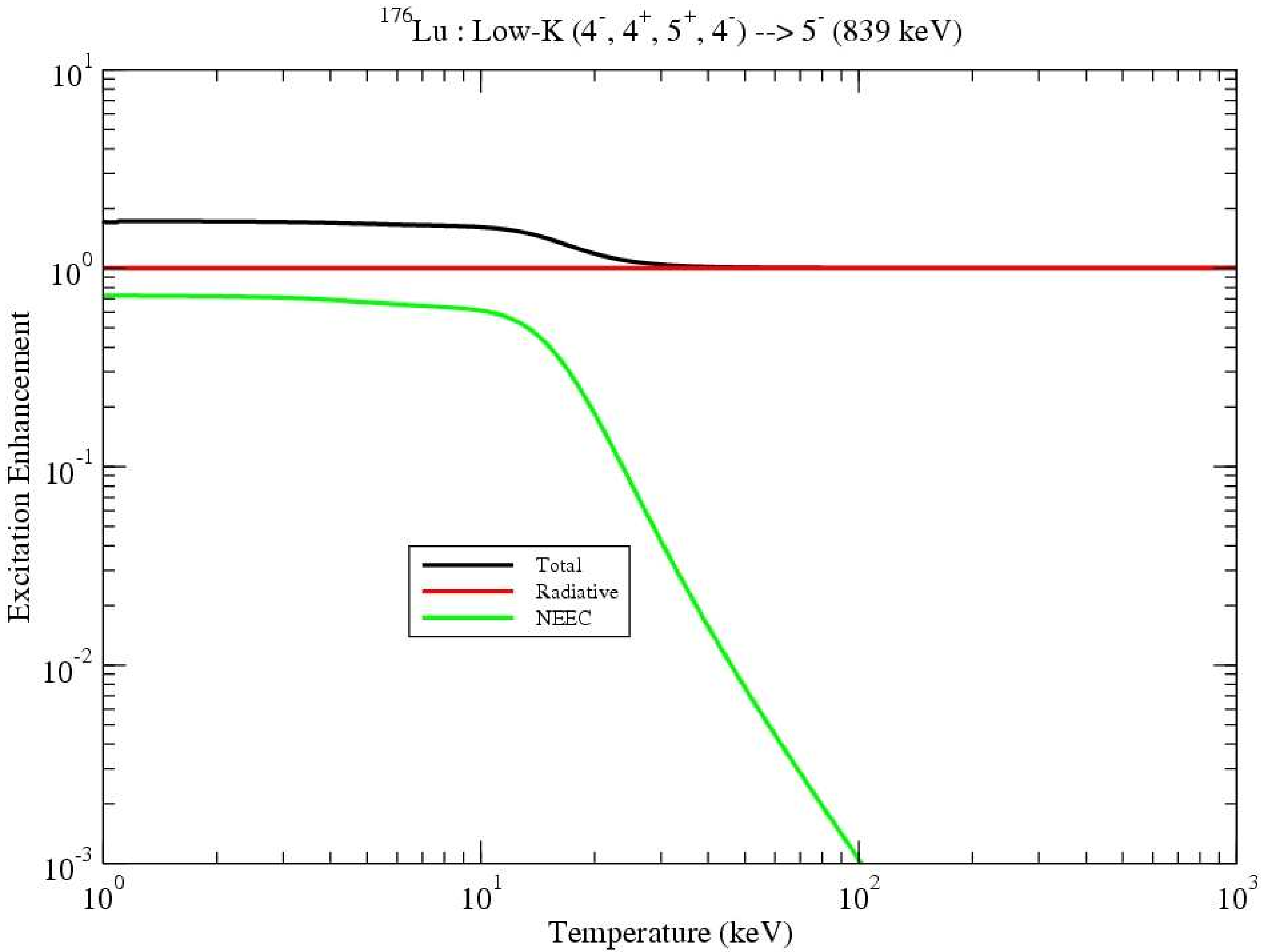
Stellar Transition Rate

- Indirect transition through intermediate state (IMS)

