Neutron capture at the *s*-process branching points ^{171}Tm and ^{204}Tl

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Close Collaborators: U. Koester (ILL), D. Schumann (PSI) and S. Heinitz (PSI)
(The n_TOF Collaboration)

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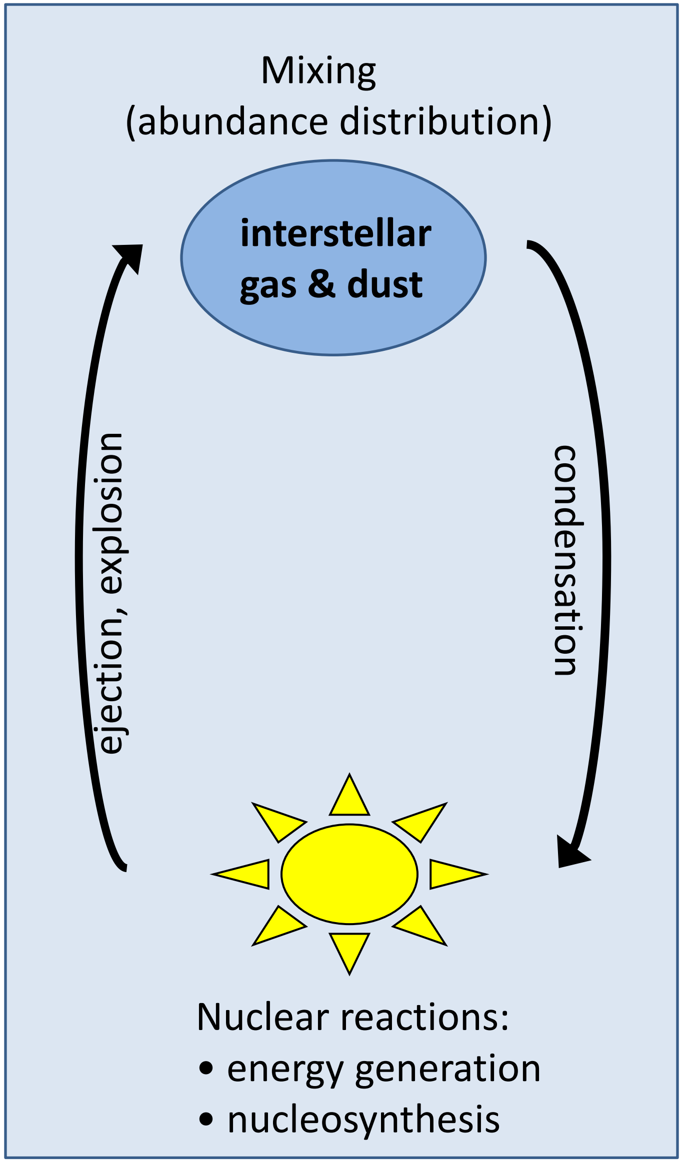
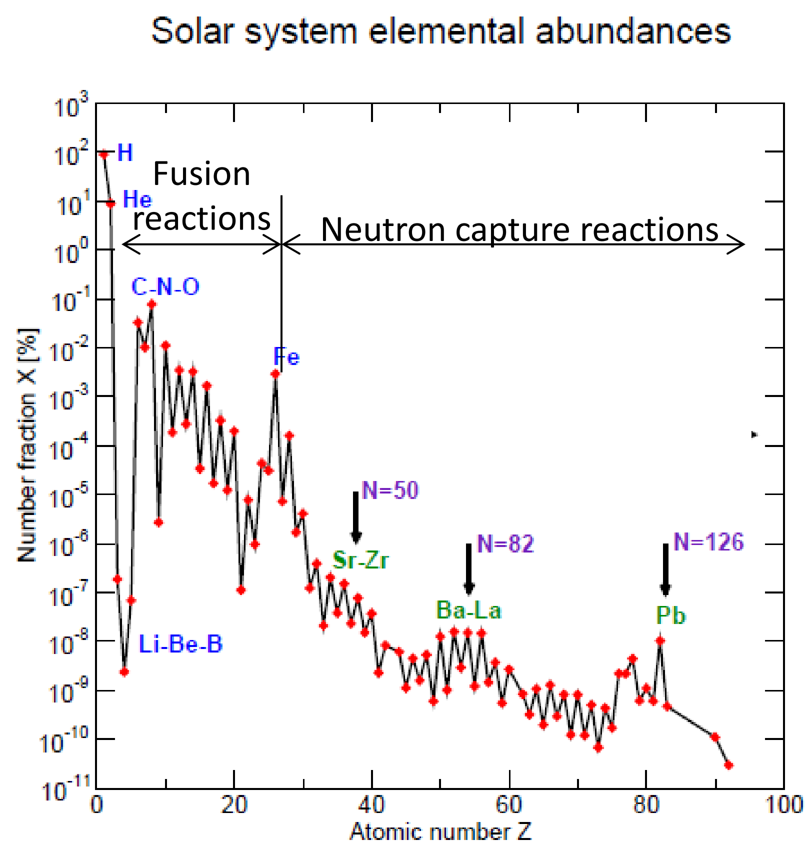
CERN INTC meeting (February 12th 2014)

