NEET in ^{84}Rb

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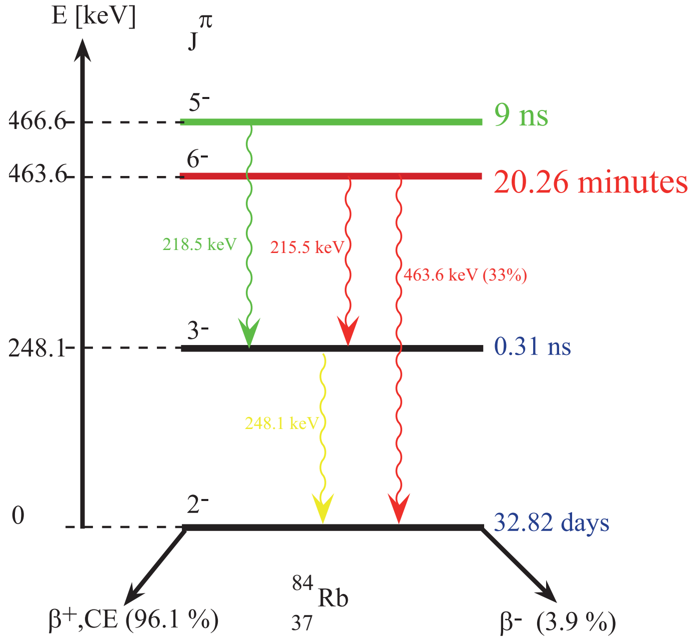
Outline

- ^{84}Rb is an unstable nucleus $T_{1/2}$= 33 days
- It has a $J^{\pi} = 6^-$,$T_{1/2}$=20,26 min state at 463.6 keV **+ ~ 3 keV above, a** $J^{\pi} = 5^-$ **state,** $T_{1/2}$= 9 ns

6^- to 5^- excitation in plasma ?

→ **Fast decay of the long lived isomeric state!**

$$T_{1/2}^{\text{effective}} = \frac{\ln 2}{\lambda_\gamma + \lambda_e + \lambda_{\text{new}}}$$



1) Calculated excitation rates

3) Results of experiments done to improve/check the calculation method

4) The experiment …

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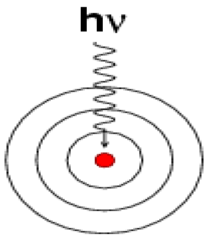
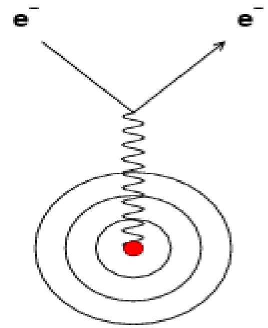
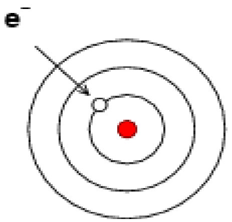
Mechanisms of N. E. in plasma?

Direct processes



Photon absorption and electron inelastic scattering



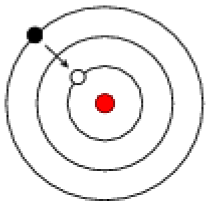


NEEC: Nuclear Excitation Via (free) Electron Capture

Inverse process of Internal Conversion, proposed by Goldanskii

Never observed

Indirect processes



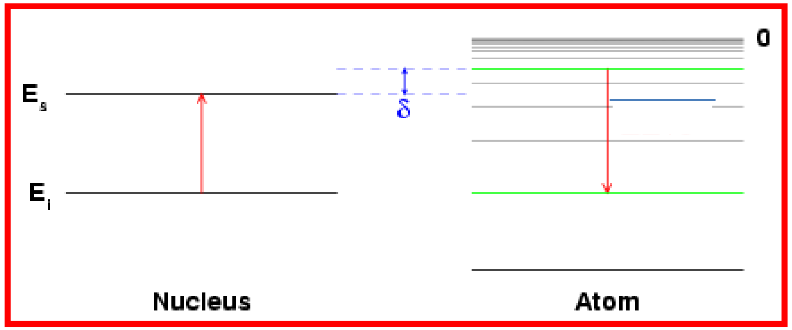
NEET: Nuclear Excitation Via Electron Transition

Inverse process of bound Internal Conversion , proposed by Morita

Observed in 3 neutral atoms irradiated with synchrotron beams:

- **^{197}Au** $P_{NEET} = (5.0 \pm 0.6)\ 10^{-8}$ — S. Kishimoto et al, PRL85,1831(2000)
- **^{189}Os** $P_{NEET} < 4.5\ 10^{-10}$ — I. Ahmad et al, PRC 61, 051304 (2000)
- **^{193}Ir** $P_{NEET} = (2.8 \pm 0.4)\ 10^{-8}$ — K. Aoki et al, PRC 64, 044609 (2001)

