Radiative neutron capture cross section measurement of germanium isotopes at the n_TOF CERN facility and its relevance for stellar nucleosynthesis

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Katedra Fizyki Jądrowej i Bezpieczeństwa Radiacyjnego, UŁ

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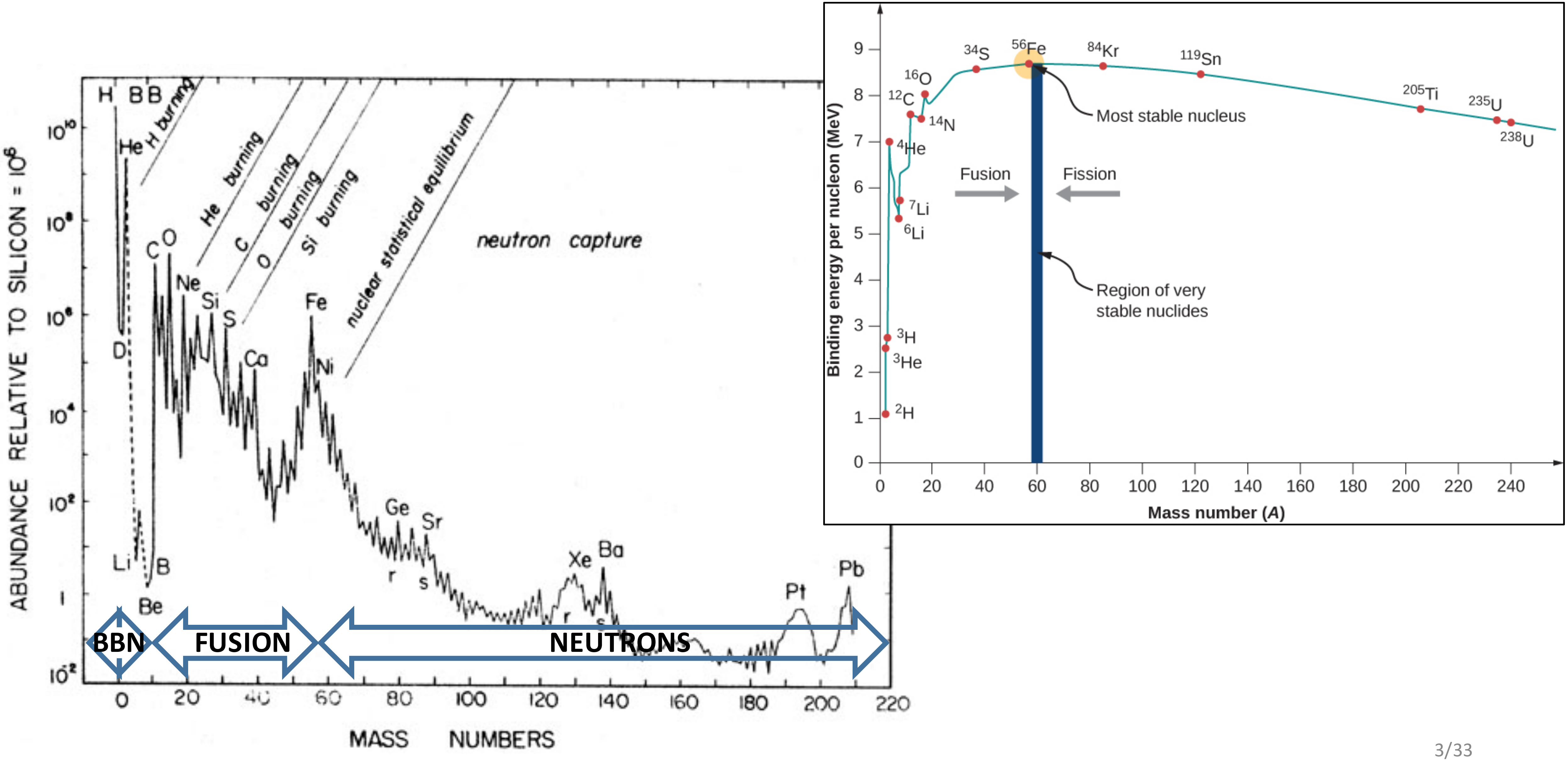
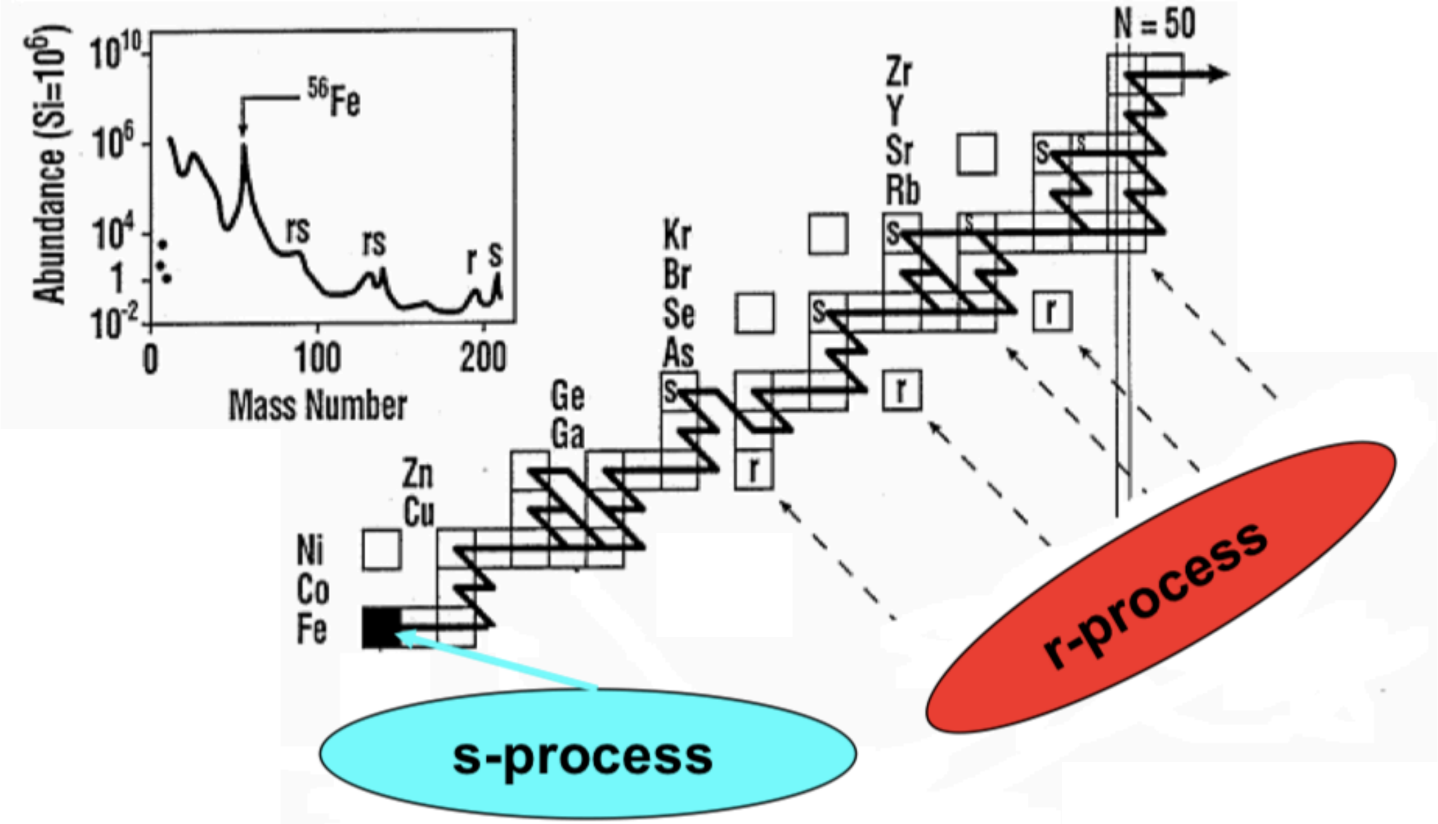
Outline

- Origin of the Elements
- Motivation
- Existing experimental data
- Spallation neutron source at CERN (n_TOF)
- Neutron resonances
- Maxwellian averaged cross section
- New data obtained thanks to n_TOF collaboration
- Astrophysical impact
- Conclusion

Origin of the Elements



Creation of heavy elements



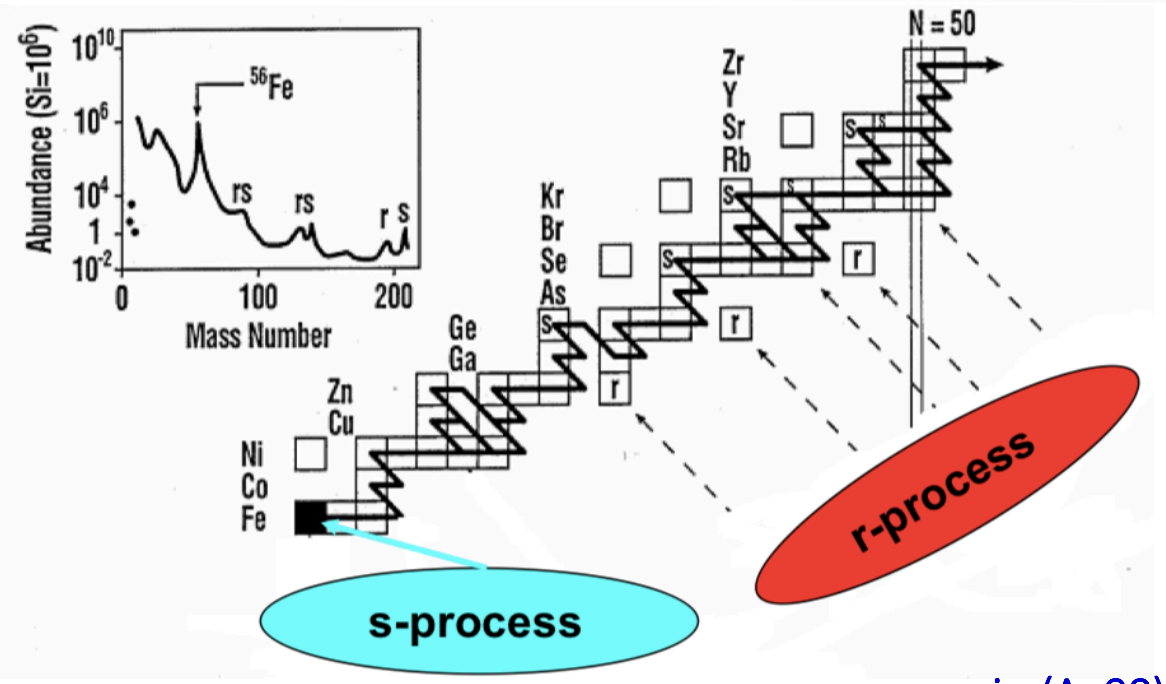
slow neutron capture

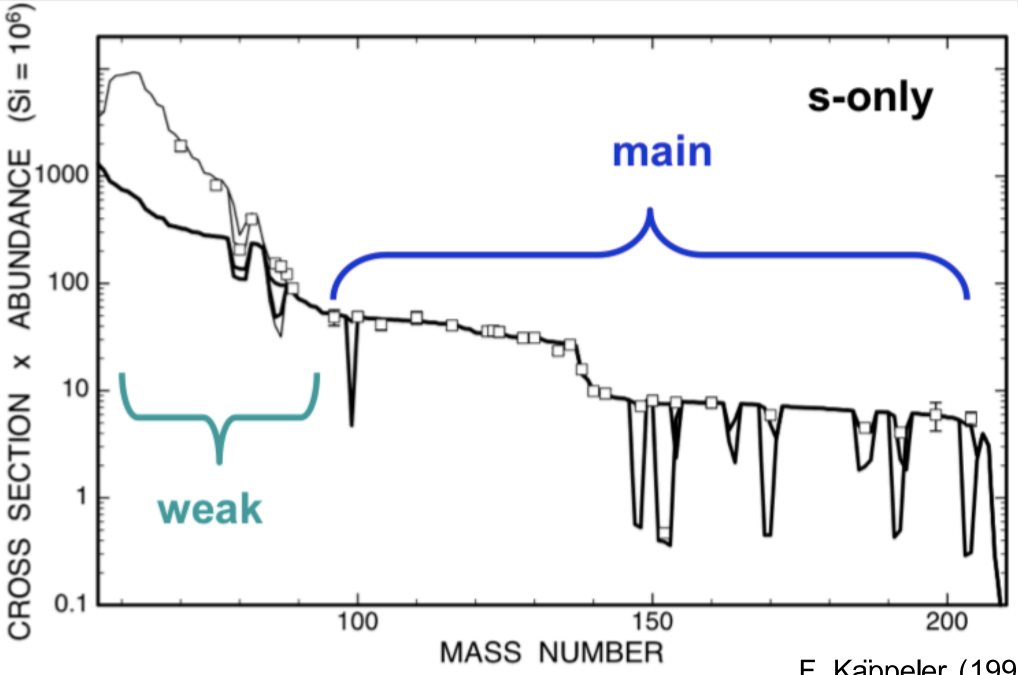
- •AGB stars, massive stars
- $\tau_{n,\gamma}$ (~100 yr) > $t_{1/2}$
- N_n~10^8 cm^{-3}

rapid neutron capture

- •explosive scenarios (supernovae)
- $\tau_{n,\gamma}$ (10^{-3}s) < $t_{1/2}$
- N_n~10^{21} cm^{-3}