Nucleosynthesis through the s-process





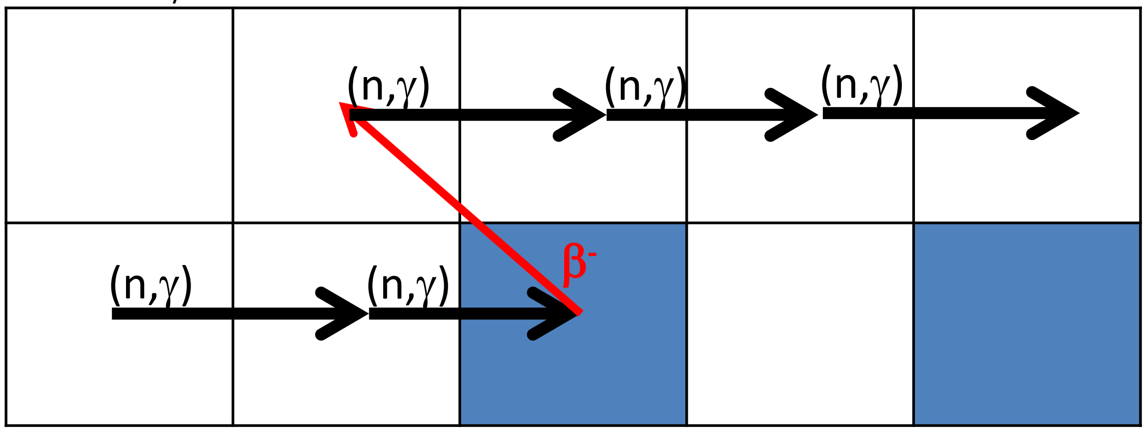
Chemical elements beyond Iron are synthesized via neutron capture reactions in stars:

~ ½ by the s-process (red giants)

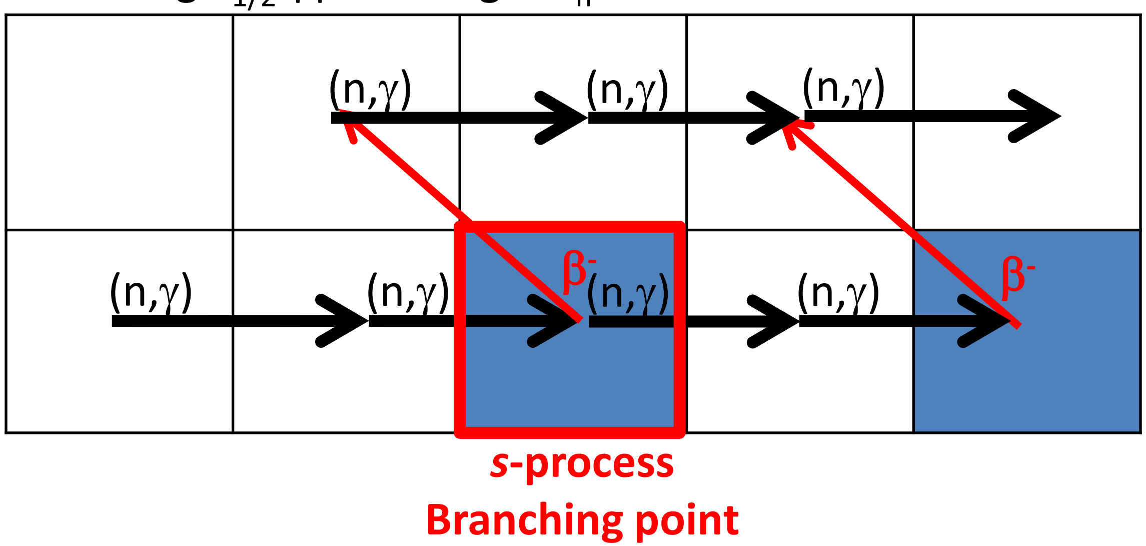
~ ½ by the r-process (explosive)

Nucleosynthesis & s-process: branching points

Short $\tau_{1/2}$ || low Φ_n



Suff. long $\tau_{1/2}$ || Suff. High Φ_n



Most relevant *s*-process branching points

REVIEW OF MODERN PHYSICS, VOLUME 83, JANUARY–MARCH 2011

n_TOF→ PRL 93, 161103 (2004)

Sample	Half-life (yr)	Q value (MeV)	
^{63}Ni	100.1	β^-, 0.066	TOF work in progress (Couture, 2009), sample with low enrichment
^{79}Se	2.95×10^5	β^-, 0.159	Important branching, constrains *s*-process temperature in massive stars
^{81}Kr	2.29×10^5	EC, 0.322	Part of ^{79}Se branching
^{85}Kr	10.73	β^-, 0.687	Important branching, constrains neutron density in massive stars
^{95}Zr	64.02 d	β^-, 1.125	Not feasible in near future, but important for neutron density low-mass AGB stars
^{134}Cs	2.0652	β^-, 2.059	Important branching at $A = 134, 135$, sensitive to *s*-process temperature in low-mass AGB stars, measurement not feasible in near future
^{135}Cs	2.3×10^6	β^-, 0.269	So far only activation measurement at $kT = 25$ keV by Patronis *et al.* (2004)
^{147}Nd	10.981 d	β^-, 0.896	Important branching at $A = 147/148$, constrains neutron density in low-mass AGB stars
^{147}Pm	2.6234	β^-, 0.225	Part of branching at $A = 147/148$
^{148}Pm	5.368 d	β^-, 2.464	Not feasible in the near future
^{151}Sm	90	β^-, 0.076	Existing TOF measurements, full set of MACS data available (Abbondanno *et al.*, 2004a; Wisshak *et al.*, 2006c)
^{154}Eu	8.593	β^-, 1.978	Complex branching at A = … density
^{155}Eu	4.753	β^-, 0.246	So far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1995)
^{153}Gd	0.658	EC, 0.244	Part of branching at $A = 154, 155$
^{160}Tb	0.198	β^-, 1.833	Weak temperature-sensitive branching, very challenging experiment
^{163}Ho	4570	EC, 0.0026	Branching at $A = 163$ sensitive to mass density during *s* process, so far only activation measurement at $kT = 25$ keV by Jaag and Käppeler (1996b)
^{170}Tm	0.352	β^-, 0.968	Important branching, constrains neutron density in low-mass AGB stars
^{171}Tm	1.921	β^-, 0.098	Part of branching at $A = 170, 171$
^{179}Ta	1.82	EC, 0.115	Crucial for *s*-process contribution to ^{180}Ta, nature's rarest stable isotope
^{185}W	0.206	β^-, 0.432	Important branching, sensitive to neutron density and *s*-process temperature in low-mass AGB stars
^{204}Tl	3.78	β^-, 0.763	Determines ^{205}Pb/^{205}Tl clock for dating of early Solar System

