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Nuclear level densities and γ-ray strength functions of ^{180,181,182}Ta and nucleosynthesis of ^{180}Ta

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Introduction

Physics Motivation for ^{180}Ta

- Almost all A>110 *p*-nuclei are thought to be produced by the photodisintegration of *s*- and *r*- process pre-existing nuclei
- However, the observed low abundant (0.012%) ^{180}Ta remain an exception
- Several processes are considered
- ^{180}Ta could be explained with p-process [1]

[1] M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003).

Introduction

Physics Motivation for ^{180}Ta

- Several processes are considered
- ^{180}Ta could be explained with p-process [1]
- The *s*-process mostly via branching in ^{179}Hf [2]

$$^{179}\mathrm{Hf} \xrightarrow{\beta^-} {}^{179}\mathrm{Ta}(n,\gamma) \longrightarrow {}^{180}\mathrm{Ta}$$

$$^{179}\mathrm{Hf}\,(n,\gamma) \longrightarrow {}^{180m}\mathrm{Hf} \xrightarrow{\beta^-} {}^{180}\mathrm{Ta}$$

[1] [1] M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003).
[2] M. Loewe et al. Nucl.Phys. A719 (2003) 275c

Introduction

Physics Motivation for ^{180}Ta

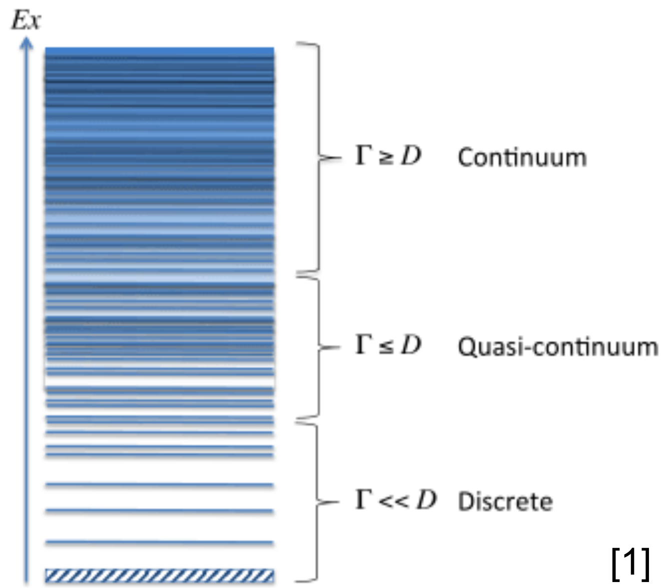
- ^{180}Hf(ν_e, e)^{180}Ta, ^{181}Ta(ν, ν'n)^{180}Ta and *p*-process contribute 50, 25 and 25% respectively [3]
- ^{180}Hf(ν_e, e)^{180}Ta 50% contribution recently supported by A. Byelikov et al. [4]

- This is unsettled, hence provoking debates
- Uncertainties in reaction rates for ^{180}Ta rest in nuclear properties
- Therefore synthesis of ^{180}Ta needs to be reinvestigated

[3] A. Heger et al. Phys.Lett. B 606, 258 (2005)
[4] A. Byelikov et al. PRL 98, 082501 (2007)

Objectives

- Nuclear level density (NLD) and γ-ray strength function (γSF) below S_n in ^{180,181,182}Ta isotopes (Oslo Method)



- Astrophysical Maxwellian-averaged (n,γ) cross sections (TALYS)
- Investigate production mechanism of ^{180}Ta

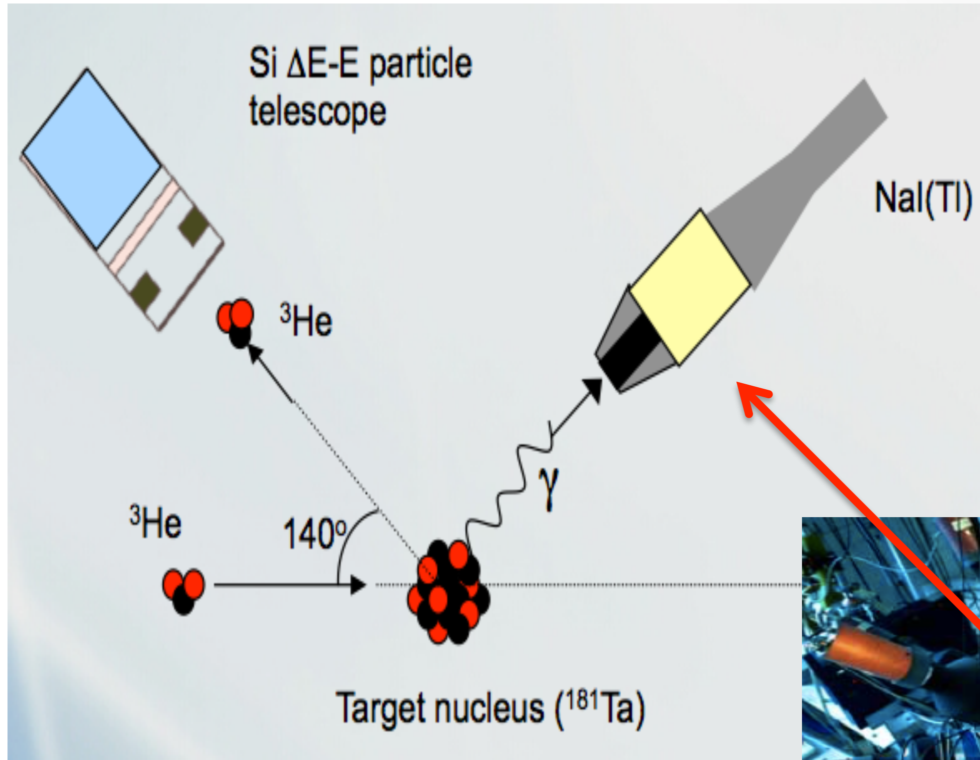
[1] Magne Guttormsen et al.: Experimental level densities of atomic nuclei

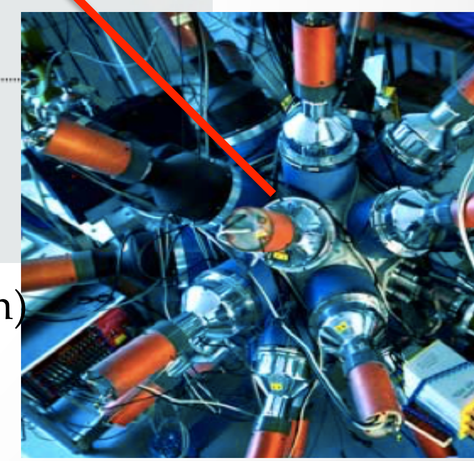
Experimental Details

Experimental setup at the Oslo cyclotron laboratory

- 0.8 mg/cm^2 thick ^{181}Ta target

- ^{181}Ta(^{3}He,X)^{180,181}Ta, 34 MeV
- ^{181}Ta(d,X)^{180,181}Ta, 15 MeV
- ^{181}Ta(d,X)^{181,182}Ta, 12.5 MeV