NEET rate calculations (1)



Strict Conditions are required for NEET:
Conservation of angular momentum & $\delta = E_n - E_{at} \sim 0$

$$\lambda_{\mathrm{NEET}} = \sum_Q P_Q \sum_{i \to f} P_i \frac{|R_{if}|^2}{\delta_{if}^2 + \frac{1}{4}(\Gamma_i + \Gamma_f)^2} \times \frac{\Gamma_i + \Gamma_f}{\hbar}$$

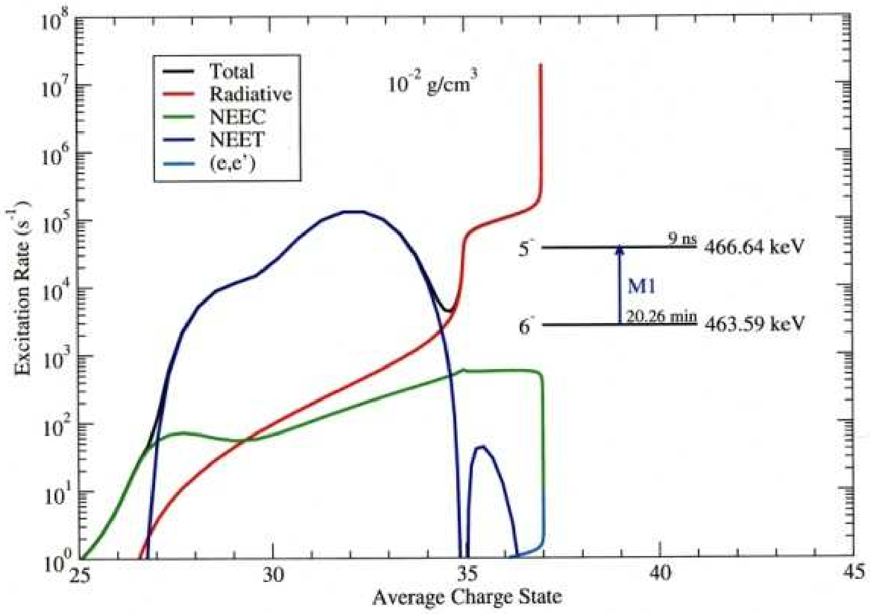
Atom-nucleus coupling matrix element

Plasma charge state distribution

Atomic state populations

Atomic state widths (in plasma!)

Predicted excitation rates for the ^{84}Rb isomer



Calculations made by G Gosselin & P Morel

ISOMEX code

Atomic physics calculations based on the Relativistic Average Atom Model (Rozsnyai 1972)
Plasma under LTE conditions

NEET is the dominant excitation process for charge states $27^+ – 34^+$

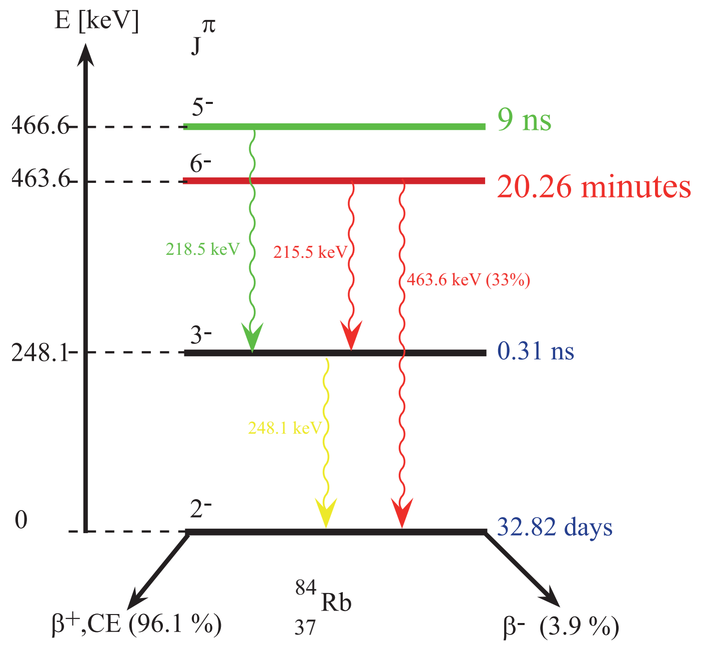
Maximum rate: ~ 10^5 s $^{-1}$

To check and confirm this prediction:

- Measure precisely the nuclear transition energy
- Perform more accurate atomic physics description