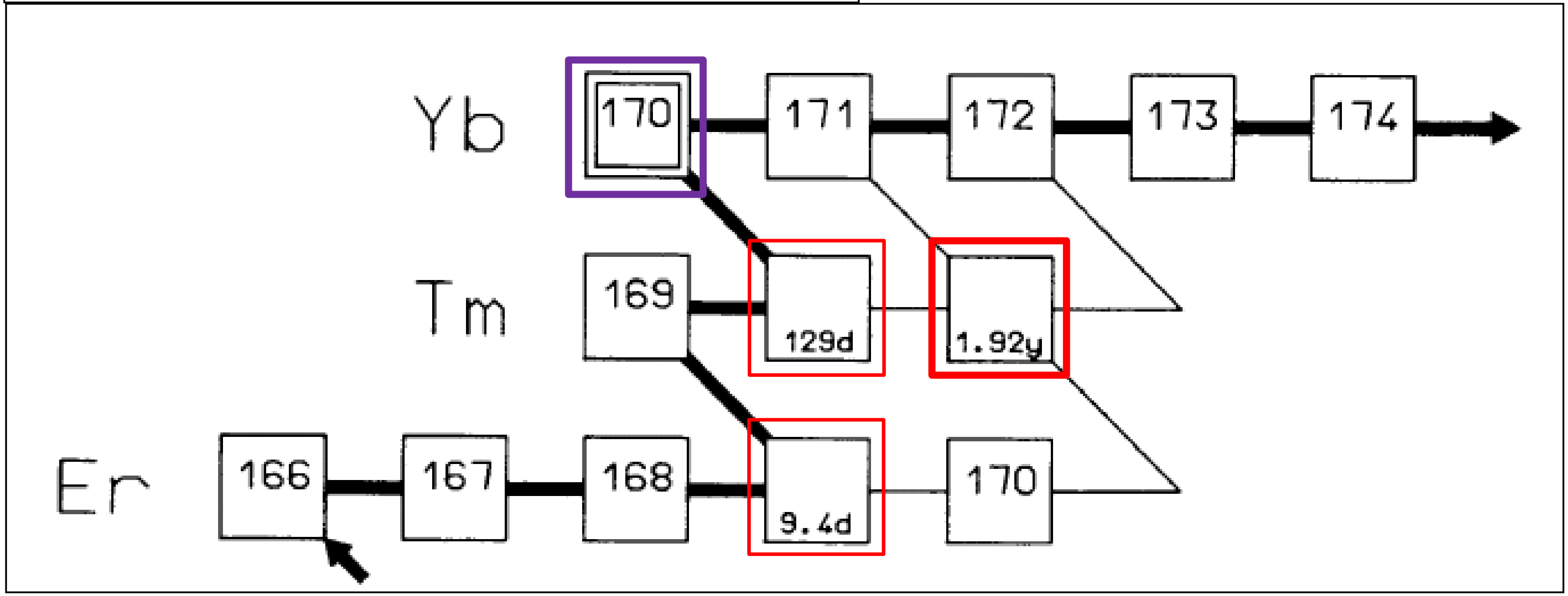
n_TOF→ PRL 110, 022501 (2013)

^{171}Tm as part of branching at A=170/171

The A=170/171 branching point is one of the branchings that is independent of stellar temperature, therefore suited for constraining the s-process neutron density in low-mass AGB stars (i.e. main s-process component).