$$\lambda^*(T) = c\sum_i n_\gamma(E_{IMS,i}, T) I_\sigma^*(E_{IMS,i}, T)$$

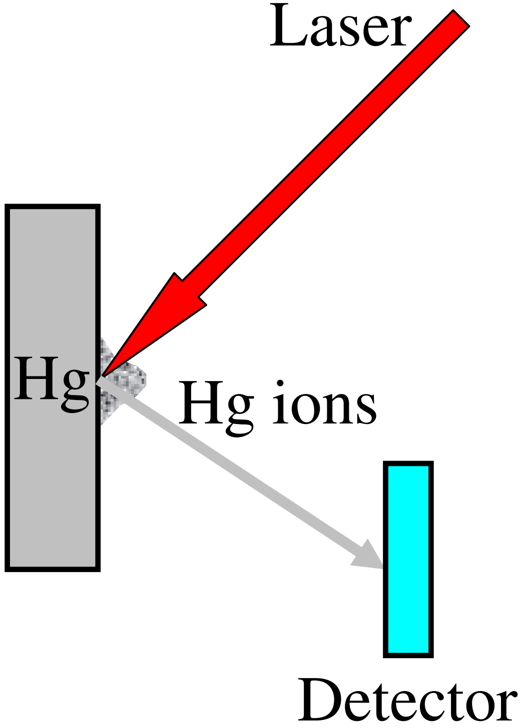
$$I_\sigma^*(E_{IMS}, T) = \int \sigma(E)dE \quad = \frac{2J_{IMS}+1}{2J_0+1}\left(\frac{\pi\hbar c}{E_{IMS}}\right)^2 \frac{\Gamma^*_{IMS\to lowK}\Gamma^*_{IMS\to highK}}{\Gamma^*_{IMS\to lowK}+\Gamma^*_{IMS\to highK}}$$

- Width enhancement
  - Induced photon emission
  - NEEC/IC
  - Electron Inelastic Scattering



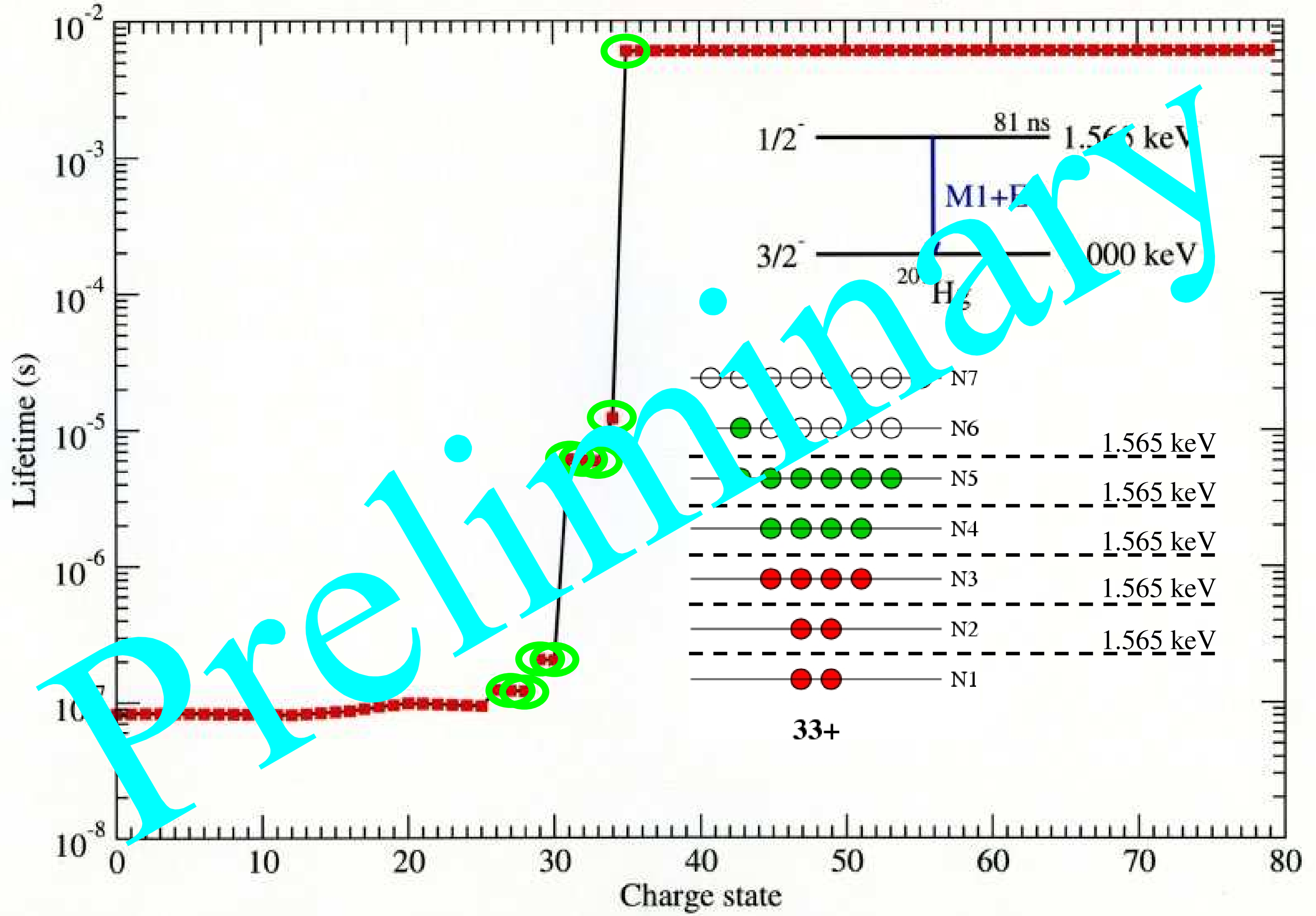
Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