Creation of heavy elements





F. Käppeler (1999)

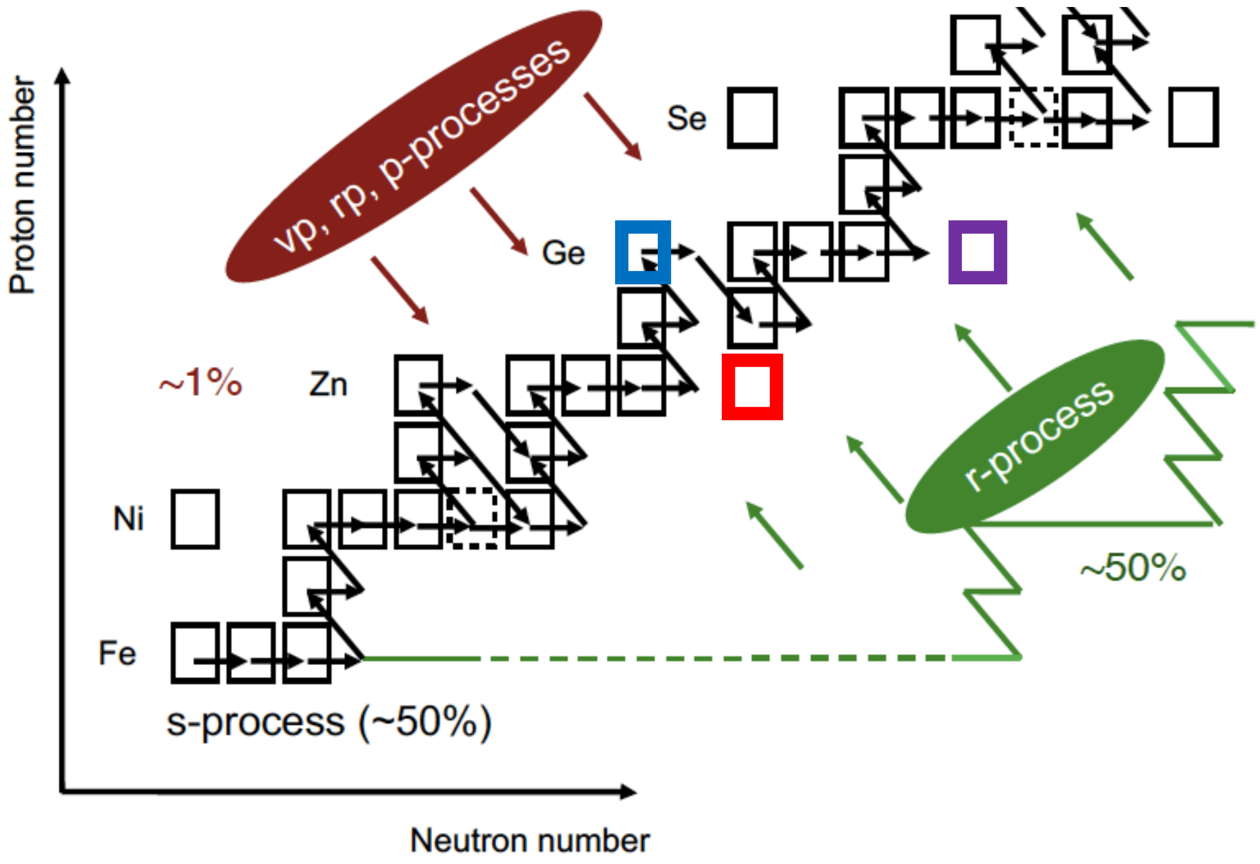
- main (A>90): N<σ> = constant
- weak (A<90): no flow equilibrium

	Main component		Weak component	
Stellar site	TP-AGB stars (1.5$M_\odot$ – 3$M_\odot$)		Massive stars (> 8$M_\odot$)	
	H-He shell		He-Core	C-shell
Neutron source	^{13}C$(\alpha,n)^{16}$O	^{22}Ne$(\alpha,n)^{25}$Mg	^{22}Ne$(\alpha,n)^{25}$Mg	
Temperature (GK)	0.09	0.3-0.35	0.3-0.35	1
Temp. (k_BT-value)	8 keV	25 keV	25 keV	90 keV
Peak neutron density (N_n)	$10^7 - 10^8$ cm^{-3}	10^{10} cm^{-3}	10^7 cm^{-3}	10^{11} cm^{-3}

$$\frac{\mathrm{dN(A)}}{dt} = N_\mathrm{n}(t)V_\mathrm{T}[N(A-1) < \sigma >_{\mathrm{A}-1} - N(A) < \sigma >_\mathrm{A}]$$

$$\mathrm{MACS} = \frac{2}{\sqrt{\pi}}\frac{1}{(k_\mathrm{B}T)^2}\int_0^\infty \sigma(E)E\mathrm{e}^{\left(-\frac{E}{k_\mathrm{B}T}\right)}\mathrm{d}E$$

Motivation



^{70}Ge is an "s-only" nuclide. "S-only" nuclides can be used to extract important s-process parameters, such as the average number of neutrons per Fe seed and the mean neutron exposure.

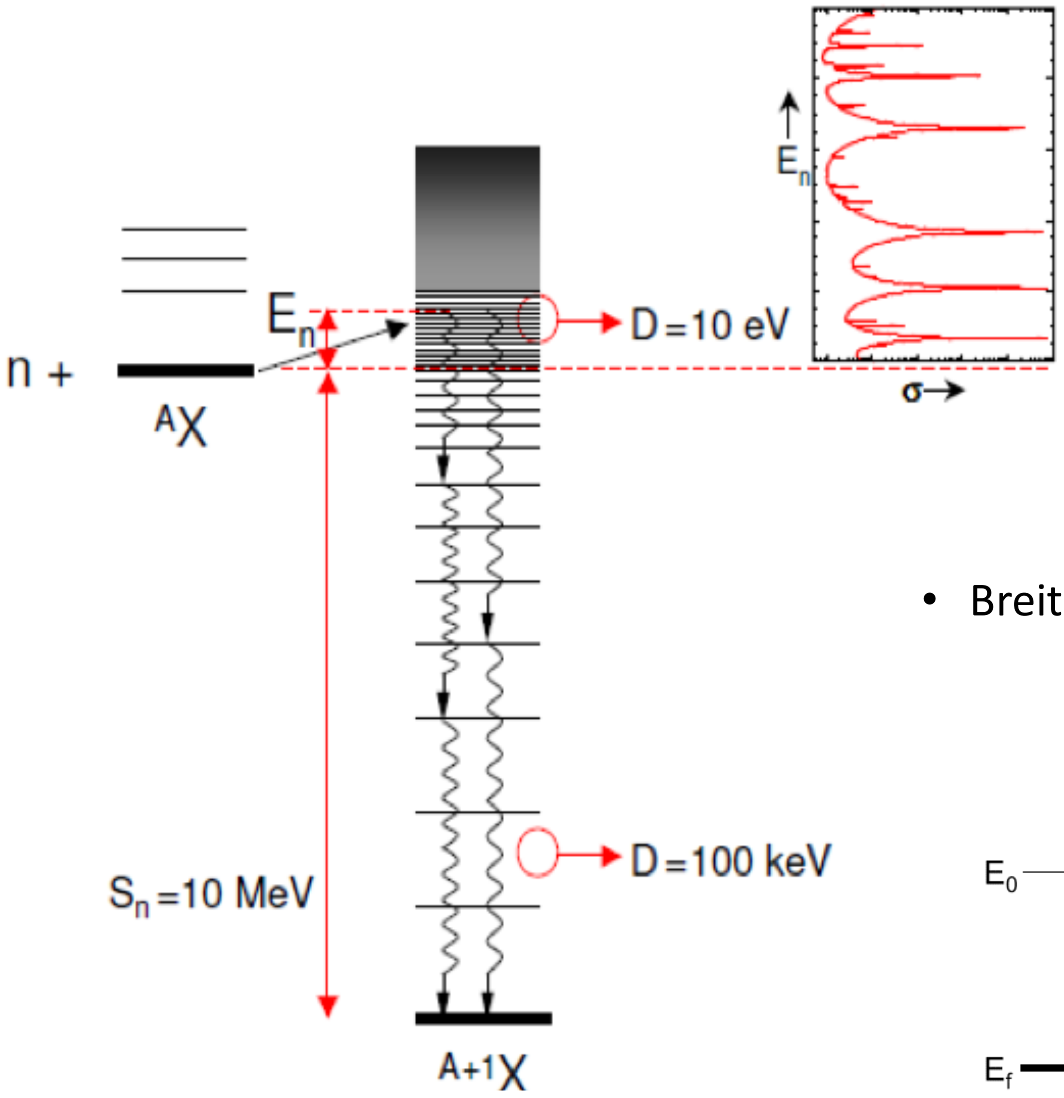
The decay of **^{76}Ge** is used as probe to investigate neutrinoless double β decay.

Neutron induced reactions on germanium play an important role in low background experiments, mostly due to the fact that Ge is used as detector material.

Neutron capture cross sections of germanium have a crucial influence on abundances of elements from germanium to yttrium.
Since the s process takes place during different burning stages of stars, temperatures range from 0.1 to 1 GK, corresponding to $k_B T$ values of 8 – 90 keV.

Experimental cross section data presently available for Ge(n,γ) are scarce and cover only a fraction of the neutron energy range of interest.

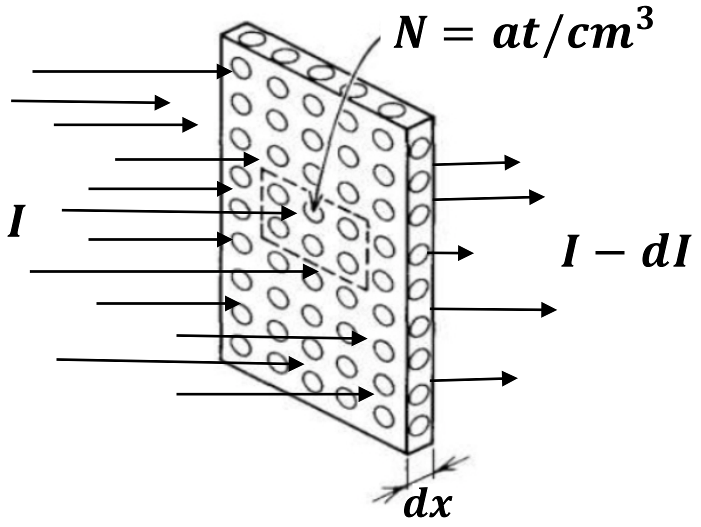
Compound nucleus and the resonance parameters



- cross section:

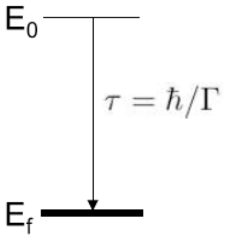
$$dI = -\sigma \cdot I \cdot N \cdot dx$$

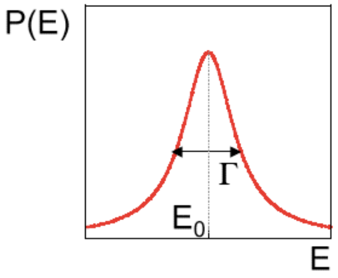
$$\frac{dI}{I} = -\sigma \cdot N \cdot dx$$



- Breit−Wigner approximation for cross section of isolated single resonance:

$$\sigma(\mathrm{n},\gamma) = \pi\lambda^2 g \frac{\Gamma_\mathrm{n}\Gamma_\gamma}{(E-E_0)^2 + \left(\frac{\Gamma}{2}\right)^2}$$





statistical factor g :

$$g = \frac{2J+1}{(2I+1)(2s+1)}$$

Existing experimental data - ^{70}Ge(n,γ)

In 1968 H. Maletski and his group from ZIBJ (Dubna) measured germanium isotopes using neutron flux from the nuclear reactor.

Based on the experimental data, Maletski et al. parameterized only 3 resonances with their partial widths Γ_γ and Γ_n.

Energy (eV) Maletski et al.	Energy (eV) n_TOF	Γ_γ (meV) Maletski et al.	Γ_γ (meV) n_TOF	Γ_n (meV) Maletski et al.	Γ_n (meV) n_TOF
1115±4	1118.4±0.1	160±25	156.0±6.0	4600±1000	4288±235
1469±5	1474.22±0.01	150±25	175.4±1.3	700±120	708±10
4378±25	4397.4±0.1	180±40	158.8±2.6	5900±1200	5780±168

K. Maletski, L. B. Pikelner, I. M. Salamatin, and E. I. Sharapov, At. Energ. USSR 24, 173 (1968).

In 1984 G. Walter and H. Beer from the Karlsruhe Institute of Technology, have measured Maxwellian averaged cross section for different $k_\mathrm{B}T$ values. As a neutron flux the used neutrons coming from ^{6}Li(p, n)^{7}Be reaction.

However, still it does not cover the entire range of astrophysical interest.

Temperature (keV)	20	30	40	50
MACS (mb)	112±6	92±5	81±5	75±4

G. Walter and H. Beer, Measurement of neutron capture cross sections of s-only isotopes – ^{70}Ge, ^{86}Sr and ^{87}Sr, Astron. Astrophys. 142, 268 (1985).

