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Laboratory for Accelerator Based Sciences

Level densities and γ strengths of ^{180,181,182}Ta and (n,γ) cross sections

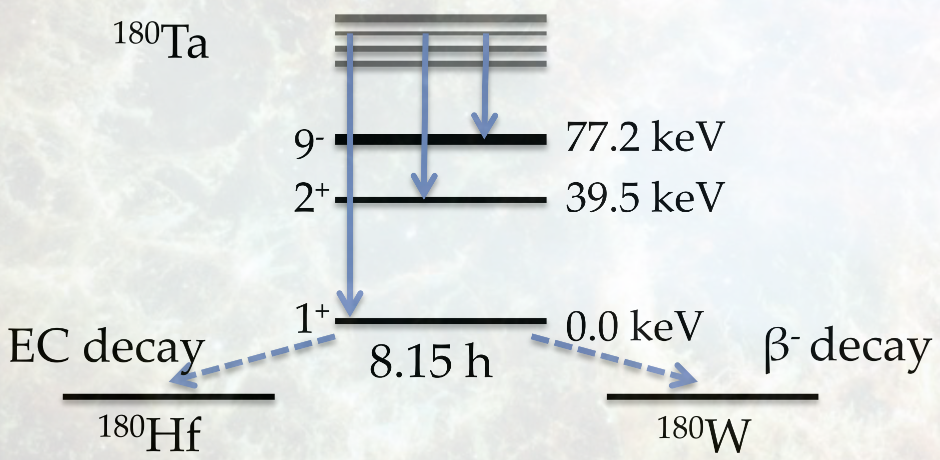
Kgashane Leroy Malatji

6th Workshop on Nuclear Level Density and Gamma Strength,
Oslo May 8-12, 2017

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 abundance (0.012%) ^{180}Ta remains an exception
- The odd-odd ^{180}Ta exist in a 9^- isomeric state at 77 keV ($t_{1/2,iso} > 10^{15}$ yrs) in nature

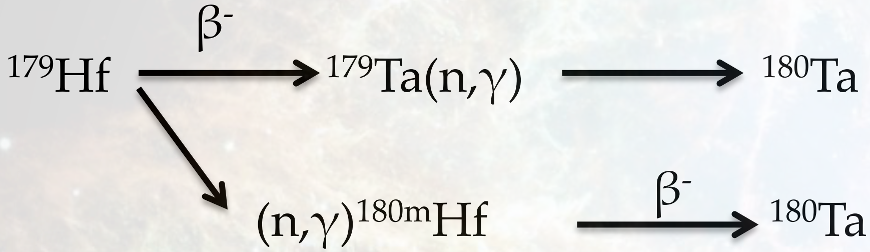


- Several processes are considered

Introduction

Physics Motivation for ^{180}Ta

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

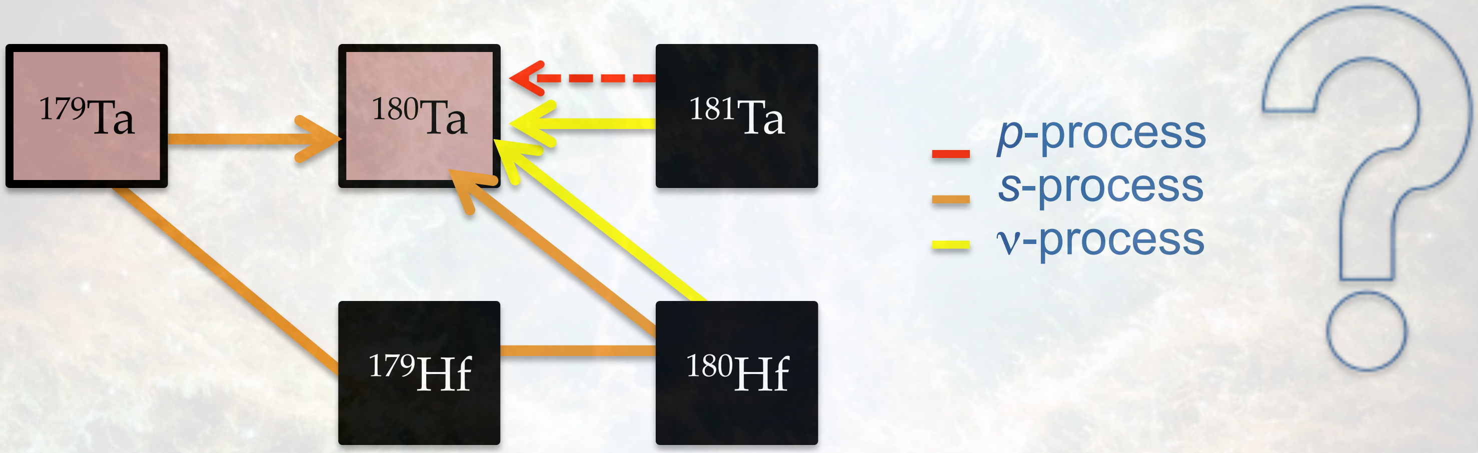


- ^{180}Hf(ν_e, *e*)^{180}Ta, ^{181}Ta(ν, ν'*n*)^{180}Ta and *p*-process contribute 50, 25 and 25%, respectively [3]
- ^{180}Hf(ν_e, *e*)^{180}Ta 50% contribution recently supported by A. Byelikov et al. [4]

[1] M. Arnould and S. Goriely, Phys. Rep. 384, 1 (2003).
[2] M. Loewe et al. Nucl.Phys. A719 (2003) 275c
[3] A. Heger et al. Phys.Lett. B 606, 258 (2005)
[4] A. Byelikov et al. PRL 98, 082501 (2007)

Introduction

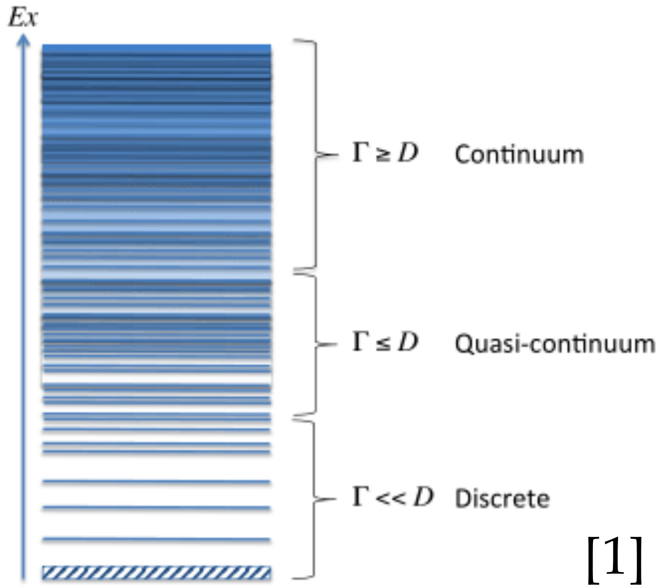
Physics Motivation for ^{180}Ta



- This is unresolved, hence provoking debates
- Uncertainties in reaction rates rest in nuclear properties
- Therefore production of ^{180}Ta needs to be reinvestigated with improved nuclear data

Objectives

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



[1]

- Astrophysical Maxwellian averaged (n,γ) cross sections (TALYS [2])
- Investigate production mechanism of ^{180}Ta
- … additional nuclear structure aspects (C.P. Brits)

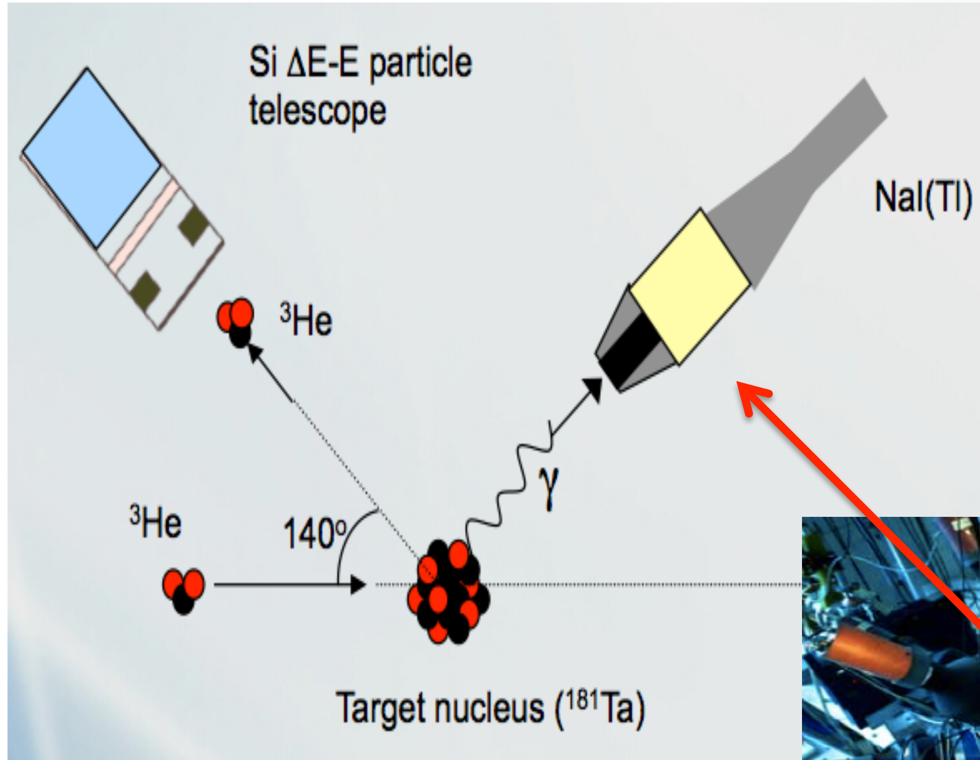
[1] Magne Guttormsen et al., Eur. Phys. J. A **51** (12), 170 (2015)

