

# *Neutron-induced reactions on U and Th – a new approach via AMS*

in collaboration with:



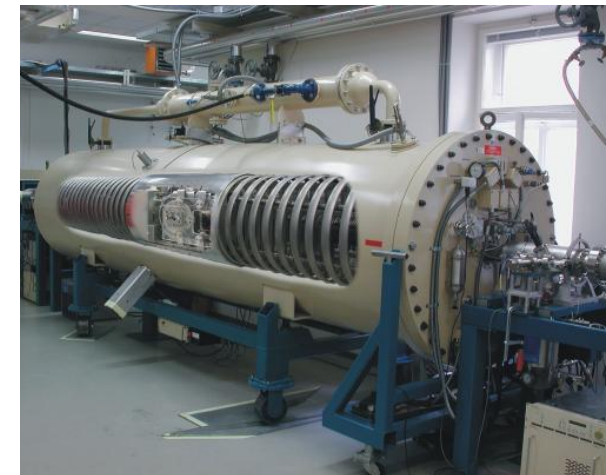
*neutrons*

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- IRMM / Geel: A. Plompen, A. Krasa
- IKI Budapest: T. Belgya, L. Szentmiklosi
- TSL Uppsala: A. Prokofiev et al.
- VERA (Vienna): P. Steier, S. Winkler, C. Lederer
- ANU (Canberra): L.K. Fifield, S. Tims, M. Srnecik
- ETH Zurich: M. Christl, J. Lachner
- ANSTO: M. Hotchkis
- Univ. Heidelberg: J. Lippold
- IAEA: R. Capote , V. Semkova

**A. Wallner**

**The Australian National  
University (ANU)**

**AMS**





## EFNUDAT



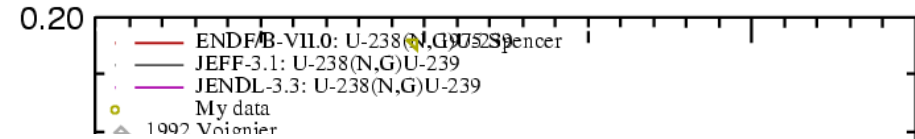
European Facilities for Nuclear Data Measurements

### AMS at VERA / ANU / ETH / ANSTO – neutron activations at IRMM / KIT / BRR / PTB

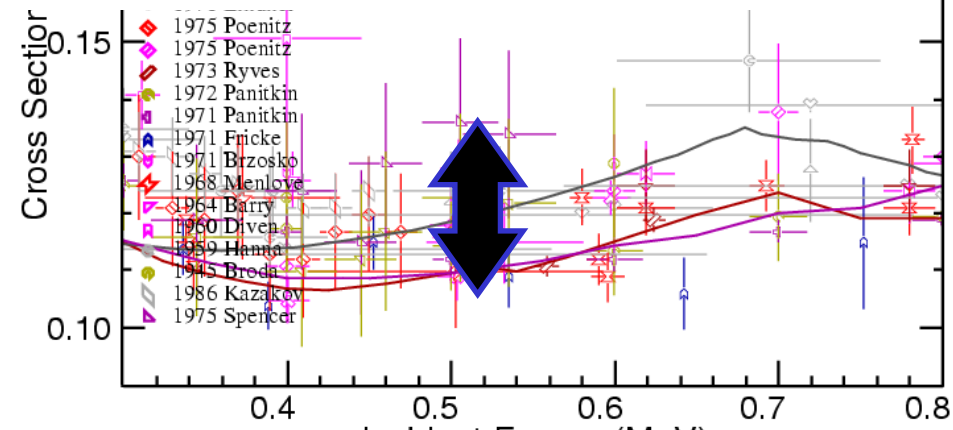
- Neutron capture cross section of  $^{235}\text{U}$  by activation and detection of  $^{236}\text{U}$  by AMS
- Thermal neutron capture cross section of  $^{235}\text{U}$  by activation and detection of  $^{236}\text{U}$  by AMS (EURATOM I3 project; collaboration IKI Budapest, Hungary / VERA, Univ. of Vienna)
- Definition of a standard neutron field with the  $^7\text{Li}(p,n)^7\text{Be}$  reaction at  $E_p = 1912$  keV
- Cross section measurements of  $^{204}\text{Pb}(n,3n)^{202g}\text{Pb}$  with the AMS technique (EU programme – EU-project EUPRAT, IRMM Geel, Belgium / VERA, Univ. of Vienna) 2010 - ...
- Cross section measurements of  $^{232}\text{Th}(n,2n)^{231}\text{Th}$ ,  $^{232}\text{Th}(n,3n)^{230}\text{Th}$  and  $^{238}\text{U}(n,3n)^{236}\text{U}$  with the AMS technique (EU programme – EU-project EUPRAT, IRMM Geel, Belgium / VERA, Univ. of Vienna) 2010 - ...
- Neutron capture in the low MeV energy range on  $^{238}\text{U}$  and  $^{232}\text{Th}$  measured with AMS (EU programme – EU-project EUPRAT, IRMM Geel, Belgium / VERA, Univ. of Vienna and ANSTO, Australia) 2011 - ...

# Motivation: $^{238}\text{U}(n,\gamma)/^{232}\text{Th}(n,\gamma): E_n > \text{thermal}$

- ratio of capture to fission of the fissile isotopes
- existing data via TOF and detections of prompt  $\gamma$ -rays;
- multiple scattering corrections due to large sample size in previous exp.? (e.g. 2 gram)
- HPRL (NEA) listed = highest priority
- large discrepancies above thermal  $E_n$
- $k_{\text{eff}}$  in reactor technology: even 5-10% discrepancy in cross section too much
- very few exp. data above thermal energies
- activation + AMS is an independent method; no influence from fission channel



**AMS: mg samples**



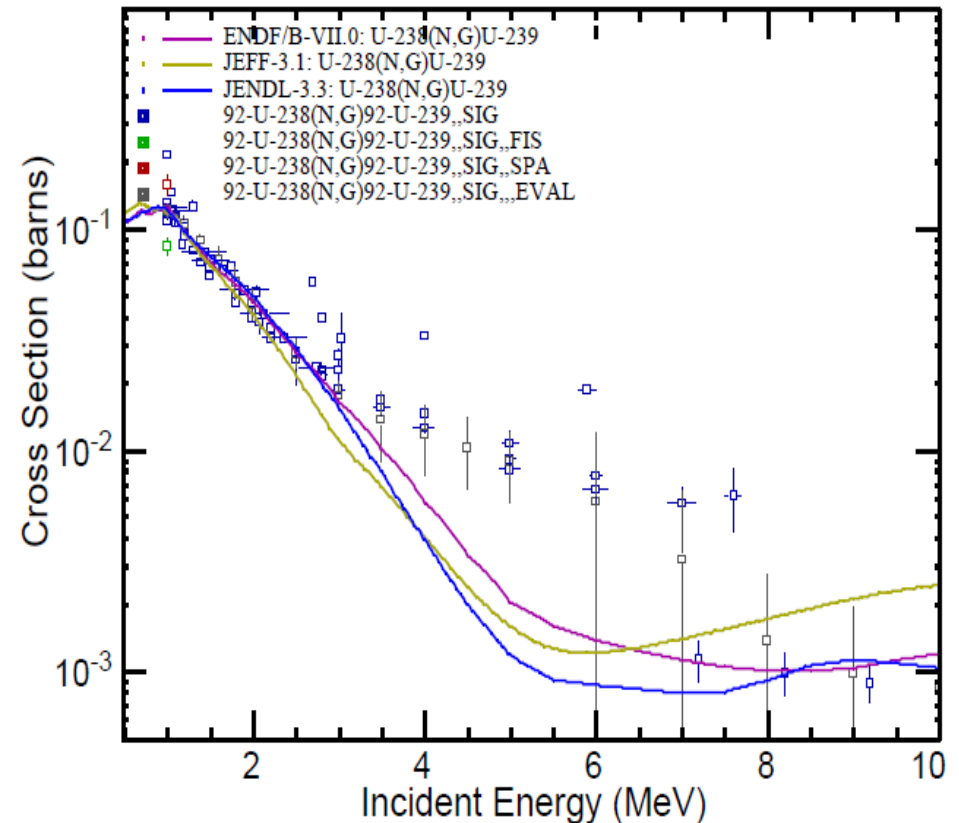
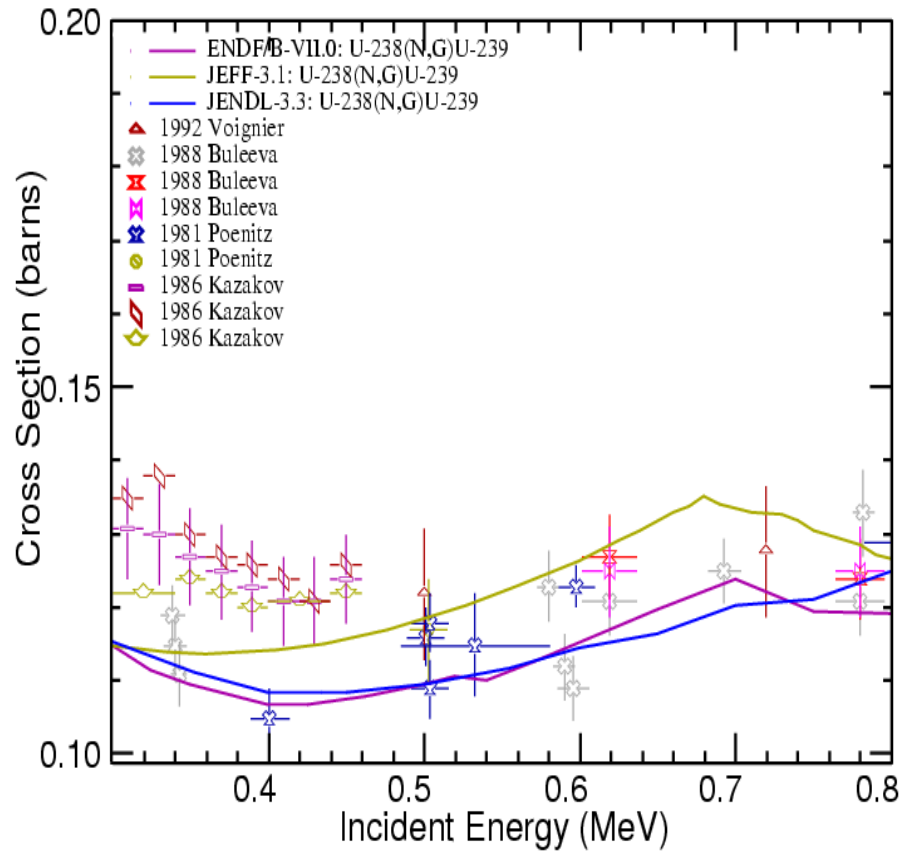
**AMS: atom counting**

- *new method* → *does not rely on previous drawbacks*
- *simple direct method!*

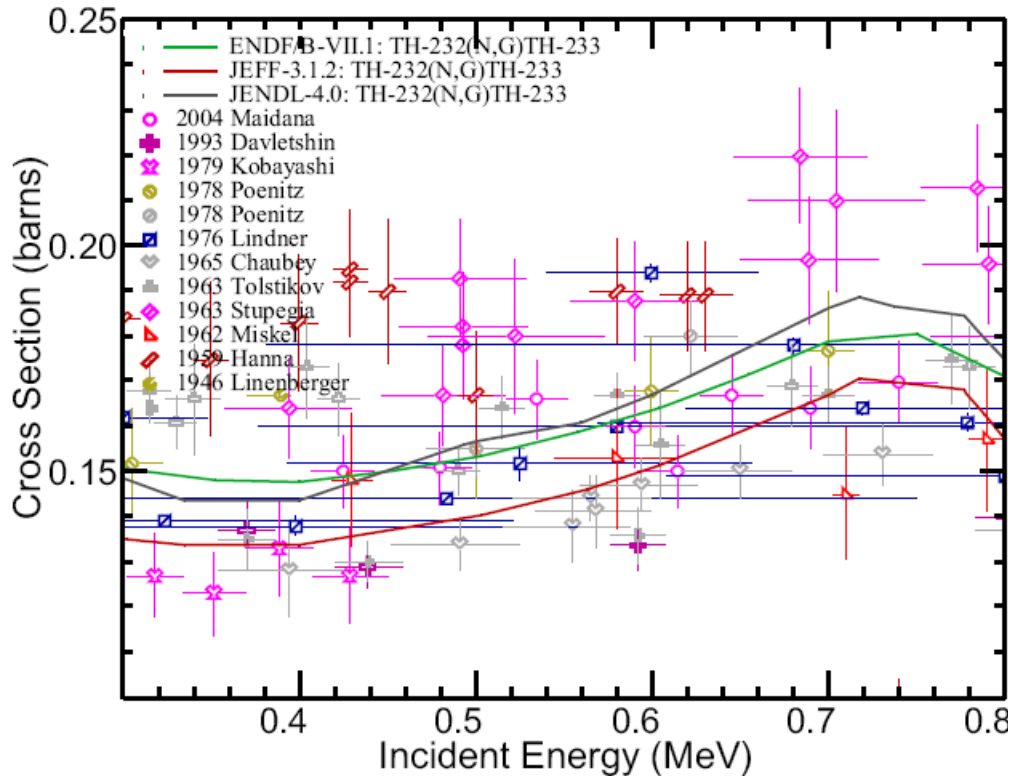
# $^{238}\text{U}(n,\gamma)^{239}\text{U}$