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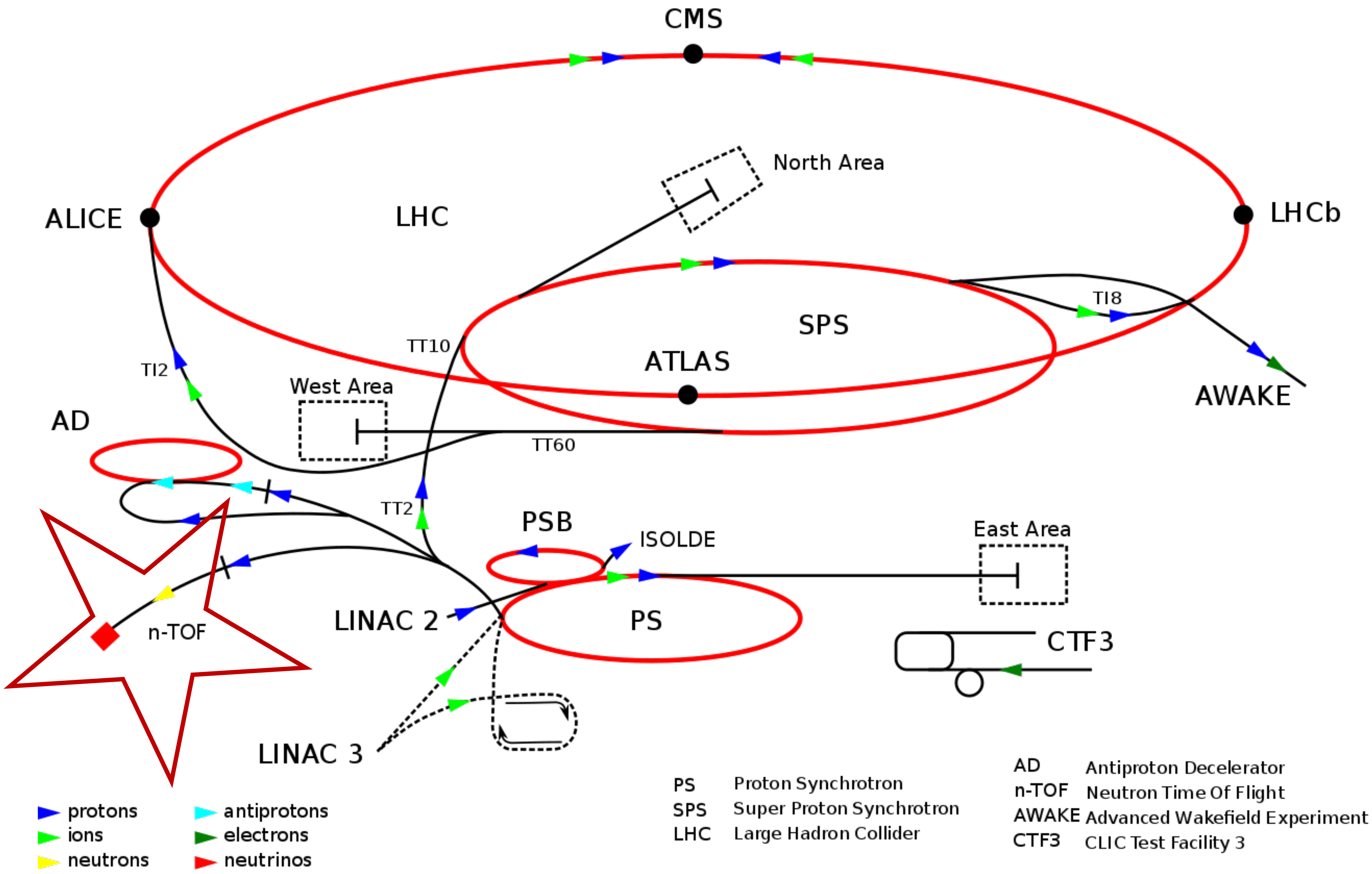
no experimental data for ^{72,73}Ge isotopes

The n_TOF facility at CERN

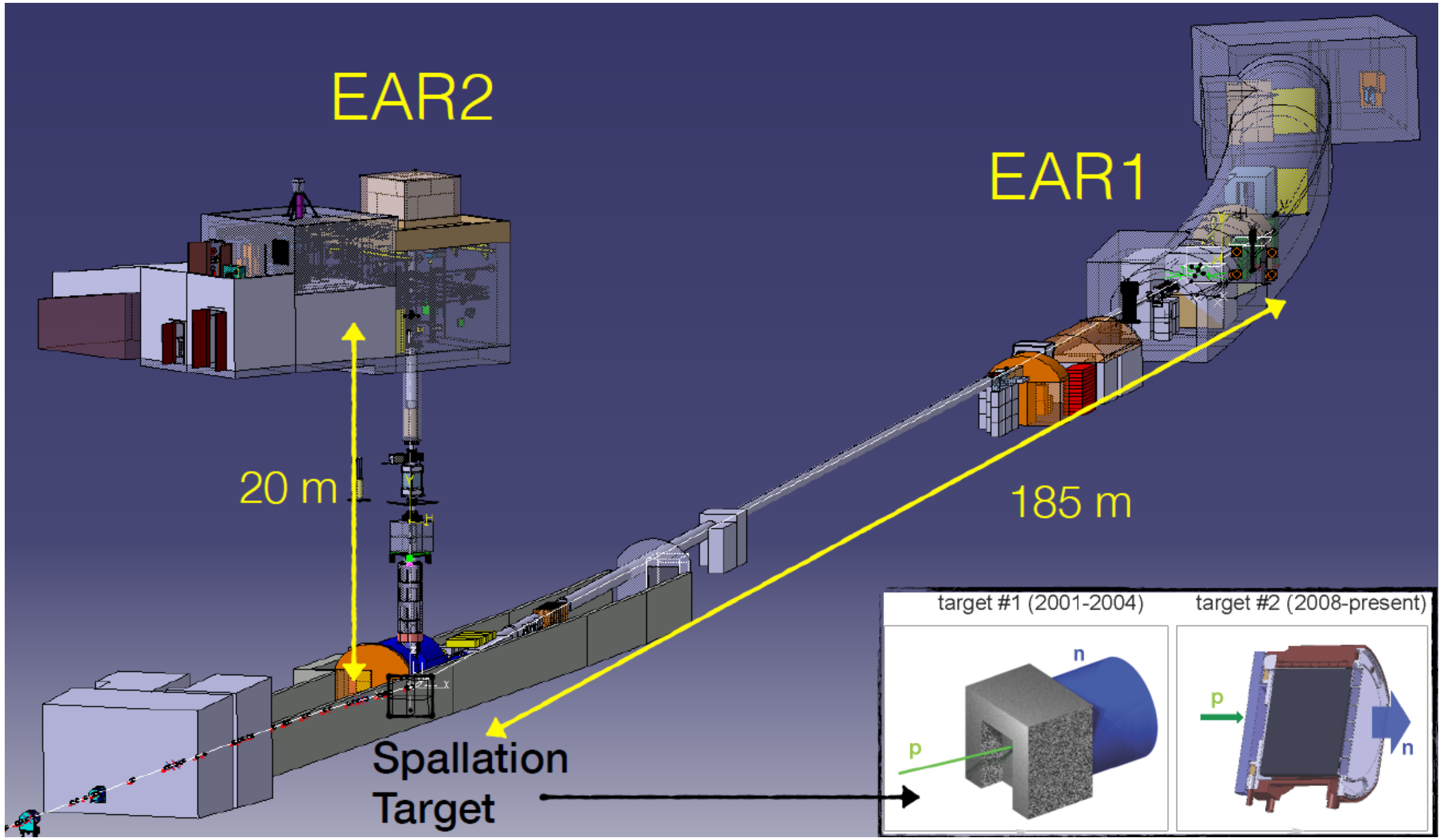


PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider
AD	Antiproton Decelerator
n-TOF	Neutron Time Of Flight
AWAKE	Advanced Wakefield Experiment
CTF3	CLIC Test Facility 3

Source: ntof-exp.web.cern.ch

The n_TOF/CERN facility – parameters

- Proton energy: 20 GeV
- 1.3 tone cylindrical lead block of 40 cm in length and 60 cm in diameter
- Proton intensity: $7 \cdot 10^{12}$ protons/pulse
- Pulse frequency: 1pulse/2.4 s (0.5 Hz)



EAR1

- Neutron energy: 25 meV – 1 GeV
- Flight path length: 185 m
- Beam size at the experimental hall: ∅3.5 cm

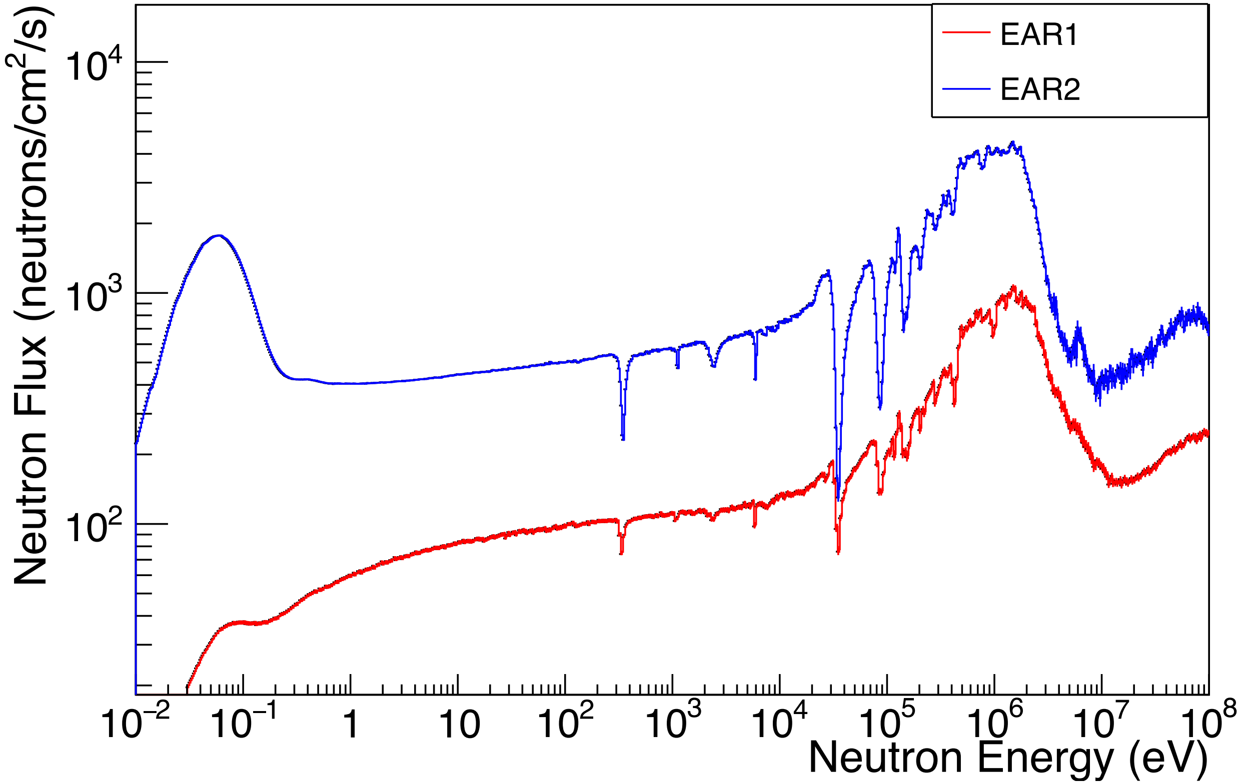
EAR2

- Neutron energy: 25 meV – 300 MeV
- Flight path length: 20 m
- Beam size at the experimental hall: ∅4.2 cm

Source: ntof-exp.web.cern.ch

The n_TOF/CERN facility – parameters

Energy dependence neutron flux for EAR1 and EAR2.



Comparison between energy resolution for EAR1 and EAR2.