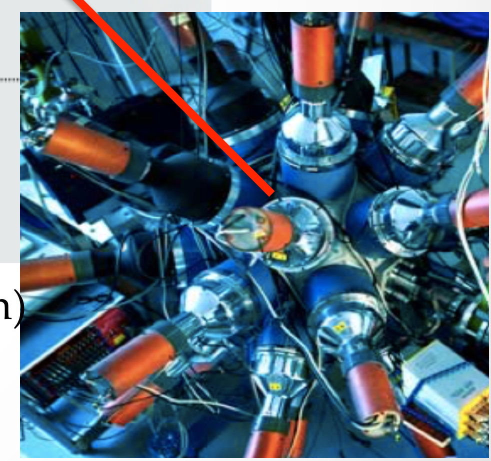
[2] A. J. Koning et al., Nuclear Data for Science and Technology (EDP Sciences; eds O. Bersillon et al.), p. 211 (2008) (see also http://www.talys.eu) version 1.6

Experimental Details
Oslo Cyclotron Laboratory

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

Oslo Cyclotron Laboratory

NRF National Research Foundation

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

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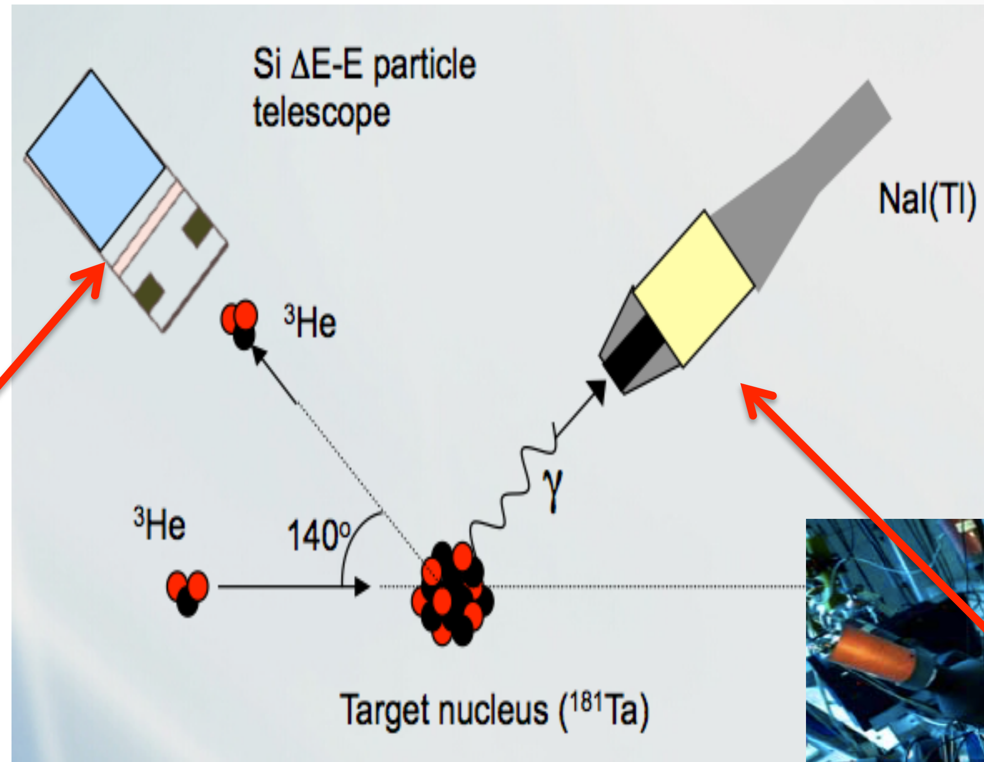
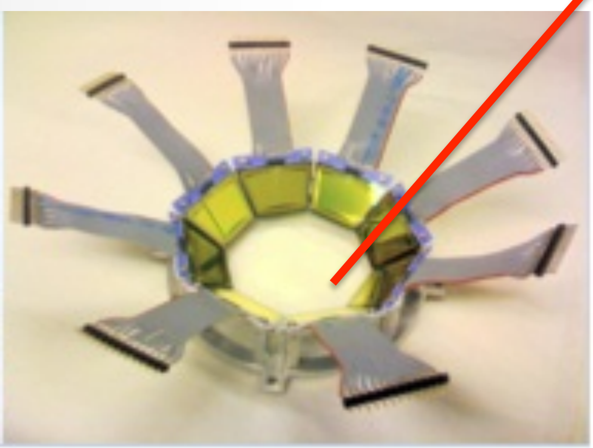
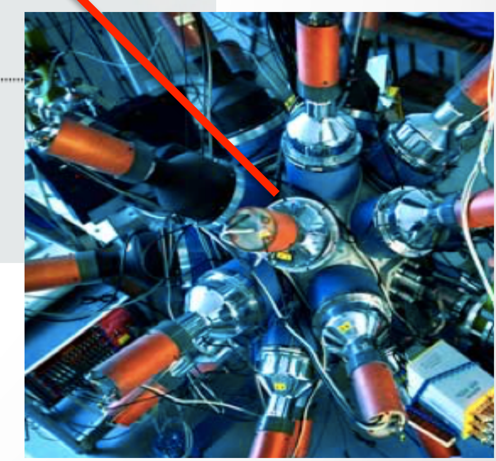




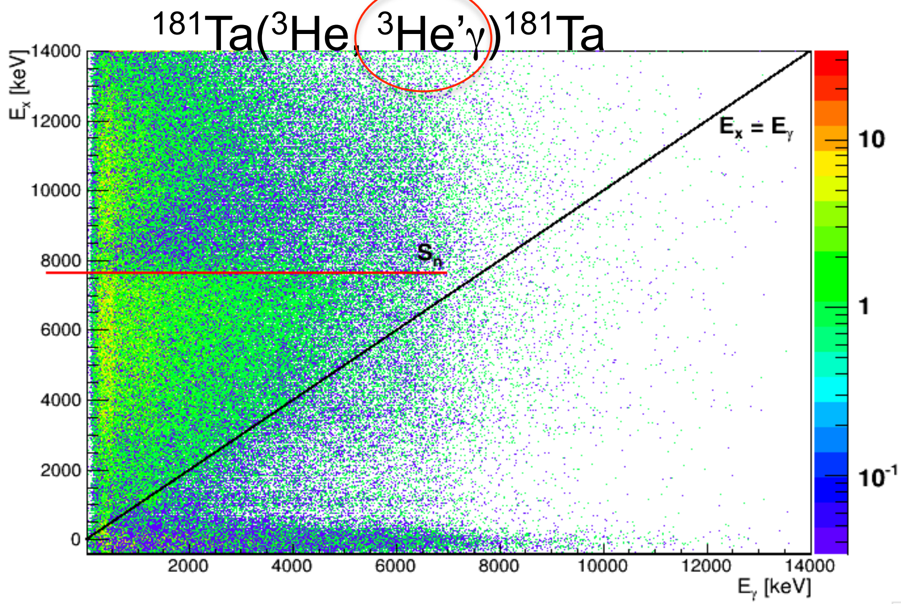


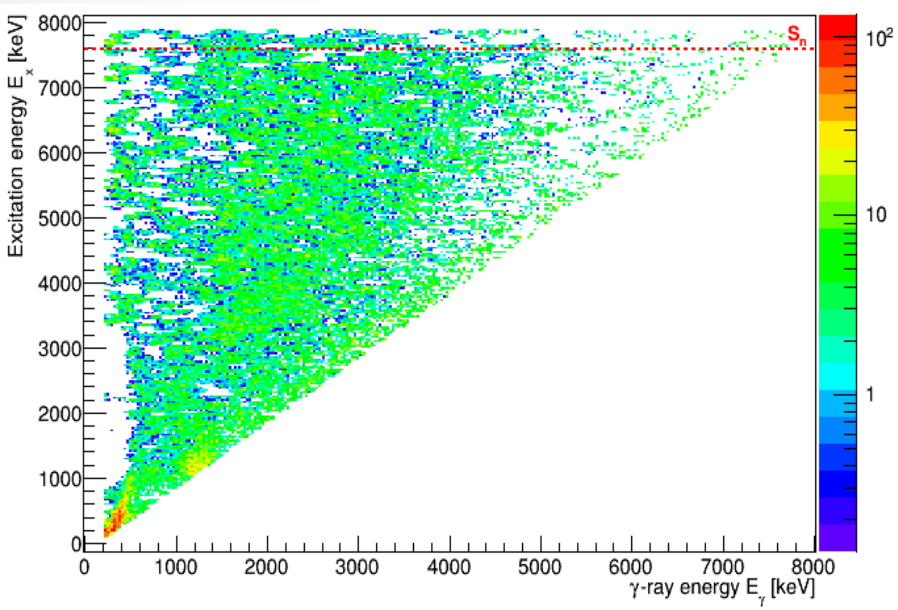
- SiRi Array, 64 ΔE-E Si particle telescopes
- ΔE, E and Al foil thicknesses (130 μm, 1550 μm and 10.5 μm)
- θ = 126° to 140°, ~ 5 cm

[1] M. Guttormsen et al., NIM 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]

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \cdot \rho(E_f)$$ Fermi's golden rule

$$P(E_i, E_\gamma) \propto \rho(E_f).\mathcal{T}(E_\gamma)$$ Assumes Brink hypothesis