- CACTUS Array: 26 collimated 5″×5″ NaI(Tl) (~22 cm)
- 14.1% eff. at Eγ= 1332 keV

https://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/

Experimental Details

Experimental setup at the Oslo cyclotron laboratory

- 0.8 mg/cm^2 thick ^{181}Ta natural target

- ^{181}Ta(^{3}He,X)^{180,181}Ta, 34 MeV
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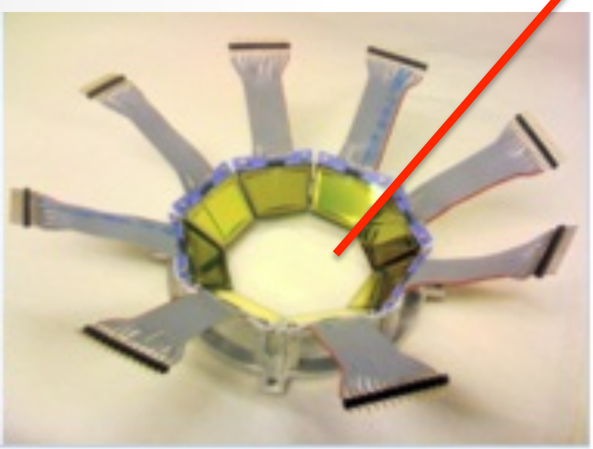
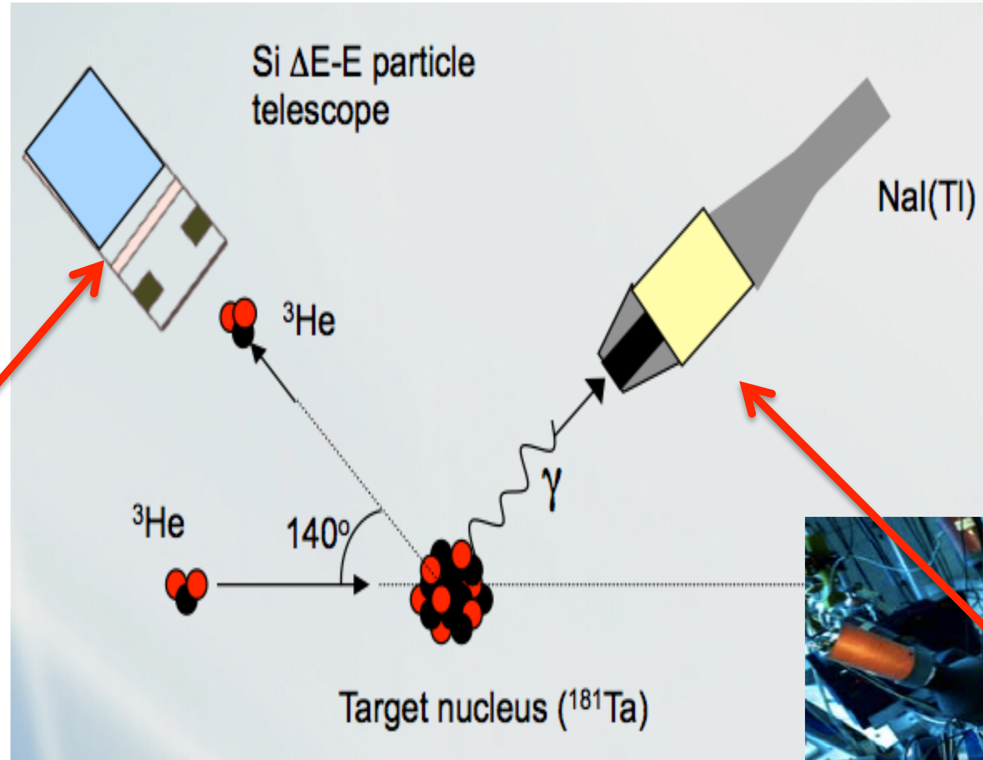
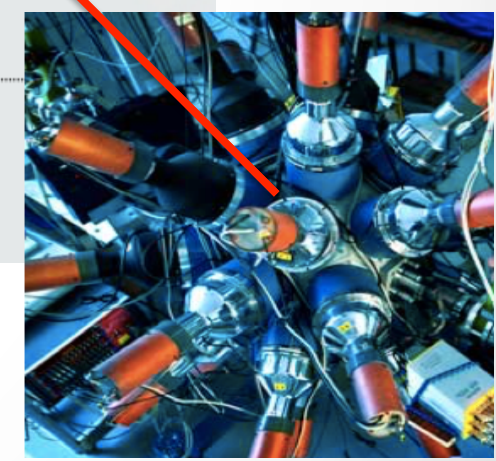