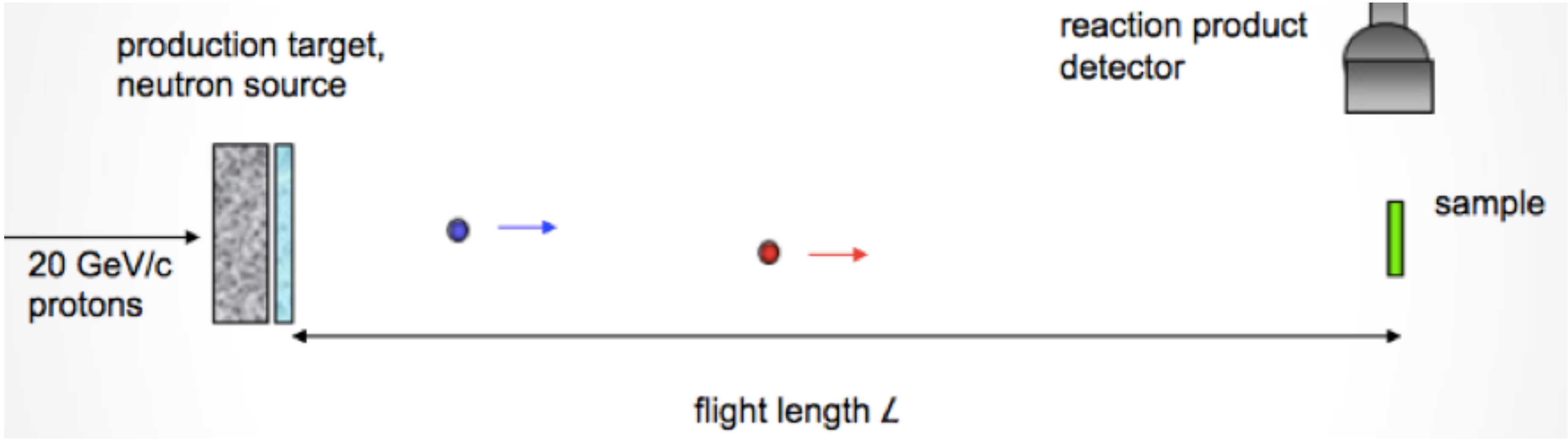
E_n	$\Delta E/E$	
	EAR1	EAR2
1 eV	3.2×10^{-4}	4.8×10^{-3}
10 eV	3.2×10^{-4}	5.7×10^{-3}
100 eV	4.3×10^{-4}	8.1×10^{-2}
1 keV	5.4×10^{-4}	1.4×10^{-2}
10 keV	1.1×10^{-3}	2.3×10^{-2}
100 keV	2.9×10^{-3}	4.6×10^{-2}
1 MeV	5.3×10^{-3}	5.6×10^{-2}

Neutron spectroscopy

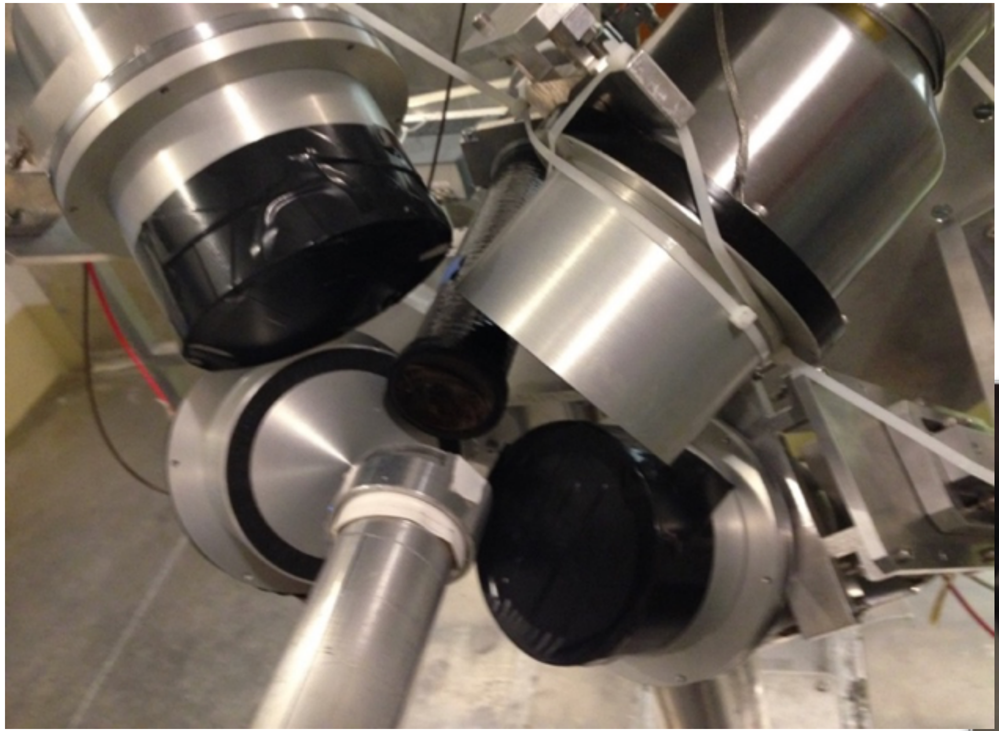
The neutron energy is determined via its time-of-flight through the relation:

$$E_\mathrm{n} = m_\mathrm{n} c^2 (\gamma - 1) \quad \gamma = \frac{1}{\sqrt{1-\left(\frac{v_\mathrm{n}}{c}\right)^2}} \qquad v_\mathrm{n} = \frac{L}{TOF}$$

$$TOF = T_\mathrm{STOP} - T_\gamma + \frac{L}{c}$$



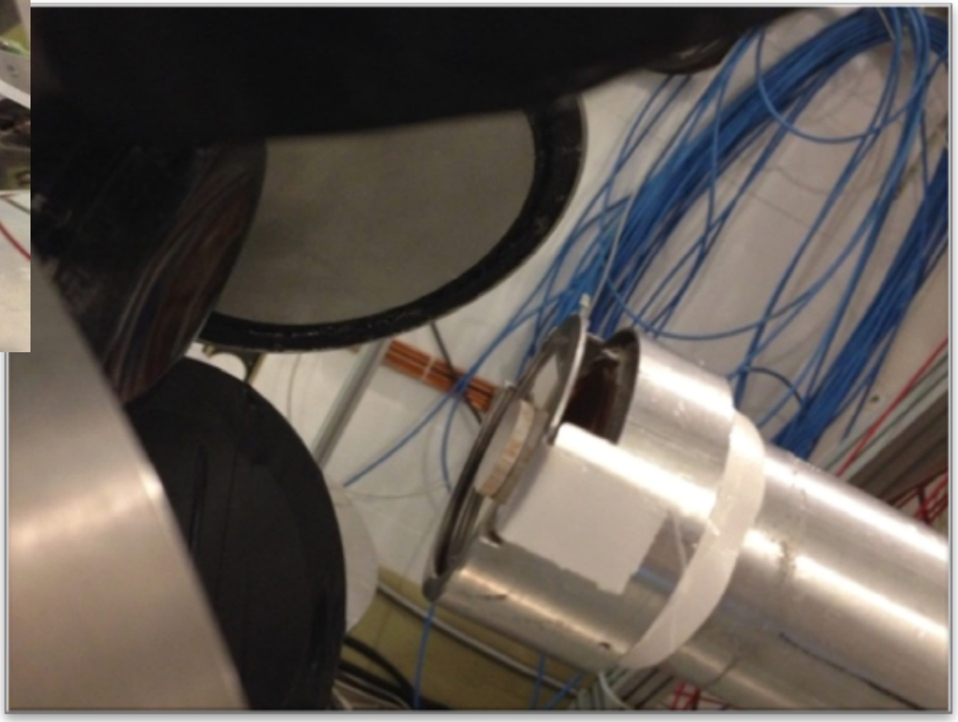
Detection setup



Detection setup for capture measurements consists of four scintillator detectors C_6D_6, advantages:

- 20% efficiency to detect a γ-ray from a capture cascade,
- low neutron sensitivity $\sim\frac{\varepsilon_n}{\varepsilon_\gamma} \approx 3 \cdot 10^{-5}$.

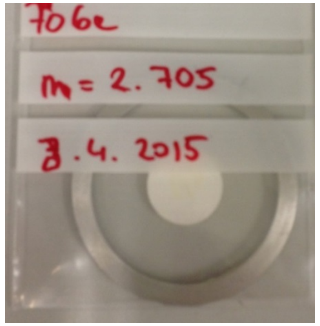
Fast recovering after γ-flash ~2 μs, enable to detect neutron energy up to ~1 MeV.

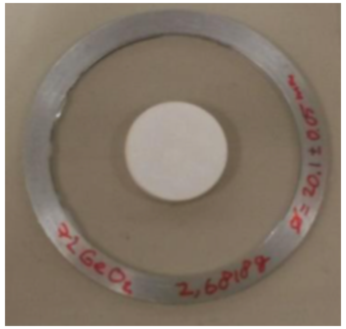


SAMPLES:

- ^{xx}Ge – pressed powder (GeO_2),
- enrichment:

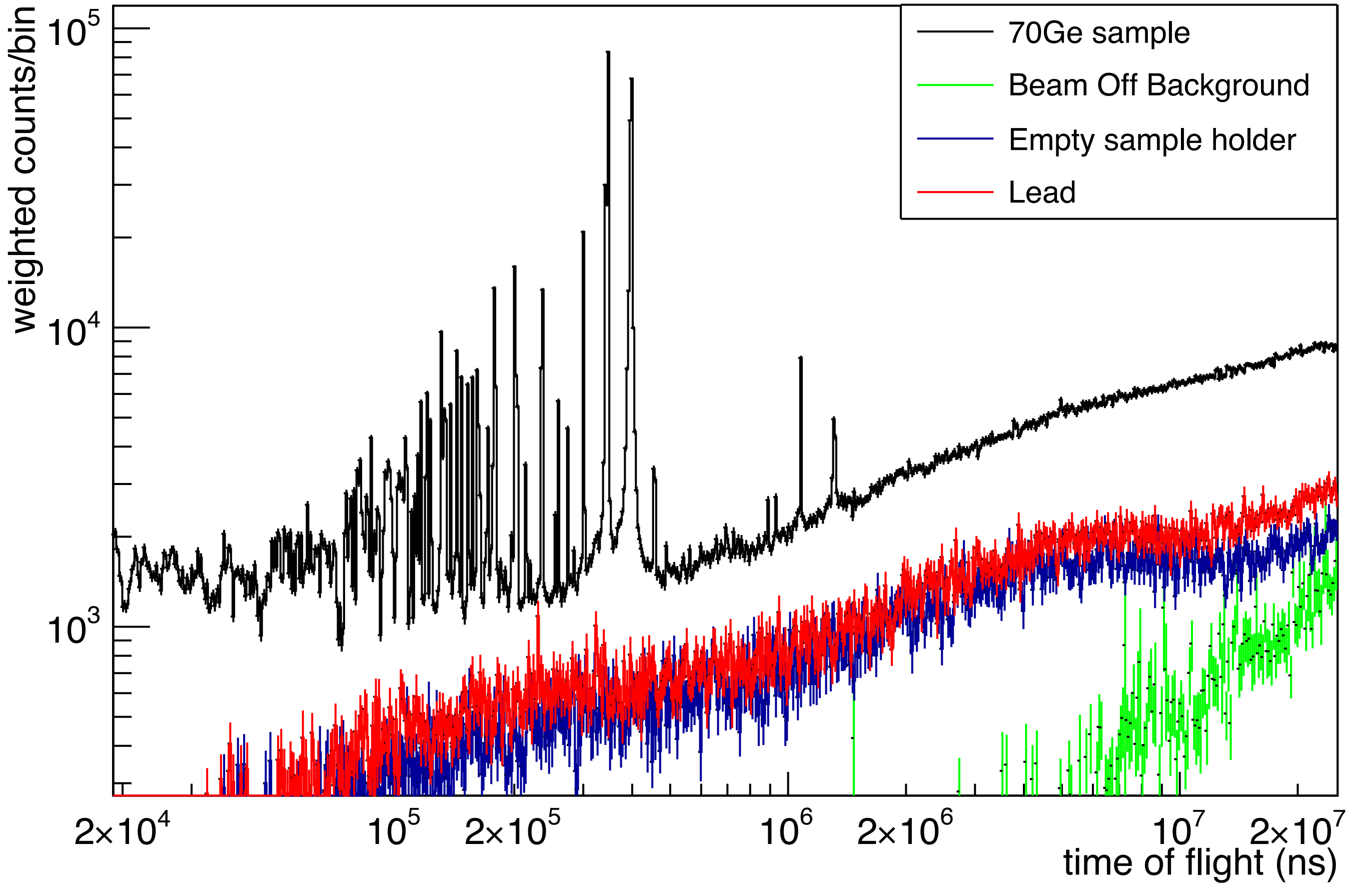
^{70}Ge – 97.71%,
^{72}Ge – 96.59%,
^{73}Ge – 96.07%,
^{74}Ge – 95.51%,
^{76}Ge – 88.46%.

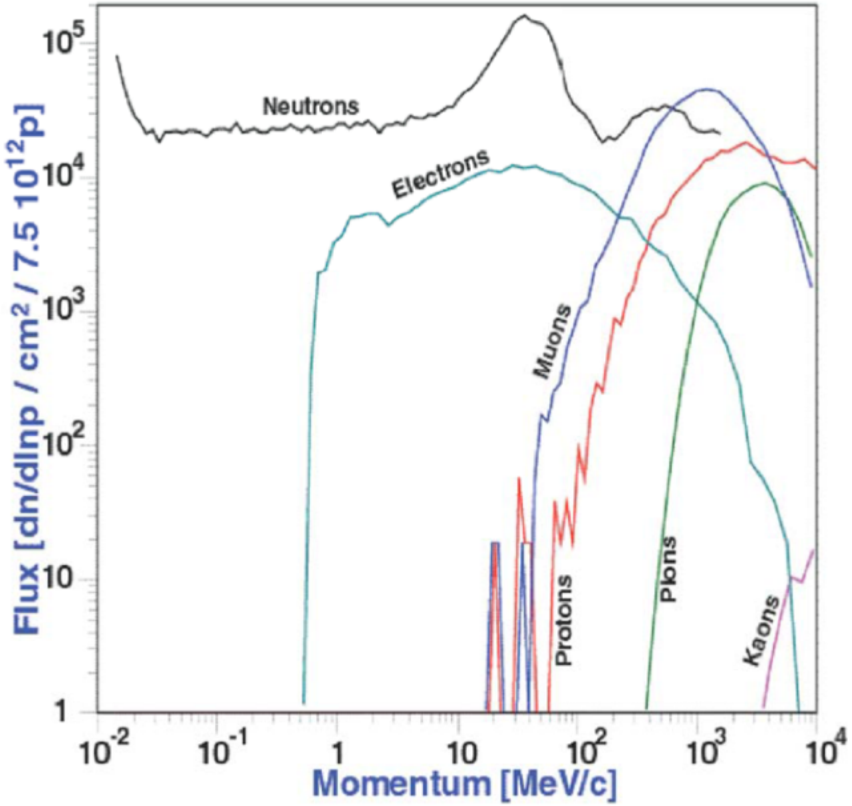




Background analysis

A 20 GeV proton beam interacting with a lead target represents a source of many charged and neutral particles.