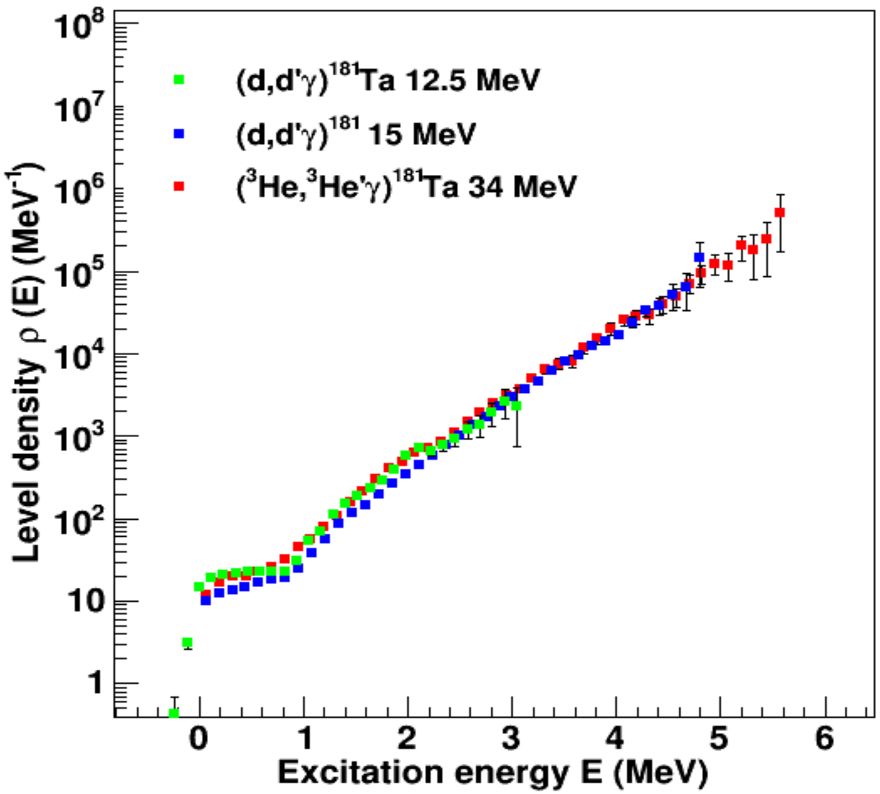
4. Normalization

[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)

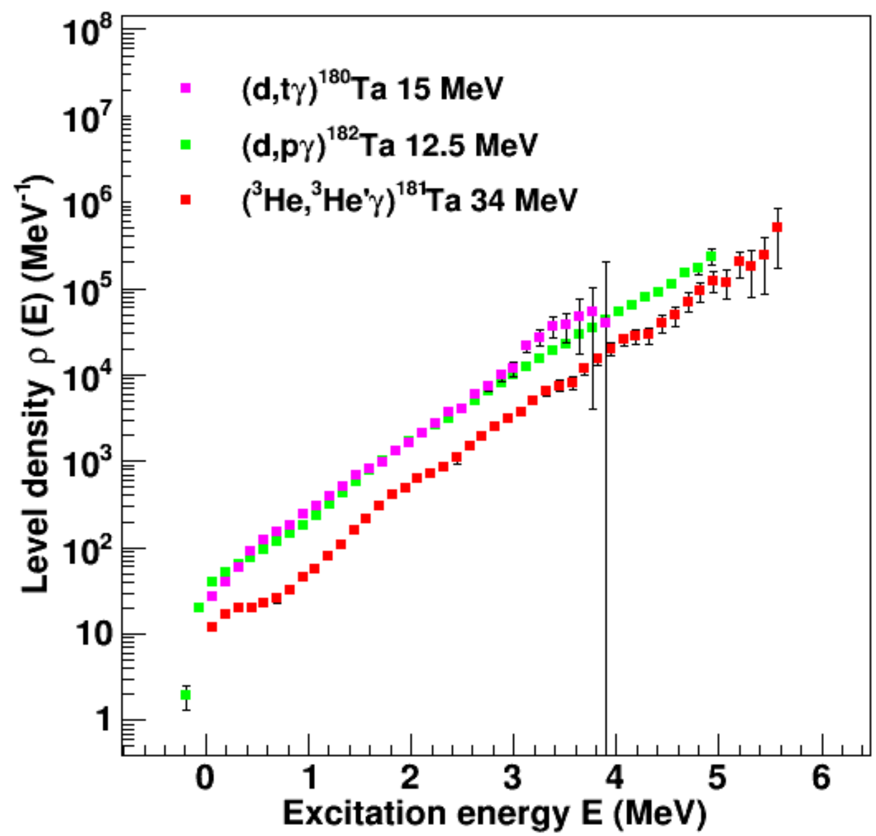
^{180,181,182}Ta Results

Nuclear Level Density

Different reactions yield similar results



NLDs of neighbouring isotopes



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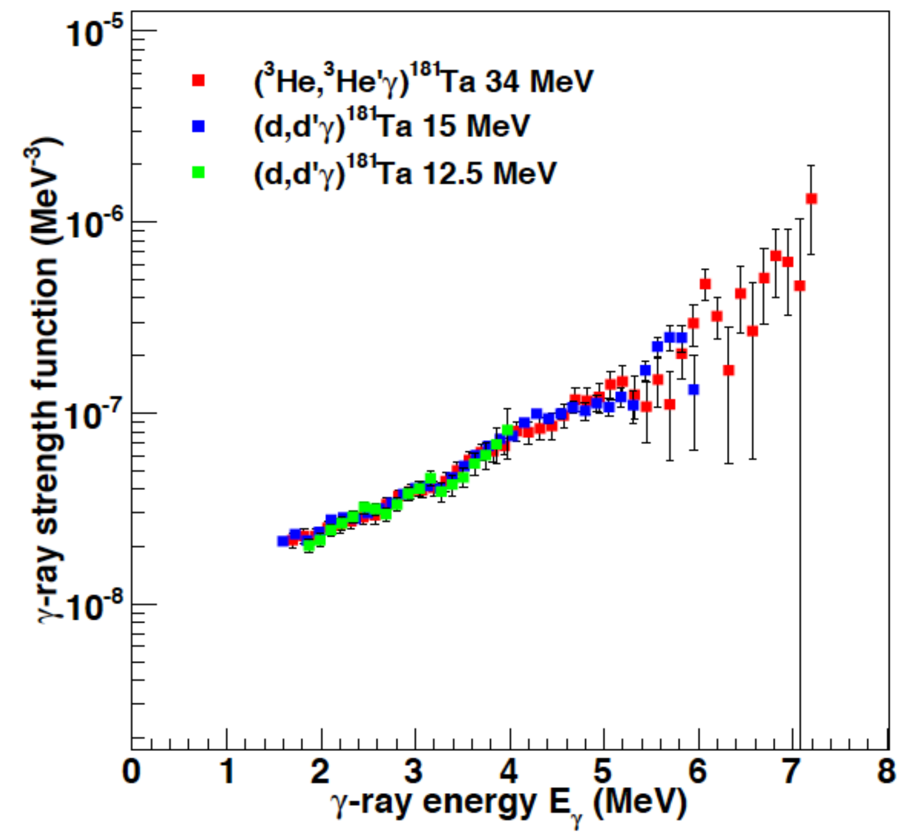
^{180,181,182}Ta Results