F. Kaeppeler et al., ApJ 354 (1990) 630-643

$$n_n = 0.7^{+4.9}_{-0.5} \cdot 10^8\ cm^{-3}$$

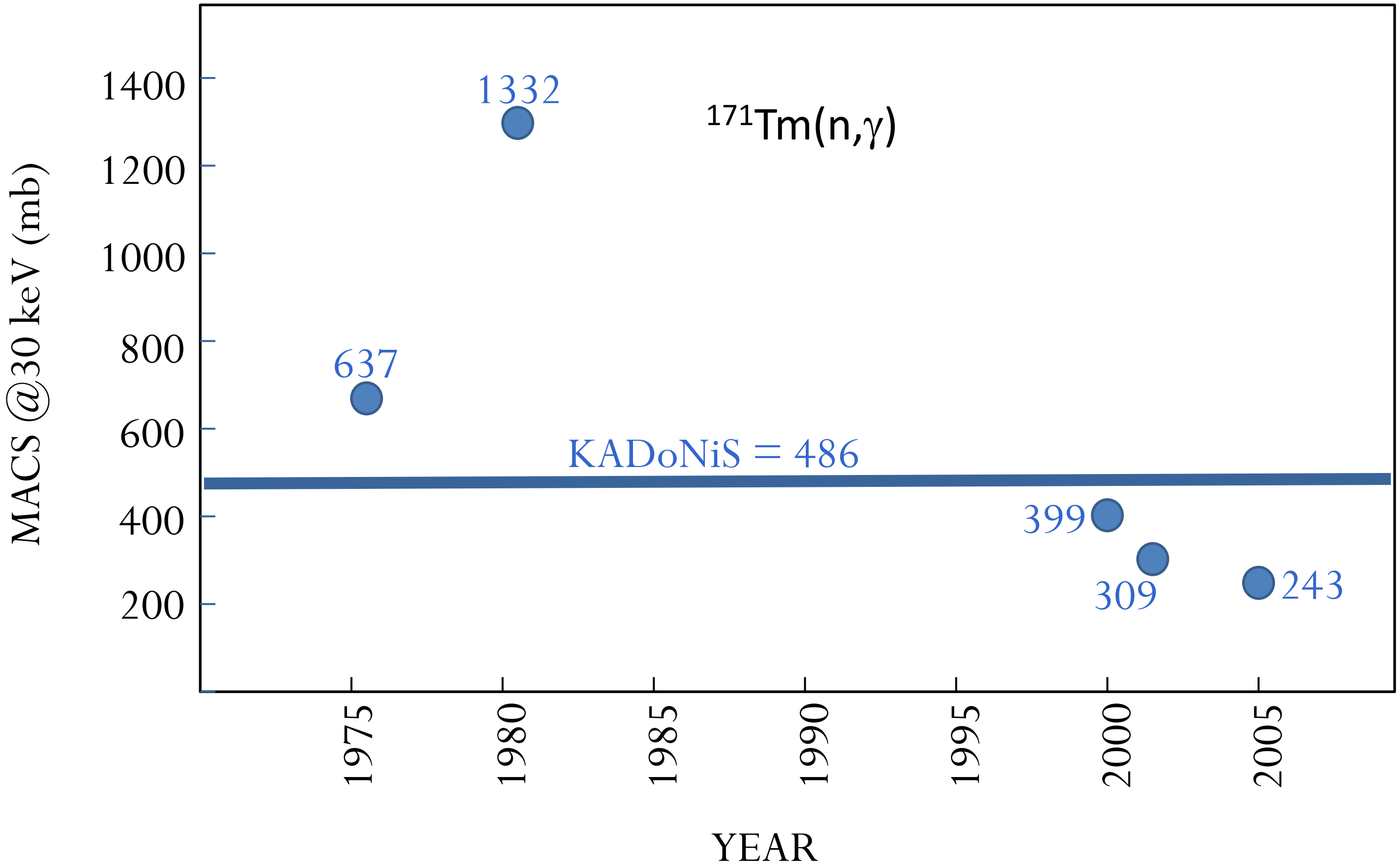


In view of the difficulties related to production of ^{170}Tm, experimental information on ^{171}Tm becomes important as part of the branching, but also as the more important for improved HF predictions of the ^{170}Tm cross section.

Status of ^{171}Tm Maxwellian averaged $\sigma(n,\gamma)$ (MACS) calculations

… such astrophysical studies require a reliable MACS for ^{171}Tm(n,g), however:

- **No experimental information available at all.**
- **Present MACS based on theoretical HF-calculations.**



At least a factor of 2 uncertainty in the ^{171}Tm(n,g) MACS is currently hindering a reliable and detailed analysis of the s-branching at $^{170/171}$Tm

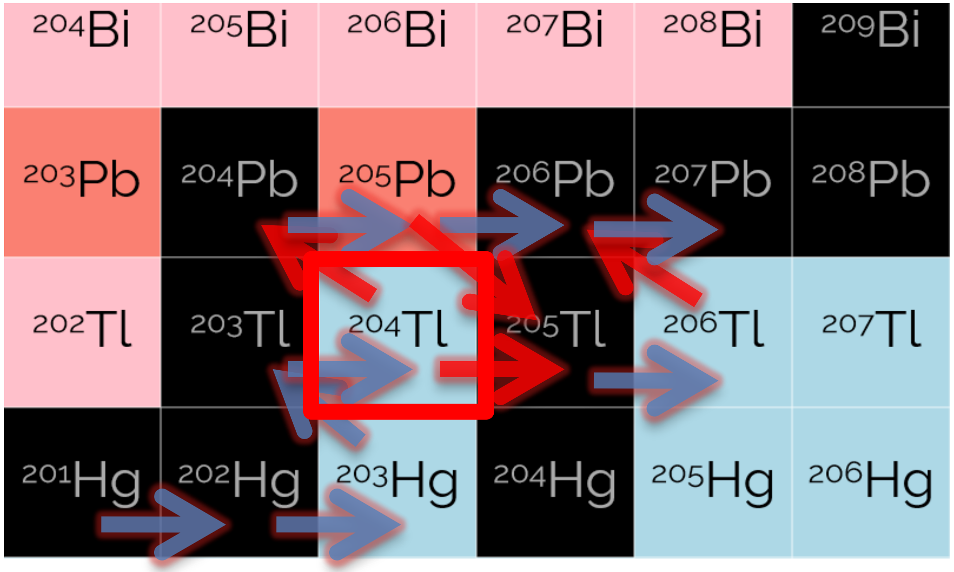
^{204}Tl determines the ^{205}Pb/^{205}Tl clock for dating of early Solar System

^{205}Pb ($t_{1/2}$ = 1.5x10^7 a) is produced only by the s-process:

The ratio ^{205}Pb/^{205}Tl provides highly interesting **chronometric information** about the time span between the last nucleosynthetic events that were able to modify the composition of the solar nebula and the formation of solar system solid bodies.

(At present, there is an upper limit for the ^{205}Pb/^{205}Tl abundance ratio of 9x10^{-5} from meteorites)