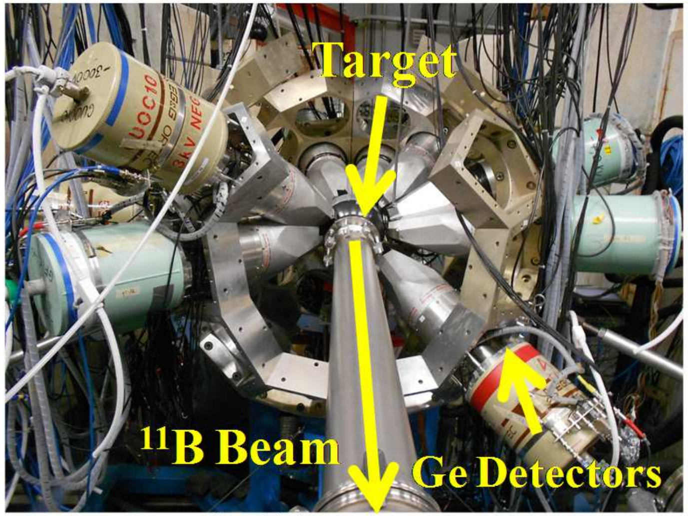
Nuclear transition energy measurement

Transition	Nudat[1]
$5^- \rightarrow 3^-$	218.3 ± 0.2 keV
$6^- \rightarrow 3^-$	215.61 ± 0.10 keV
$5^- \rightarrow 6^-$	2.69 ± 0.23 keV (γ) 3.05 ± 0.18 keV (levels) 3.4 keV (suggested)