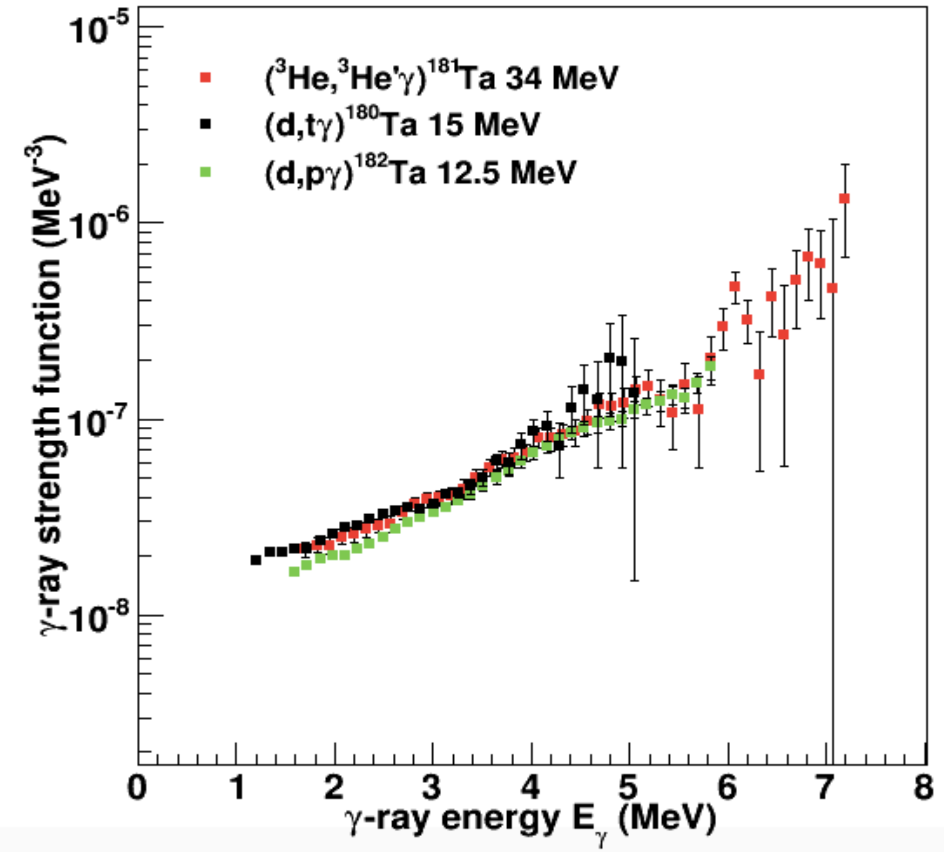
γ-ray Strenghth Function

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

Different reactions yield similar results



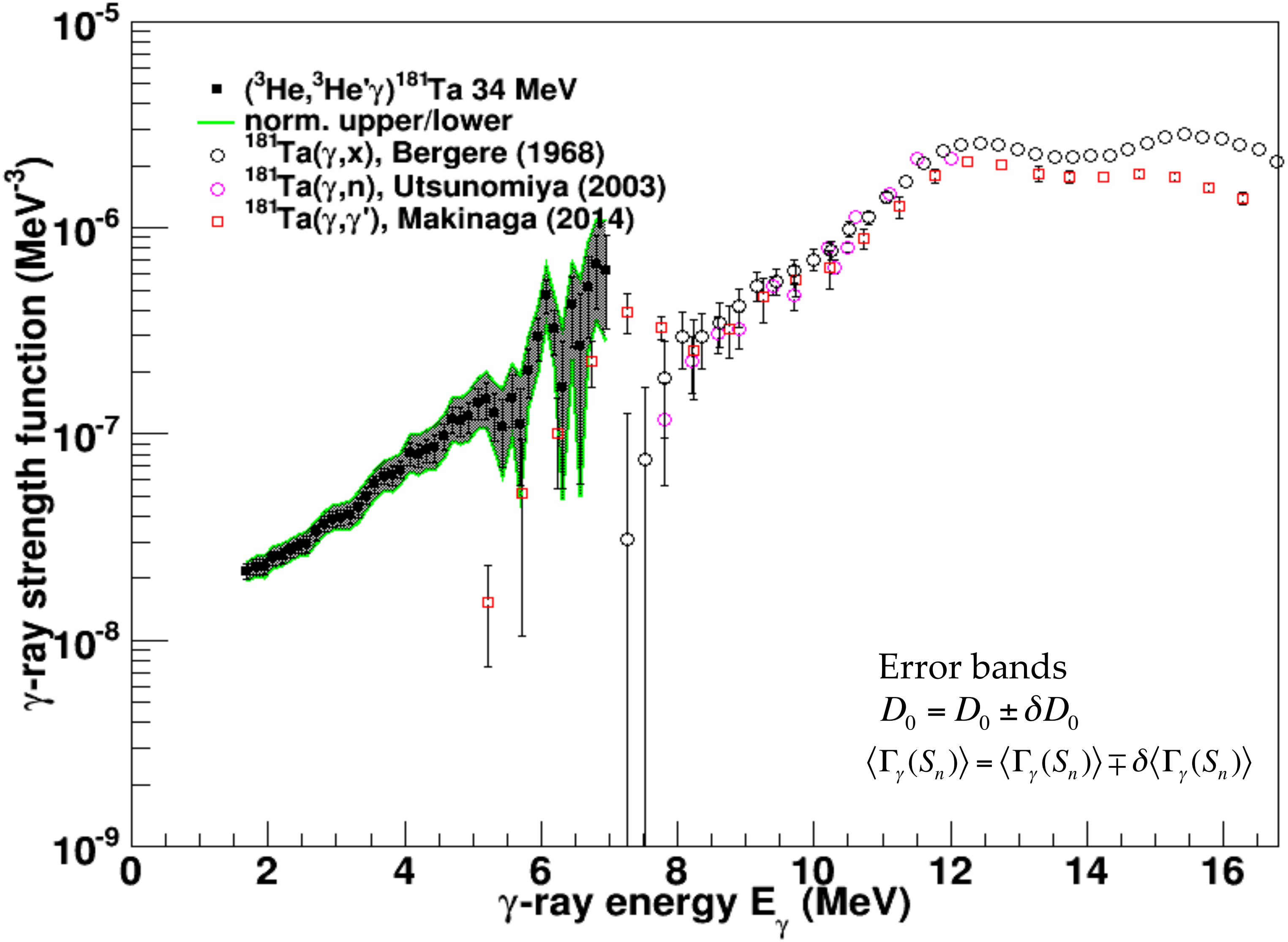
γSFs of neighbouring isotopes



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

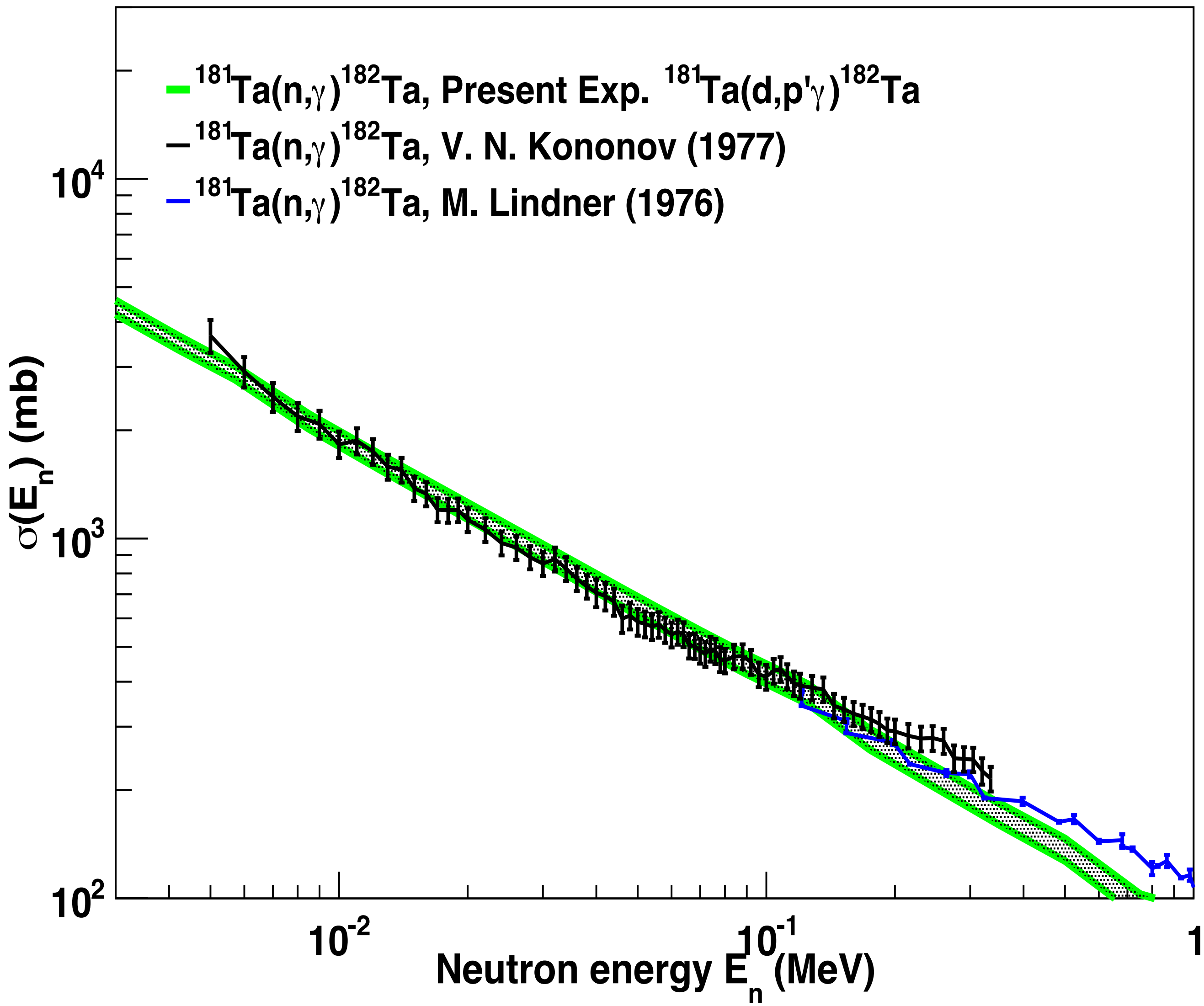
^{181}Ta Results

Comparison of ^{181}Ta(^{3}He,^{3}He′γ) γSF with photoabsorption data



^{182}Ta Results

Neutron Capture Cross Cection Calculations

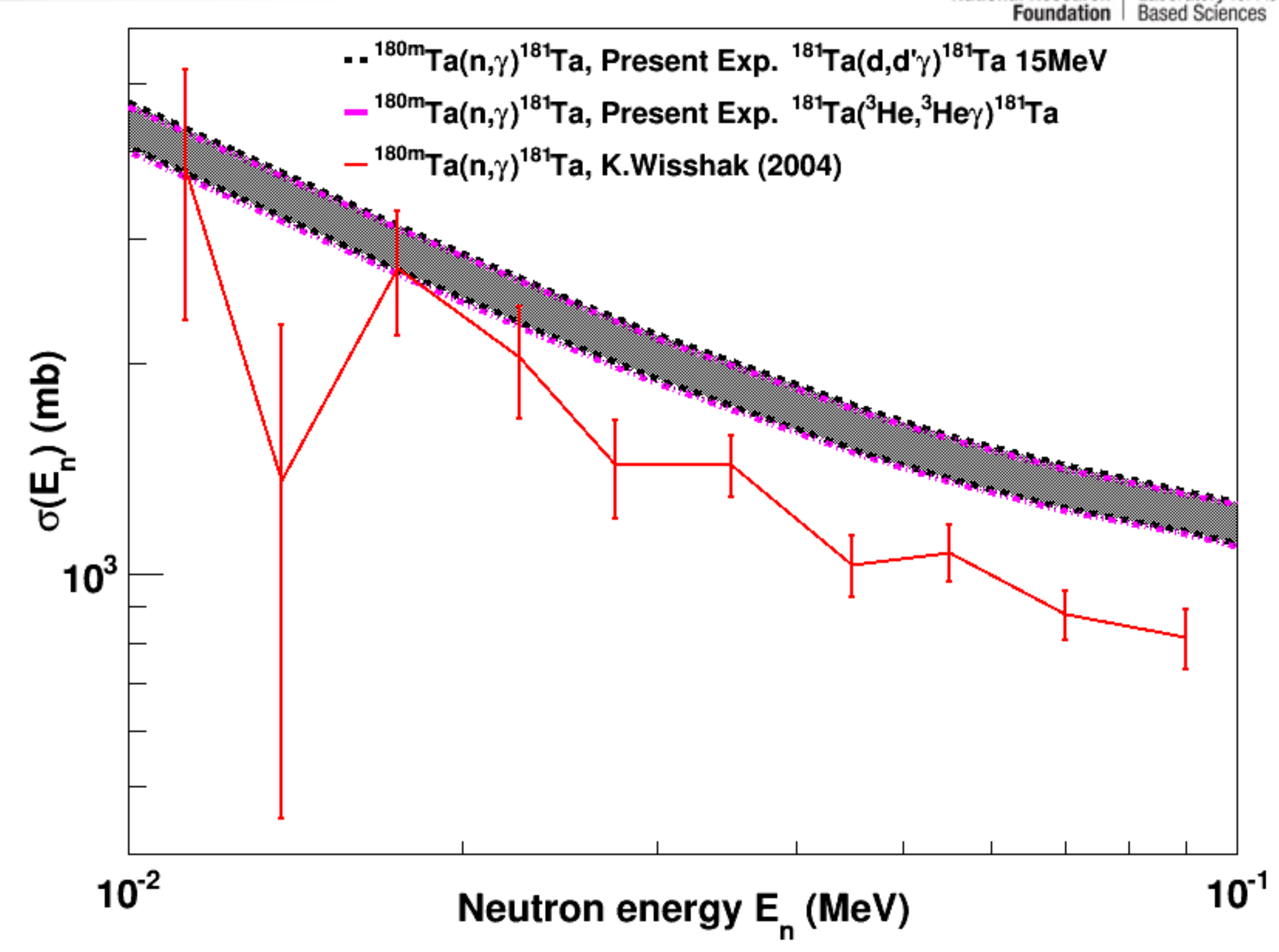


TALYS

Key ingredients
(HF approach)
- γSF, NLD and OMP

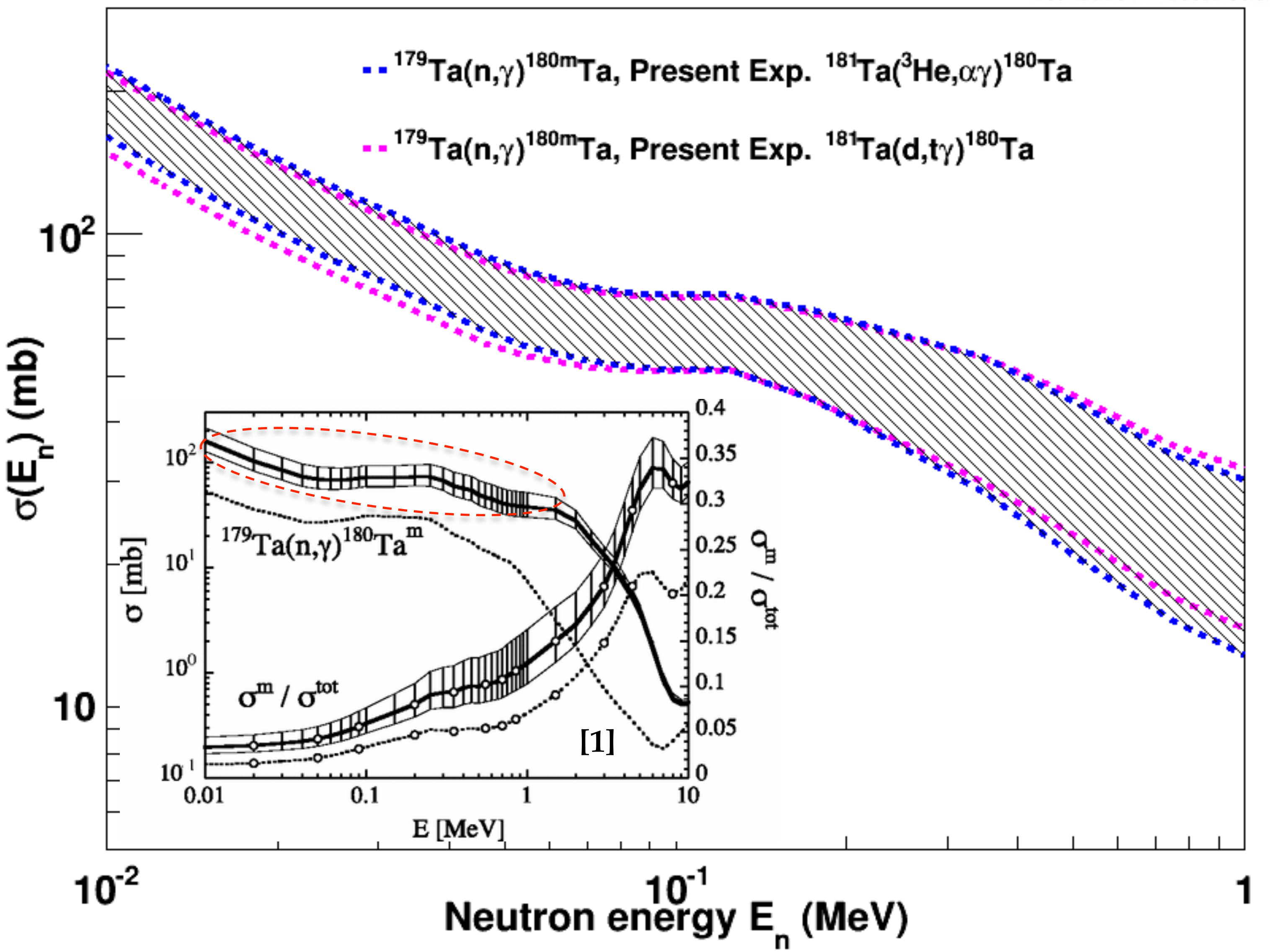
^{181}Ta Results

Neutron Capture Cross Section Calculations



^{180}Ta Results

Neutron capture Cross Section Calculations



[1] S. Goko *et al.*, Phys. Rev. Lett. **96**, 192501 (2006).

^{180,181,182}Ta Results

Maxwellian Averaged (n,γ) Cross Sections

Reaction	⟨E⟩ (keV)	MACS (mb)	KADoNiS. MACS (mb) [1]
^{179}Ta(n,γ)	30	2613 ± 681	1334 ± 422
	215	825 ± 292	
^{180m}Ta(n,γ)	30	2224 ± 169	1465 ± 100
	215	803 ± 78	
^{180gs}Ta(n,γ)	30	2191 ± 178	1640 ± 260
	215	619 ± 70	
^{181}Ta(n,γ)	30	936 ± 52	766 ± 15
	215	243 ± 17	