K. Yokoi et al., Astronomy and Astrophysics 145, 339-346 (1985)

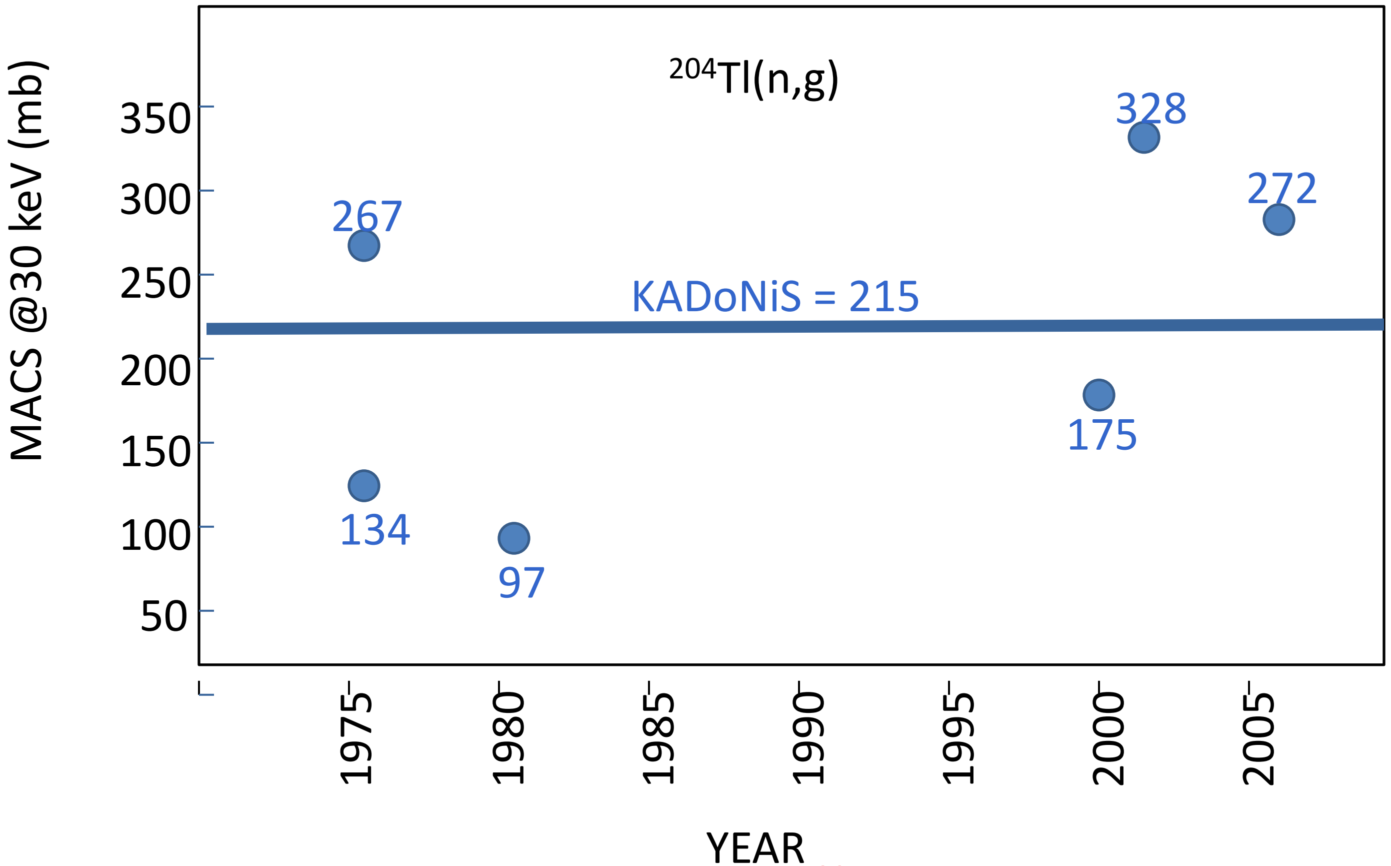


Anders & Stevens, J. Geoph. Res., 1961
Huey & Kohman, Earth Plan. Sci. Lett., 1972
Blake et al., Nature, 1973
Blake and Schramm, ApJ, 1975

Status of ^{204}Tl(n,g) MACS calculations

… such astrophysical studies require a reliable MACS for ^{204}Tl(n,g), however:

- **No experimental information available at all.**
- **Present MACS based on theoretical HF-calculations.**



At least a factor of 2 uncertainty in the ^{204}Tl(n,g) MACS is currently hindering a reliable and detailed analysis of the s-branching at ^{204}Tl

Samples production in three steps: step 1

Branching points are radioactive!

Production via (n,γ) or (n, γ)β^- in the ILL research reactor [Contact: Ulli Koester]

Neutron flux: 1.5×10^{15} n/cm^2/s (highest $F_{n,th}$ worldwide)

Irradiation time: 60 days (1.3 cycles) [March –June 2012]

Step 1: purchase of the stable isotopes and production of pellets to be irradiated.

Samples transformed into pellets at PSI [Contact: J. Neuhausen, D. Shumann]

- Pressed 5 mm diameter pellets
- Sintered at 1150^{o}C

Successfully completed in Spring 2013!

Samples production in two: step 2

Branching points are radioactive!

Production via (n,γ) or (n, γ)β^- in the ILL research reactor [Contact: Ulli Koester]

Neutron flux: $1.5\text{x}10^{15}$ n/cm^2/s (highest $F_{n,th}$ worldwide)

Irradiation time: 60 days (1.3 cycles) [March –June 2012]

Step 2: irradiation during 60 days at ILL

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^{171}Tm: ^{170}Er(n,g)^{171}Er (b$^-$, 7.5h)^{171}Tm (enrichment 1.8%)

3.63 mg of ^{171}Tm (1.9 y) [1.3e19 atoms]

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^{204}Tm: ^{203}Tl(n,g)^{204}Tl (enrichment 5.3%)

11 mg of ^{204}Tm (3.78 y) [3.25e19 atoms]