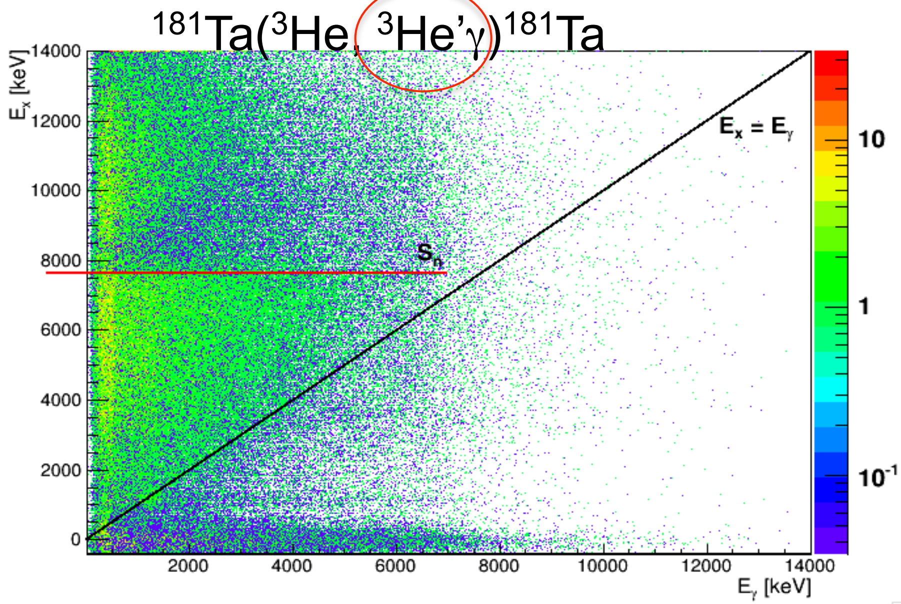


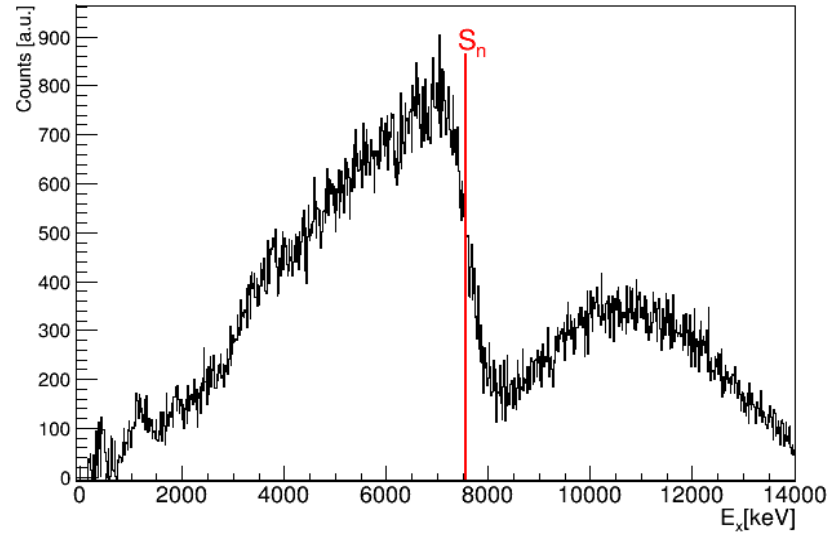
- SiRi Array, 64 ΔE-E Si particle telescopes
- ΔE, E and Al foil thicknesses (130 μm, 1550 μm and 10.5 μm)
- θ = 126° to 140°, ~ 5 cm

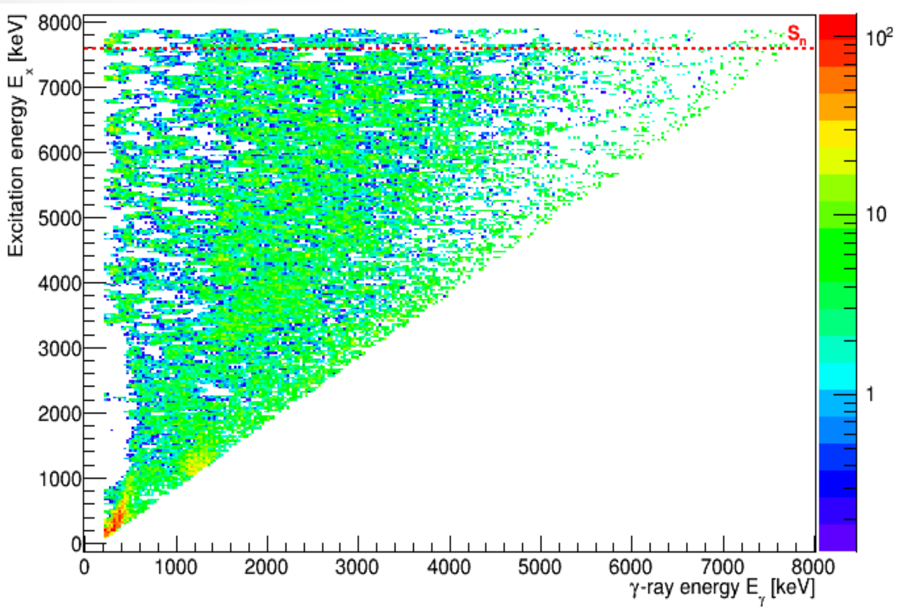
[1] M. Guttormsen et al., Nucl. Instrum. Methods Phys. Res. A 648, 168 (2011)