[1] I. Dillmann et al. , AIP Conf. Proc. 819 , 123; online at http:// www.kadonis.org

Summary and Outlook

- Experiments successfully performed at the Oslo cyclotron laboratory
- The 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 ^{179,180,181}Ta MACS will be used in a continued collaboration with S. Goriely
- Evaluate galactic production mechanism of ^{180}Ta and possibly constrain the astrophysical enviroments.
- TALYS calculation using theoretical models…

Acknowledgements

K. L. Malatji[1,2], B. V. Kheswa[2,3], M. Wiedeking[2], F. L. Bello Garrote[3], D. L. Bleuel[4], C.P Brits[1,2], F. Giacoppo[5,6], S. Goriely[7], A. Görgen[3], M. Guttormsen[3], K. Hadynska-Klek[3], T. W. Hagen[3] , V. W. Ingeberg[3] , M. Klintefjord[3], A. C. Larsen[3], H. T. Nyhus[3], T. Renstrøm[3], S. Rose[3], E. Sahin[3], S. Siem[3], G. M. Tveten[3] and F. Zeiser[3].

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[5] *Helmholtz Institute Mainz, 55099 Mainz, Germany*
[6] *GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[7] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, B-1050 Brussels, Belgium*

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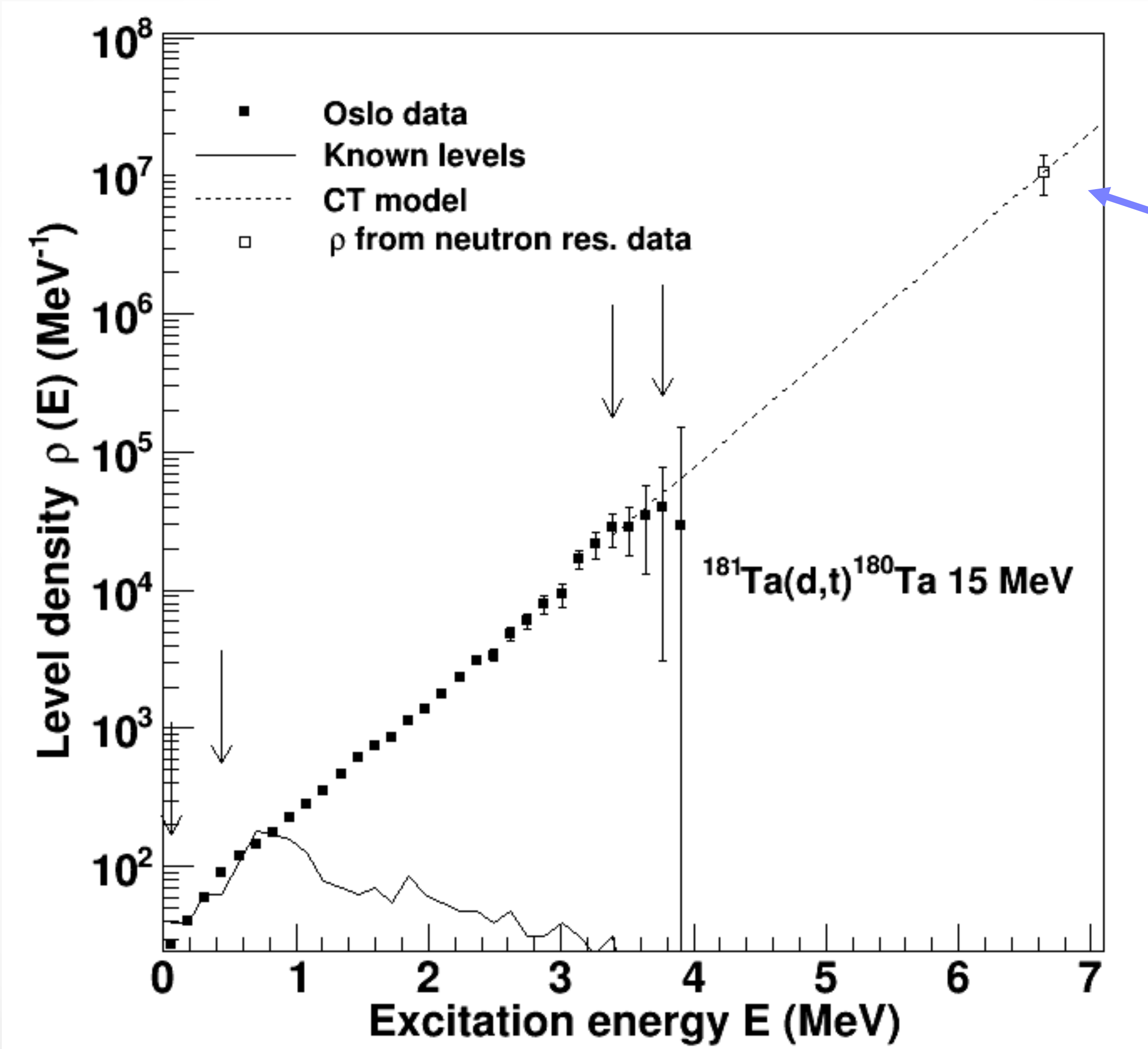
Thank You For Your Attention!!!