EXFOR database

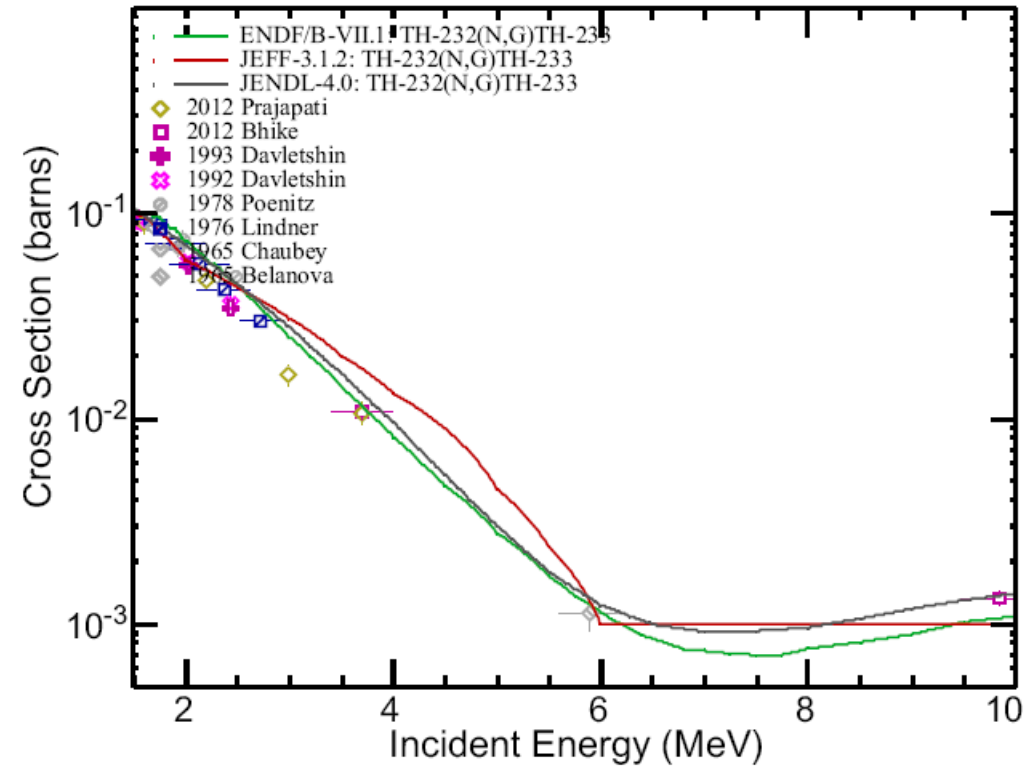
0.3 – 10 MeV



# $^{232}\text{Th}(n, \gamma)^{233}\text{Th}$



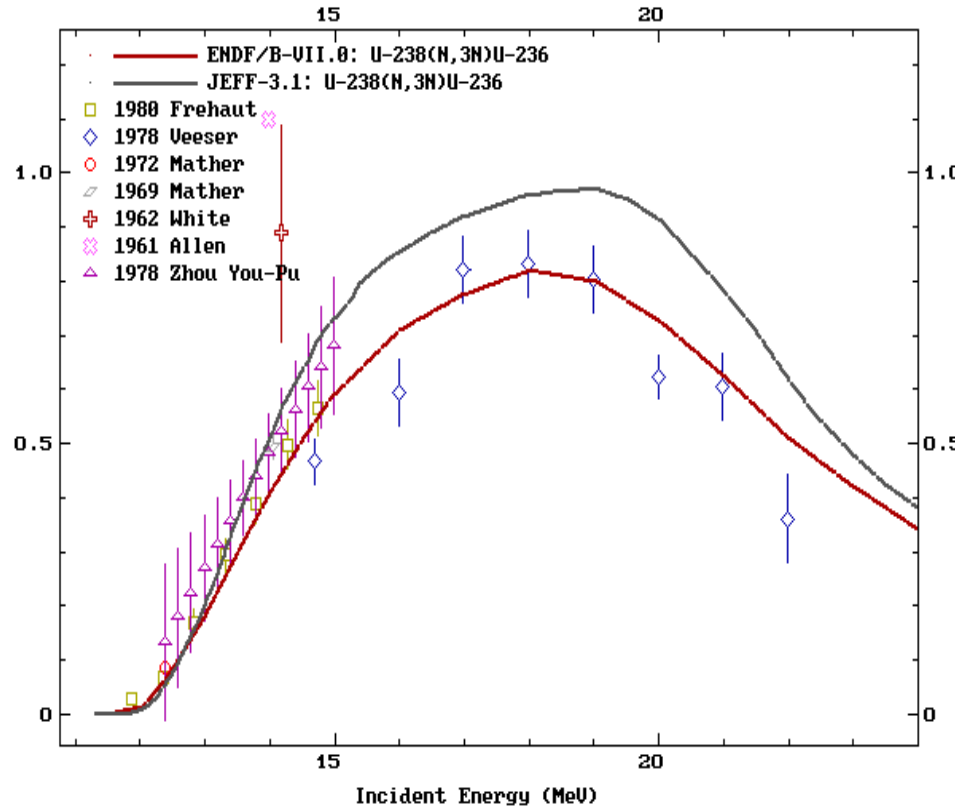
0.3 – 0.8 MeV



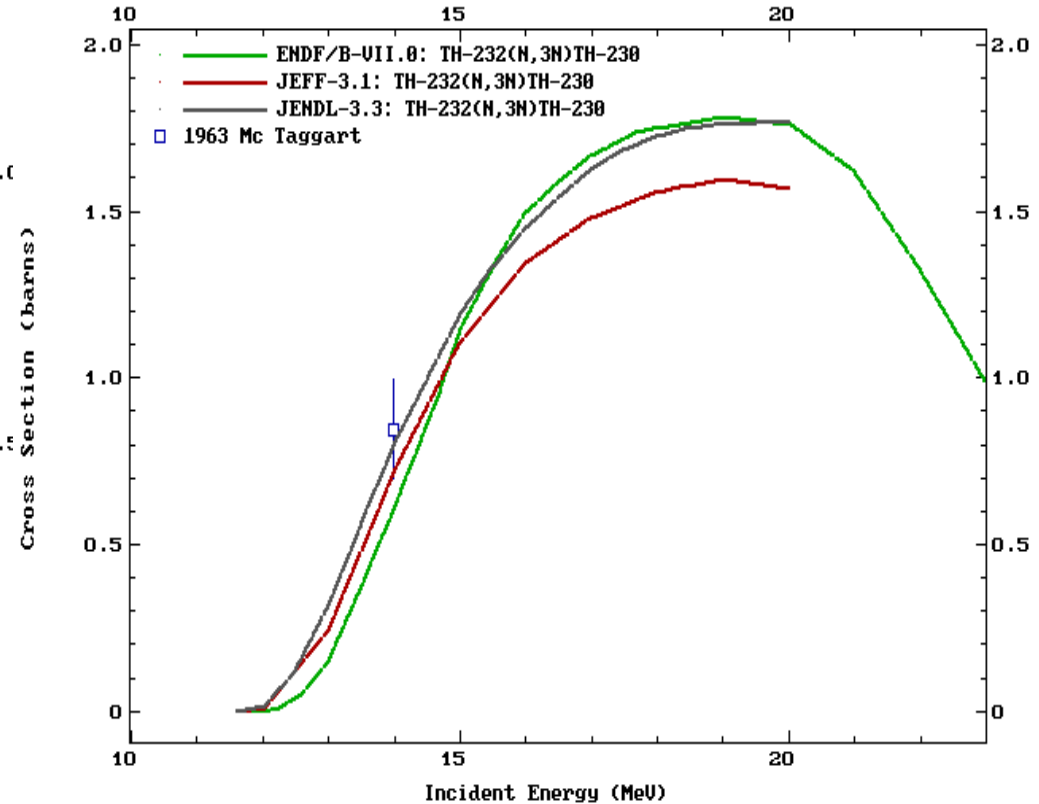
1.5 – 10 MeV

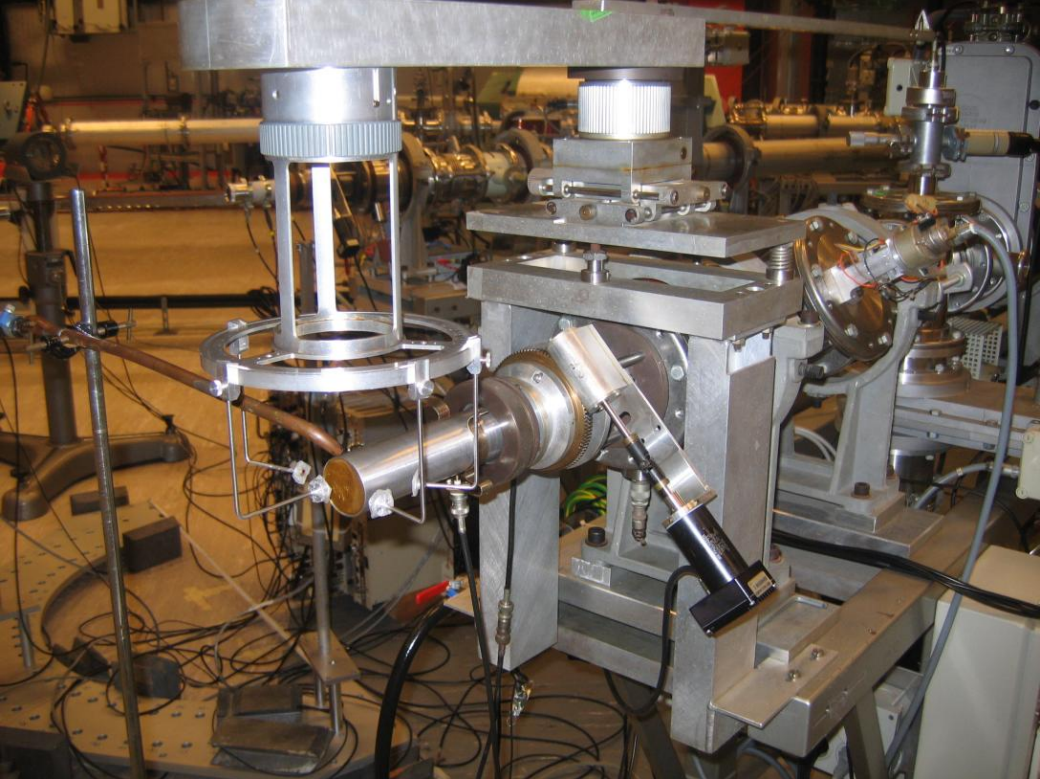
# $(n,3n)$ for $^{238}\text{U}$ and $^{232}\text{Th}$

ENDF Request 2262, 2009-Oct-15,09:17:38  
EXFOR Request: 7704/1, 2009-Oct-15 09:17:10

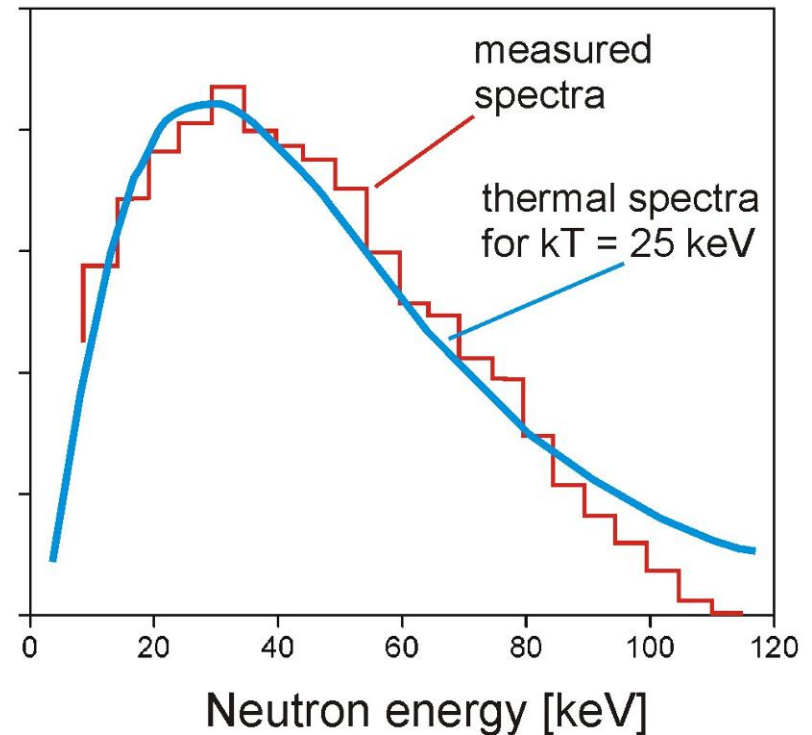


ENDF Request 2264, 2009-Oct-15,09:22:50  
EXFOR Request: 7705/1, 2009-Oct-15 09:22:35





Neutron intensity

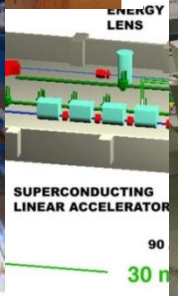
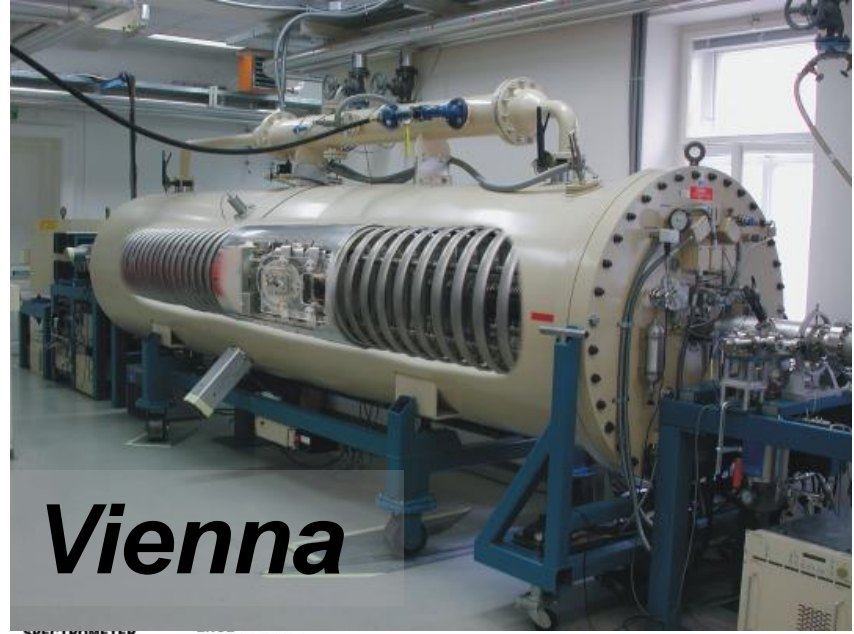
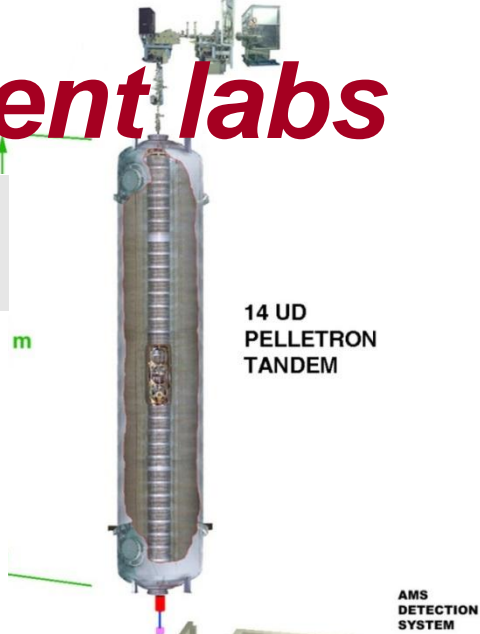
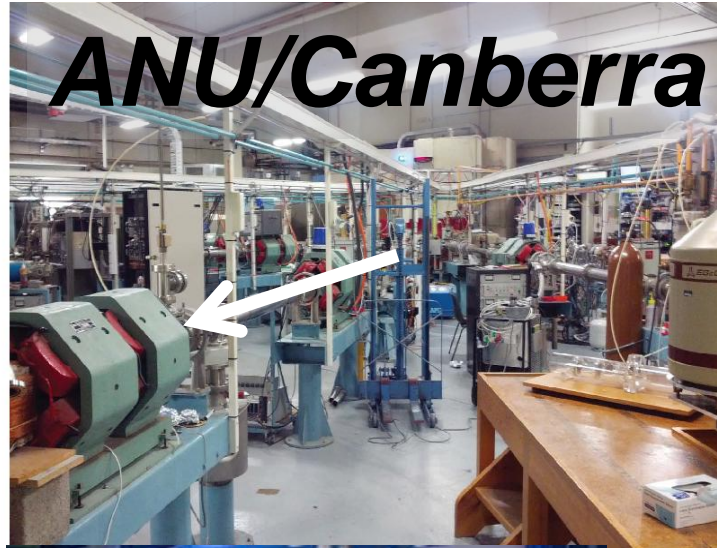


→ **products using the most sensitive technique: AMS**

- Atoinstitut Vienna: **research reactor, thermal neutrons**
- ▪ IKI Budapest: **research reactor, thermal neutrons; cold neutrons**
- TSL Uppsala: **cyclotron,  ${}^7\text{Li}(p,n)$ : 45 MeV neutrons**