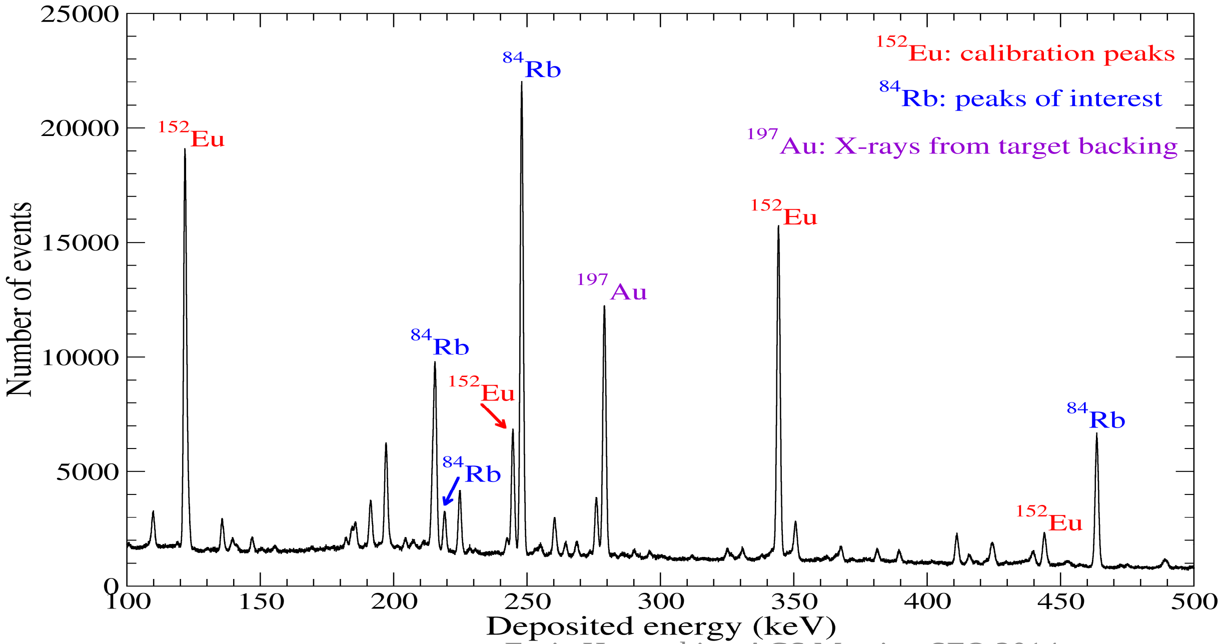


Orsay Tandem experiment

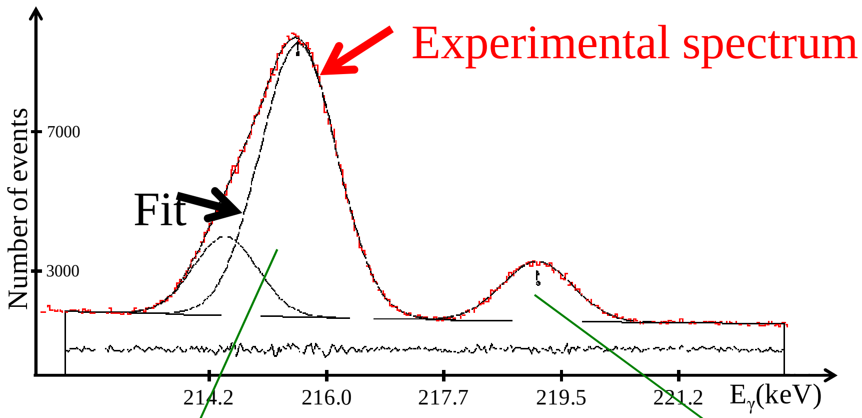
- Measurement of the ^{84}Rb γ spectrum below 500 keV
  γ array facility: ORGAM at TANDEM/ALTO accelerator (IPN Orsay)
  - Production via ^{76}Ge(^{11}B,3n)^{84}Rb reaction. ^{11}B at 30MeV
  - Calibration source and target counted simultaneously
  - Peak centroid determined (Radware code)