^{180}Ta Results

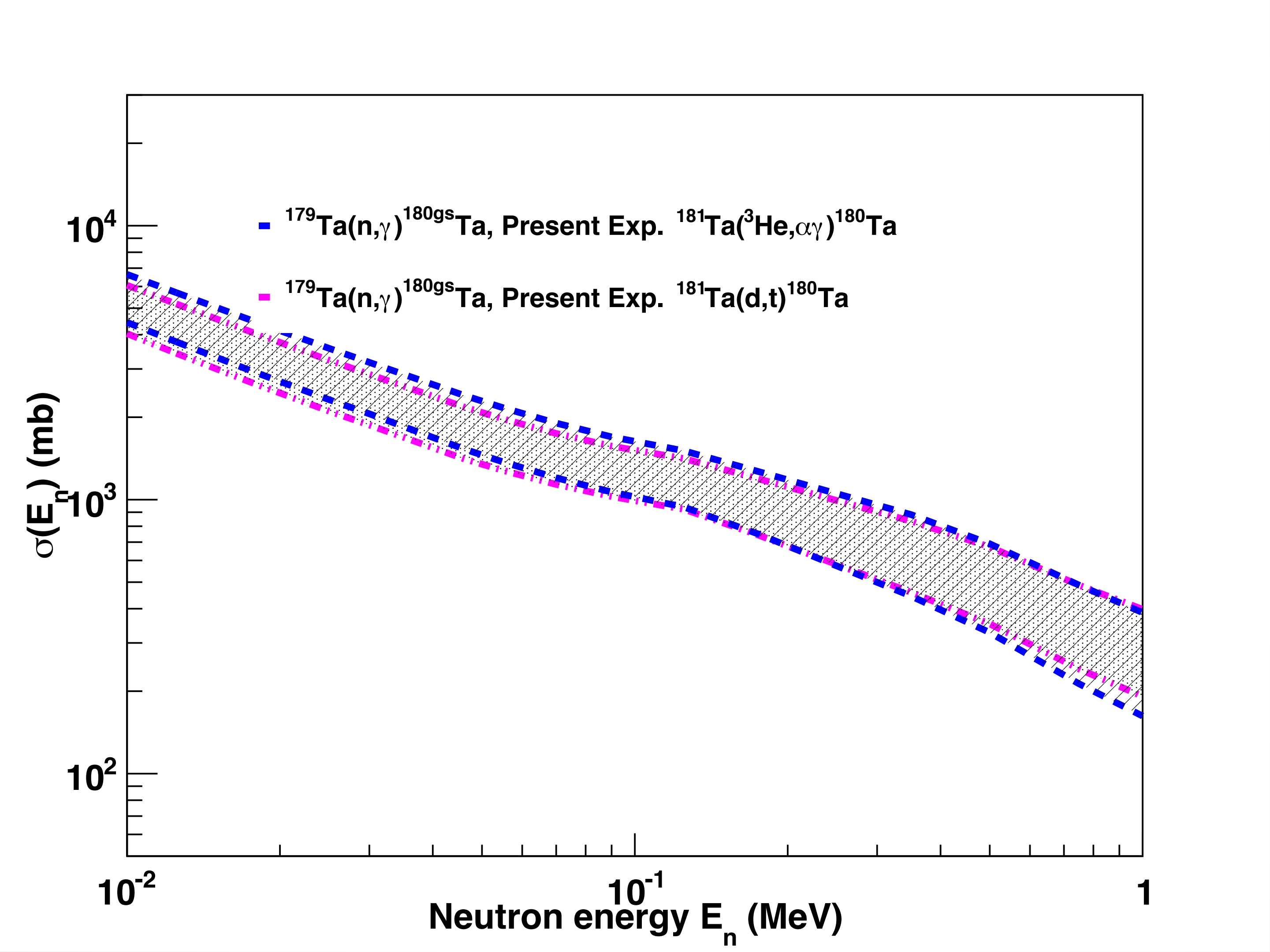
Normalization of the NLD

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

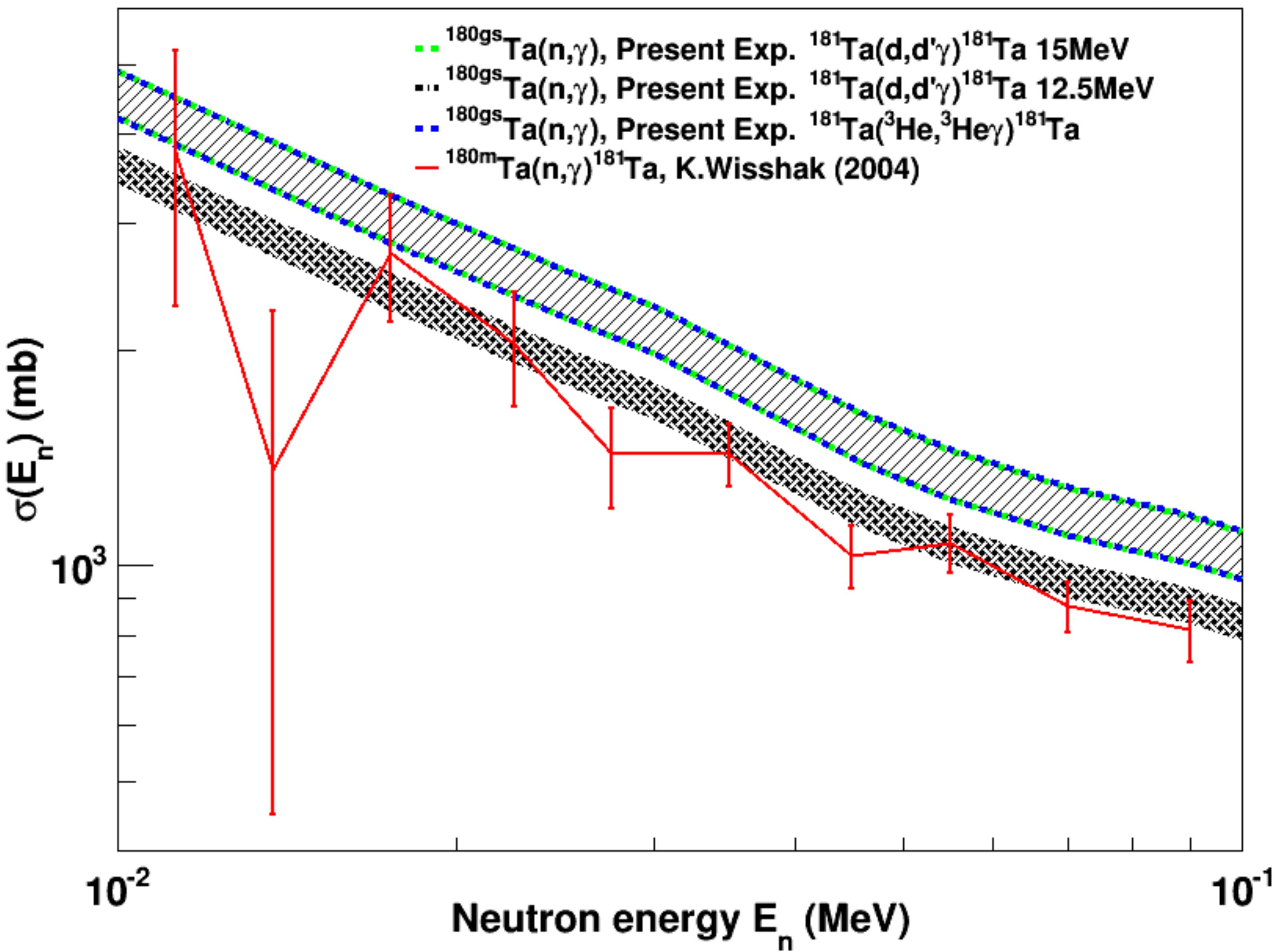


No neutron resonance data available (^{180}Ta)