C. Guerrero et al., European Physics Journal A 49, 27, (2013).

^{70}Ge spectrum and the main background contributions.

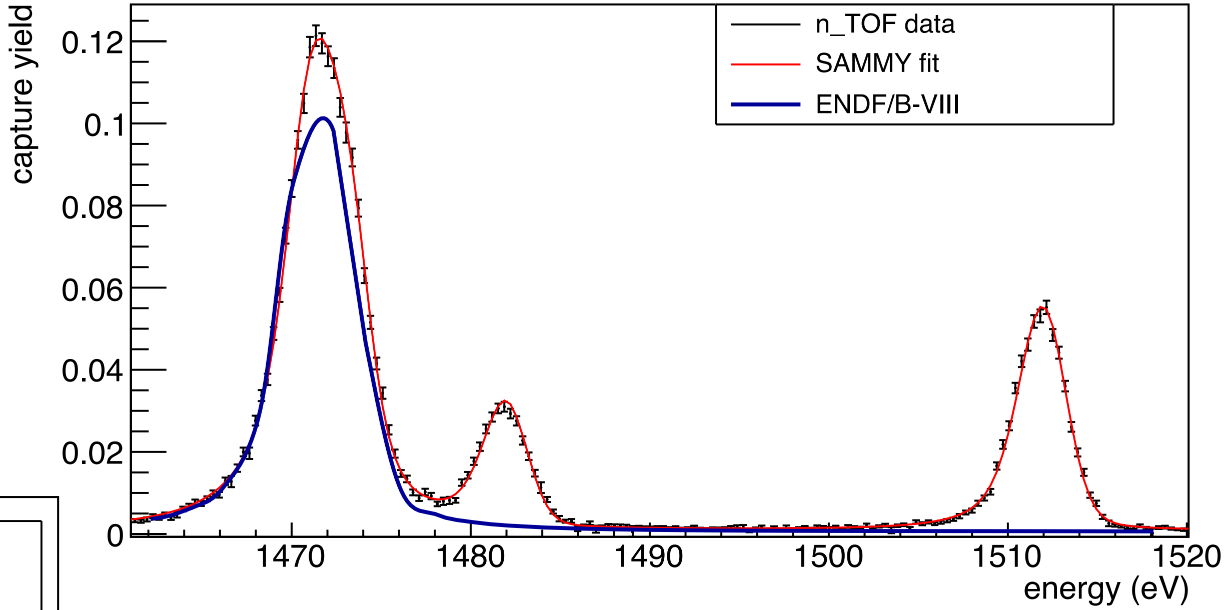
Neutron resonances - ^{70}Ge

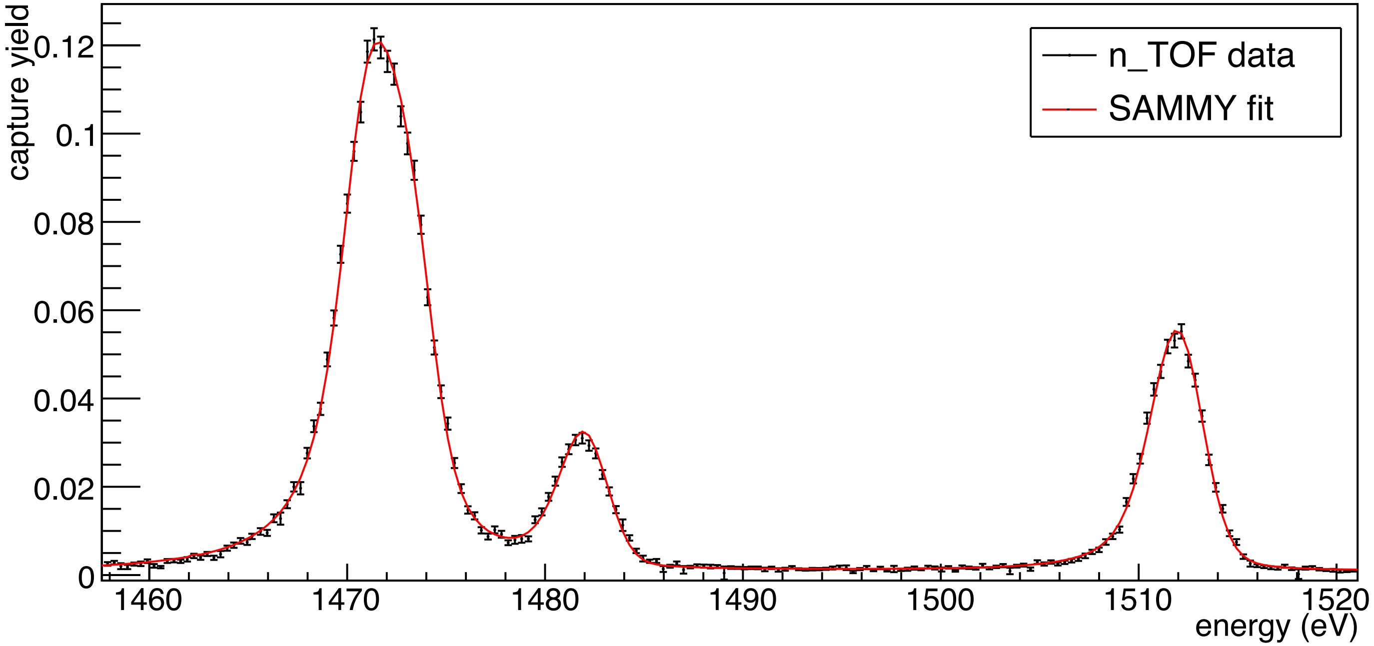
Extract cross-section by determining reaction-yield:

$$Y_{\mathrm{exp}}(E_{\mathrm{n}}) = \frac{C(E_{\mathrm{n}}) - B(E_{\mathrm{n}})}{\varepsilon\, \phi(E_{\mathrm{n}})\, \Lambda}$$

Statistics:

- 110 resonances up to 40 keV
- 90 new resonances
- 73 in the RRR





$E_{\mathrm{n}}\ (eV)$	$\Gamma_{\gamma}(meV)$	$\Gamma_{\mathrm{n}}(meV)$
1474	150	700
1474.2	175.9	708

A. Gawlik, C. Lederer-Woods et al., Measurement of the ^{70}Ge(n, γ) cross section up to 300 keV at the CERN n_TOF facility, Phys. Rev. C 100, 045804 (2019).

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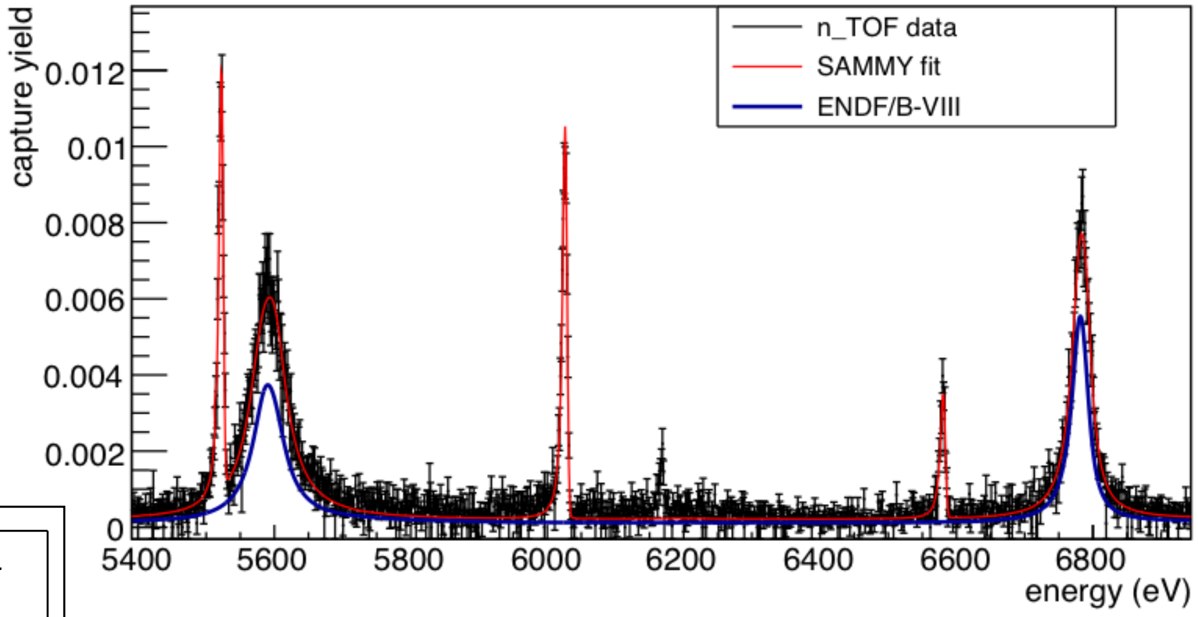
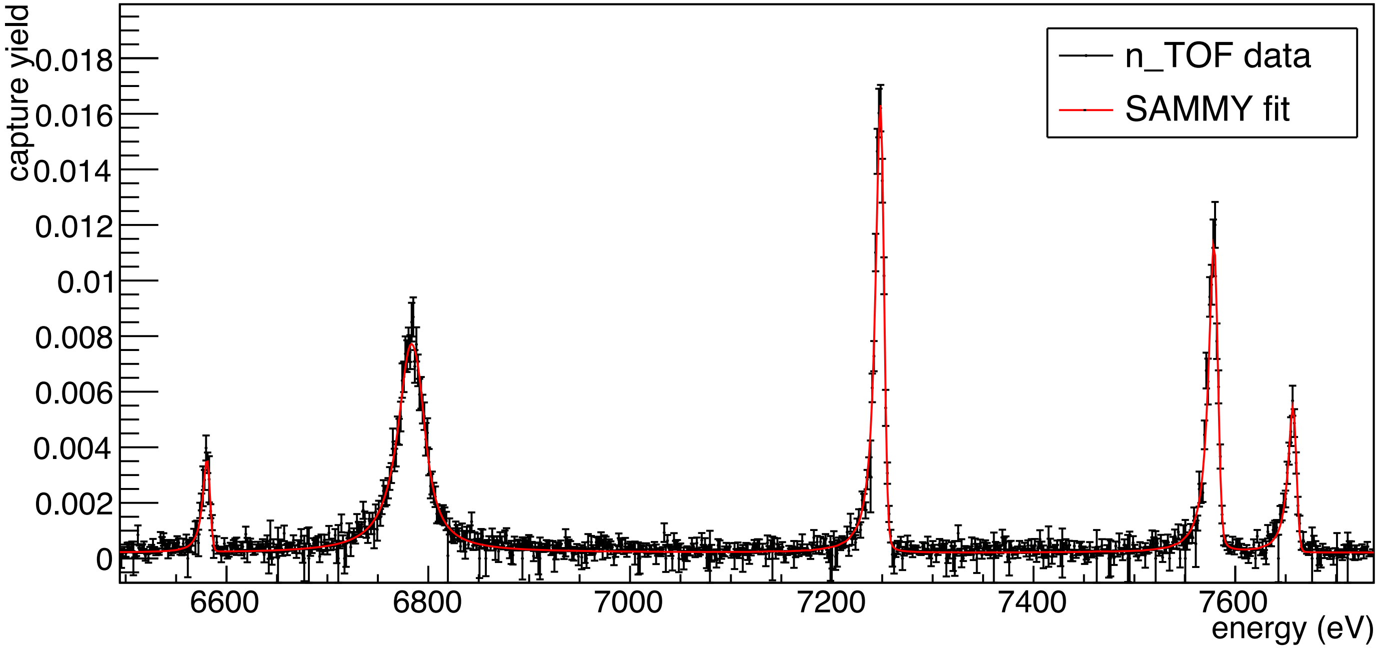


$E_{\mathrm{n}}\ (eV)$	$\Gamma_{\gamma}(meV)$	$\Gamma_{\mathrm{n}}(meV)$
5603	160	29000
5601.96	273.28	32246.62
6795	160	15000
6796.84	235.61	17133.74