Data Analysis

Particle-γ Coincidence Matrices







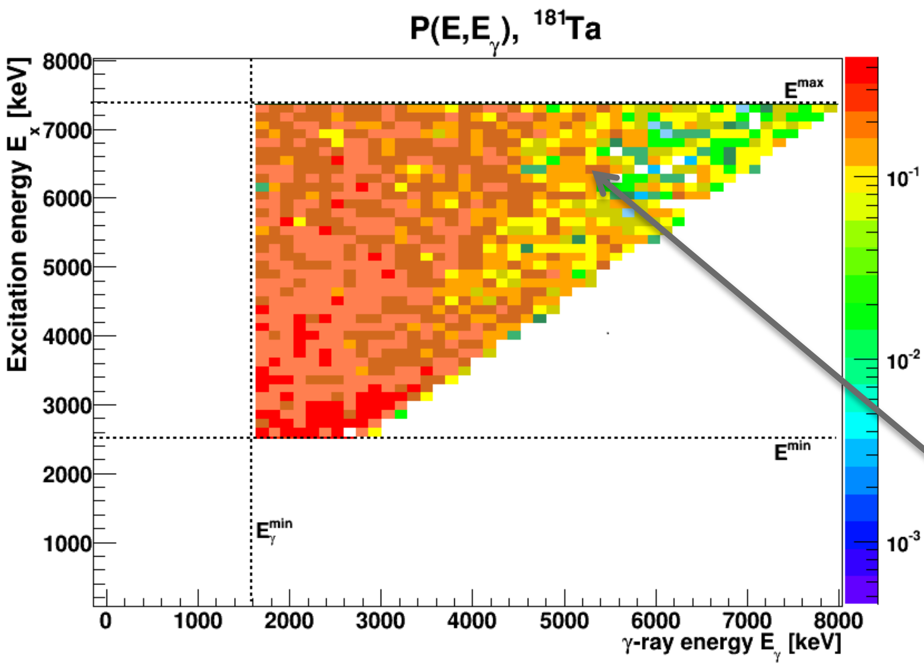
The Oslo Method

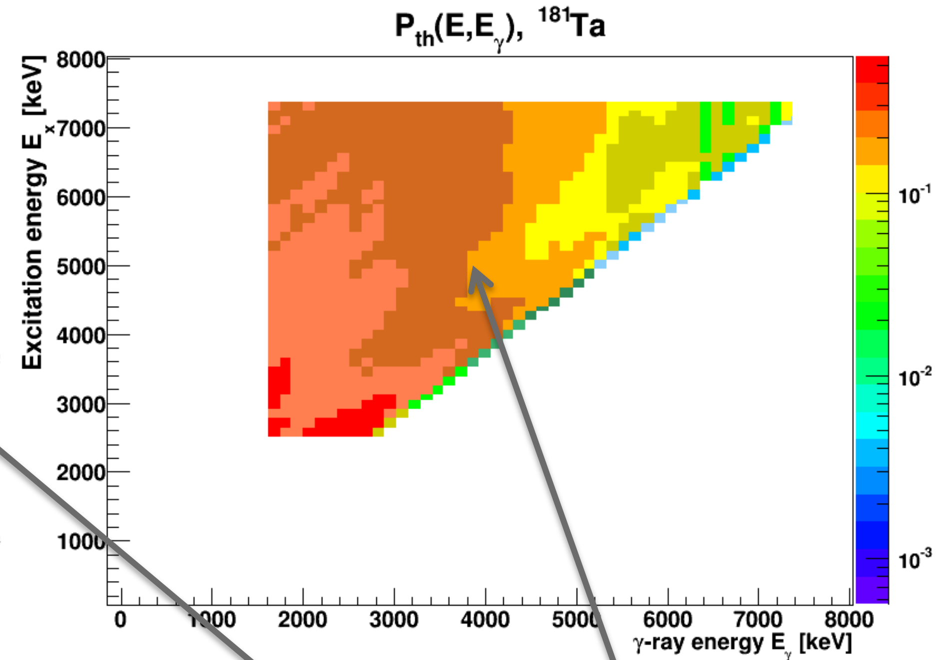
1. Unfolding γ-ray continuum spectra[1]
   > Unfolding iterative procedure
2. Extraction of primary γ-rays [2]
   > first-generation method
3. Simultaneous extraction of level density and strength function[3]
   > Assumes a ccompound state

[1] M. Guttormsen et al., NIM Phys. Res. A 374, 371 (1996)
[2] M. Guttormsen et al., NIM Phys. Res. A 255, 518 (1987)
[3] A. Schiller et al., NIM Phys. Res. A 447, 498 (2000)

Data Analysis

Experimental vs. Fitted FG Matrices





$$P(E, E_\gamma) \propto \rho(E_f)\mathcal{T}(E_\gamma)$$

- Assumptions: Brink Hypothesis
- The $\rho(E_f)$ and $\mathcal{T}(E_\gamma)$ are extracted by fitting to $P(E_x, E_\gamma)$ and performing χ^2 minimum.

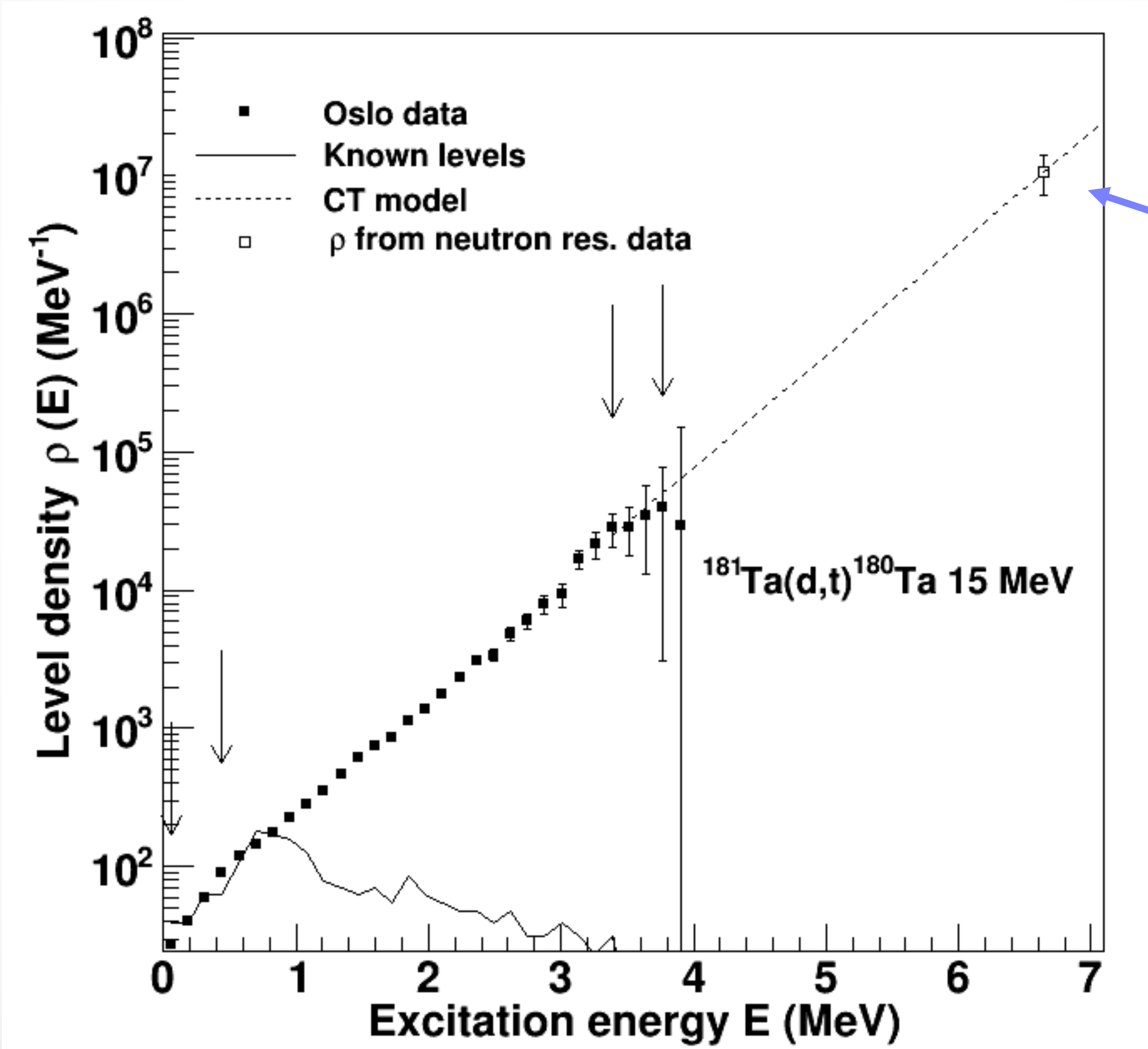
The Oslo Method

- Normalization of (γ transmission coefficient) $\mathcal{T}(E_\gamma)$ and $\rho(E_f)$
- Calculation of γSF from $\mathcal{T}(E_\gamma)$