^{180gs}Ta Cross Section



^{181}Ta Cross Section



^{181}Ta Cross Section

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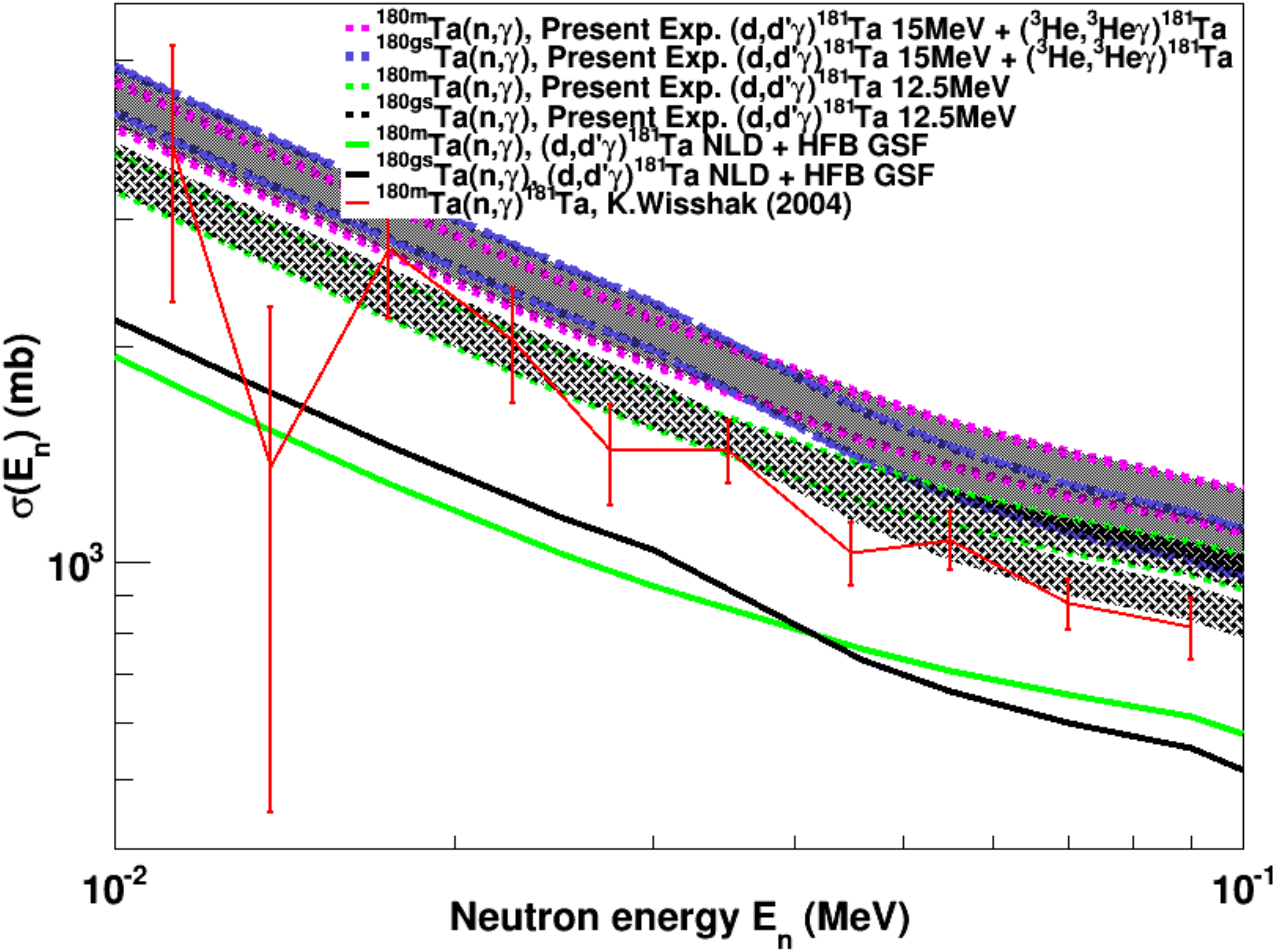
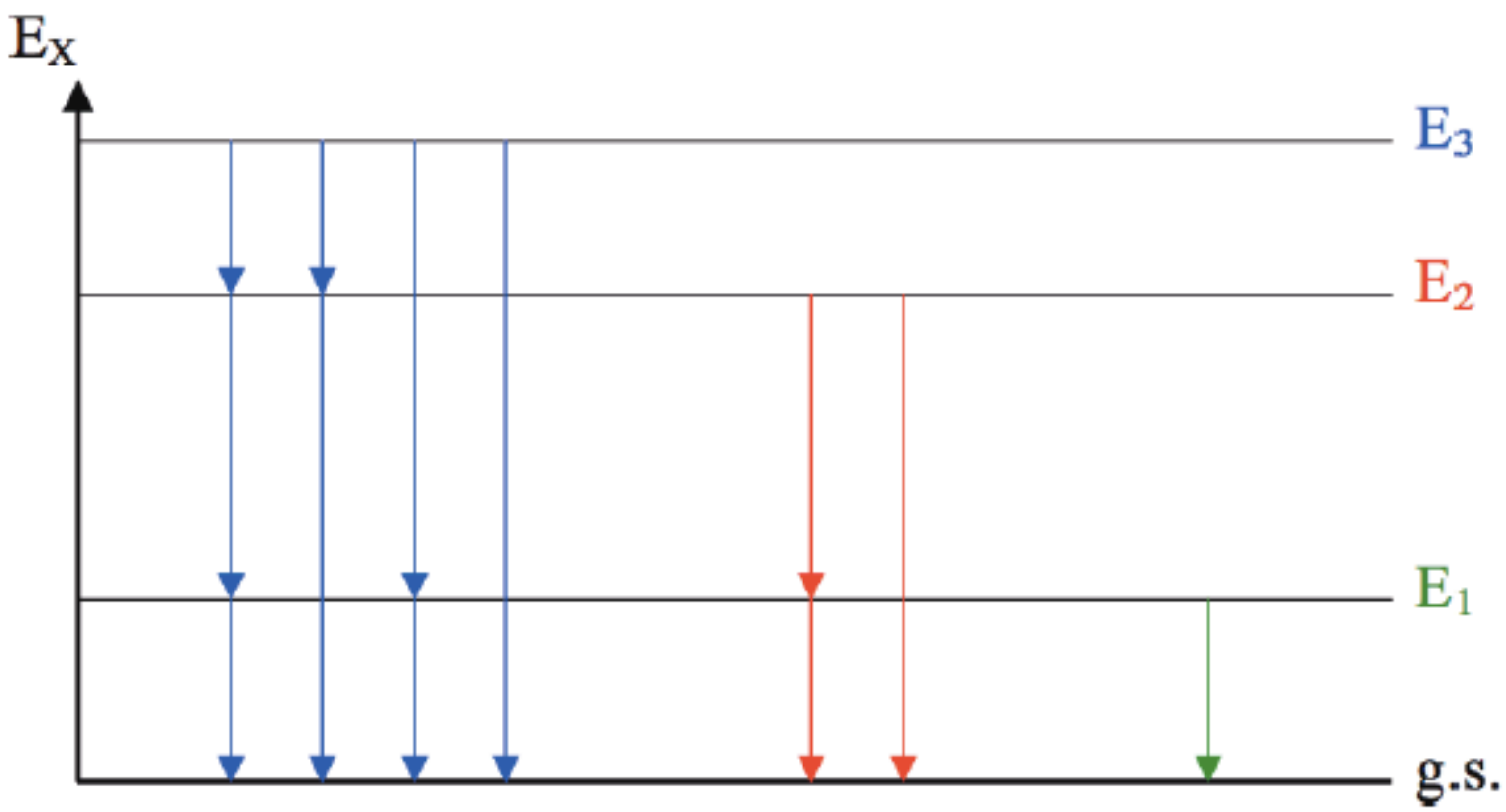
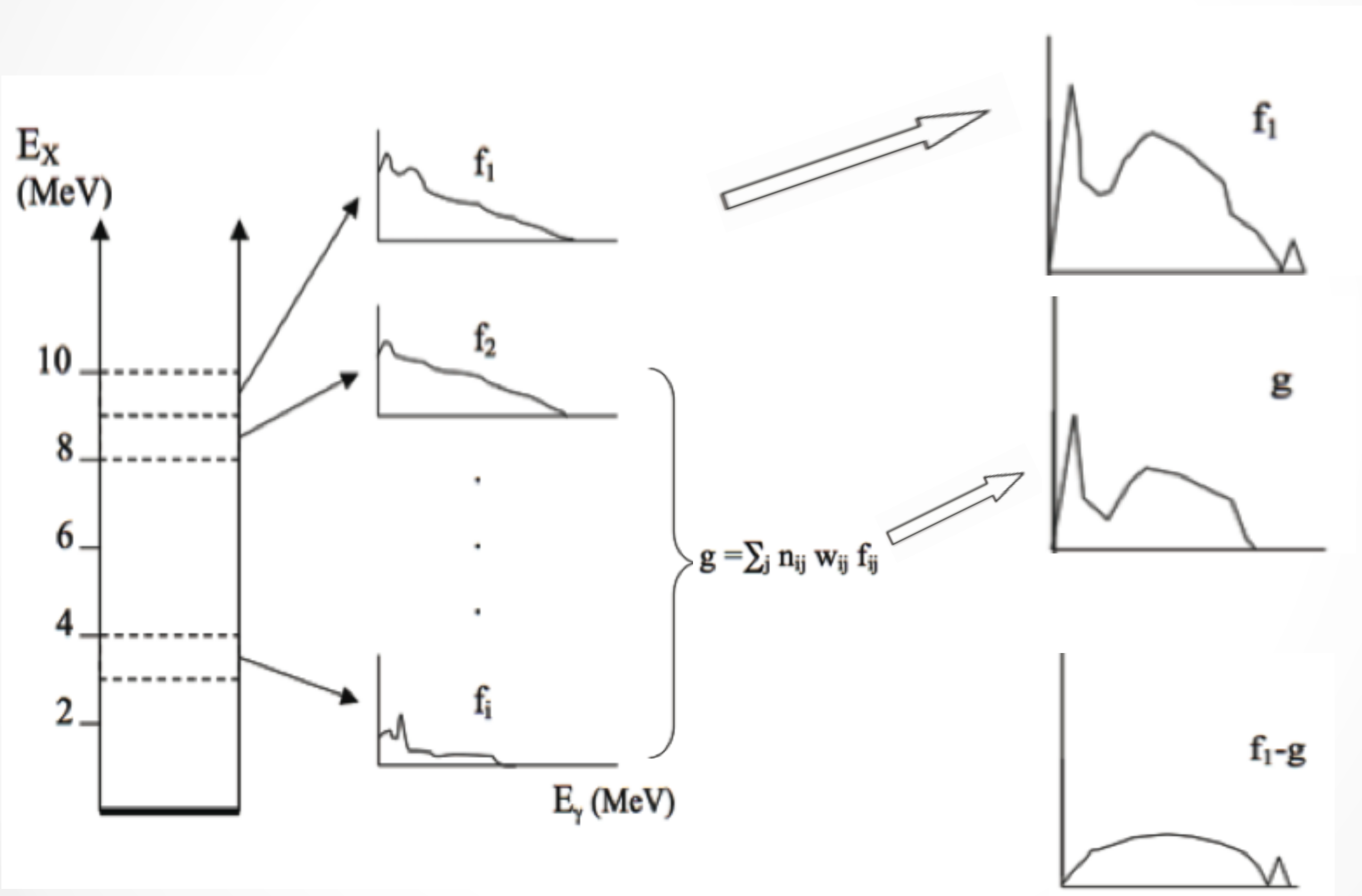