# AMS at different labs

**ANU/Canberra**

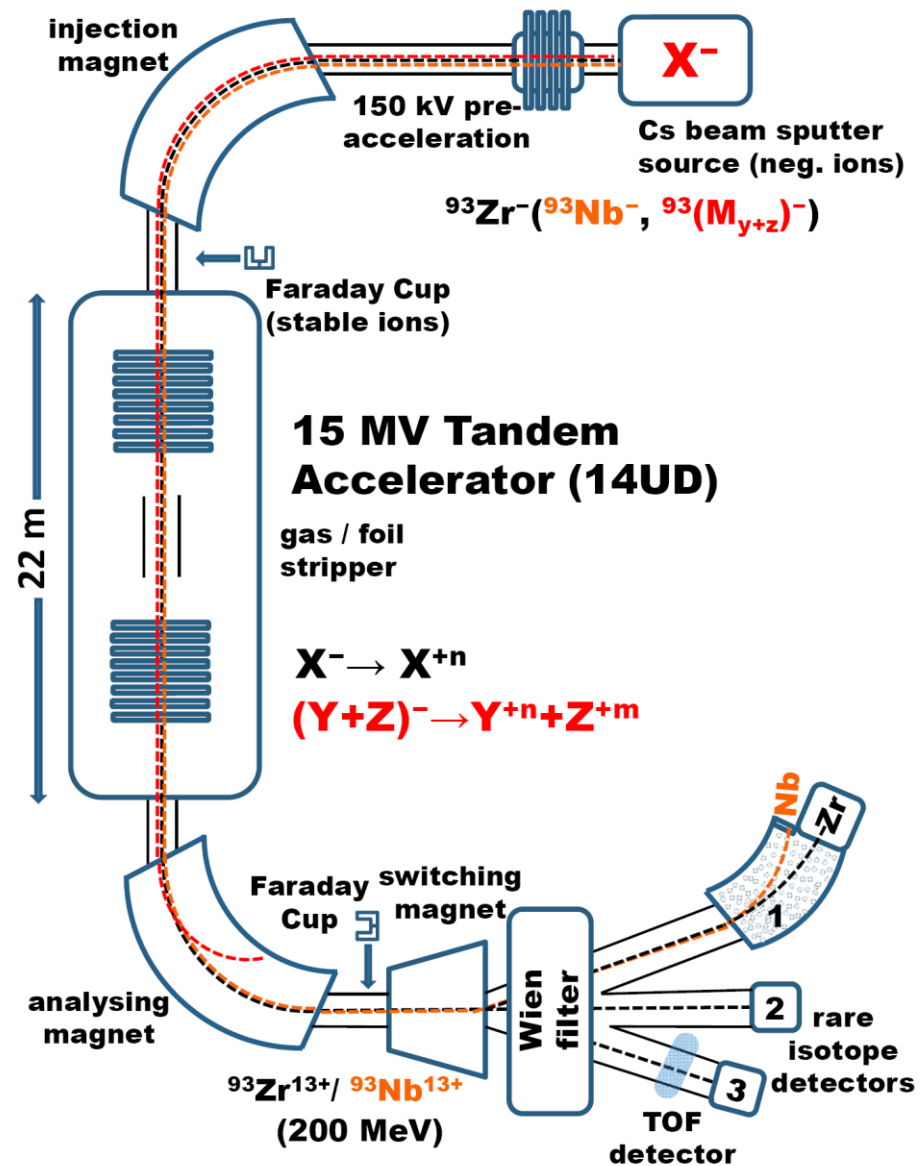


Wallner M



# ANU's AMS facility

- AMS determines isotope ratios – **atom counting technique**
- $^{14}\text{C}/^{12}\text{C}$  – radiocarbon dating
- highest sensitivity:  $10^{-12}$  –  $10^{-16}$
- no isobaric background ( $\leftrightarrow$  ICPMS) (molecules are completely destroyed)
- isotopic background clearly identified



# How to derive cross sections?

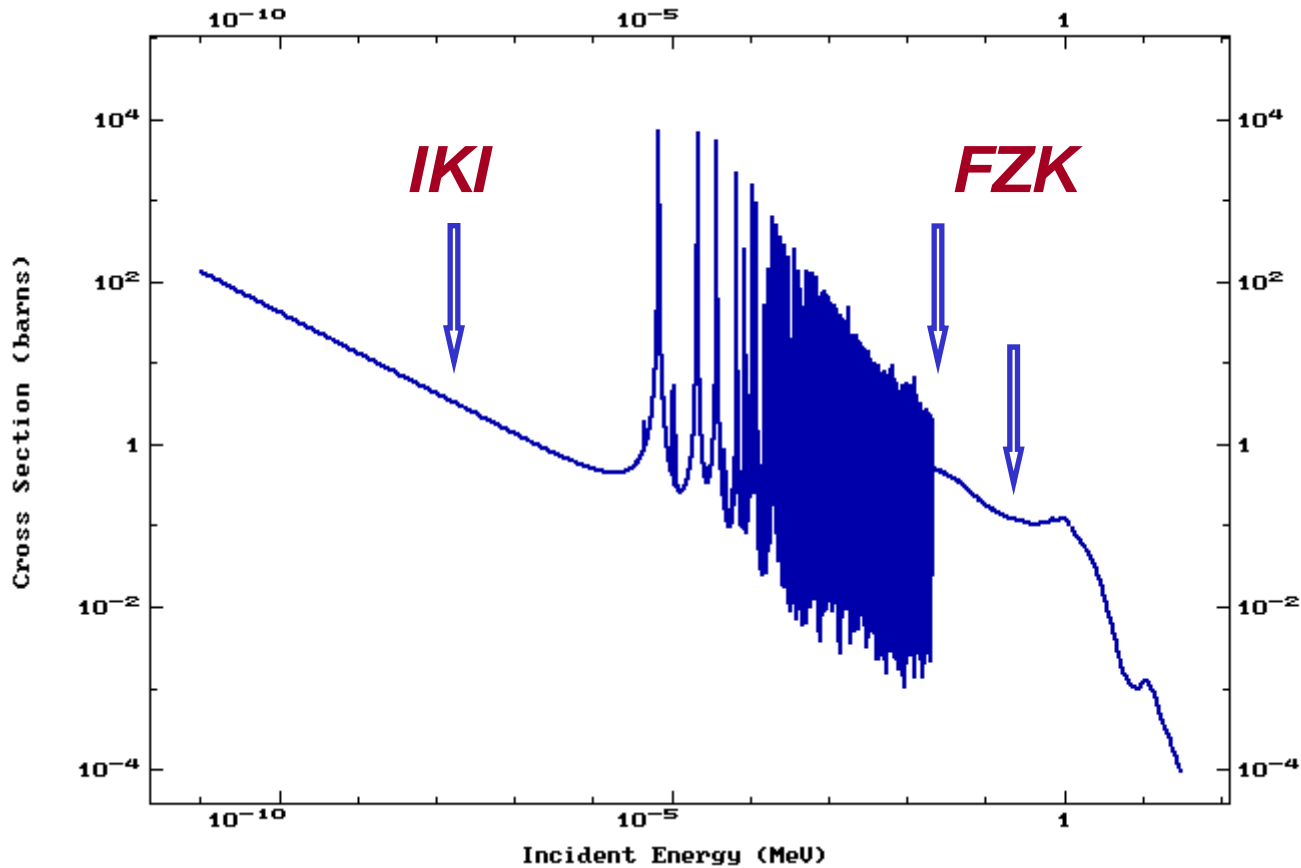
$$\sigma_{\text{exp}} = \frac{N_{\text{product}}}{N_{\text{target}}} \times \frac{1}{\Phi}$$

AMS-  
isotope ratio

Monitor  
(Au, Nb,...)

*AMS monitor reaction (Au)*

*U*



# $^{236}\text{U}$ & $^{239}\text{U}$ : Production & Decay

	<b>Cm 237</b> ? $\alpha$ 6.656	<b>Cm 238</b> 2.4 h $\alpha$ 6.558; 6.503 $\gamma$ 55	<b>Cm 239</b> 3 h $\epsilon$ 188... g	<b>Cm 240</b> 27 d sf $\alpha$ 6.291; 6.248... sf g	<b>Cm 241</b> 32.8 d sf $\alpha$ 5.939... $\gamma$ 472; 431; 132... $\epsilon$ - g	<b>Cm 242</b> 162.94 d sf $\alpha$ 6.113; 6.069... sf; g $\gamma$ (44...); $\epsilon$ - $\alpha$ -20 $\sigma$ 130; $\sigma_f$ 620	<b>Cm 243</b> 29.1 a sf $\alpha$ 5.785; 5.742... $\epsilon$ ; sf; g $\gamma$ 278; 228; 210...; $\epsilon$ - $\sigma$ 130; $\sigma_f$ 620	<b>Cm 244</b> 18.10 a sf $\alpha$ 5.805; 5.762... sf; g $\gamma$ (43...); $\epsilon$ - $\sigma$ 15; $\sigma_f$ 1.1	<b>Cm 245</b> 8500 a sf $\alpha$ 5.361; 5.304... sf; g $\gamma$ 175; 133... $\sigma$ 350; $\sigma_f$ 2100	<b>Cm 246</b> 4730 a sf; g $\alpha$ 5.386; 5.343... sf; g $\gamma$ (45); $\epsilon$ - $\sigma$ 1.2; $\sigma_f$ 0.16
<b>Am 235</b> 10.3 m $\epsilon$ 6.457 $\gamma$ 291; 224; 270; 739; 749...	<b>Am 236</b> 2.9 m 3.6 m $\epsilon$ 6.15 7 $\gamma$ 583; 654; 713... $\epsilon$ 6.15 7 $\gamma$ 719; 880; 320...	<b>Am 237</b> 73.0 m sf $\alpha$ 6.042... $\gamma$ 280; 438; 474; 909... g	<b>Am 238</b> 1.63 h sf $\alpha$ 5.94 $\gamma$ 963; 919; 561; 605... g	<b>Am 239</b> 11.9 h sf $\alpha$ 5.774... $\gamma$ 278; 228... 608; 808... g	<b>Am 240</b> 50.8 h sf $\alpha$ 5.378... $\sigma$ 308; 808... g	<b>Am 241</b> 432.2 a sf $\alpha$ 5.486; 5.443... sf; $\gamma$ 60; 26... $\epsilon$ -; g; $\sigma$ 60 + 640 $\sigma_f$ 3.15	<b>Am 242</b> 141 a 16 h sf $\beta$ (49); $\epsilon$ - $\alpha$ 5.206... sf; $\gamma$ (49...); $\epsilon$ - $\sigma$ 1700 $\sigma_f$ 5900	<b>Am 243</b> 7370 a sf $\alpha$ 5.275; 5.233... sf; $\gamma$ 75; 44... $\sigma$ 75 + 5 $\sigma_f$ 0.079	<b>Am 244</b> 26 m 10.1 h sf $\beta$ 1.5... $\beta$ 0.4 $\gamma$ 744; 898; 154...; $\epsilon$ - $\sigma$ 1800 $\sigma_f$ 2200	<b>Am 245</b> 2.05 h sf $\beta$ 0.9... $\gamma$ 253; (241; 296...); $\epsilon$ -; g
<b>Pu 234</b> 8.8 h $\alpha$ 6.15... $\gamma$ ; $\epsilon$ -	<b>Pu 235</b> 25.3 m sf $\alpha$ 5.65 $\gamma$ 49; (756; 34...) $\epsilon$ -	<b>Pu 236</b> 2.858 a sf $\alpha$ 5.788; 5.721... sf; Mg 28 $\gamma$ (46; 109...); $\epsilon$ - $\sigma$ 160	<b>Pu 237</b> 45.2 d sf $\alpha$ 5.334... $\gamma$ (43; 100...); $\epsilon$ - $\sigma_f$ 2300	<b>Pu 238</b> 87.74 a sf $\alpha$ 5.499; 5.44... sf; Si; Mg $\gamma$ (43; 100...); $\epsilon$ - $\sigma$ 510; $\sigma_f$ 17	<b>Pu 239</b> $2.411 \cdot 10^4$ a sf $\alpha$ 5.157; 5... sf; $\gamma$ (52...) $\epsilon$ -; m $\sigma$ 270; $\sigma_f$ 752	<b>Pu 240</b> 6563 a sf $\alpha$ 5.168; 5.124... $\gamma$ (45...) $\epsilon$ -; g; $\sigma$ 290; $\sigma_f$ -0.059	<b>Pu 241</b> 14.35 a sf $\beta$ 0.02; g $\alpha$ 4.896... $\gamma$ (149...); $\epsilon$ - $\sigma$ 370; $\sigma_f$ 1010	<b>Pu 242</b> $3.750 \cdot 10^5$ a sf $\alpha$ 4.901; 4.856... sf; $\gamma$ (45...) $\epsilon$ -; g $\sigma$ 19; $\sigma_f$ <0.2	<b>Pu 243</b> 4.956 h sf $\beta$ 0.6... $\gamma$ 84...; g $\sigma$ <100; $\sigma_f$ 200	<b>Pu 244</b> $8.00 \cdot 10^7$ a sf $\alpha$ 4.589; 4.546 sf; $\gamma$ $\epsilon$ - $\sigma$ 1.7
<b>Np 233</b> 36.2 m $\epsilon$ 5.54 $\gamma$ (312; 299; 547...)	<b>Np 234</b> 4.4 d $\epsilon$ ; $\beta$ +... $\gamma$ 1559; 1528; 1602... $\sigma_f$ -900	<b>Np 235</b> 396.1 d $\epsilon$ ; $\alpha$ 5.025... 5.007... $\gamma$ (26; 84...); $\epsilon$ - g; $\sigma$ 180 + ?	<b>Np 236</b> 225 h $1.54 \cdot 10^5$ a sf $\epsilon$ ; $\beta$ 0.5... $\gamma$ (84); 688...; $\epsilon$ - g; $\sigma_f$ 2700	<b>Np 237</b> 2.144 $\cdot 10^6$ a sf $\epsilon$ ; $\beta$ 0.5... $\gamma$ (84); 104...; $\epsilon$ - g; $\sigma_f$ 3000	<b>Np 238</b> 2.117 d $\beta$ 1.2... $\gamma$ 984; 1029; 1026; 924...; $\epsilon$ - $\sigma$ 2600	<b>Np 239</b> 2.355 d $\beta$ 0.4; 0.7... $\gamma$ 106; 278; 228...; $\epsilon$ -; g $\sigma$ 32 + 19; $\sigma_f$ <1	<b>Np 240</b> 7.22 m 65 m $\beta$ 2.2... $\gamma$ 555; 597... $\sigma$ 1800 $\sigma_f$ 27; $\sigma_f$ 6	<b>Np 241</b> 13.9 m $\beta$ 1.3... $\gamma$ 175; (133...) g	<b>Np 242</b> 2.2 m 5.5 m $\beta$ 2.7... $\gamma$ 736; 780; 1473... g	<b>Np 243</b> 1.85 m $\beta$ - $\gamma$ 288 g
<b>U 232</b> 68.9 a $\alpha$ 5.262... $\gamma$ (51; 29...); $\epsilon$ - $\sigma$ 73; $\sigma_f$ 74	<b>U 233</b> $1.592 \cdot 10^5$ a $\alpha$ 4.824; 4.783... Ne 25; $\gamma$ (42; 97...); $\epsilon$ - $\sigma$ 47; $\sigma_f$ 530	<b>U 234</b> 0.0054 $2.455 \cdot 10^5$ a $\alpha$ 4.775; 4.723... Mg 28; Ne; $\gamma$ (53; 121...) $\epsilon$ -; $\sigma$ 96; $\sigma_f$ 0.07	<b>U 235</b> 0.7204 26 m $7.038 \cdot 10^8$ a $\alpha$ 4.398... Ne; $\gamma$ 18... $\sigma$ 95; $\sigma_f$ 2	<b>U 236</b> $120$ ns $2.342 \cdot 10^7$ a $\alpha$ 4.494; 4.445... $\gamma$ 1783; sf; $\gamma$ (49...); 642...; 113... $\epsilon$ -; $\sigma$ 100; $\sigma_f$ <0.35	<b>U 237</b> 6.75 d $\beta$ 0.2... $\gamma$ 60; 208... $\epsilon$ - $\sigma$ 100; $\sigma_f$ <0.35	<b>U 238</b> 99.2742 298 ns $4.468 \cdot 10^8$ a $\alpha$ 4.198... 1800...; $\sigma$ 27; $\sigma_f$ 6	<b>U 239</b> 23.5 m $\beta$ 1.2; 1.3... $\gamma$ 75; 44... $\sigma$ 22; $\sigma_f$ 15	<b>U 240</b> 14.1 h $\beta$ 0.4... $\gamma$ 44; (190...) $\epsilon$ - m		
<b>Pa 231</b> $3.276 \cdot 10^4$ a $\alpha$ 5.014; 4.952; 5.028...; Ne 24; F 237 $\gamma$ 27; 300; 303...; $\epsilon$ - $\sigma$ 200; $\sigma_f$ 0.020	<b>Pa 232</b> 1.31 d $\beta$ 0.3; 1.3...; $\epsilon$ $\gamma$ 969; 894; 150...; $\epsilon$ - $\sigma$ 460; $\sigma_f$ 1500	<b>Pa 233</b> 27.0 d $\beta$ 0.3; 0.6... $\gamma$ 312; 300; 341...; $\epsilon$ - $\sigma$ 20 + 19; $\sigma_f$ <0.1	<b>Pa 234</b> 1.17 m 6.70 h $\beta$ 2.3... $\gamma$ (1001); 787...; $\sigma$ 131; 861; $\gamma$ (74...); $\epsilon$ - $\sigma$ <500 $\sigma_f$ <3000	<b>Pa 235</b> 24.2 m $\beta$ 1.4... $\gamma$ 128 - 659 m	<b>Pa 236</b> 9.1 m $\beta$ 2.0; 3.1... $\gamma$ 642; 687; 1763...; g bsf ?	<b>Pa 237</b> 8.7 m $\beta$ 1.4; 2.3... $\gamma$ 854; 865; 529; 541... g	<b>Pa 238</b> 2.3 m $\beta$ 1.7; 2.9... $\gamma$ 1015; 635; 448; 680... g	<b>Pa 239</b> 1.8 h $\beta$ - $\gamma$ 522-681		
<b>Th 230</b> $7.54 \cdot 10^4$ a $\alpha$ 4.687; 4.621... $\gamma$ (68; 144...); $\epsilon$ - Ne 24; $\sigma$ 23.4 $\sigma_f$ <0.0005	<b>Th 231</b> 25.5 h $\beta$ 0.3; 0.4... $\gamma$ 26; 84... $\epsilon$ -	<b>Th 232</b> 100 $1.405 \cdot 10^{10}$ a $\alpha$ 4.013; 3.950...; sf $\gamma$ (64...); $\epsilon$ - $\sigma$ 7.37; $\sigma_f$ 0.000006	<b>Th 233</b> 22.3 m $\beta$ 1.2... $\gamma$ 87; 29; 459...; $\epsilon$ - $\sigma$ 1500; $\sigma_f$ 15	<b>Th 234</b> 24.10 d $\beta$ 0.2... $\gamma$ 63; 92; 93... $\epsilon$ -; m $\sigma$ 1.8; $\sigma_f$ <0.01	<b>Th 235</b> 7.1 m $\beta$ 1.4... $\gamma$ 417; 727; 696...	<b>Th 236</b> 37.5 m $\beta$ 1.0... $\gamma$ 111; (647; 196...)	<b>Th 237</b> 5.0 m $\beta$ -	<b>Th 238</b> 9.4 m $\beta$ - $\gamma$ 89		