Laser Experiment



- Hg ions in flight
  - Highly ionized
  - Atom in fundamental state
  - Lifetime governed by IC
- How far can we detect them ?
  - MCDF calculations Ł V(r)
  - IC coefficients Ł Lifetime

ISOMEX/MCDF Calculation (CEA Bruyeres-le-Chatel)



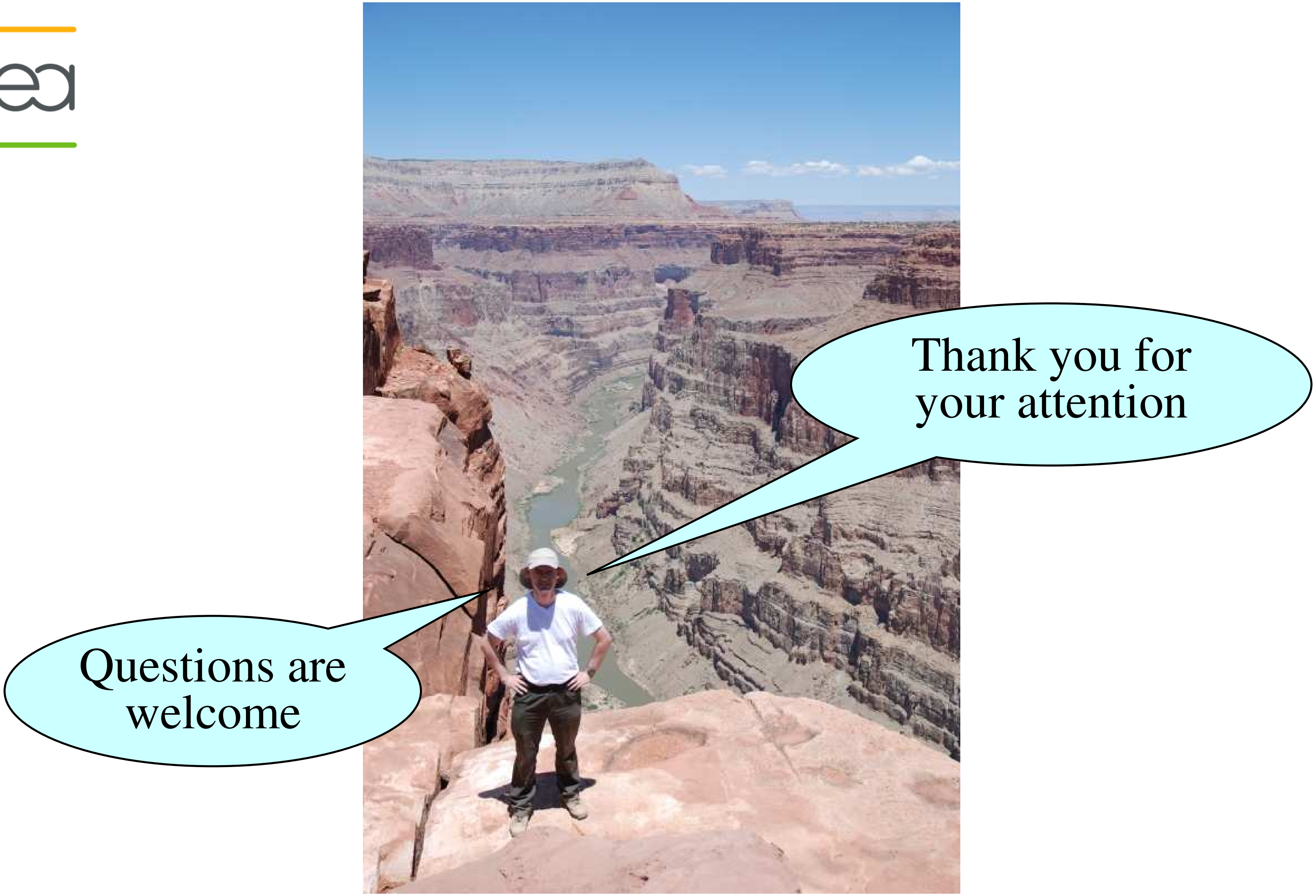
Gilbert GOSSELIN, Vincent MEOT, Pascal MOREL, CEA-DAM Ile-de-France

What we have done

- LTE modelization of excitation processes
  - Radiative
  - NEEC
  - NEET (when atomic transitions overlap)
  - (e,e') (unscreened potential)
- Non-LTE
  - NEET with SHAAM
- Experimental proofs
  - (p,n) reactions in plasma

What we are trying to do

- LTE modelization of excitation processes
  - NEET (when atomic transitions do not overlap)
  - Multi Atom plasmas
  - (e,e’) (screened potential)
- Non-LTE
  - NEET with MCDF
- Future experiments
  - Isomer decay in plasma
  - Lifetime variations in plasma
  - Isotopic and/or isomeric ratios modification in Tm


Thank you for your attention
Questions are welcome