^{180}Ta Results

Normalization of the NLD

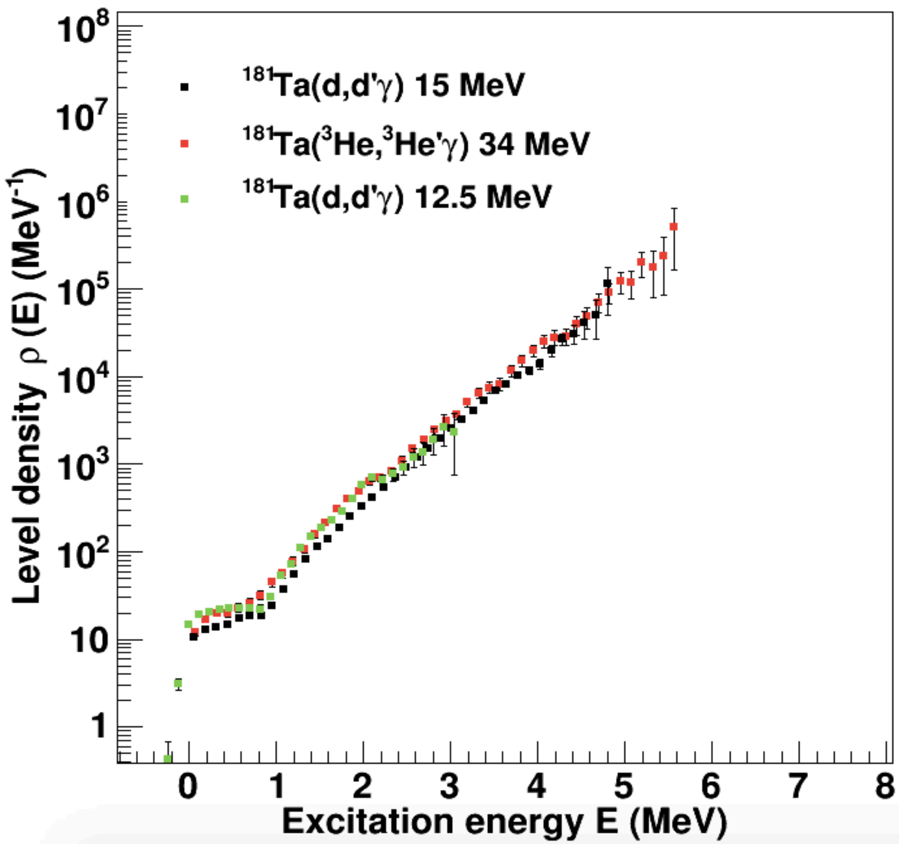
$$\rho(S_n) = \frac{2\sigma^2}{D_0(J_T+1)e^{[-(J_T+1)^2/2\sigma^2]} + e^{\left(-J_T^2/2\sigma^2\right)} J_T}$$



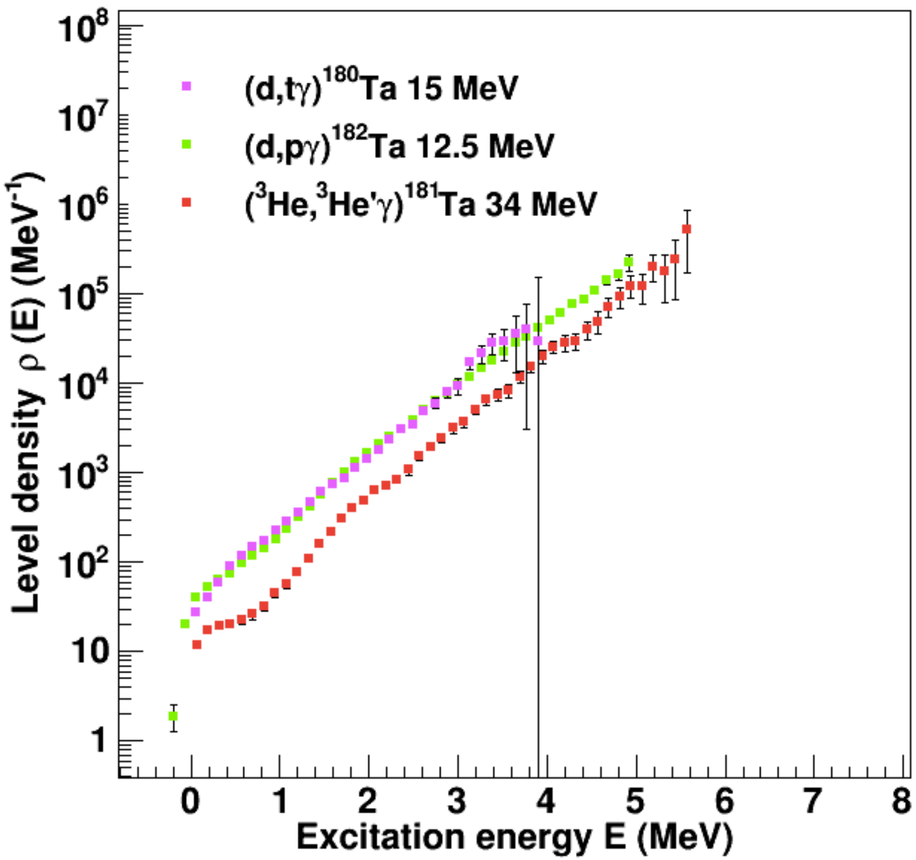
No neutron resonance data available (^{180}Ta)