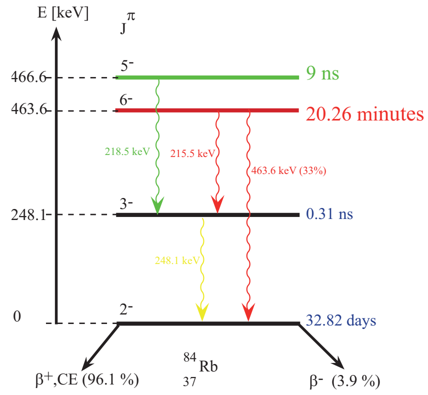


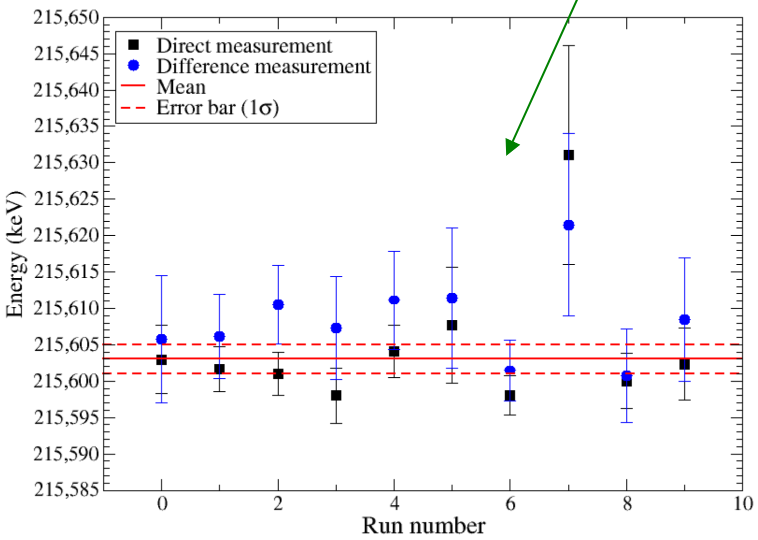
ORGAM detector

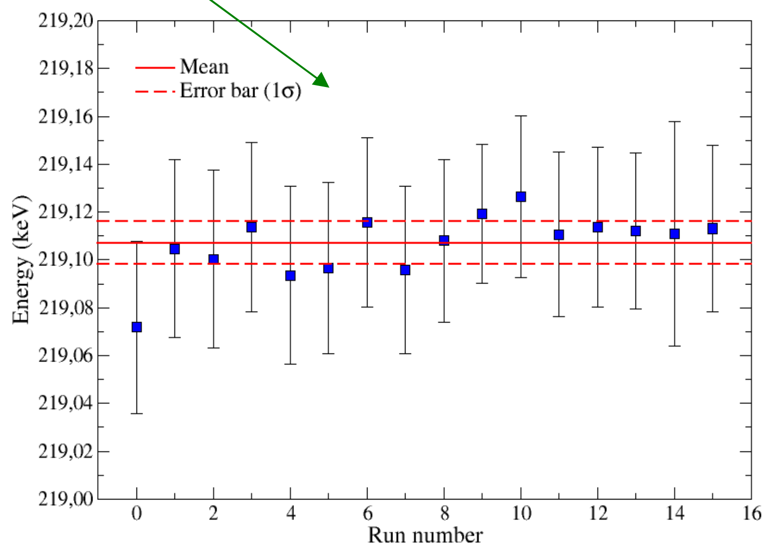


Nuclear transition energy measurement









215.603 ± 0.002 keV

219.107 ± 0.009 keV

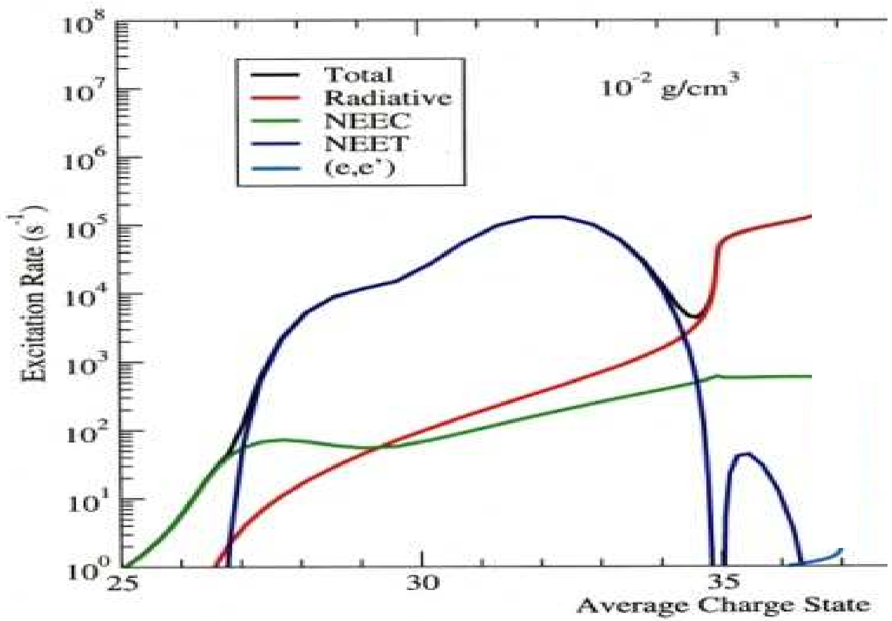
Δ E = 3.504 ± 0.010 keV *D. Denis Petit PhD 2014*

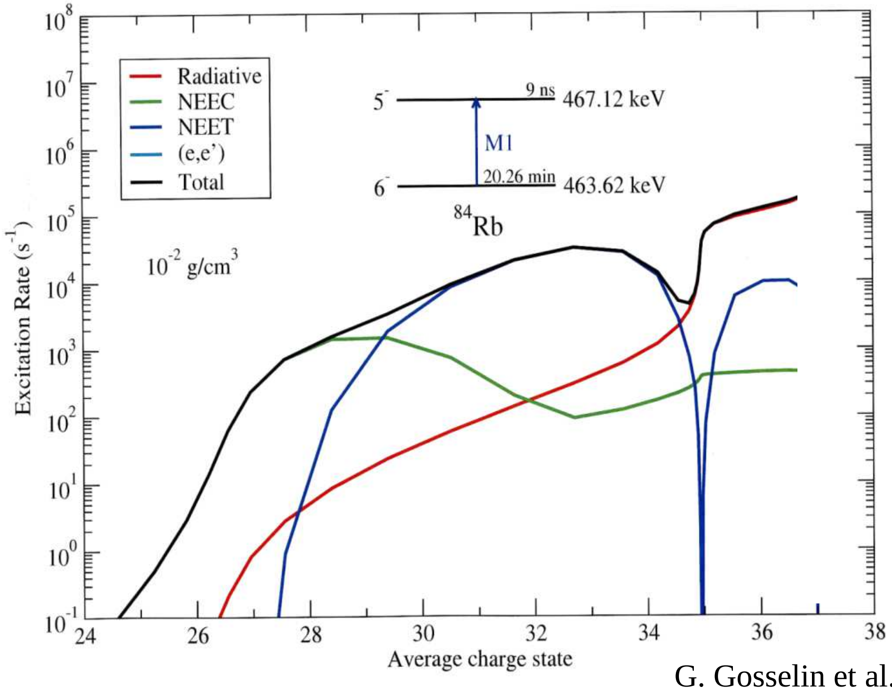
Consequences on NEET rates?