$^{236}\text{U}$ :  $t_{1/2} = 23.4$  Myr

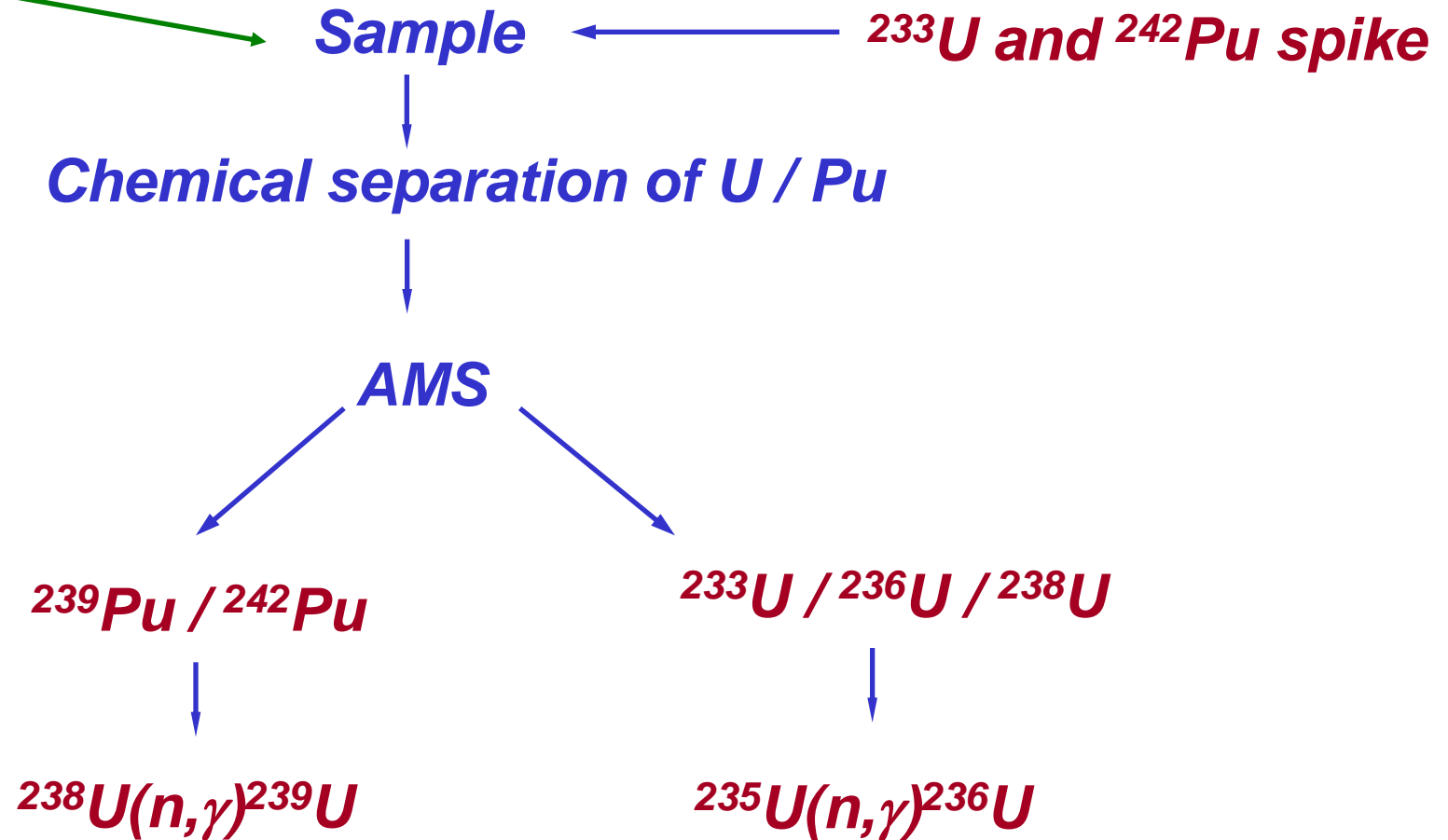
$^{239}\text{U}$ :  $t_{1/2} = 23.5$  min

$^{239}\text{Np}$ :  $t_{1/2} = 2.35$  days

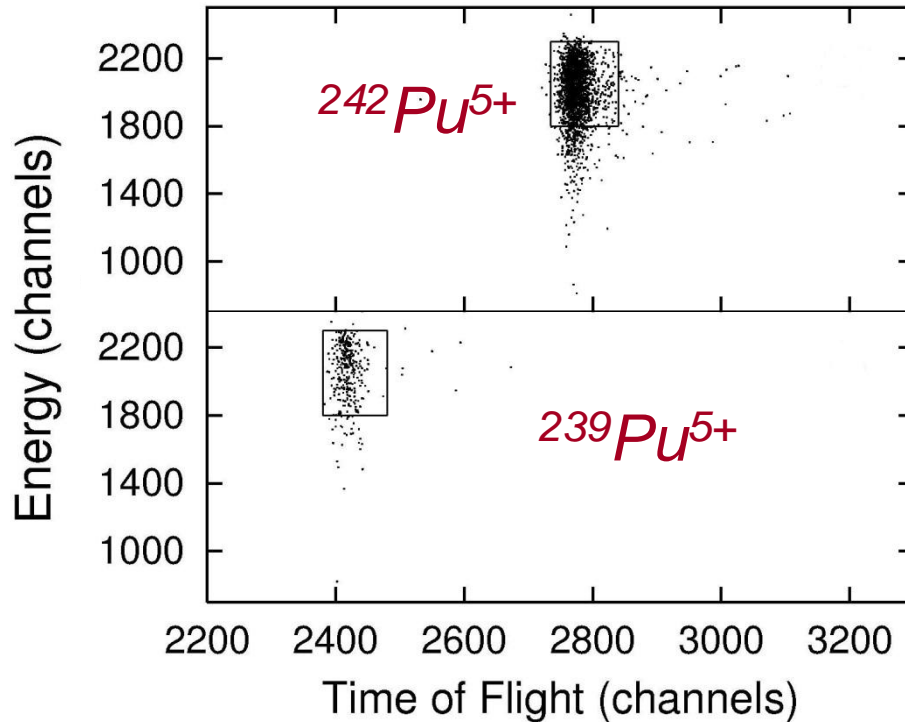
$^{239}\text{Pu}$ :  $t_{1/2} = 24.1$  kyr

# Analytical Strategy

*Au for fluence*



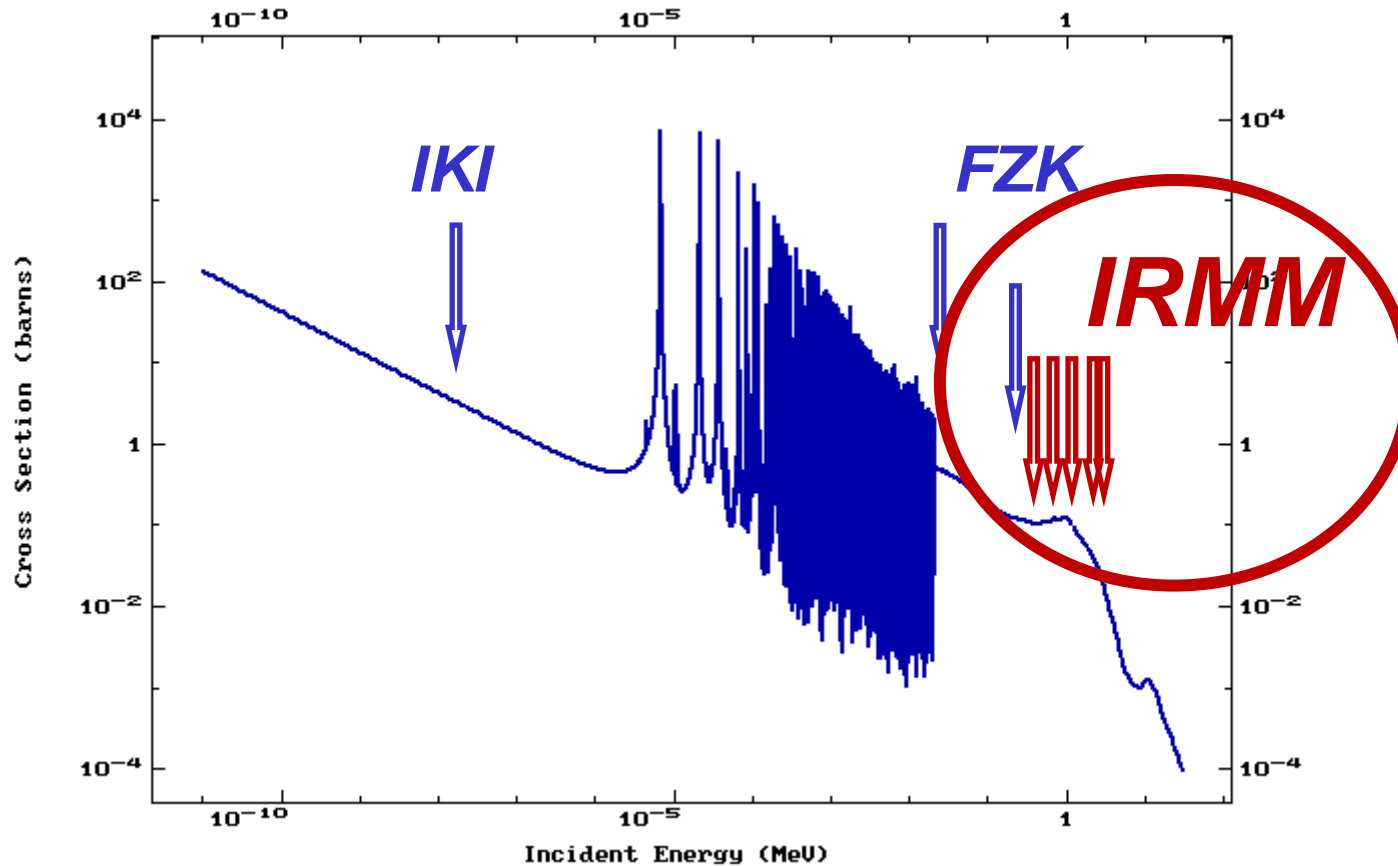
# *typical AMS-spectrum for Pu measurements*



**clear separation /  
no interference  
&  
 $^{236}\text{U}$ -sensitivity:  
 $^{236}\text{U}/^{238}\text{U} \sim 10^{-12}$**