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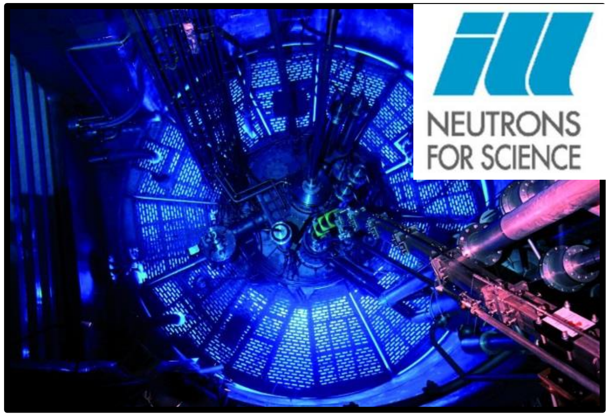
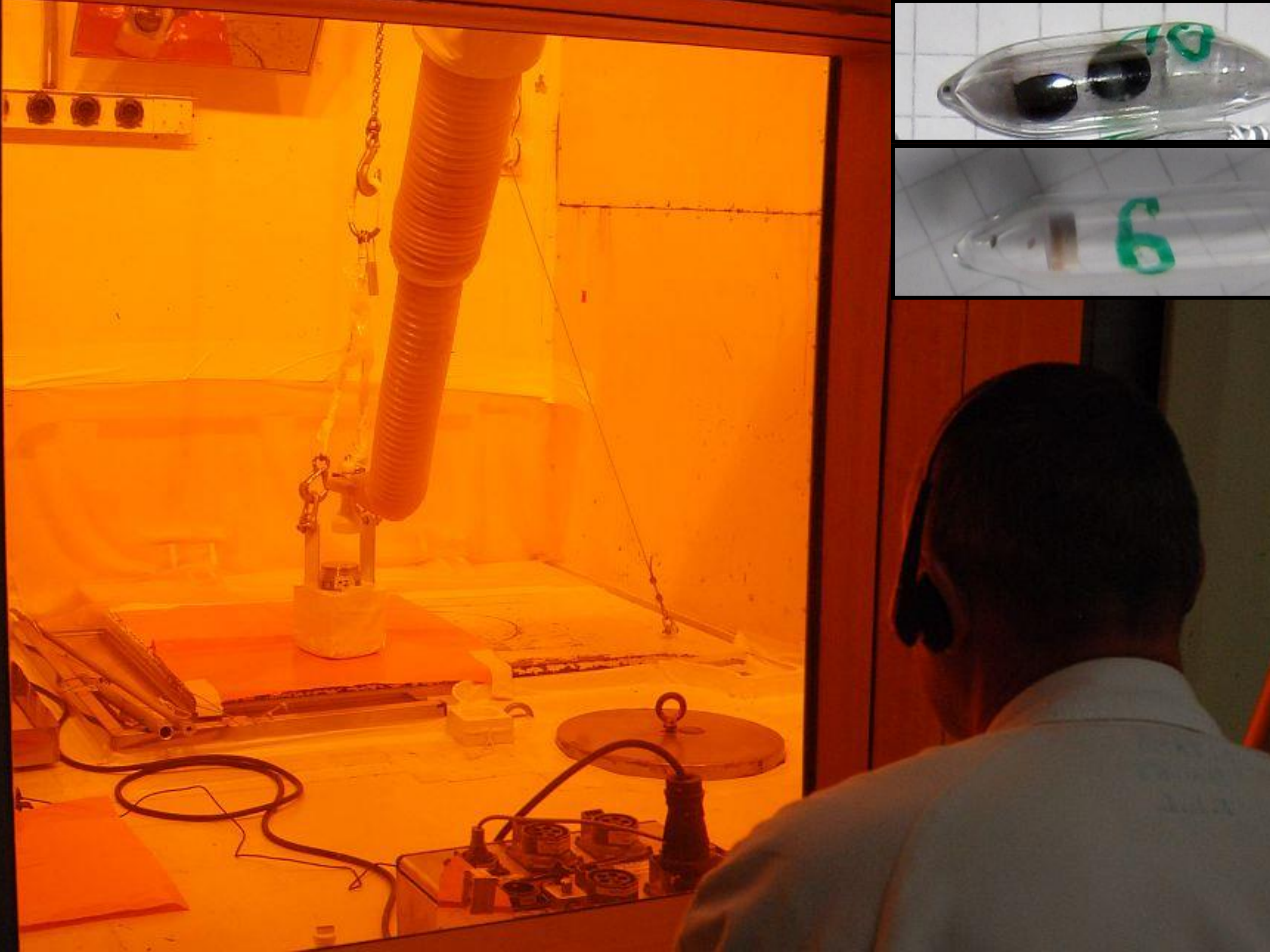
^{147}Pm: ^{146}Nd(n,g)^{147}Nd (b$^-$, 10d)^{147}Pm (enrichment 0.35%)

0.29 mg of ^{147}Pm (2.6 y) [1.2e18 atoms] (→EAR-2!)



A new source of radioactive samples for n_TOF

Successfully completed in Summer 2013!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Samples production in three steps: step 3 and 4

Branching points are radioactive!

Production via (n,γ) or (n, γ)β^- in the ILL research reactor [Contact: Ulli Koester]

Neutron flux: 1.5×10^{15} n/cm^2/s (highest $F_{n,th}$ worldwide)

Irradiation time: 60 days (1.3 cycles) [March –June 2012]

Step 3: chemical purification at PSI

We have now:

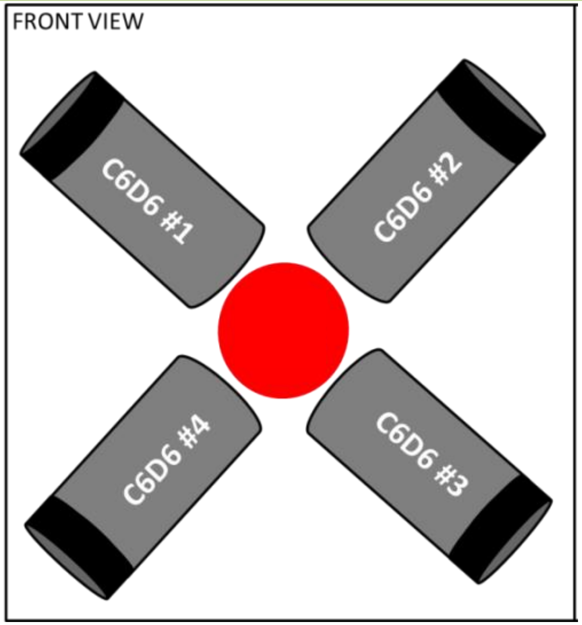
^{171}Tm: 1.80% in a ^{170}Er pellet of 5 mm in diameter