Nuclear Level Densities

Different reactions yield similar results

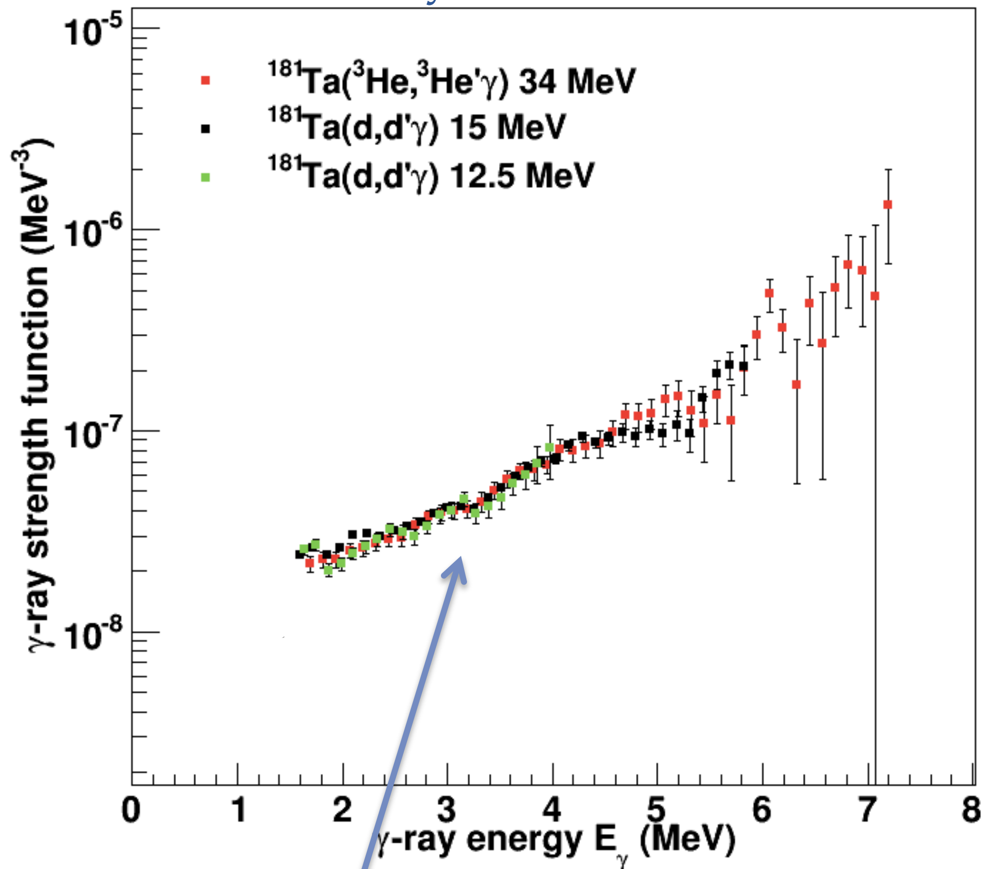


NLDs of neighbouring isotopes



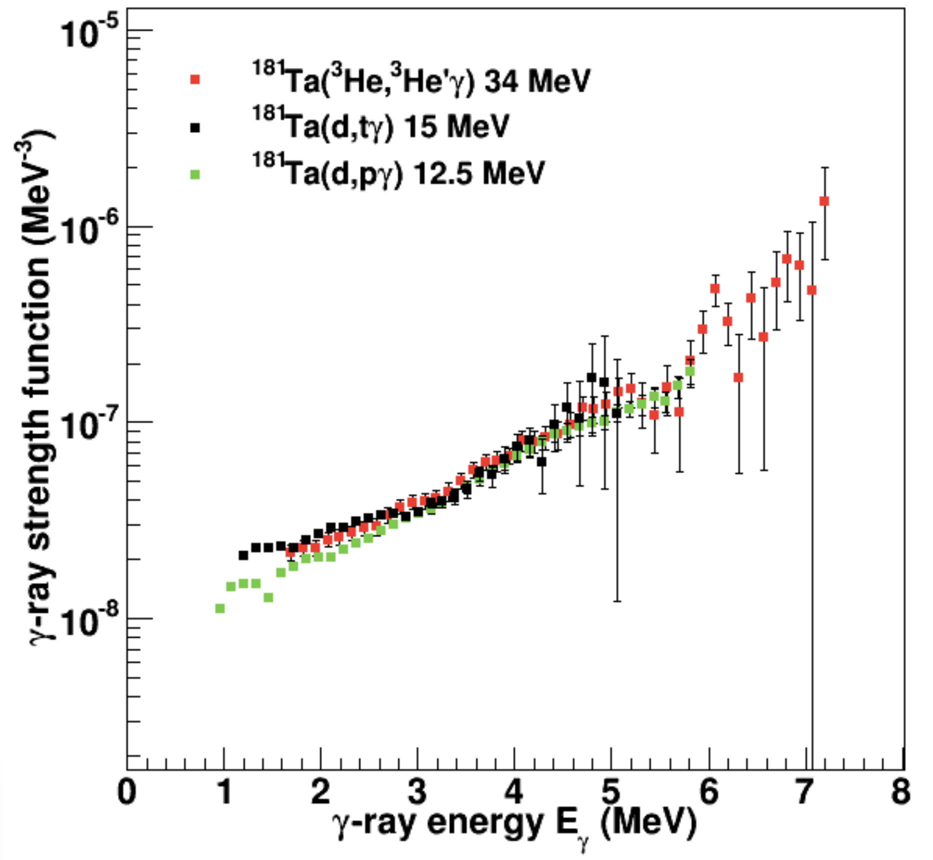
γ-ray Strength Functions

Different reactions yield similar results



$$f(E_\gamma) = \frac{1}{2\pi E_\gamma^3} B\mathcal{T}(E_\gamma)$$ [1]

γSFs of neighbouring isotopes



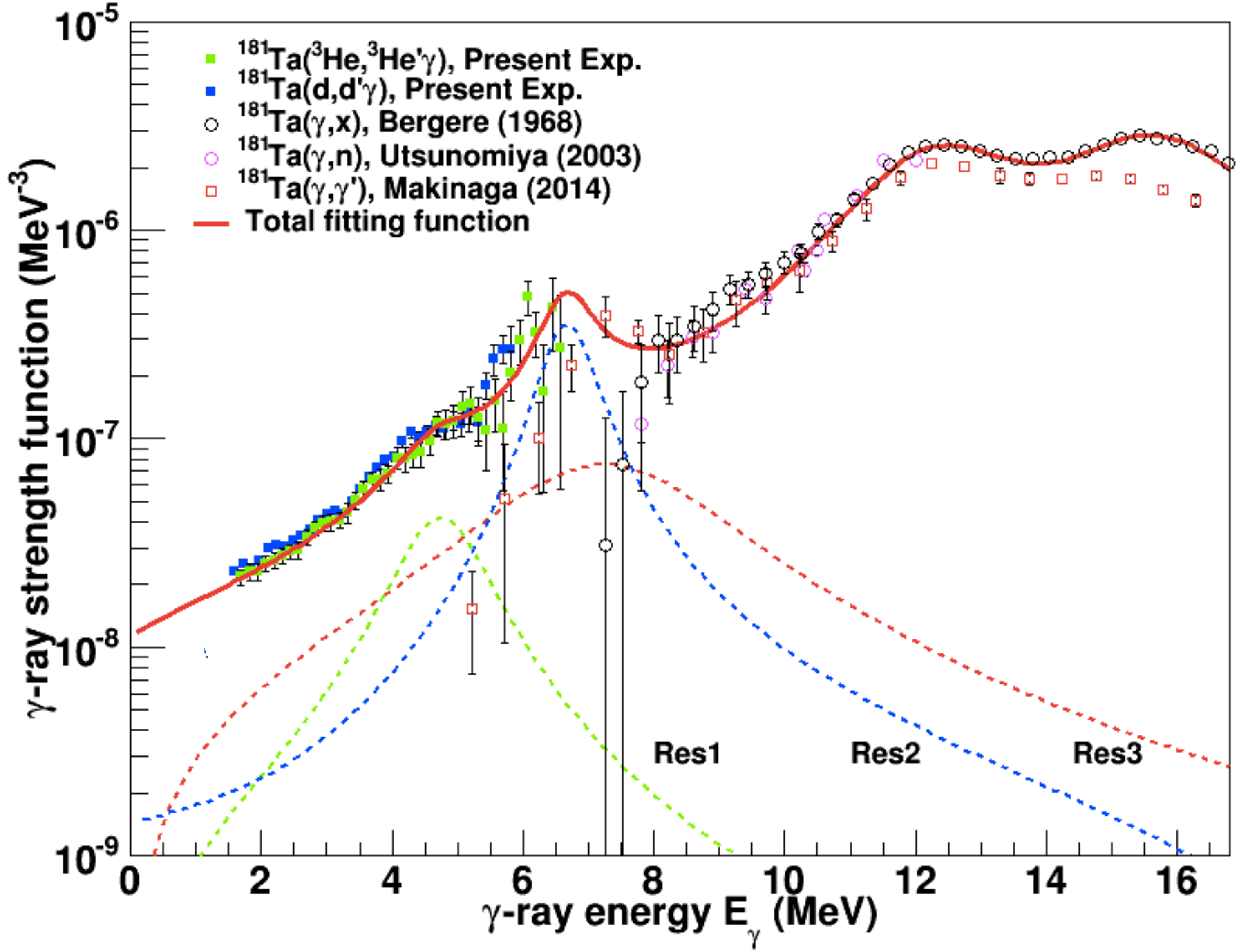
C.P Brits (Poster: Search for scissors resonance in ^{181,182}Ta) 15/09/2016