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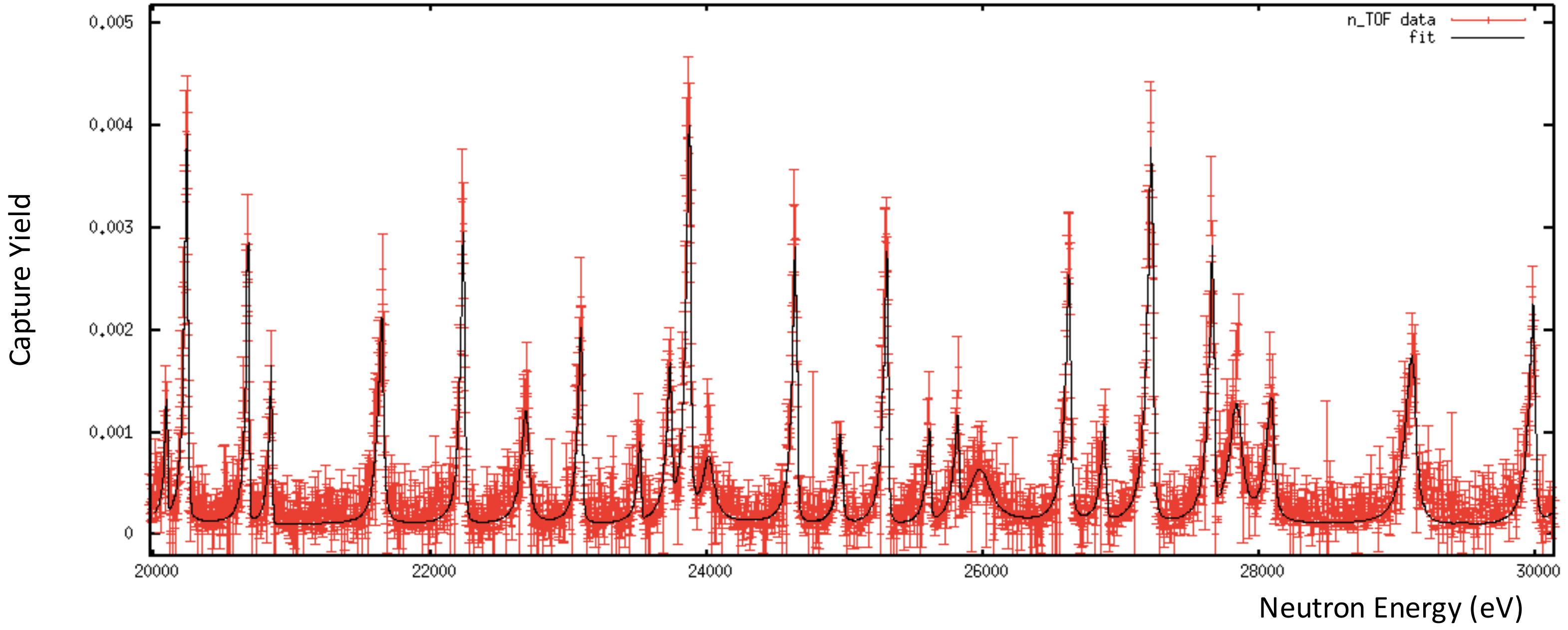

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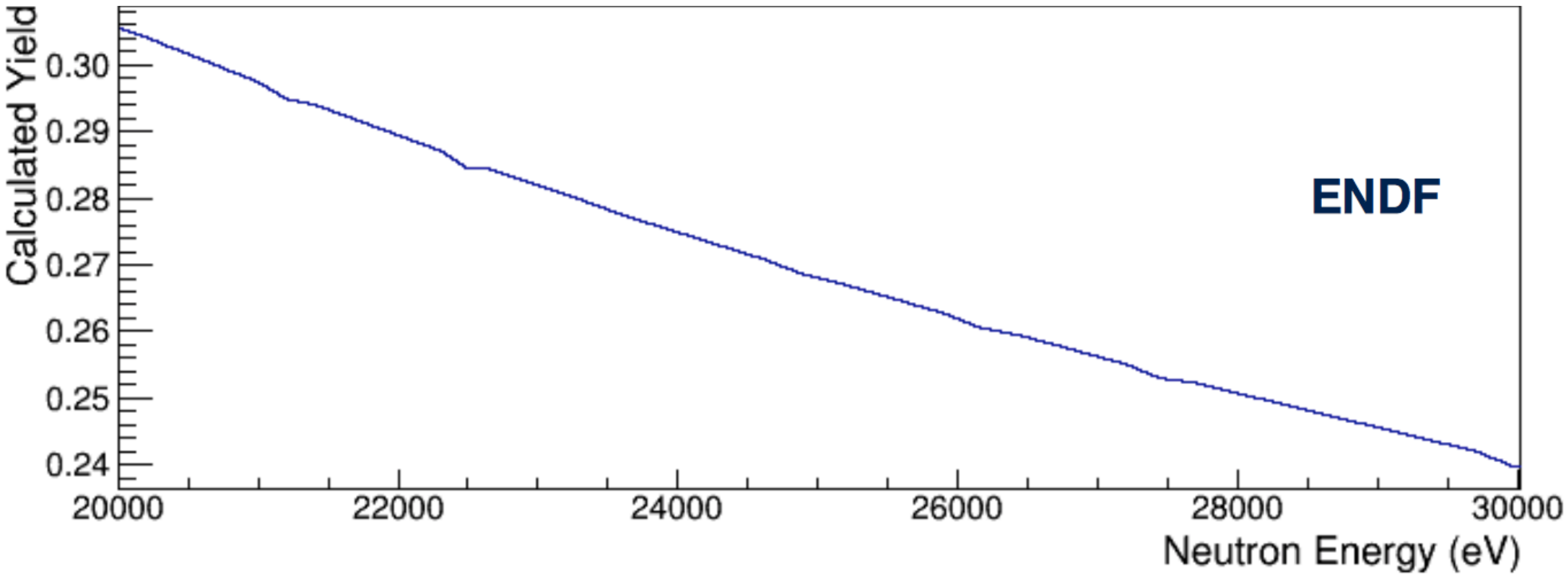


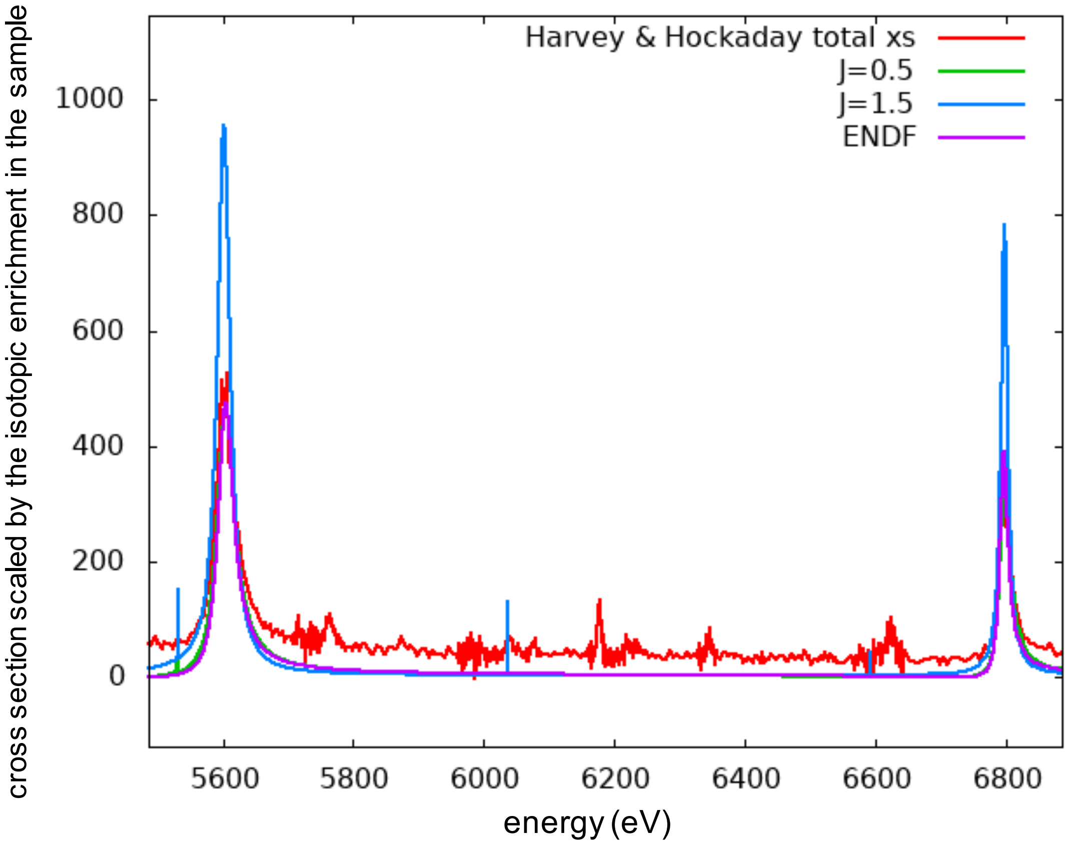
Neutron resonances - ^{70}Ge

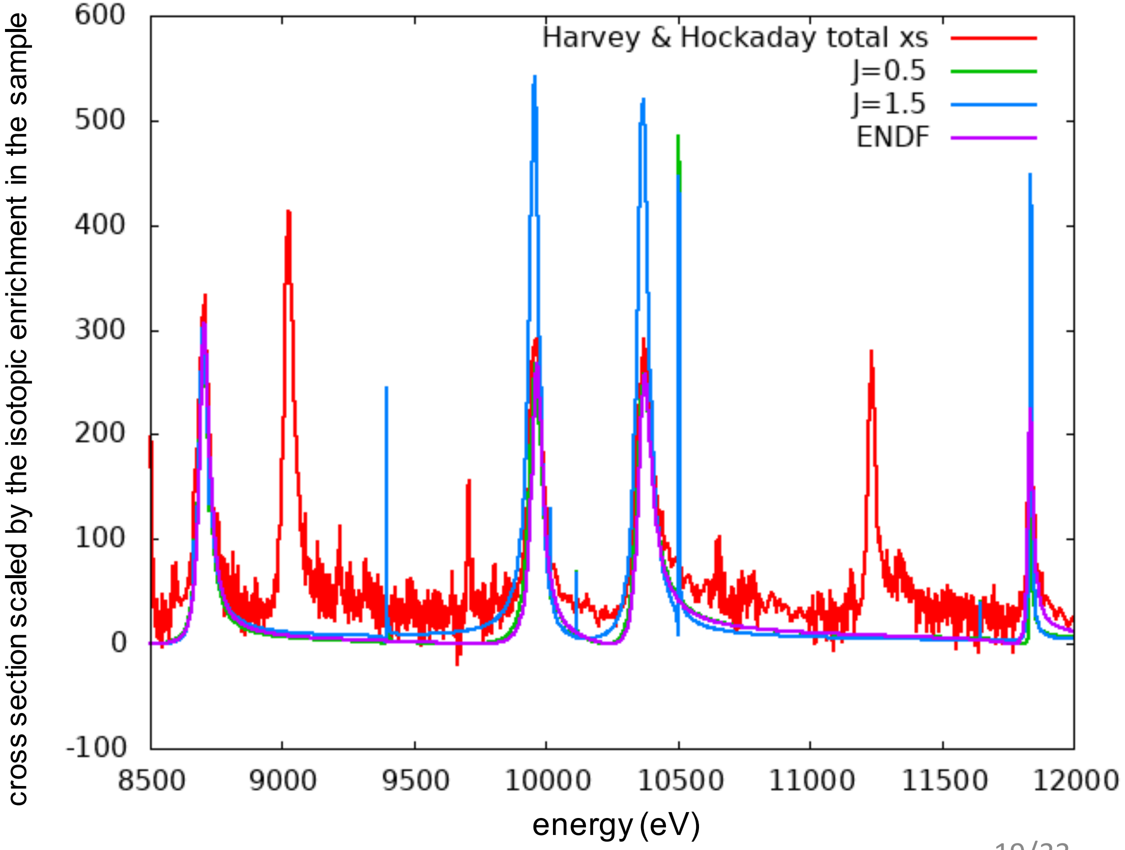
SAMMY was used to extract resonance capture kernels κ, proportional to the area of a capture resonance.

$$A_\mathrm{r} = \int \sigma_\mathrm{r}(E_\mathrm{n})\mathrm{d}E_\mathrm{n} = 2\pi^2 n\lambda \underbrace{g\,\frac{\Gamma_\mathrm{n}\Gamma_\gamma}{\Gamma}}_{\kappa}$$

Capture data themselves do not usually allow a reliable determination of individual resonance parameters, such as resonance spin J.

We used the kernels determined from n_TOF data and the spins from a transmission measurement (J.A. Harvey, M. Hockaday, EXFOR Entry 13770.004).