NEW

$E_{\gamma} \sim 3{,}05$ keV

$E_{\gamma} = 3{,}504 \pm 0{,}010$ keV





G. Gosselin et al.

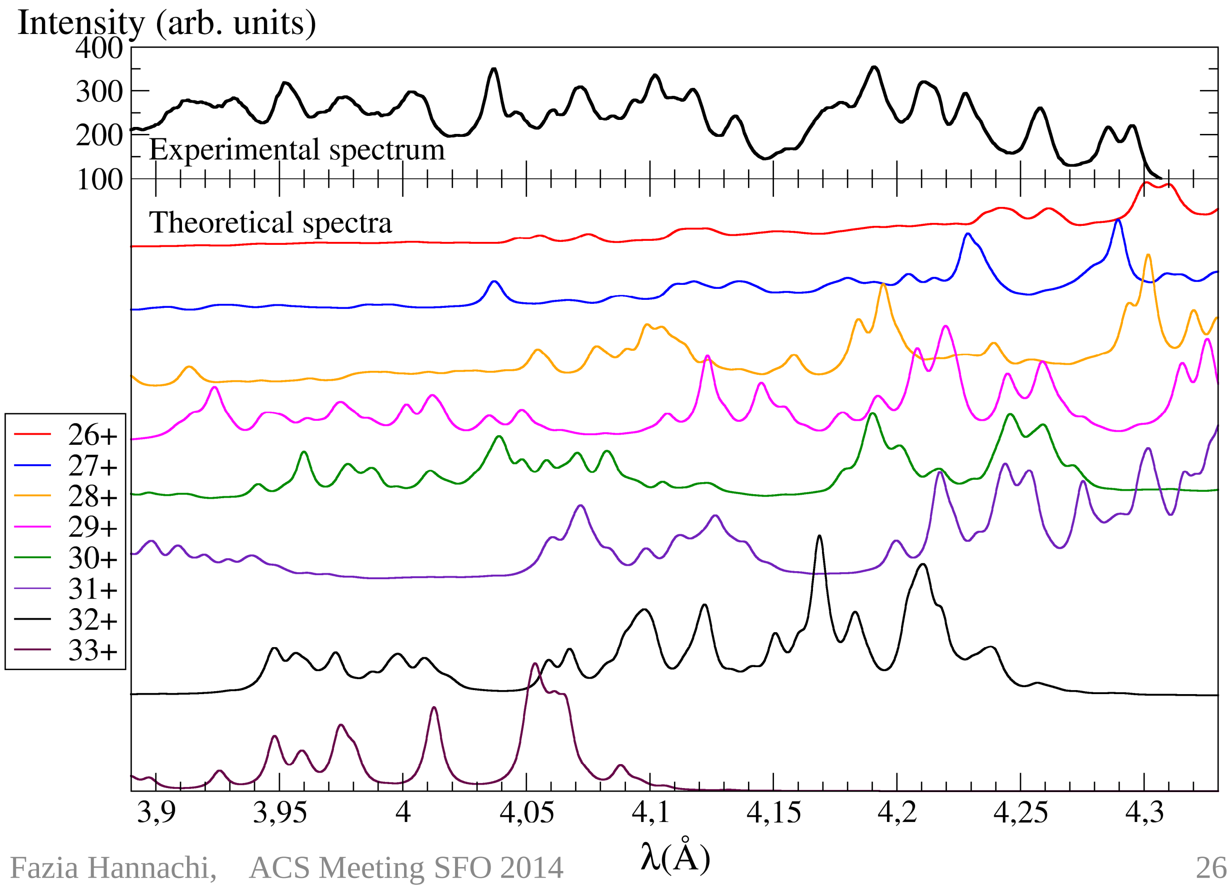
NEET is dominant for higher charge states: Q > 30 !

λ_{NEET} is Lower by one order of magnitude!

M1 Atomic transition rates

- **Detailed Multi Configuration Dirac-Fock (MCDF) calculations**
  - **Most probable electronic configurations** taken into account
  - Calculations with JJ coupling
  - E1 transitions N,O,P→L, with K shell full
  - Weighting with a partition function: **LTE temperature of 400 eV**
  - Line broadening : experimental resolution