**overall 10 AMS-beamtime sessions for  $^{235}\text{U}(n,\gamma)$ : +- 3 %**

**overall 6 AMS-beamtime sessions for  $^{238}\text{U}(n,\gamma)$ : +- 3 %**



# $^{233}\text{Th}$ & $^{239}\text{U}$ : Production & Decay: $(n,\gamma)$

	Cm 237 ?	Cm 238 2.4 h	Cm 239 3 h	Cm 240 27 d	Cm 241 32.8 d	Cm 242 162.94 d	Cm 243 29.1 a	Cm 244 18.10 a	Cm 245 8500 a	Cm 246 4730 a	
	Am 235 10.3 m	Am 236 2.9 m 3.6 m	Am 237 73.0 m	Am 238 1.63 h	Am 239 11.9 h	Am 240 50.8 h	Am 241 432.2 a	Am 242 141 a 16 h	Am 243 7370 a	Am 244 26 m 10.1 h	Am 245 2.05 h
	Pu 234 8.8 h	Pu 235 25.3 m	Pu 236 2.858 a	Pu 237 45.2 d	Pu 238 87.74 a	Pu 239 2.411 · 10 <sup>4</sup> a	Pu 240 6563 a	Pu 241 14.35 a	Pu 242 3.750 · 10 <sup>5</sup> a	Pu 243 4.956 h	Pu 244 8.00 · 10 <sup>7</sup> a
	Np 233 36.2 m	Np 234 4.4 d	Np 235 396.1 d	Np 236 225 h 1.54 · 10 <sup>5</sup> a	Np 237 2.144 · 10 <sup>6</sup> a	Np 238 2.117 d	Np 239 2.355 d	Np 240 7.22 m 65 m	Np 241 13.9 m	Np 242 2.2 m 5.5 m	Np 243 1.85 m
	U 232 68.9 a	U 233 1.592 · 10 <sup>5</sup> a	U 234 0.0054 a	U 235 0.7204 a	U 236 120 ns 2.342 · 10 <sup>7</sup> a	U 237 6.75 d	U 238 99.2742 a	U 239 23.5 m	U 240 14.1 h		
	Pa 231 3.276 · 10 <sup>4</sup> a	Pa 232 1.31 d	Pa 233 27.0 d	Pa 234 1.17 m 6.70 h	Pa 235 24.2 m	Pa 236 9.1 m	Pa 237 8.7 m	Pa 238 2.3 m	Pa 239 1.8 h		
	Th 230 7.54 · 10 <sup>4</sup> a	Th 231 25.5 h	Th 232 100 a	Th 233 22.3 m	Th 234 24.10 d	Th 235 7.1 m	Th 236 37.5 m	Th 237 5.0 m	Th 238 9.4 m		



low  
MeV

$^{233}\text{Th}$ :  $t_{1/2} = 22.3$  min

$^{233}\text{Pa}$ :  $t_{1/2} = 27$  days

$^{233}\text{U}$ :  $t_{1/2} = 159$  kyr

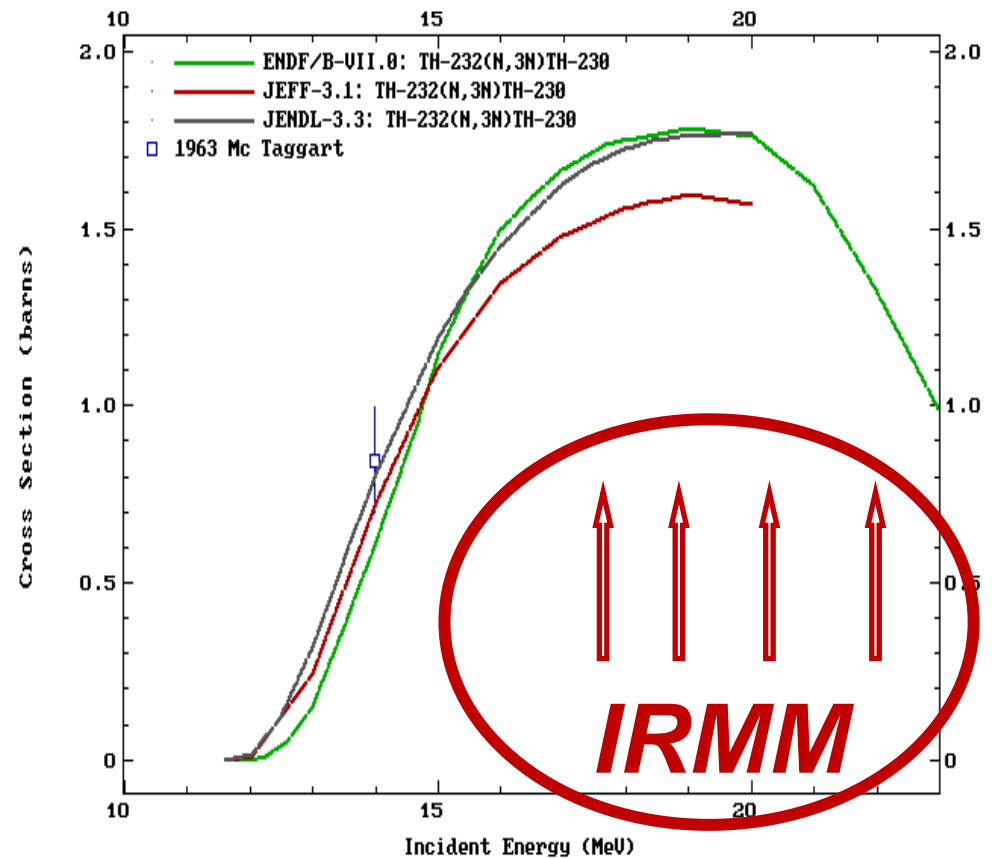
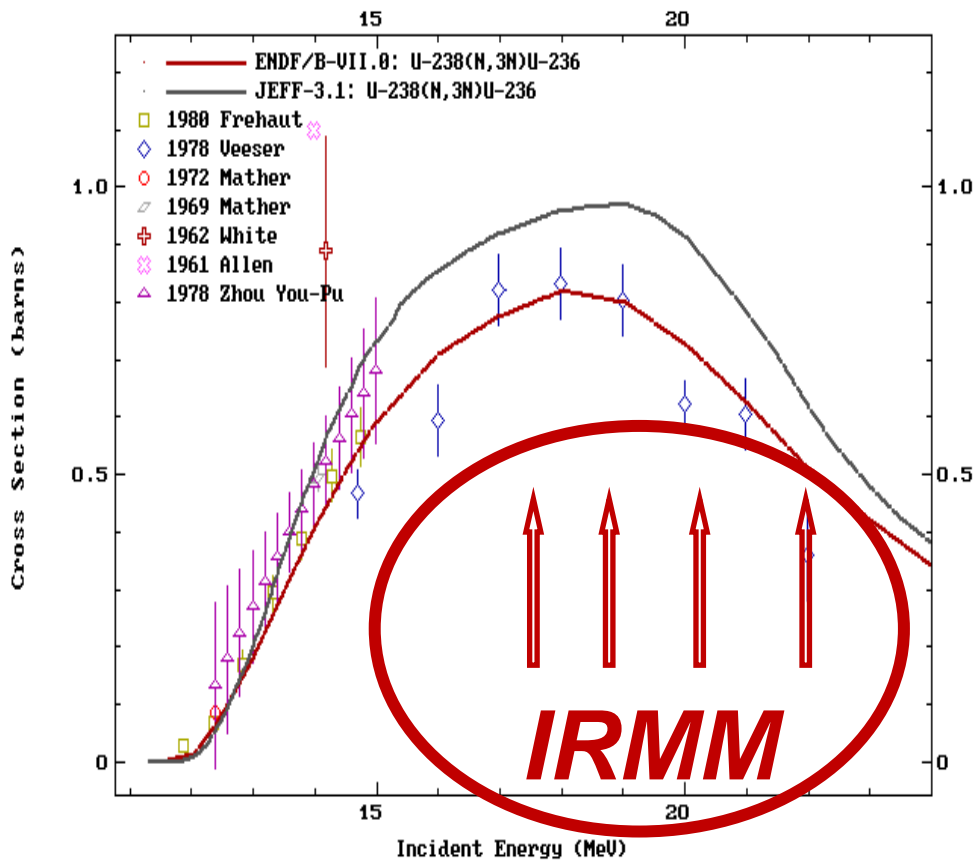
$^{239}\text{U}$ :  $t_{1/2} = 23.5$  min

$^{239}\text{Np}$ :  $t_{1/2} = 2.35$  days

$^{239}\text{Pu}$ :  $t_{1/2} = 24.1$  kyr



# Fast neutron induced reactions: Th / U



**U/Th simultaneously – the same geometry – the same fluence – (n,3n), (n,4n), (n,2n), (n, $\alpha$ ) in the same irradiation**

# $^{232}\text{Th}$ & $^{238}\text{U}$ : Production & Decay: (n,x)

	<b>Cm 237</b> ? $\alpha$ 6.656	<b>Cm 238</b> 2.4 h $\alpha$ 6.558; 6.503 $\gamma$ 55	<b>Cm 239</b> 3 h $\epsilon$ $\gamma$ 188... g	<b>Cm 240</b> 27 d sf $\alpha$ 6.291; 6.248... sf g	<b>Cm 241</b> 32.8 d sf $\alpha$ 5.939... $\gamma$ 472; 431; 132... $\sigma$ -20 $\sigma$ - $\gamma$ g	<b>Cm 242</b> 162.94 d sf $\alpha$ 6.113; 6.069... sf; g $\gamma$ (44...); $e^-$ $\sigma$ -20 $\sigma$ - $\gamma$ g	<b>Cm 243</b> 29.1 a sf $\alpha$ 5.785; 5.742... sf; g $\gamma$ 278; 228; 210...; $e^-$ $\sigma$ 130; $\sigma$ 620	<b>Cm 244</b> 18.10 a sf $\alpha$ 5.805; 5.762... sf; g $\gamma$ (43...); $e^-$ $\sigma$ 15; $\sigma$ 1.1	<b>Cm 245</b> 8500 a sf $\alpha$ 5.361; 5.304... sf; g $\gamma$ 175; 133... $\sigma$ 350; $\sigma$ 2100	<b>Cm 246</b> 4730 a sf $\alpha$ 5.386; 5.343... sf; g $\gamma$ (45); $e^-$ $\sigma$ 1.2; $\sigma$ 0.16
<b>Am 235</b> 10.3 m $\epsilon$ 6.457 $\gamma$ 291; 224; 270; 739; 749...	<b>Am 236</b> 2.9 m 3.6 m $\epsilon$ 6.15 7 $\gamma$ 583; 654; 713... $\sigma$ 880; 320	<b>Am 237</b> 73.0 m sf $\alpha$ 6.042... $\gamma$ 280; 438; 474; 909... g	<b>Am 238</b> 1.63 h sf $\alpha$ 5.94 $\gamma$ 963; 919; 561; 605... g	<b>Am 239</b> 11.9 h sf $\alpha$ 5.774... $\gamma$ 278; 228... g	<b>Am 240</b> 50.8 h sf $\alpha$ 5.378... $\gamma$ 988; 889... g	<b>Am 241</b> 432.2 a sf $\alpha$ 5.486; 5.443... sf; $\gamma$ 60; 26... $\sigma$ - $\gamma$ g	<b>Am 242</b> 141 a 16 h sf $\beta$ (49); $e^-$ $\beta$ (0.7); $e^-$ $\alpha$ 5.206... $\gamma$ (42...) sf; $\gamma$ (49...); $e^-$ $\sigma$ 330 $\sigma$ 5900; $\sigma$ 2100	<b>Am 243</b> 7370 a sf $\alpha$ 5.275; 5.233... sf; $\gamma$ 75; 44... $\sigma$ 75 + 5 $\sigma$ 0.079	<b>Am 244</b> 26 m 10.1 h sf $\beta$ 1.5... $\beta$ 0.4 $\gamma$ (1084...); 898; $\sigma$ 154...; $e^-$ $\sigma$ 1800; $\sigma$ 2200	<b>Am 245</b> 2.05 h sf $\beta$ 0.9... $\gamma$ 253; (241; 296...); $e^-$ ; g
<b>Pu 234</b> 8.8 h $\epsilon$ 6.202; 6.151... $\gamma$ ; $e^-$	<b>Pu 235</b> 25.3 m sf $\alpha$ 5.65 $\gamma$ 49; (756; 34...) $e^-$	<b>Pu 236</b> 2.858 a sf $\alpha$ 5.788; 5.721... sf; Mg 28 $\gamma$ (46; 109...); $e^-$ $\sigma$ 160	<b>Pu 237</b> 45.2 d sf $\alpha$ 5.334... $\gamma$ (43; 100...); $e^-$ $\sigma$ 2300	<b>Pu 238</b> 87.74 a sf $\alpha$ 5.499; 5.456... sf; Si; Mg $\gamma$ (43; 100...); $e^-$ $\sigma$ 510; $\sigma$ 17	<b>Pu 239</b> 2.411 $\cdot 10^4$ a sf $\alpha$ 5.157; 5.144... sf; $\gamma$ (52...) $\sigma$ 270; $\sigma$ 752	<b>Pu 240</b> 6563 a sf $\alpha$ 5.168; 5.124... sf; $\gamma$ (45...) $\sigma$ 290; $\sigma$ -0.059	<b>Pu 241</b> 14.35 a sf $\beta$ 0.02; g $\alpha$ 4.896... $\gamma$ (149...); $e^-$ $\sigma$ 370; $\sigma$ 1010	<b>Pu 242</b> 3.750 $\cdot 10^5$ a sf $\alpha$ 4.901; 4.856... sf; $\gamma$ (45...) $\sigma$ 19; $\sigma$ <0.2	<b>Pu 243</b> 4.956 h sf $\beta$ 0.6... $\gamma$ 84...; g $\sigma$ <100; $\sigma$ 200	<b>Pu 244</b> 8.00 $\cdot 10^7$ a sf $\alpha$ 4.589; 4.546 sf; $\gamma$ $\sigma$ 1.7
<b>Np 233</b> 36.2 m $\epsilon$ 5.54 $\gamma$ (312; 299; 547...)	<b>Np 234</b> 4.4 d $\epsilon$ ; $\beta^+$ ... $\gamma$ 1559; 1528; 1600... $\sigma$ -900	<b>Np 235</b> 396.1 d $\epsilon$ ; $\alpha$ 5.025...; 5.007... $\gamma$ (26; 84...); $e^-$ g; $\sigma$ 180 + ?	<b>Np 236</b> 225 h 1.54 $\cdot 10^5$ a sf $\epsilon$ ; $\beta^+$ 0.5... $\epsilon$ ; $\beta^+$ ... $\gamma$ (84...); $e^-$ $\sigma$ 2700; g; $\sigma$ 3000	<b>Np 237</b> 2.144 $\cdot 10^6$ a sf $\alpha$ 4.790; 4.774... $\gamma$ 29; 87...; $e^-$ $\sigma$ 170; $\sigma$ 0.020	<b>Np 238</b> 2.117 d $\beta^-$ 1.2... $\gamma$ 984; 1029; 1026; 924...; $e^-$ g; $\sigma$ 2600	<b>Np 239</b> 2.355 d $\beta^-$ 0.4; 0.7... $\gamma$ 106; 278; 228...; $e^-$ ; g $\sigma$ 32 + 19; $\sigma$ <1	<b>Np 240</b> 7.22 m 65 m $\beta^-$ 2.2... $\beta^-$ 0.9 $\gamma$ 555; 597... $\sigma$ 1800; $\sigma$ 27...; $\sigma$ 6	<b>Np 241</b> 13.9 m $\beta^-$ 1.3... $\gamma$ 175; (133...) g	<b>Np 242</b> 2.2 m 5.5 m $\beta^-$ 2.7... $\beta^-$ 0.9 $\gamma$ 736; 780; 1473...; 786; 945; 159... g	<b>Np 243</b> 1.85 m $\beta^-$ $\gamma$ 288 g
<b>U 232</b> 68.9 a $\alpha$ 5.320; 5.262... Ne 25; $\gamma$ (58; 129...); $e^-$ $\sigma$ 73; $\sigma$ 74	<b>U 233</b> 1.592 $\cdot 10^5$ a $\alpha$ 4.824; 4.783... Ne 25; $\gamma$ (42; 97...); $e^-$ $\sigma$ 47; $\sigma$ 530	<b>U 234</b> 0.0054 a 2.455 $\cdot 10^4$ a $\alpha$ 4.75; 4.723...; sf Mg 28; Ne; $\gamma$ (53; 121...); $e^-$ $\sigma$ 96; $\sigma$ 0.07	<b>U 235</b> 0.7204 a 26 m 7.038 $\cdot 10^8$ a $\beta^-$ 2.3... $\beta^-$ 0.5 $\gamma$ (1001; 787...); $e^-$ $\sigma$ 1500; $\sigma$ 15	<b>U 236</b> 120 n 2.342 $\cdot 10^7$ a $\beta^-$ 2.3... $\beta^-$ 0.5 $\gamma$ (1001; 787...); $e^-$ $\sigma$ 1500; $\sigma$ 15	<b>U 237</b> 6.75 d $\beta^-$ 0.2... $\gamma$ 507; 200... $\sigma$ -100; $\sigma$ <0.35	<b>U 238</b> 99.2742 a 296 ns 4.468 $\cdot 10^9$ a $\beta^-$ 2.2... $\beta^-$ 0.9 $\gamma$ 555; 597... $\sigma$ 1800; $\sigma$ 27...; $\sigma$ 6	<b>U 239</b> 23.5 m $\beta^-$ 1.2; 1.3... $\gamma$ 75; 44... $\sigma$ 22; $\sigma$ 15	<b>U 240</b> 14.1 h $\beta^-$ 0.4... $\gamma$ 44; (190...) $e^-$ m		
<b>Pa 231</b> 3.276 $\cdot 10^4$ a $\alpha$ 5.014; 4.952; 5.028...; Ne 24; F 237 $\gamma$ 27; 300; 303... $\sigma$ 200; $\sigma$ 0.020	<b>Pa 232</b> 31 d $\beta^-$ 1.3; 1.3...; $\epsilon$ $\gamma$ 939; 894; 150...; $e^-$ $\sigma$ 460; $\sigma$ 1500	<b>Pa 233</b> 27.0 d $\beta^-$ 0.3; 0.6... $\gamma$ 312; 300; 341...; $e^-$ $\sigma$ 20 + 19; $\sigma$ <0.1	<b>Pa 234</b> 1.17 m 6.70 h $\beta^-$ 2.3... $\beta^-$ 0.5 $\gamma$ (1001; 787...); $e^-$ $\sigma$ 1500; $\sigma$ 15	<b>Pa 235</b> 24.2 m $\beta^-$ 1.4... $\gamma$ 128 - 659 m	<b>Pa 236</b> 9.1 m $\beta^-$ 2.0; 3.1... $\gamma$ 642; 687; 1763...; g bsf ?	<b>Pa 237</b> 8.7 m $\beta^-$ 1.4; 2.3... $\gamma$ 854; 865; 529; 541... g	<b>Pa 238</b> 2.3 m $\beta^-$ 1.7; 2.9... $\gamma$ 1015; 635; 448; 680... g	<b>Pa 239</b> 1.8 h $\beta^-$ $\gamma$ 522 - 681		
<b>Th 230</b> 1.54 $\cdot 10^4$ a 4.687; 4.621 (68; 144...); $e^-$ Ne 24; $\sigma$ 23.4 $\sigma$ <0.0005	<b>Th 231</b> 25.5 h $\beta^-$ 0.3; 0.4... $\gamma$ 26; 84... $e^-$	<b>Th 232</b> 100 a 1.405 $\cdot 10^{10}$ a $\beta^-$ 1.1... $\beta^-$ 0.5 $\gamma$ (64...); $e^-$ $\sigma$ 7.37; $\sigma$ 0.000006	<b>Th 233</b> 22.3 m $\beta^-$ 1.1... $\beta^-$ 0.5 $\gamma$ (64...); $e^-$ $\sigma$ 1500; $\sigma$ 15	<b>Th 234</b> 24.10 d $\beta^-$ 0.2... $\gamma$ 63; 92; 93... $e^-$ ; m $\sigma$ 1.8; $\sigma$ <0.01	<b>Th 235</b> 7.1 m $\beta^-$ 1.4... $\gamma$ 417; 727; 696...	<b>Th 236</b> 37.5 m $\beta^-$ 1.0... $\gamma$ 111; (647; 196...)	<b>Th 237</b> 5.0 m $\beta^-$	<b>Th 238</b> 9.4 m $\beta^-$ $\gamma$ 89		