Oslo Method
First Generation Method



Oslo Method
First Generation Method



Oslo Method

Factorization of the First-Generation Matrix

- According Fermi's golden rule: $\lambda_{if} \propto |\langle f|H'|i\rangle|^2 \rho(E_f)$

  where $\rho(E_f)$ is the NLD at a final state

  is the matrix elements $|\langle f|H'|i\rangle|$

- Equivalent equation for the FG matrix: $P(E_i, E\ ) \propto \rho(E_f)\mathcal{T}_{if}$

  where is the γ tra$\mathcal{T}_{if}$mission coefficient

- Brink Hypothesis: GEDR can be built on every state, and its properties don't depend on the properties of the initial and final state.

- $\mathcal{T}_{if}$ only depend on the γ-ray energy

Oslo Method

Simultaneous Extraction of T and NLD

- The $\mathcal{T}(E_\gamma)$ and $\rho(E_f)$ are extracted by fitting $P_{th}(E_x, E_\gamma)$ to $P(E_x, E_\gamma)$

  and minimizing

$$\chi^2 = \frac{1}{N}\sum_{E_x}\sum_{E_\gamma}\frac{(P_{th}(E_x, E_\gamma) - P(E_x, E_\gamma))}{\Delta P(E_x, E_\gamma)}$$

Where $$P_{th}(E_x, E_\gamma) = \frac{\rho(E_f)\mathcal{T}(E_\gamma)}{\sum_{E_\gamma}\rho(E_f)\mathcal{T}(E_\gamma)}$$

and N, $\Delta P(E_x, E_\gamma)$ re degrees of freedom and uncertainly in $P(E_x, E_\gamma)$

Oslo Method

Normalization of T and NLD

- Once $\rho(E_f)$ and $\mathcal{T}(E_\gamma)$ are extracted
- Infinitely many solutions can be found of the form

$$\tilde{\rho}(E_f) = A\rho(E_f)e^{\alpha E_f} \text{.....................(1)}$$

$$\tilde{\mathcal{T}}(E_\gamma) = B\mathcal{T}(E_\gamma)e^{\alpha E_\gamma} \text{....................(2)}$$

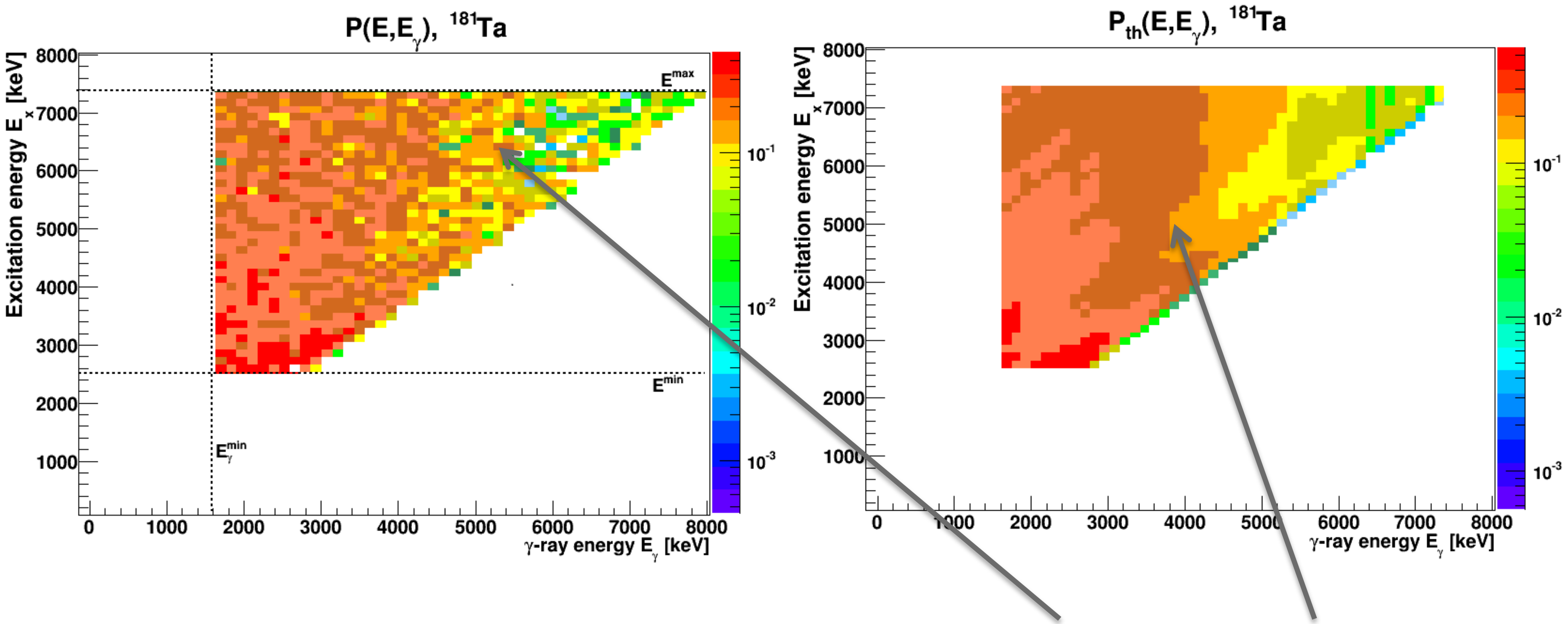
Where α ; a common slope between $\tilde{\rho}(E_f)$ ıd $\tilde{\mathcal{T}}(E_\gamma)$

A ıd B ʼe normalization parameters

- α and A are obtained by normalizing $\tilde{\rho}(E_f)$ to $\rho(S_n)$ and ρ of known discrete states
- B can be calculated from experimental $\langle\Gamma_\gamma\rangle$ and D_0 @ neutron threshold

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 $\mathcal{T}(E_\gamma)$

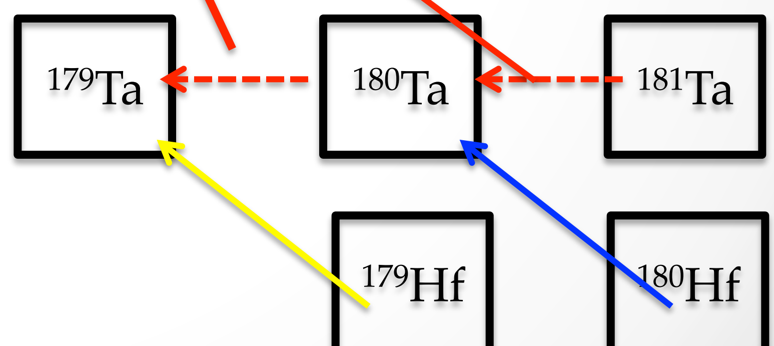
^{180,181,182}Ta Preliminary Results

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	

Assumption: Detailed balance

s-process??



Radiative width and neutron resonance level spacing 180Ta.

The NLD and TSF were normalized to those of neighbouring isotes (182ta) with the requirement of having the same slope. Then obtained level density at the Sn was the used to determine the resonance spacing. This normalization does not give the uncertainties of D0 and Radiative width, so we assume 3 times the percentage of the uncertainties of the neighbouring isotopes(182Ta).

Spin dependence on of the gSF and NLD

So the ultimate question is: is the gamma-decay strength function the same for the high-spin states as the low-spin states?

The Brink-Axel hypothesis says yes, and experimentally it seems to be true too (for example Mathis' PRL from 2012 on 95Mo), although such extremely narrow spin windows have not been tested. But, depending on the neutron energies, p-wave capture might contribute, and this will make the populated spin range broader.

We did some DICEBOX simulations a long time ago with Milan Krticka from Prague University. For light nuclei (57Fe), a very narrow high-spin window for the initial states produced an artificial "upbend" at low gamma energies due to few available levels (Larsen et al, PRC 83, 034315 (2011). But for 180Ta I would not expect such an effect, as it is a heavy, odd-odd nucleus with lots of levels.