➡ **G Gosselin presentation**

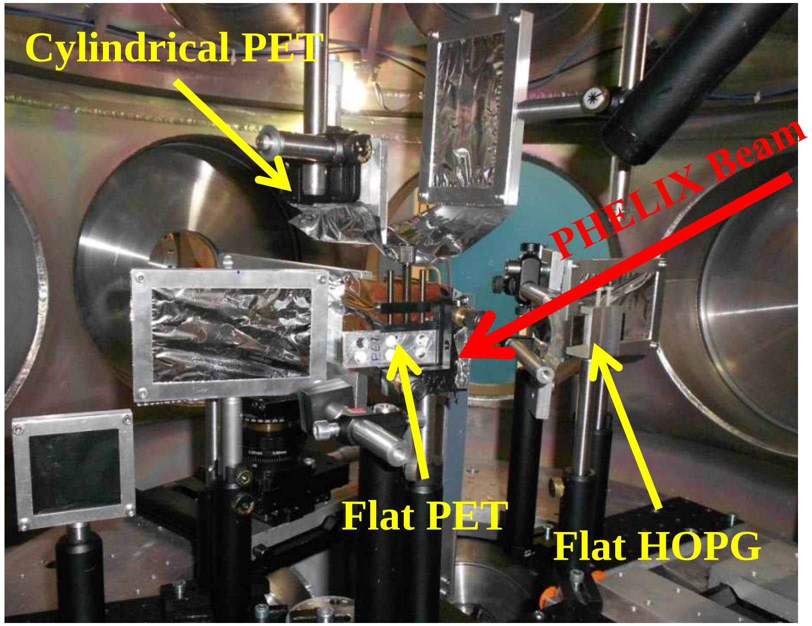


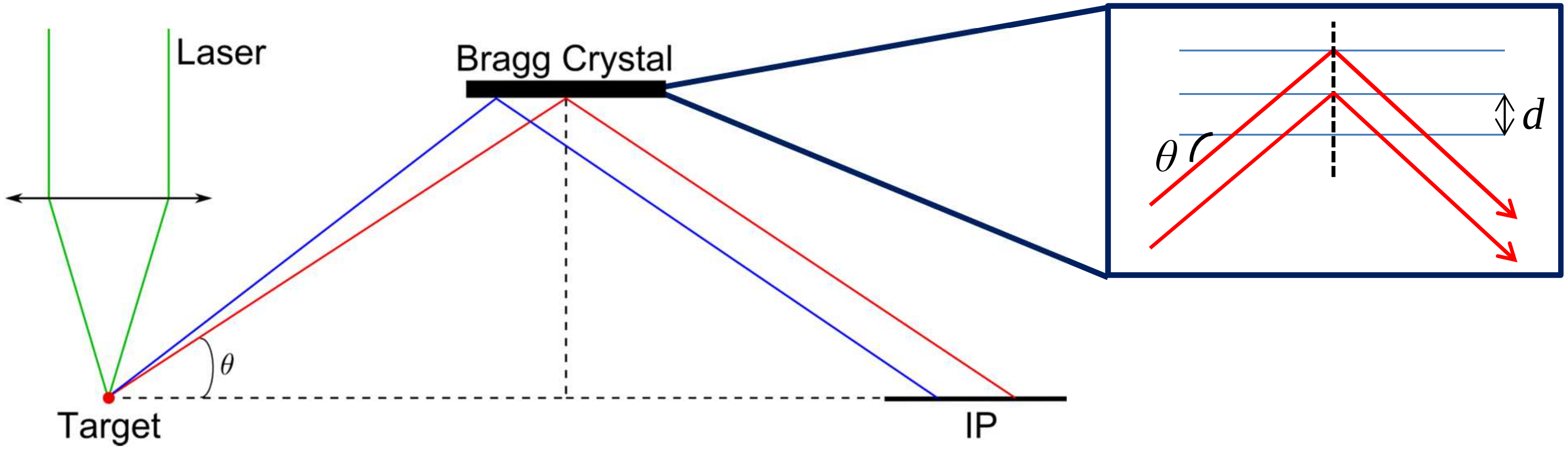
Measurement of the E1 X-spectrum from a Rb plasma

- Goal: Check the validity of atomic calculations
  - Determine plasma conditions available with PHELIX
    - Plasma temperature
    - Charge state distribution

    } suitable for NEET ??
- Experimental setup:
  - PHELIX beam (527nm at 2ω, 2.10^{14}W/cm²)
  - 3 Bragg crystals + Image Plates (IP)

Th Bonnet et al, Rev. Sci. Instrum. 84, 103510 (2013)

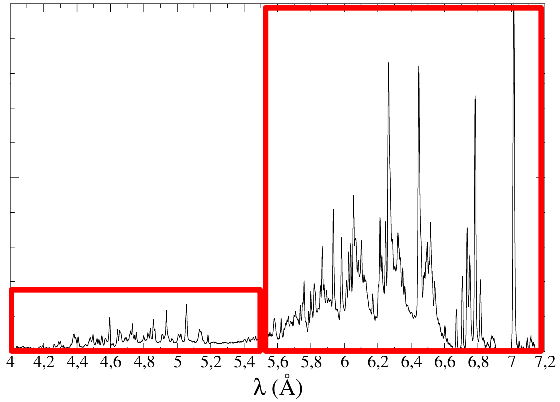




Bragg relation: $2d\sin\theta = k\lambda$ *k*: interference order

Comparison with theoretical spectra

- Detailed Multi Configuration Dirac-Fock (MCDF) calculations
  - Most probable electronic configurations taken into account
  - E1 transitions M,N,O,P→L, with K shell full
  - Weighting with a partition function: LTE temperature of 400 eV
  - Line broadening taking into account the experimental resolution