[1] A. Schiller et al., NIM Phys. Res. A 447, 498 (2000)

^{181}Ta Results

Comparison of ^{181}Ta(^{3}He,^{3}He′γ) and ^{181}Ta(d,d′γ) γSF with photoabsorption cross-section data

$$f(E_\gamma) = \frac{1}{3\pi\hbar^2c^2}\left[\frac{\sigma(E_\gamma)}{E_\gamma}\right]$$



^{182}Ta Preliminary Results

Neutron capture Cross Section Calculations

Upper error bands

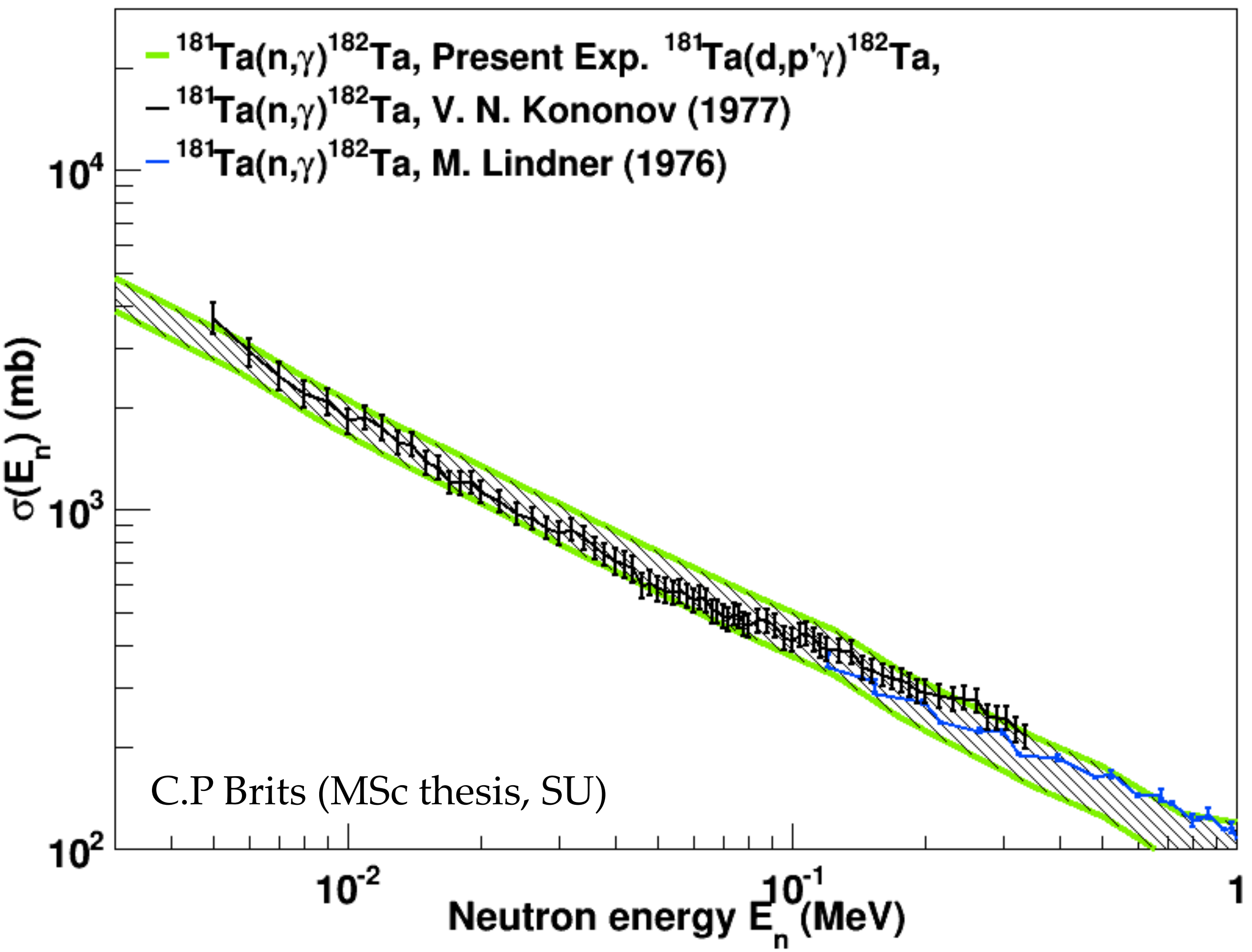
$$D_0 = D_0 - \delta D_0$$

$$<\Gamma(S_n)> = <\Gamma(S_n)> + <\delta\Gamma(S_n)>$$

Lower error bands

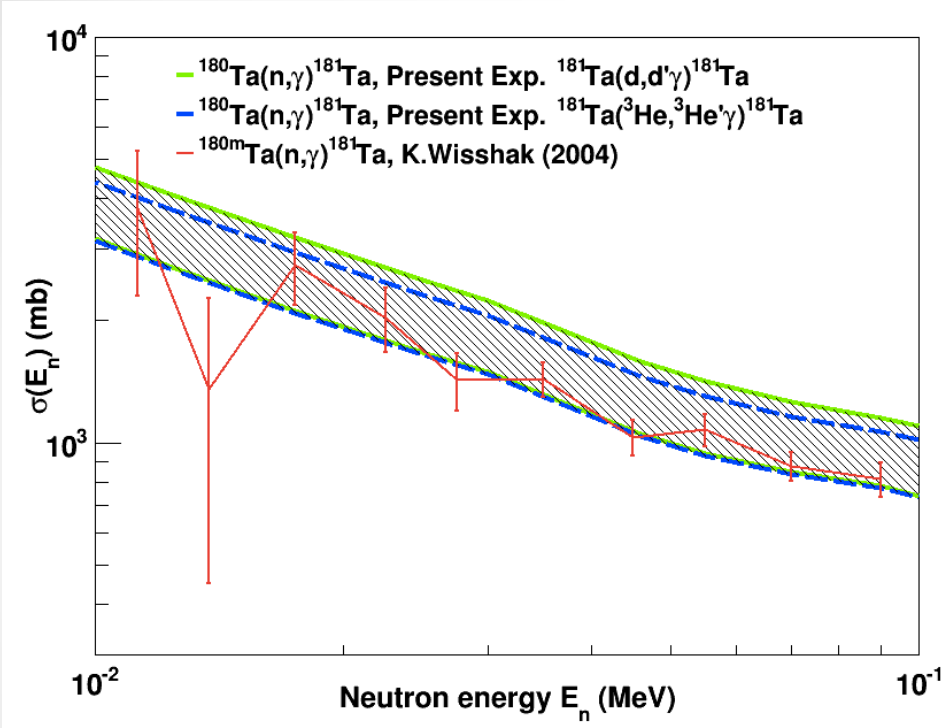
$$D_0 = D_0 + \delta D_0$$

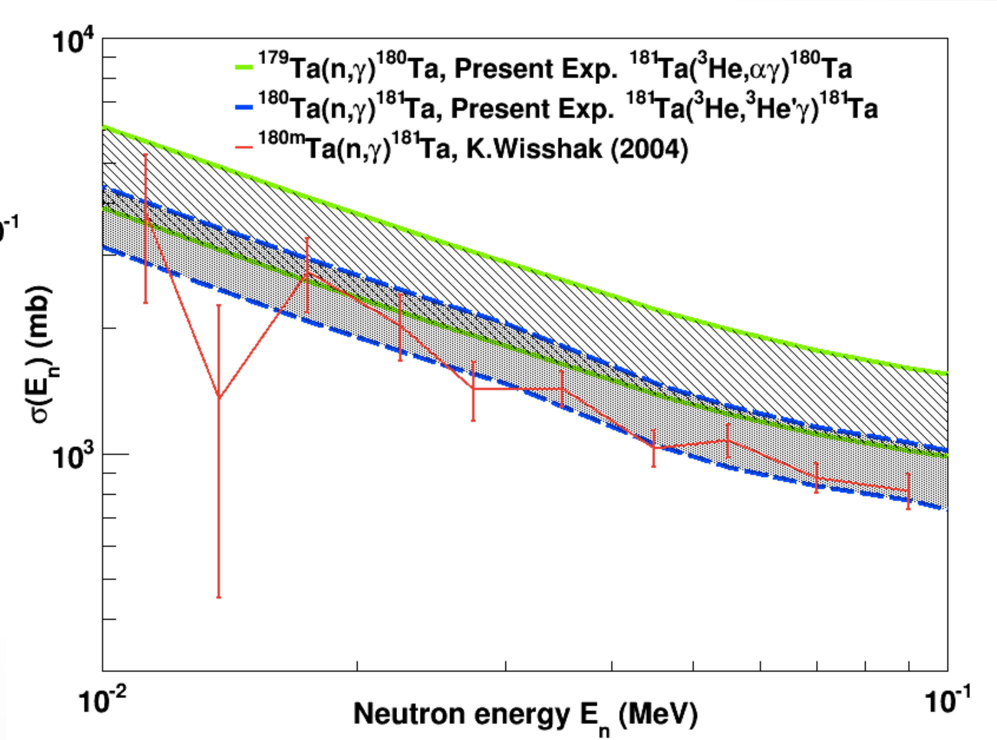
$$<\Gamma(S_n)> = <\Gamma(S_n)> - <\delta\Gamma(S_n)>$$



Preliminary Results

Neutron capture Cross Section Calculations





^{180,181,182}Ta Preliminary Results

Maxwellian-Average Cross Sections (MACS)

Reaction	⟨E⟩ (keV)	MACS (mb)	Rec. MACS (mb)
^{179}Ta(n,γ)	30	2469 ± 508	1334±422 [1]
	215	828 ± 288	
^{180}Ta(n,γ)	30	2051 ± 148	1465±100 [2,3]
	215	589 ± 53	
^{181}Ta(n,γ)	30	950 ± 136	766±15 [4]
	215	259 ± 46	

[1] Z. Y. Bao et al. , Atomic Data and Nuclear Data Tables 76 , 70 (2000).
[2] K. Wisshak et al. , Phys. Rev. C 69 , 055801 (2004).
