NEET in $^{84}$Rb

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• $^{84}$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 …
Mechanisms of N. E. in plasma?

**Direct processes**

- Photon absorption and electron inelastic scattering

**Indirect processes**

**NEEC: Nuclear Excitation Via (free) Electron Capture**

*Inverse process of Internal Conversion, proposed by Goldanskii*

- Never observed

**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 $\quad P_{\text{NEET}} = (5.0\pm0.6) \times 10^{-8}$ S. Kishimoto et al, PRL85,1831(2000)
  - $^{189}$Os $\quad P_{\text{NEET}} < 4.5 \times 10^{-10}$ I. Ahmad et al, PRC 61, 051304 (2000)
  - $^{193}$Ir $\quad P_{\text{NEET}} = (2.8\pm0.4) \times 10^{-8}$ K. Aoki et al, PRC 64, 044609 (2001)
Strict Conditions are required for NEET:
Conservation of angular momentum & $\delta = E_n - E_{at} \sim 0$

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

- Plasma charge state distribution
- Atomic state populations
- Atomic state widths (in plasma!)
- Atom-nucleus coupling matrix element
Predicted excitation rates for the $^{84}\text{Rb}$ 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: $\sim 10^5$ s$^{-1}$

To check and confirm this prediction:

- Measure precisely the nuclear transition energy
- Perform more accurate atomic physics description
<table>
<thead>
<tr>
<th>Transition</th>
<th>Nudat[1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5^- \rightarrow 3^-$</td>
<td>$218.3 \pm 0.2$ keV</td>
</tr>
<tr>
<td>$6^- \rightarrow 3^-$</td>
<td>$215.61 \pm 0.10$ keV</td>
</tr>
<tr>
<td>$5^- \rightarrow 6^-$</td>
<td>$2.69 \pm 0.23$ keV ($\gamma$) $\quad 3.05 \pm 0.18$ keV (levels) $\quad 3.4$ keV (suggested)</td>
</tr>
</tbody>
</table>

Nuclear transition energy measurement

Fazia Hannachi, ACS Meeting SFO 2014
• Measurement of the $^{84}$Rb $\gamma$ spectrum below 500 keV
  $\gamma$ 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)
Nuclear transition energy measurement

Experimental spectrum

215.603 ± 0.002 keV

219.107 ± 0.009 keV

ΔE = 3.504 ± 0.010 keV

D. Denis Petit PhD 2014
Consequences on NEET rates?

**NEW**

\[ E_\gamma \sim 3.05 \text{ keV} \]

\[ E_\gamma = 3.504 \pm 0.010 \text{ keV} \]

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

\( \lambda_{\text{NEET}} \) is Lower by one order of magnitude!
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

![Experimental and Theoretical Spectrum](image)
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
  
- **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

- Suitable for NEET??

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![Bragg Crystal Diagram](https://via.placeholder.com/150)
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!


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