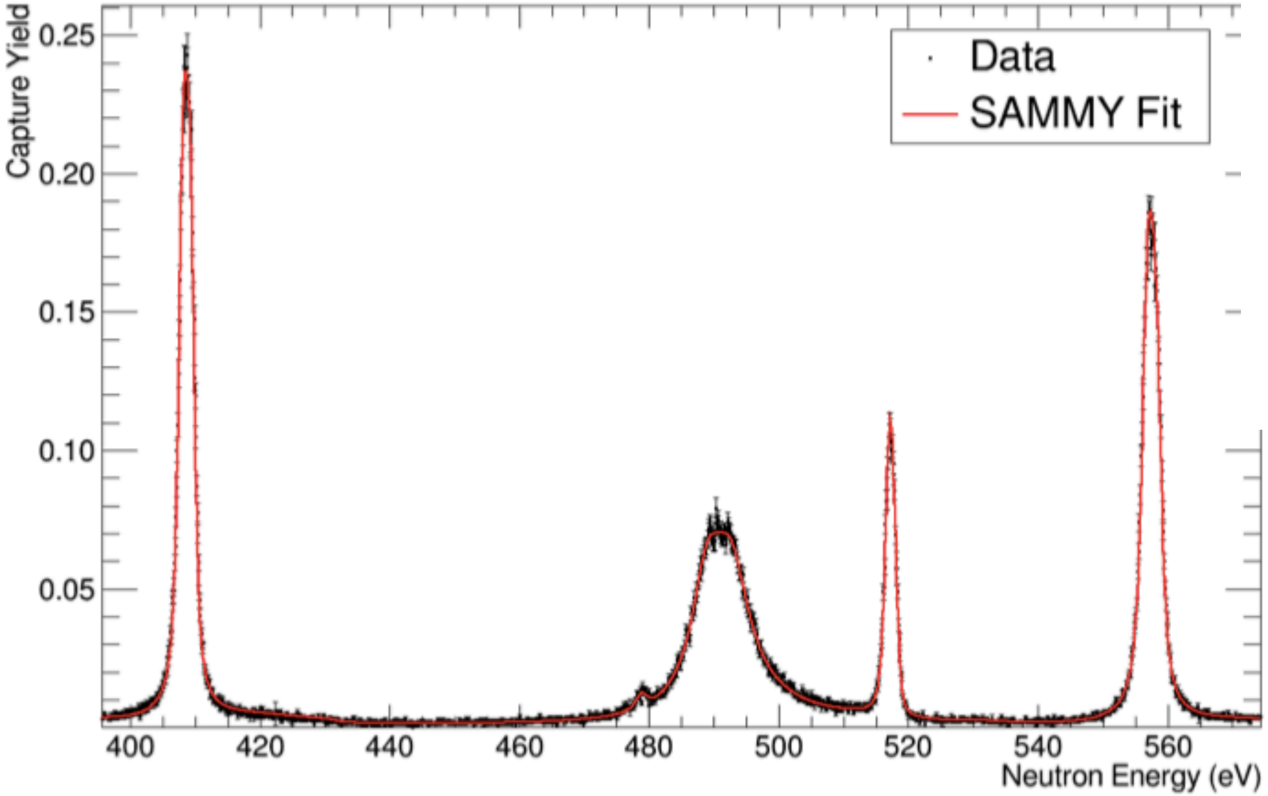
Neutron resonances - ^{73}Ge

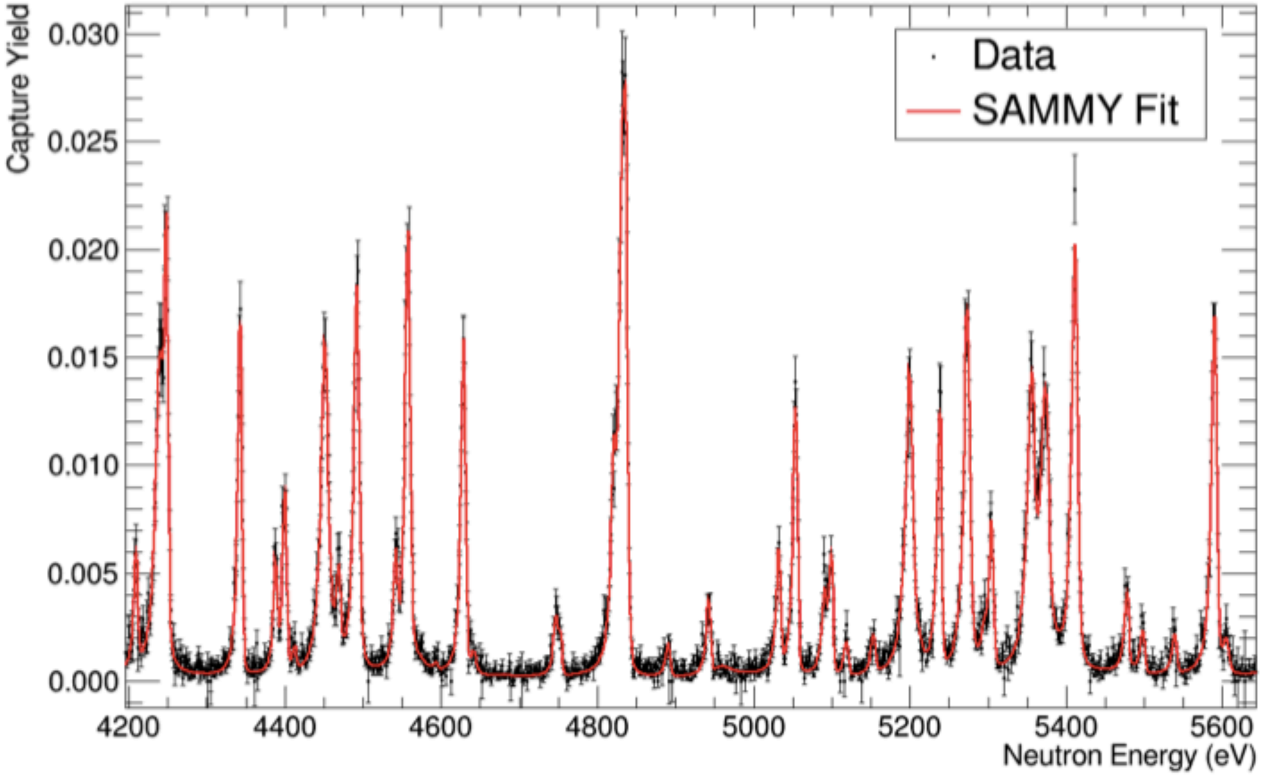
Extract cross-section by determining reaction-yield:

$$Y_{\mathrm{exp}}(E_{\mathrm{n}}) = \frac{C(E_{\mathrm{n}}) - B(E_{\mathrm{n}})}{\varepsilon\, \phi(E_{\mathrm{n}})\, \Lambda}$$

Statistics:

- 334 resonances in total up to 14 keV





C. Lederer-Woods, A. Gawlik et al., “Measurement of ^{73}Ge(n, γ) cross sections and implications for stellar nucleosynthesis”, Physics Letters B 790, 458, (2019).

Neutron resonances - ^{73}Ge

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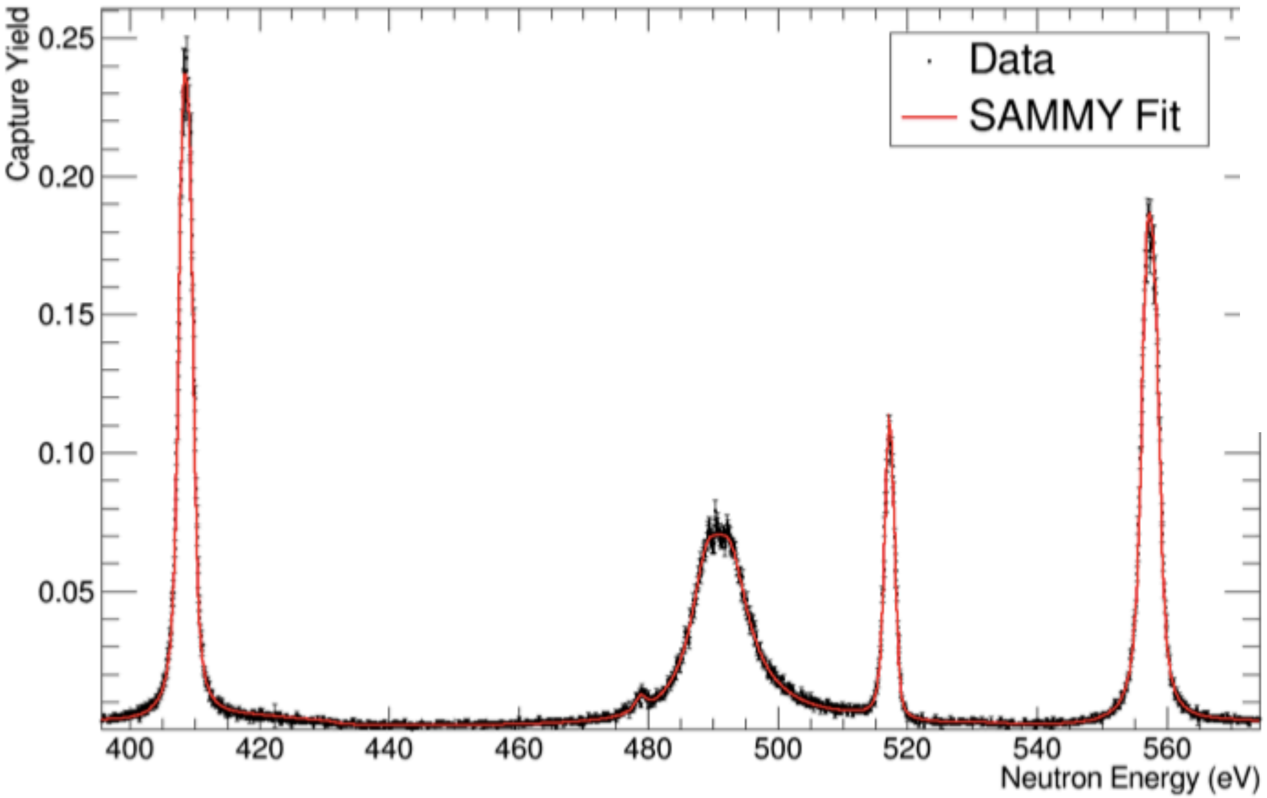
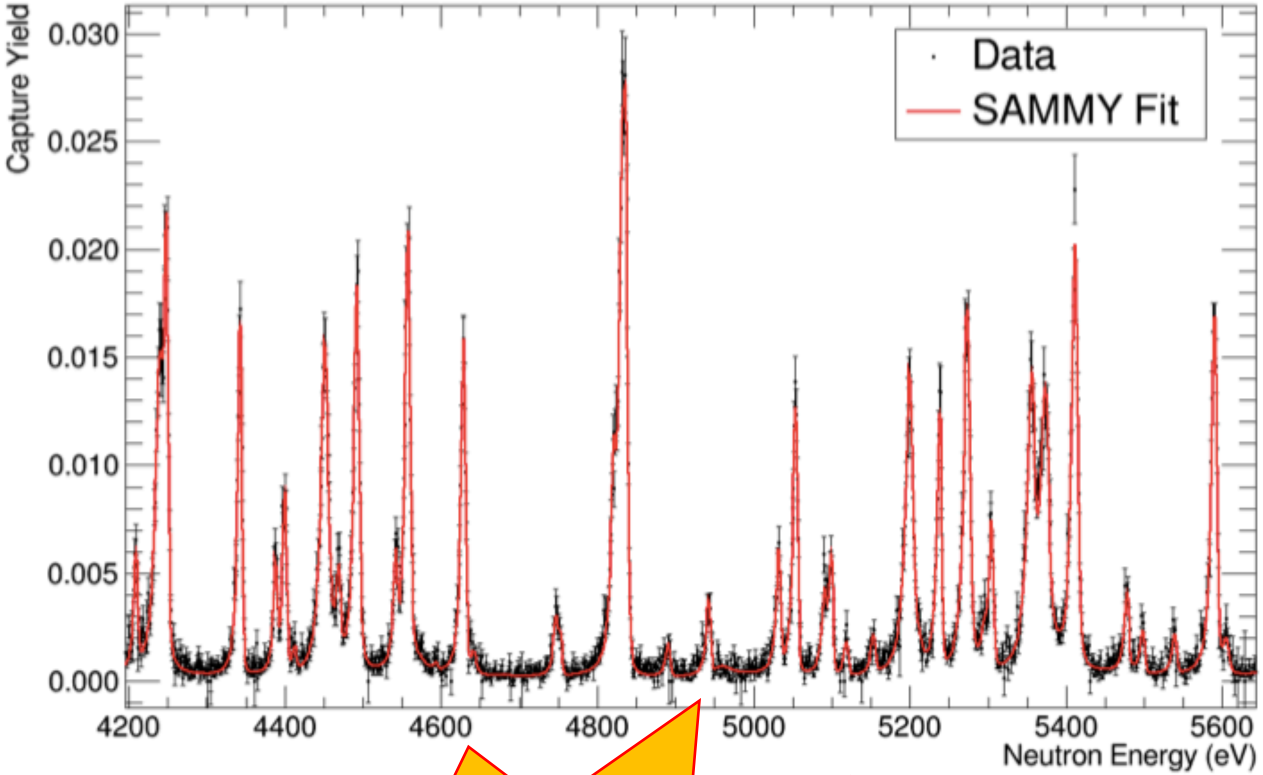




^{71}Ge: S_n= 7.4 MeV
^{73}Ge: S_n= 6.8 MeV
^{74}Ge: S_n= 10.2 MeV
^{75}Ge: S_n= 6.5 MeV
^{77}Ge: S_n= 6.1 MeV

C. Lederer-Woods, A. Gawlik et al., “Measurement of ^{73}Ge(n, γ) cross sections and implications for stellar nucleosynthesis”, Physics Letters B 790, 458, (2019).