[3] K. Wisshak et al. , Phys. Rev. Lett. 87 , 251102 (2001).
[4] K. Wisshak, F. Voss, F. Käppeler, and G. Reffo, Phys. Rev. C 42, 1731 (1990).

^{180,181,182}Ta Preliminary Results

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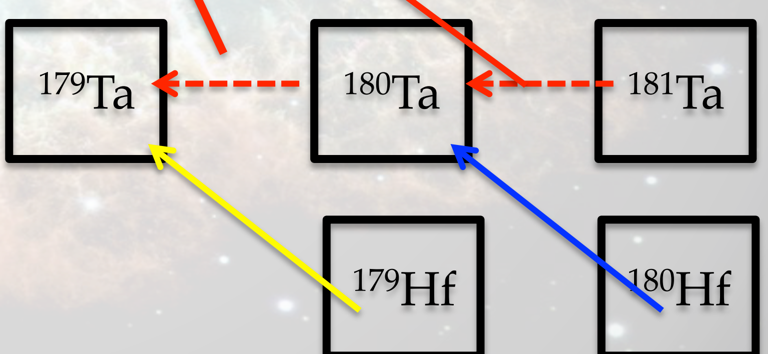
Assumption: Detailed balance



s-process??

Summary And Future Plans

- Experiments successfully performed at the Oslo cyclotron laboratory

^{181}Ta(3He,X)^{180,181}Ta, 34 MeV
^{181}Ta(d,X)^{180,181}Ta, 15 MeV
^{181}Ta(d,X)^{181,182}Ta, 12.5 MeV

- γSF and NLD of ^{180,181,182}Ta extracted with the Oslo Method
- First time, measurements of NLD and γSF below Sn in ^{180}Ta and below 5 MeV in ^{181}Ta experimentally.

- The experimental γSF and NLD used to investigate (n,γ) cross sections

- The newly deduced ^{179,180}Ta(n,γ) cross sections are to be utilized in astrophysical network calculations to investigate and constrain the galactic production mechanism of ^{180}Ta

- C.P Brits (Poster: Search for scissors resonance in ^{181,182}Ta) 15/09/2016

Acknowledgements

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[4] Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA, USA
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