*fast n*

$^{231}\text{Th}$ :  $t_{1/2} = 25.5$  h

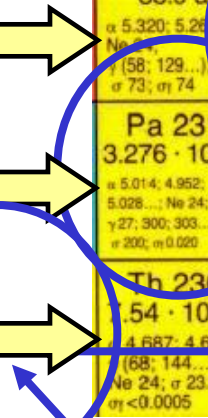
$^{231}\text{Pa}$ :  $t_{1/2} = 32.8$  kyr

$^{229}\text{Th}$ :  $t_{1/2} = 7.88$  kyr

$^{236}\text{U}$ :  $t_{1/2} = 23.4$  Myr

$^{237}\text{U}$ :  $t_{1/2} = 6.75$  days

$^{237}\text{Np}$ :  $t_{1/2} = 2.14$  Myr



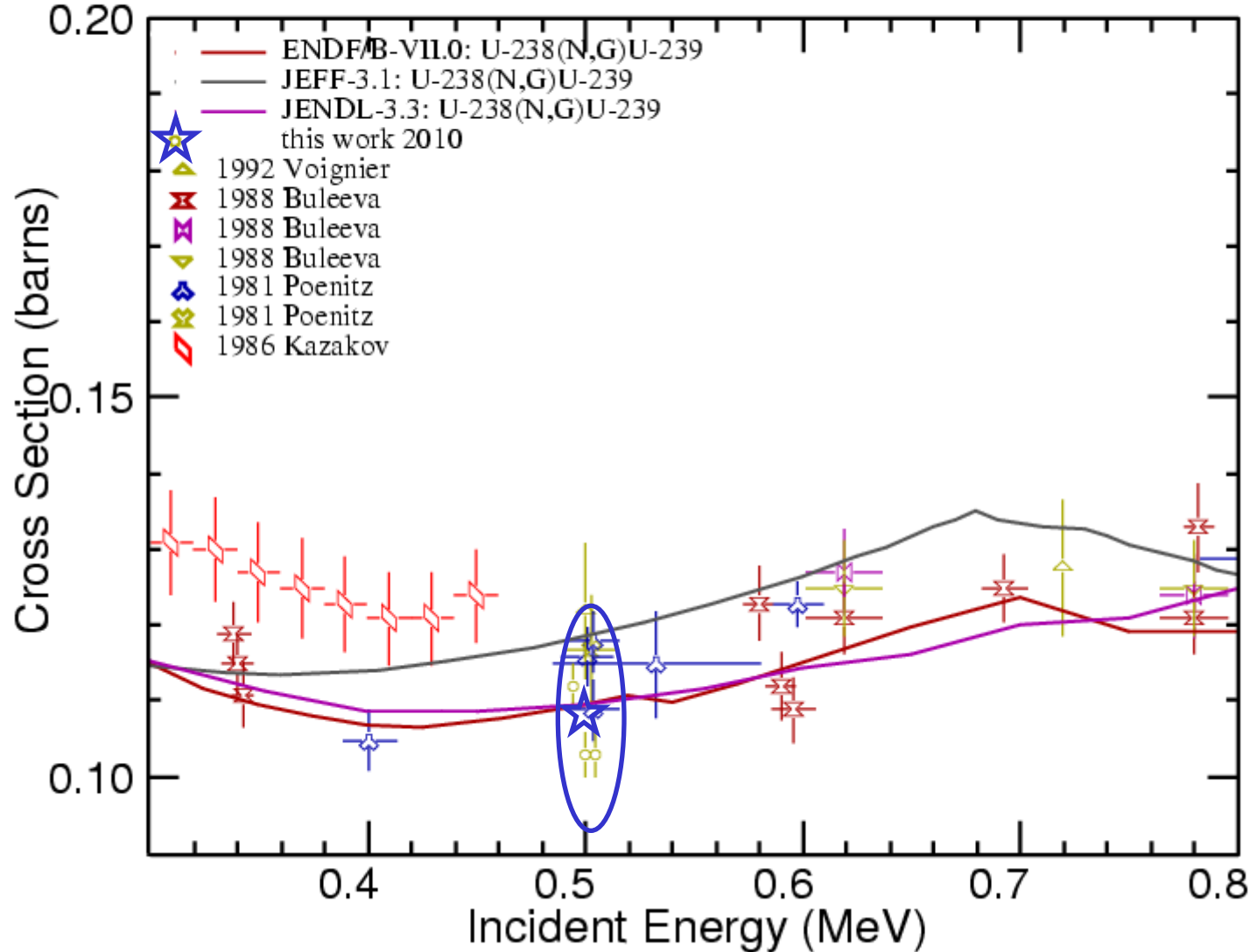
*new data*

$^{238}\text{U}(n,\gamma)^{239}\text{U}$

EXFOR database

300 – 800 keV

exp. data > 1980

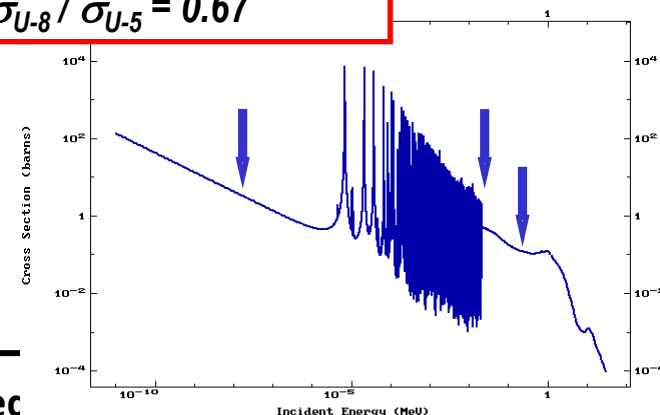


# Status – keV data

	$^{235}\text{U}(n,\gamma)^{236}\text{U}$ this work	$^{235}\text{U}(n,\gamma)^{236}\text{U}$ „recommended“	$^{238}\text{U}(n,\gamma)^{239}\text{U}$ this work	$^{238}\text{U}(n,\gamma)^{239}\text{U}$ „recommended“
$\sigma_{\text{thermal}}$	IKI-1: $99.5 \pm 3$ barn* IKI-2: $101.5 \pm 3$ barn*	98.96 barn 98.96 barn	IKI-1: reference for AMS IKI-2: reference for AMS	2.68 barn (2.72 barn JENDL)
$\sigma_{25 \text{ keV}}$	KIT-1: $646 \pm 38$ mbarn	ENDF: 679 mbarn (ENDF = JEFF)	KIT-1: $386 \pm 25$ mbarn	401 mbarn (ENDF,JEFF)
<div style="border: 1px solid red; padding: 5px; display: inline-block;"> <b>this work (AMS ratio): <math>\sigma_{U-8} / \sigma_{U-5} = 0.60 \pm 0.05</math></b>  <b>ENDF: <math>\sigma_{U-8} / \sigma_{U-5} = 0.59</math></b> </div>				
$\sigma_{426 \text{ keV}}$	KIT-2: $161 \pm 7$ mbarn	163 mbarn (ENDF,JEFF) 171 mbarn (JENDL)	KIT-2: $108 \pm 4$ mbarn	109 mbarn (ENDF, JENDL) 119 mbarn (JEFF)
<div style="border: 1px solid red; padding: 5px; display: inline-block;"> <b>this work (AMS ratio): <math>\sigma_{U-8} / \sigma_{U-5} = 0.67 \pm 0.04</math></b>  <b>ENDF: <math>\sigma_{U-8} / \sigma_{U-5} = 0.67</math></b> </div>				

- relative to  $^{233}\text{U}$ -spike

AMS vs ENDF:  $\sigma_{U-5} (25 \text{ keV}) = 0.95 \pm 0.06$   
 AMS vs ENDF:  $\sigma_{U-8} (25 \text{ keV}) = 0.96 \pm 0.06$   
 AMS vs ENDF:  $\sigma_{U-5} (426 \text{ keV}) = 0.99 \pm 0.04$   
 AMS vs ENDF:  $\sigma_{U-8} (426 \text{ keV}) = 0.99 \pm 0.04$



## New Precision Measurements of the $^{235}\text{U}(n, \gamma)$ Cross Section

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R. C. Haight,<sup>1</sup> T. Kawano,<sup>1</sup> R. Reifarh,<sup>1,†</sup> R. S. Rundberg,<sup>1</sup> J. L. Ullmann,<sup>1</sup> D. J. Vieira,<sup>1</sup> J. M. Wouters,<sup>1,‡</sup>  
J. B. Wilhelmy,<sup>1</sup> C. Y. Wu,<sup>2</sup> and J. A. Becker<sup>2</sup>