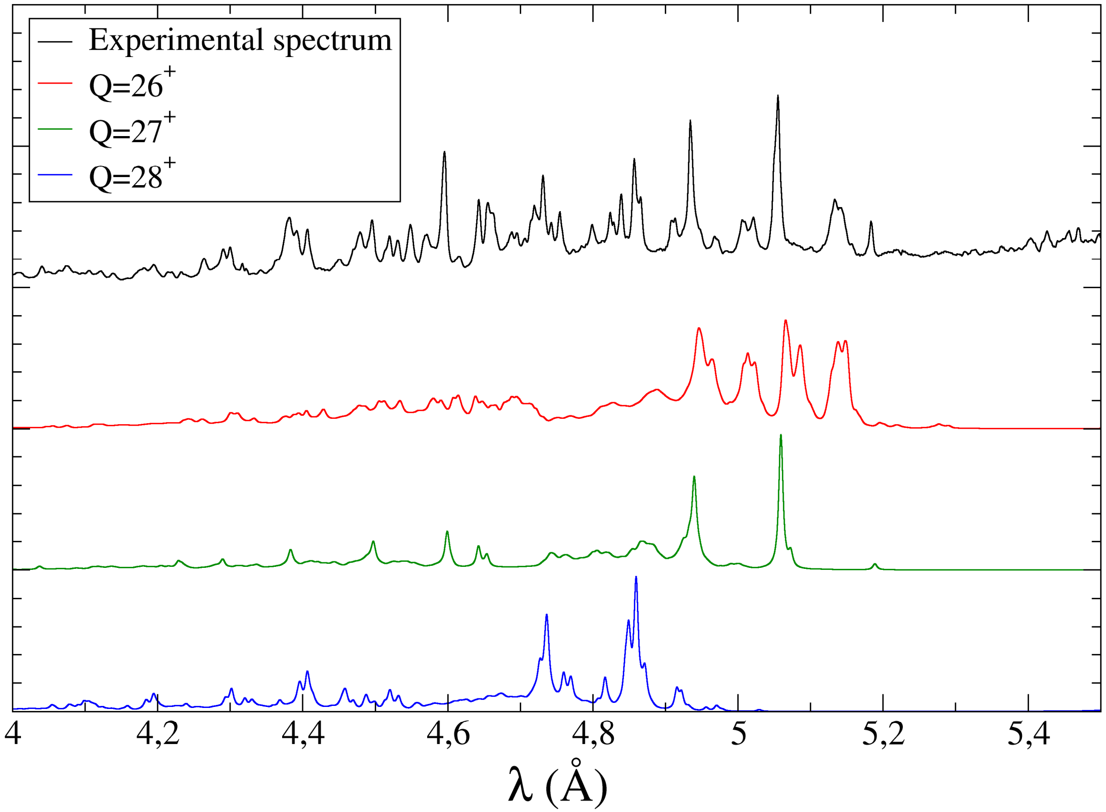
Main lines can be identified with $Q=26^+$, 27^+ and 28^+

$Q=27^+$ is dominant at PHELIX

Identifications compatible with earlier published data [2,3,4]
All big lines identified

Calculations valid !

D Denis Petit et al, Journal of Quantitative Spectroscopy and Radiative Transfer Volume 148, Nov 2014, Pages 70–89



[2] H. Godon et al., J. Phys. B. **12**, 881 (1979)
[3] R. J. Hutcheon et al., Phys. Scr. **21**, 89 (1980)
[4] S. Elliott et al., Phys. Rev. A. **47**, 1403 (1993)

NEET rate calculations (2)

Atom-nucleus coupling matrix element

$$\lambda_{\text{NEET}} = \sum_Q P_Q \sum_{i \to f} P_i \frac{|R_{if}|^2}{\delta_{if}^2 + \frac{1}{4}(\Gamma_i + \Gamma_f)^2} \times \frac{\Gamma_i + \Gamma_f}{\hbar}$$

Plasma charge state distribution

Atomic state populations

Atomic state widths (in plasma!)

Calculations are being done for all charge states Q> 27+ based on the new nuclear transition energy and the MCDF atomic M1 transitions

The plasma charge state distribution must be calculated if not measured

The atomic state widths in plasma must be evaluated: difficult task!

Conclusion

- To demonstrate nuclear excitations in plasma is not easy but a lot of work has already been done in the Rb case and in the Hg case (M Comet)

- We need reliable predictions and data to convince PACs

- Still a lot of work required on the detectors