Step 4: shaping of the samples for use at n_TOF

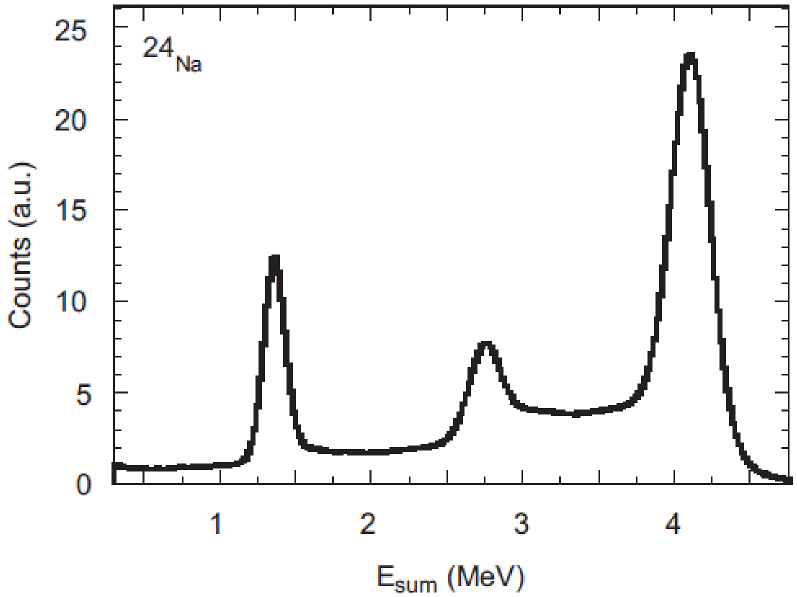
Work Ongoing

Experimental set-up

P. Mastinu et al., "*New C_6D_6 detectors: reduced neutron sensitivity and improved safety*", CERN-n_TOF-PUB-2013-002,



C. Guerrero, "The n_TOF Total Absorption Calorimeter for neutron capture measurements at CERN", NIM-A 608 (2009) 424-433

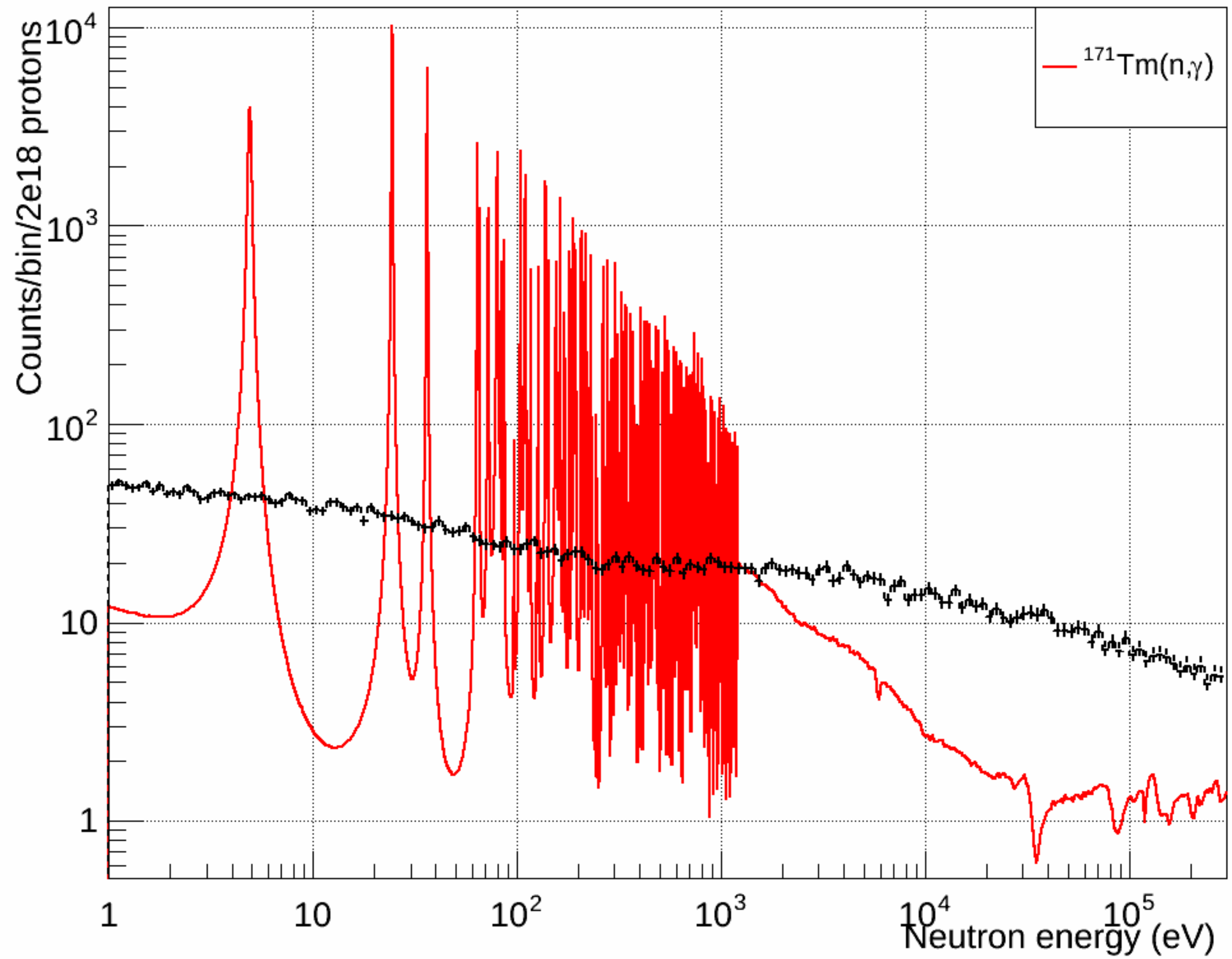


C6D6 vs. TAC:

- TAC: higher neutron sensitivity, but powerful background rejection capabilities (^{204}Tl)
- C6D6: lower neutron sensitivity, but less background discrimination (^{171}Tm)

Beam Time request: $^{171}Tm(n,\gamma)$

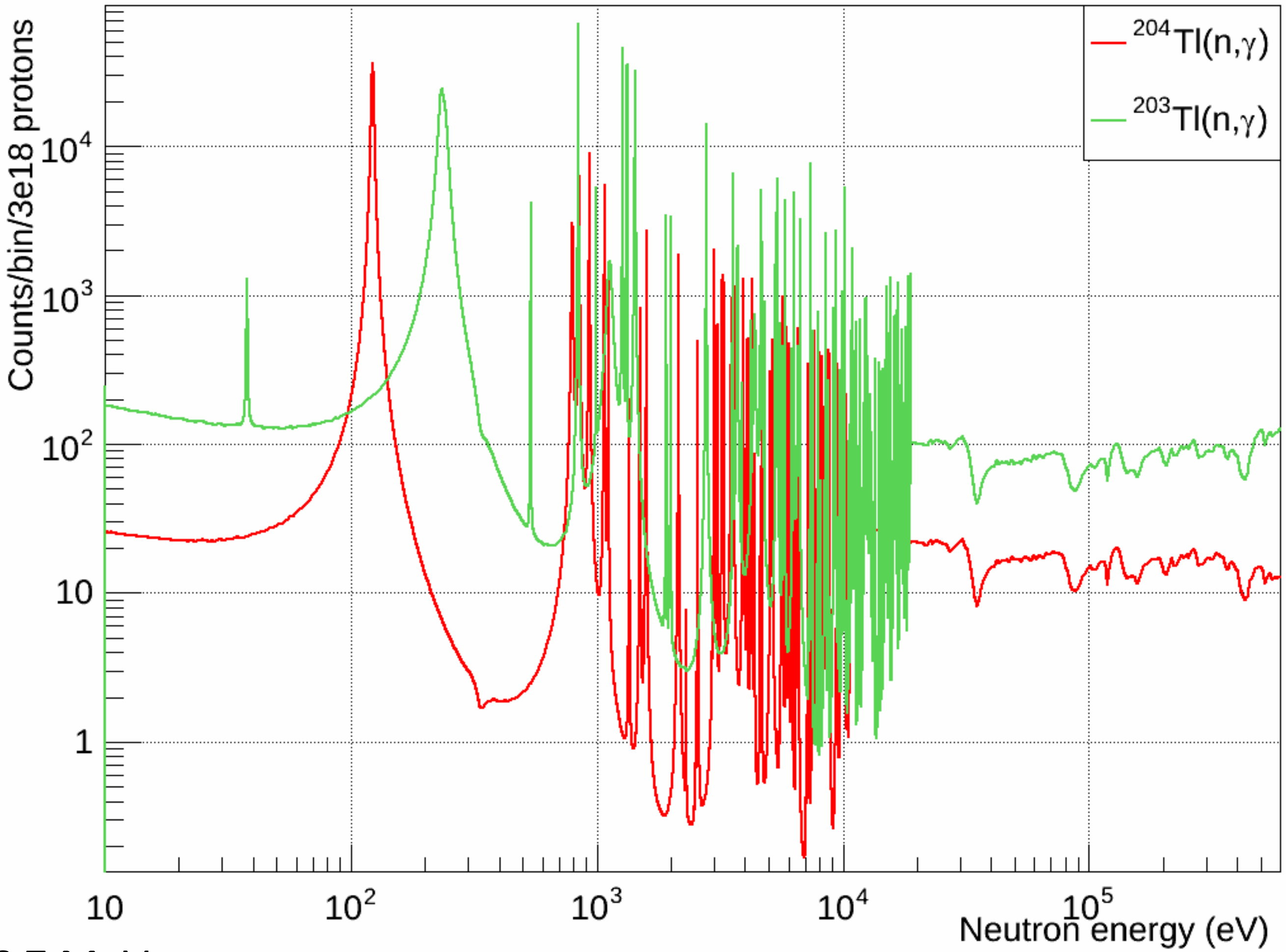
Beam time request based on the only evaluation available: TENDL-2012 (TALYS)



Background scaled by 0.33 (gain after PHWF)

Beam Time request: ^{204}Tl(n,γ)

Beam time request based on the only evaluation available: TENDL-2012 (TALYS)



$S_n(^{203+1}Tl)$=6.7 MeV

$S_n(^{204+1}Tl)$=7.5 MeV

Summary of beam request

In addition to the beam time allocated to the ^{171}Tm and ^{204}Tl measurements, background and normalization measurements will be carried out. The overall beam time request is summarized in Table 1.

Sample / Set-Up	Objective	Protons
^{171}Tm/C_6D_6	Capture Cross section of ^{171}Tm with C_6D_6	$2x10^{18}$
^{204}Tl / TAC	Capture Cross section of ^{204}Tl with TAC	$2.5x10^{18}$
^{203}Tl / TAC	Background from ^{203}Tl on the ^{204}Tl sample with TAC	$1x10^{18}$
Empty / C_6D_6	Overall beam-on background	$0.6x10^{18}$
Dummy / C_6D_6&TAC	Sample backing related background	$0.8x10^{18}$
^{197}Au / C_6D_6&TAC	Normalization and validation	$0.6x10^{18}$
Total		$7.5x10^{18}$

If approved by the INTC, the measurements should be scheduled within 2014 for avoiding decay leading to smaller amounts of ^{171}Tm (1.9 y) and ^{204}Tl (3.8 y)