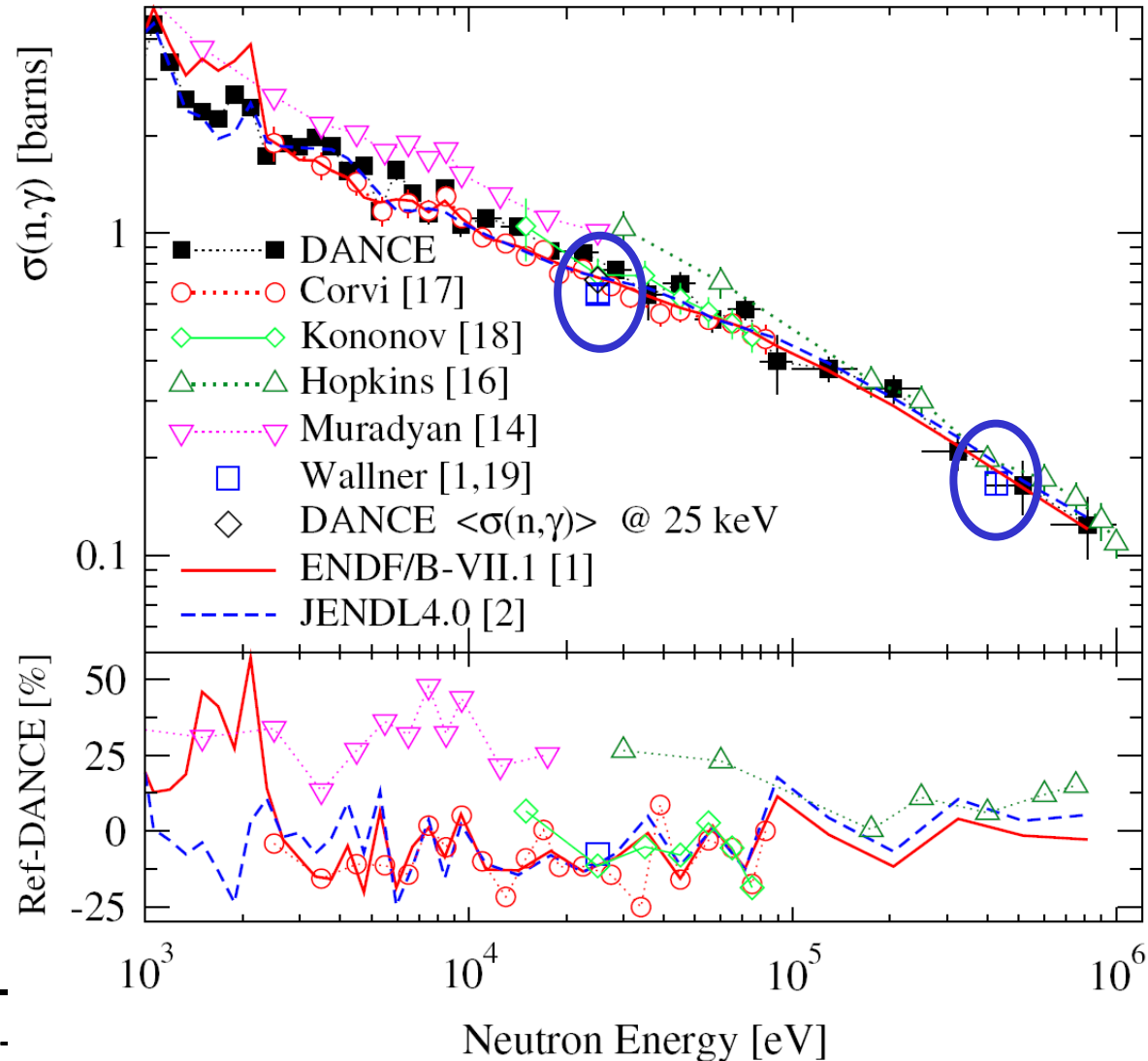
**25 keV – Maxwell-Boltzmann:**

**JANDEL - 2012:**  $\sigma_{U-5} = 0.70 \pm 0.06$

**ENDF/B-VII.1**  $\sigma_{U-5} = 0.679$

**this work (AMS):**  $\sigma_{U-5} = 0.646 \pm 0.038$

**AMS vs JANDEL:**  $\sigma_{U-5} (25 \text{ keV}) = 0.92 \pm 0.10$

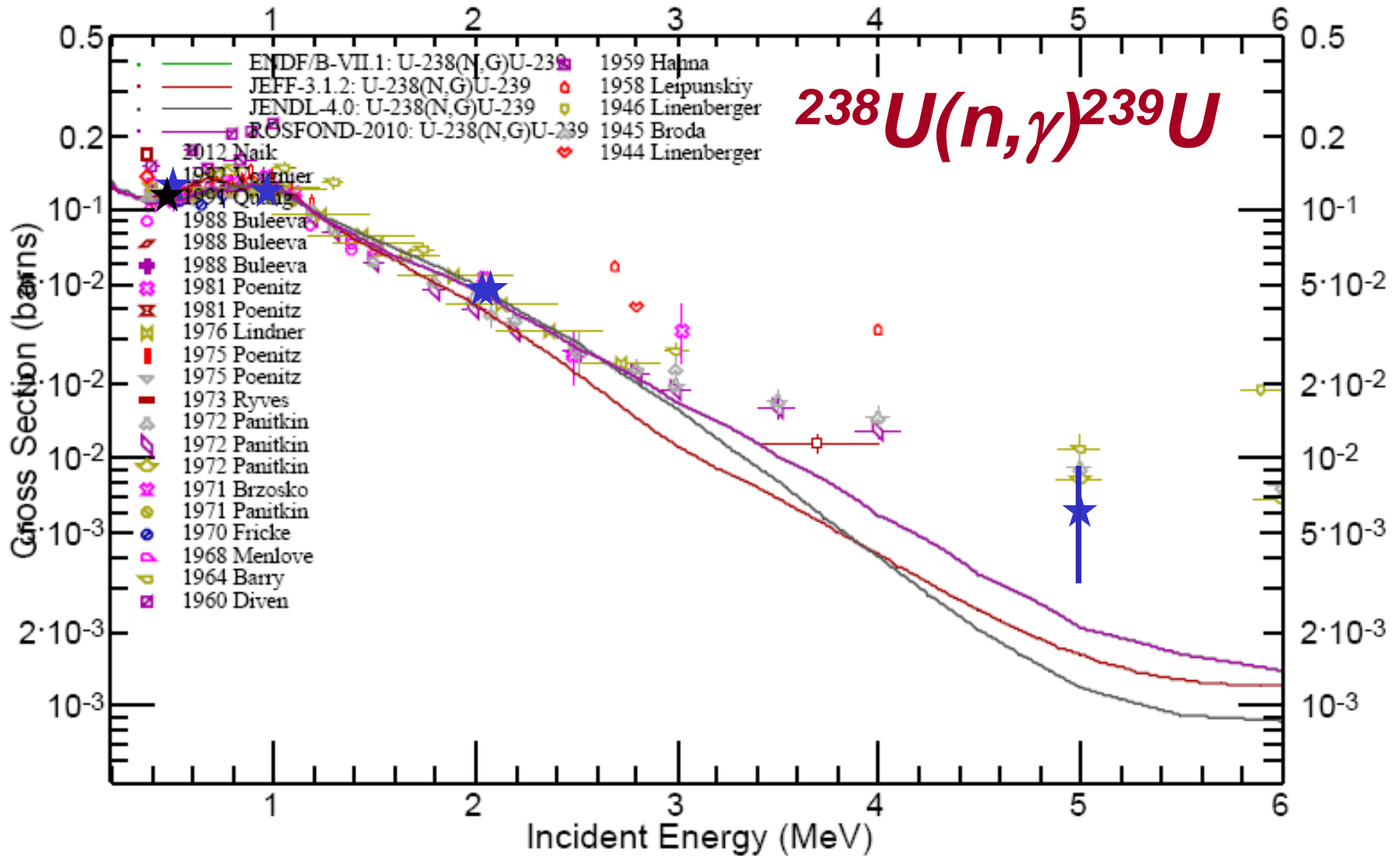


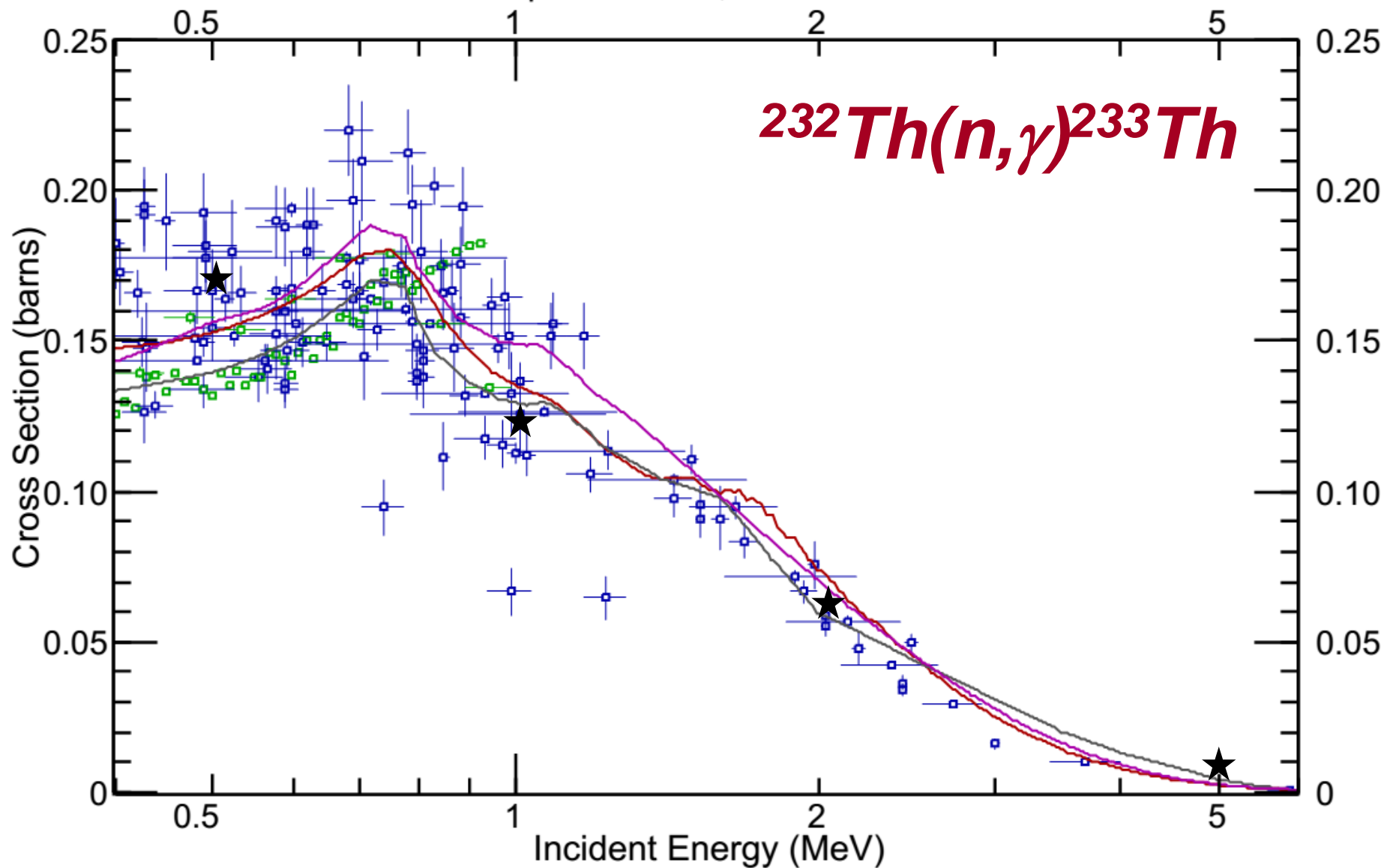
# Status $^{232}\text{Th}(n,\gamma)^{233}\text{Th}$ & $^{238}\text{U}(n,\gamma)^{239}\text{U}$ for 0.5 / 1.0 / 2.1 / 5.0 MeV

Preliminary data for  $^{232}\text{Th}(n,\gamma)$  and  $^{238}\text{U}(n,\gamma)$

$E_n$ (MeV)	Th-AMS (mbarn)	ENDF-Th (mbarn)	U-AMS (mbarn)	ENDF-U (mbarn)	AMS/ENDF - Th	AMS / ENDF - U
0.46	--		$108 \pm 4$	109		$1.00 \pm 0.03$
0.52	$172 \pm 15$	153	$123 \pm 6$	110	$1.12 \pm 0.10$	$1.12 \pm 0.05$
1.0	$118 \pm 10$	136	$108 \pm 5$	128	$0.87 \pm 0.07$	$0.85 \pm 0.04$
2.1	$59 \pm 3$	68	$42 \pm 2$	43	$0.86 \pm 0.03$	$0.97 \pm 0.05$
2.1		68	$40 \pm 7$	43		$0.92 \pm 0.10$
5.0	$\sim 10$	2.8	$6 \pm 3$	2.1	3.7	$3 \pm 2$

## AMS at the ANU







# First results - $^{238}\text{U}(n,3n)^{236}\text{U}$

17.55 | Preliminary data for  $^{238}\text{U}(n,3n)^{236}\text{U}$  (VERA)

20.05 |

! Preliminary da

$E_n$ (MeV)	AMS (barn)	evaluations (barn)
17.55	$0.76 \pm 0.04$	0.7 – 1.0
18.80	$0.89 \pm 0.30$	0.7 – 1.0
20.05	$0.86 \pm 0.04$	0.6 – 0.9
22.00	$0.42 \pm 0.10$	0.45 – 0.65

n“  
n”

**Fluence!**  $\leftrightarrow$  **number of neutrons/sample**

# First results - $^{232}\text{Th}(n,2n)^{231}\text{Th}$

VERY preliminary data for  $^{232}\text{Th}(n,2n)^{231}\text{Th}$   
(via  $^{231}\text{Pa}$ : VERA & ETH & ANSTO)

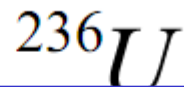
$E_n$ (MeV)	AMS-VERA (ratio)	AMS-ETH (ratio)	AMS-ANSTO (ratio)	AMS (barn)	evaluations (barn)
17.55	$1.6 \pm 0.3$	$1.5 \pm 0.2$	$1.65 \pm 0.3$	$0.20 \pm 0.05$	0.3 – 0.5
18.80	$2.9 \pm 0.3$	$3.0 \pm 0.2$	$2.9 \pm 0.3$		0.25 – 0.45
20.05	$29 \pm 2$	$32 \pm 1.2$	$24 \pm 4$	$0.18 \pm 0.01$	0.2 – 0.4
22.00	$2.2 \pm 0.2$	$2.0 \pm 0.2$	$2.2 \pm 0.2$		~ 0.2

# First results - $^{232}\text{Th}(n,4n+\alpha)^{229}\text{Th}$

Preliminary data for  $^{232}\text{Th}(n,4n+\alpha)$  (VERA & ETH)

$E_n$ (MeV)	AMS (mbarn)	evaluations (mbarn)
17.55	< 5	0.2 - 2
20.05	$6 \pm 2$	10 - 50
22.0	$345 \pm 35$	$\sim 200 (\pm \times 3)$

# AMS & neutron fluence



$$\frac{\sigma_{U-5(n,\gamma)}}{\sigma_{U-8(n,\gamma)}} = \frac{\frac{^{236}\text{U}}{^{235}\text{U}}}{\frac{^{239}\text{Pu}}{^{238}\text{U}}}$$



**AMS-ratio  
only !!!**

**this work (AMS ratio):**  $\sigma_{U-8} / \sigma_{U-5} = 0.60 \pm 0.05$

**ENDF:**  $\sigma_{U-8} / \sigma_{U-5} = 0.59$

**this work (AMS ratio):**  $\sigma_{U-8} / \sigma_{U-5} = 0.67 \pm 0.04$

**ENDF:**  $\sigma_{U-8} / \sigma_{U-5} = 0.67$

systematic study of Maxwellian-averaged xs from precise AMS measurements

***addendum:***

***Fe – AMS  $d\epsilon$***

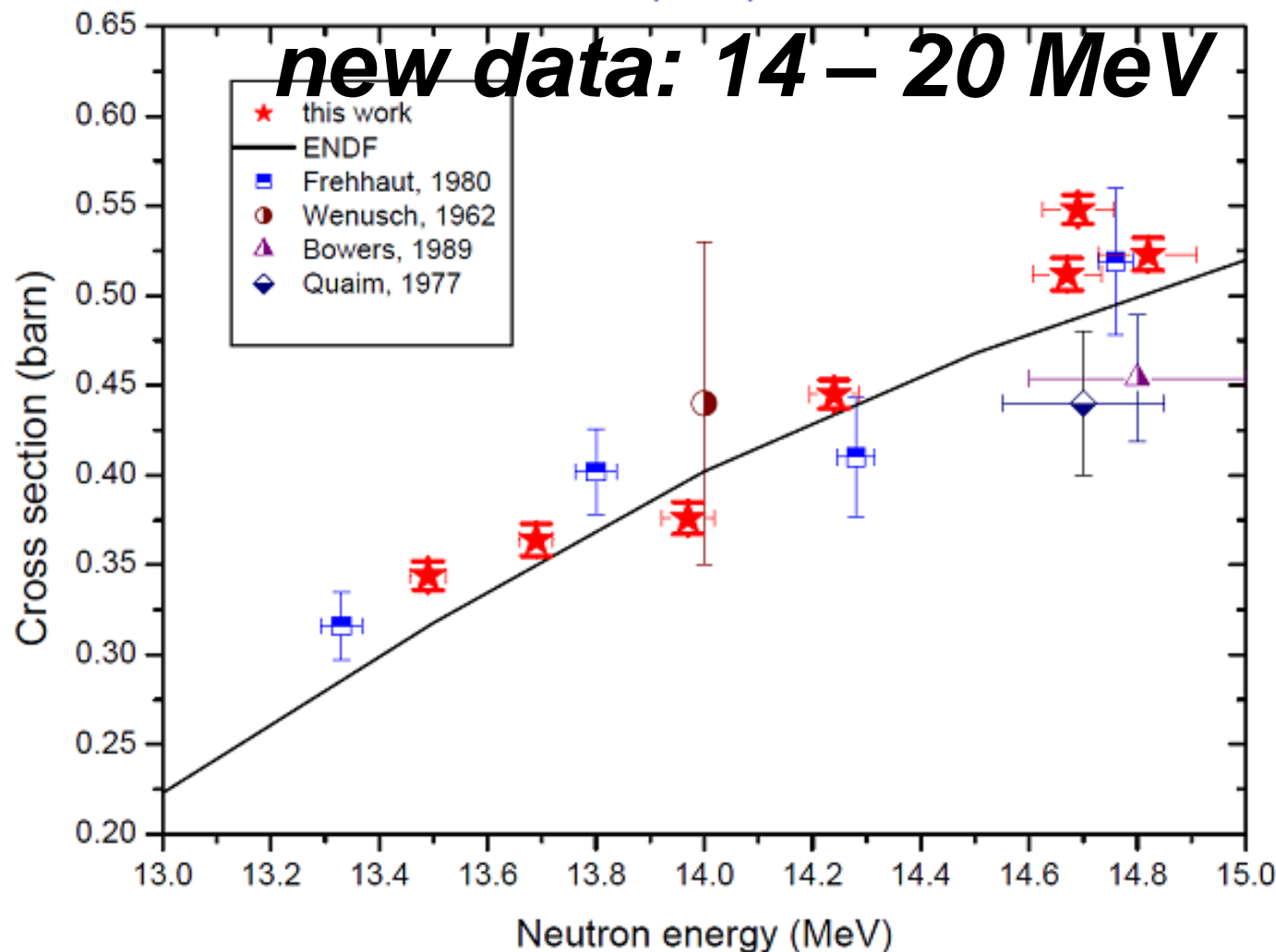
**long-lived reaction**

**products:**

- $^{56}\text{Fe}(n,2n)^{55}\text{Fe}$
- $^{54}\text{Fe}(n,2n)^{53}\text{Fe} \left[ \rightarrow ^{53}\text{Mn} \right]$
- $^{54}\text{Fe}(n,\gamma)^{55}\text{Fe}$
- $^{54}\text{Fe}(n,np+d)^{53}\text{Fe} \rightarrow ^{53}\text{Mn}$
- $^{58}\text{Ni}(n,\alpha)^{55}\text{Fe}$

$^{56}\text{Fe}(n,2n)^{55}\text{Fe}$

***new data: 14 – 20 MeV***

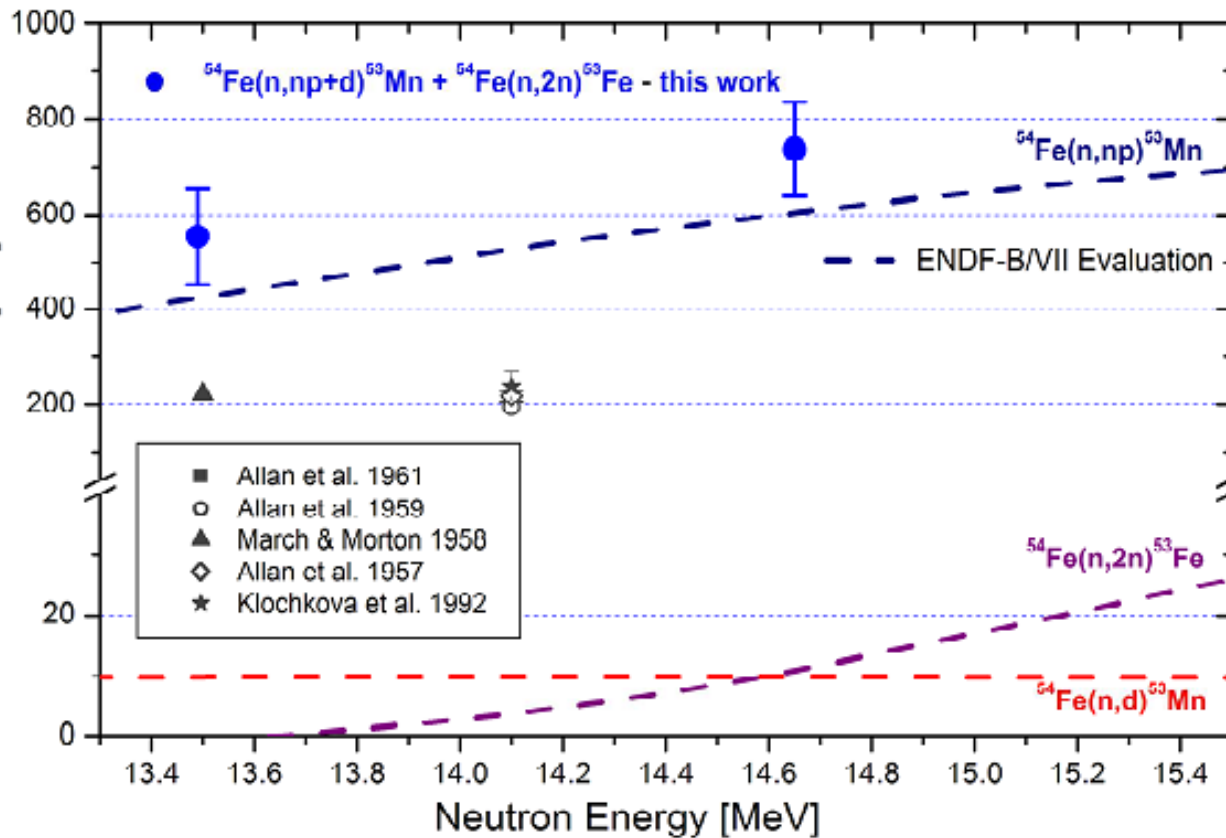
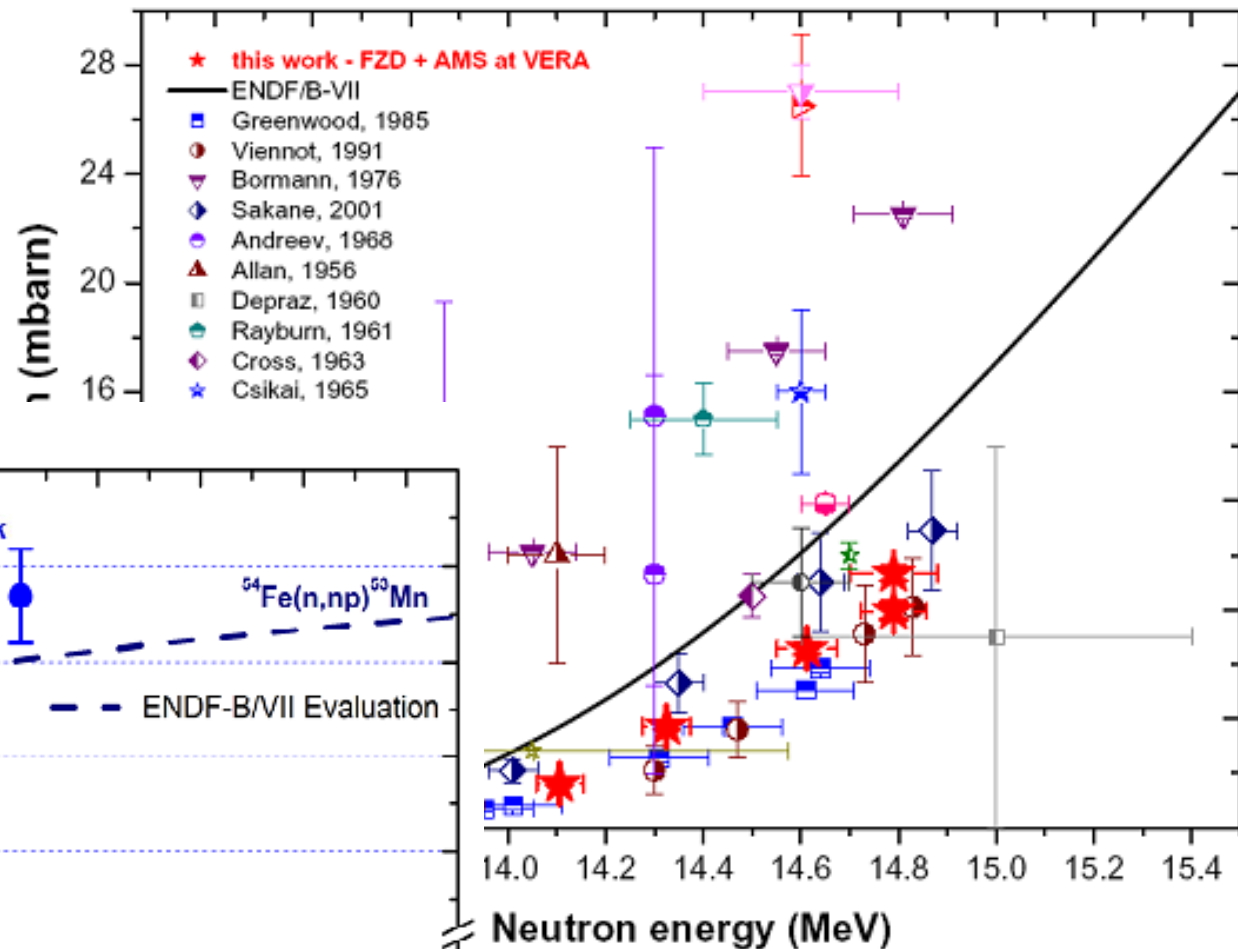


***$^{55}\text{Fe}$  - AMS:  $\pm 2\%$***

# $^{53}\text{Fe} / ^{53}\text{Mn}$

$^{53}\text{Mn}$ :  $t_{1/2} = 3.7 \text{ My}$

## $^{54}\text{Fe}(n,2n)^{53}\text{Fe}$



# ***Conclusion - actinides***

- AMS represents an independent method for studying nuclear reactions leading to long-lived radionuclides
- direct method: atom counting as isotope ratio; i.e. no sophisticated data reduction or corrections required
- not a universal method – AMS is used for some 25 radionuclides
- if it can be applied – usually very (the most) sensitive method
- can serve as an important tool to provide some anchor points
- can it help to solve the Au-standard issue?
- new neutron-producing facilities (FRANZ, Frankfurt, Germany), SARAF (Israel) offer a much higher keV-neutron flux





# Comparison AMS – other meas. / ENDF

Reaction		AMS (25keV)	other detection technique (KADONIS)	ENDF/B-VII.1/KADONIS
${}^9\text{Be}(n,\gamma){}^{10}\text{Be}$	EXP	9.5 $\mu\text{barn}$	13 $\mu\text{barn}$	$0.88 \pm 0.17$
${}^{13}\text{C}(n,\gamma){}^{14}\text{C}$	EXP	13.3 $\mu\text{barn}$	20 $\mu\text{barn}$	-- (JENDL 13, JEFF 7 $\mu\text{b}$ )
${}^{14}\text{N}(n,p){}^{14}\text{C}$	EXP	1.74 mbarn	2 mbarn	-- (ENDF: 1.70 mbarn)
${}^{35}\text{Cl}(n,\gamma){}^{36}\text{Cl}$	EXP	8.84 mbarn	11.3 mbarn	$0.78 \pm 0.03$
${}^{40}\text{Ca}(n,\gamma){}^{41}\text{Ca}$	MACS	5.74 mbarn	6.7 mbarn	$0.89 \pm 0.07$
${}^{54}\text{Fe}(n,\gamma){}^{55}\text{Fe}$	EXP	mbarn	29.6 mbarn	$0.73 \pm 0.06$
${}^{235}\text{U}(n,\gamma){}^{236}\text{U}$	EXP	$646 \pm 38$ mbarn	--	-- (ENDF: 679 mbarn)
${}^{238}\text{U}(n,\gamma){}^{239}\text{U}$	EXP	$386 \pm 25$ mbarn	--	-- (ENDF: 401 mbarn)

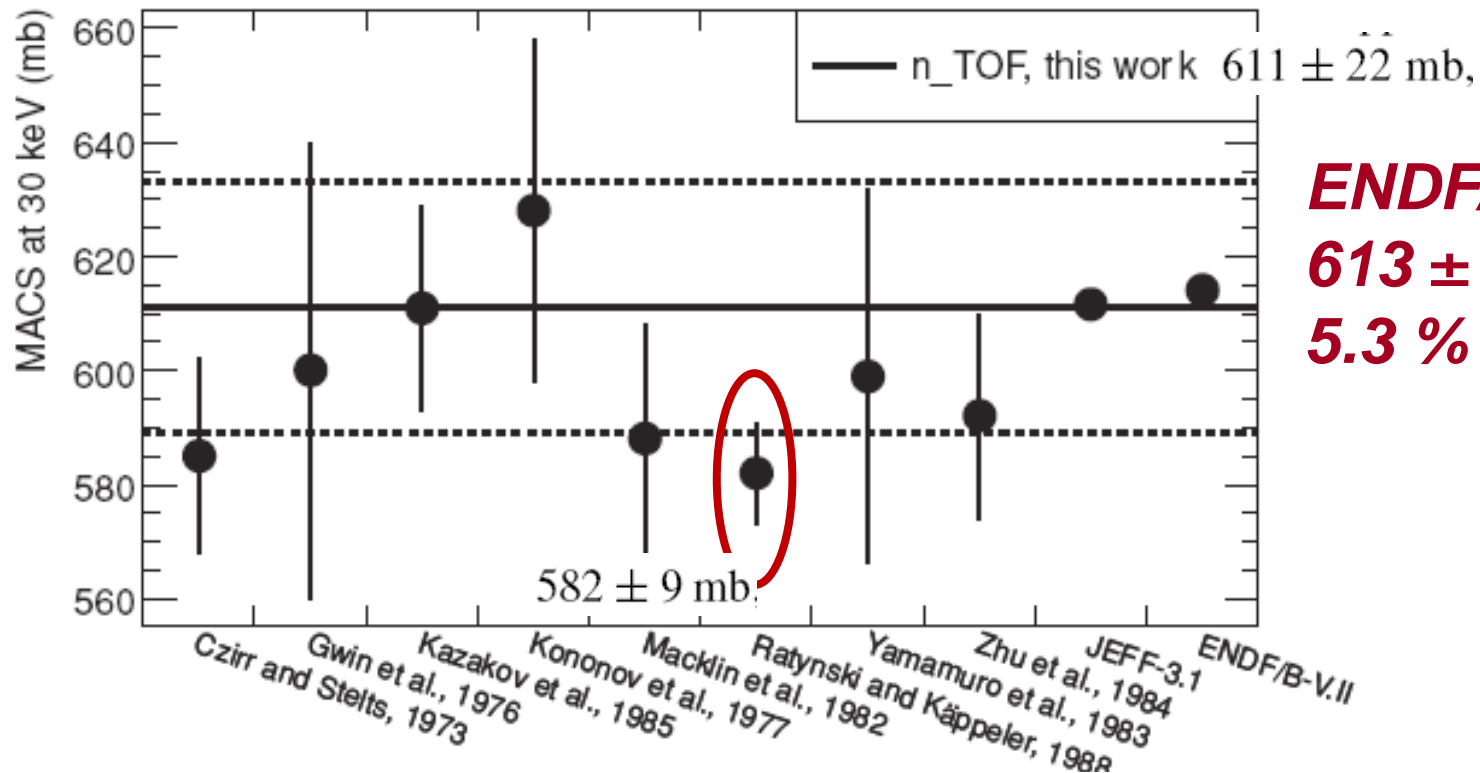
**AMS is generally lower than ,other' techniques, but**

- fluence value via  ${}^{197}\text{Au}(n,\gamma) \rightarrow \text{Au}$  cross section enters directly! (see above)
- background in other methods ?
- AMS: individual reactions via independent reference materials  $\rightarrow$  no correlation in AMS

AMS data (not U) relative to Au- Ratynski-Käppeler for 25 keV

all activations with the same geometry at KIT – as used in “Ratynski & Käppeler

# 30 keV MACS for $^{197}\text{Au}(n,\gamma)$ (Maxwellian-averaged cross sections)



PHYSICAL REVIEW C 83, 034608 (2011)

C. LEDERER *et al.*

$^{197}\text{Au}(n,\gamma)$  cross section in the unresolved resonance region