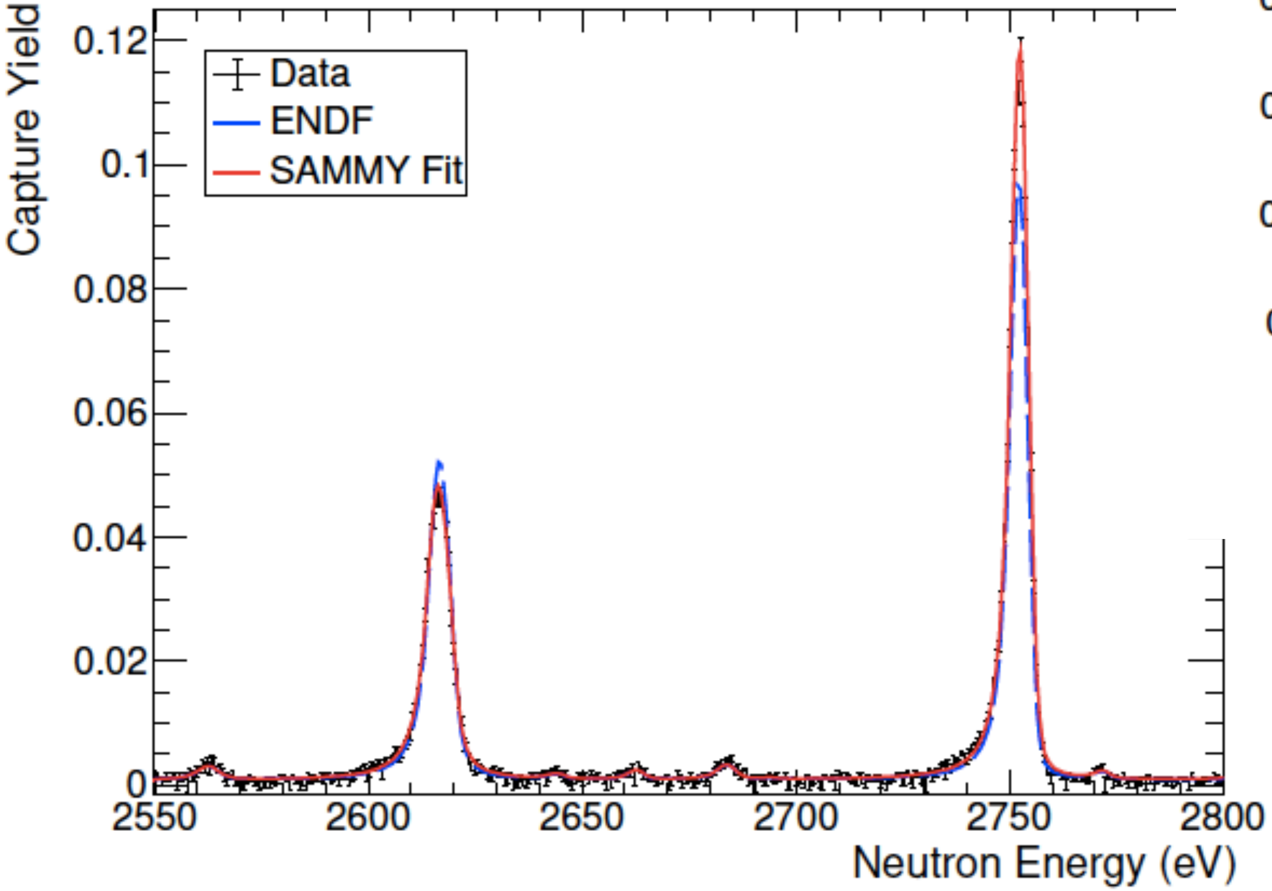
Neutron resonances - ^{72}Ge

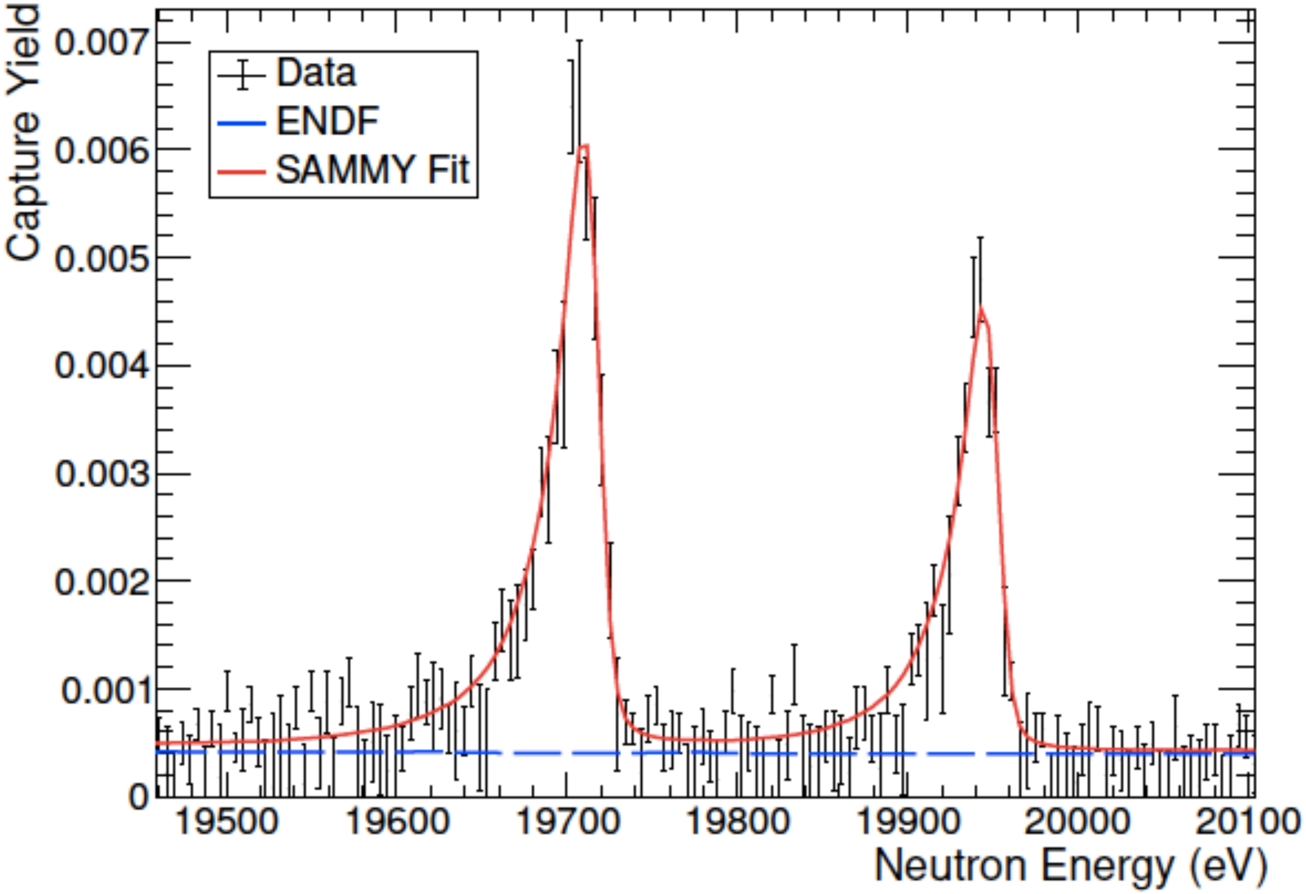
Extract cross-section by determining reaction-yield:

$$Y_{\mathrm{exp}}(E_{\mathrm{n}}) = \frac{C(E_{\mathrm{n}}) - B(E_{\mathrm{n}})}{\varepsilon\,\phi(E_{\mathrm{n}})\,\Lambda}$$

Statistics:

- 93 resonances in total up to 43 keV





M. Dietz, C. Lederer-Woods, A. Gawlik et al., Measurement of the ^{72}Ge(n,γ) cross section over a wide energy range at the CERN n TOF facility, submitted to PL B

Neutron resonances - ^{76}Ge preliminary results

Extract cross-section by determining reaction-yield:

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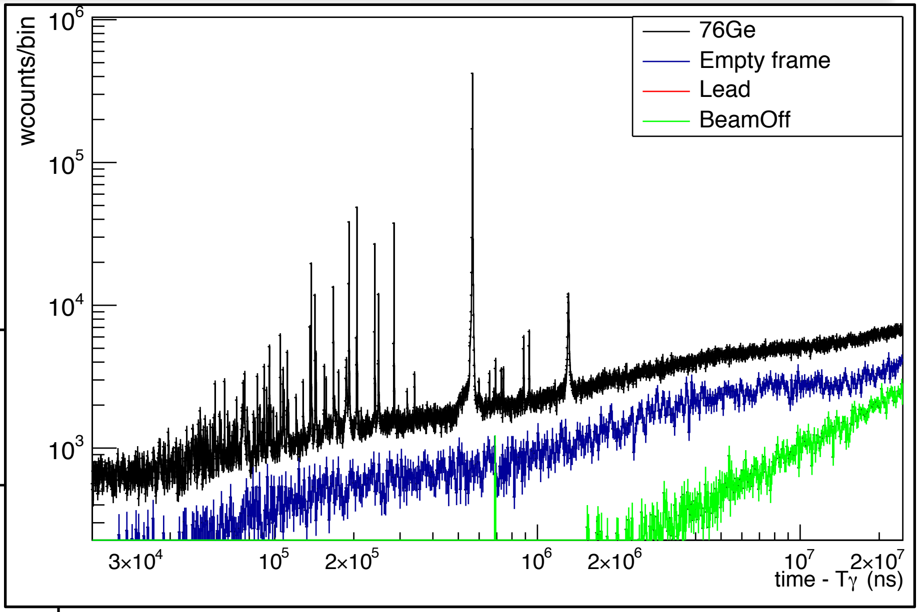

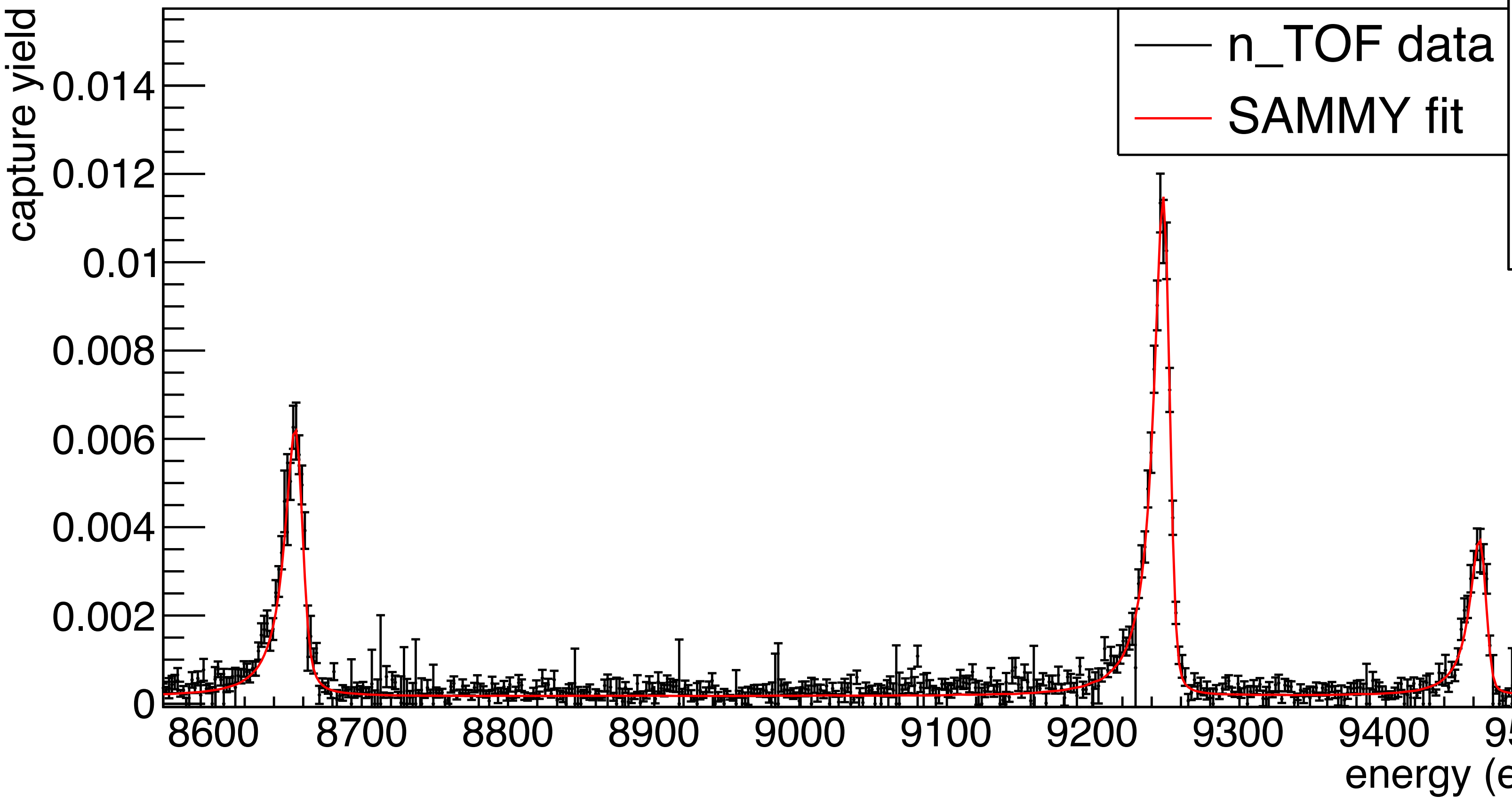

Statistics:

- 47 resonances in total up to 94 keV
- 37 resonances in the RRR up to 52 keV

Neutron resonances - ^{76}Ge preliminary results

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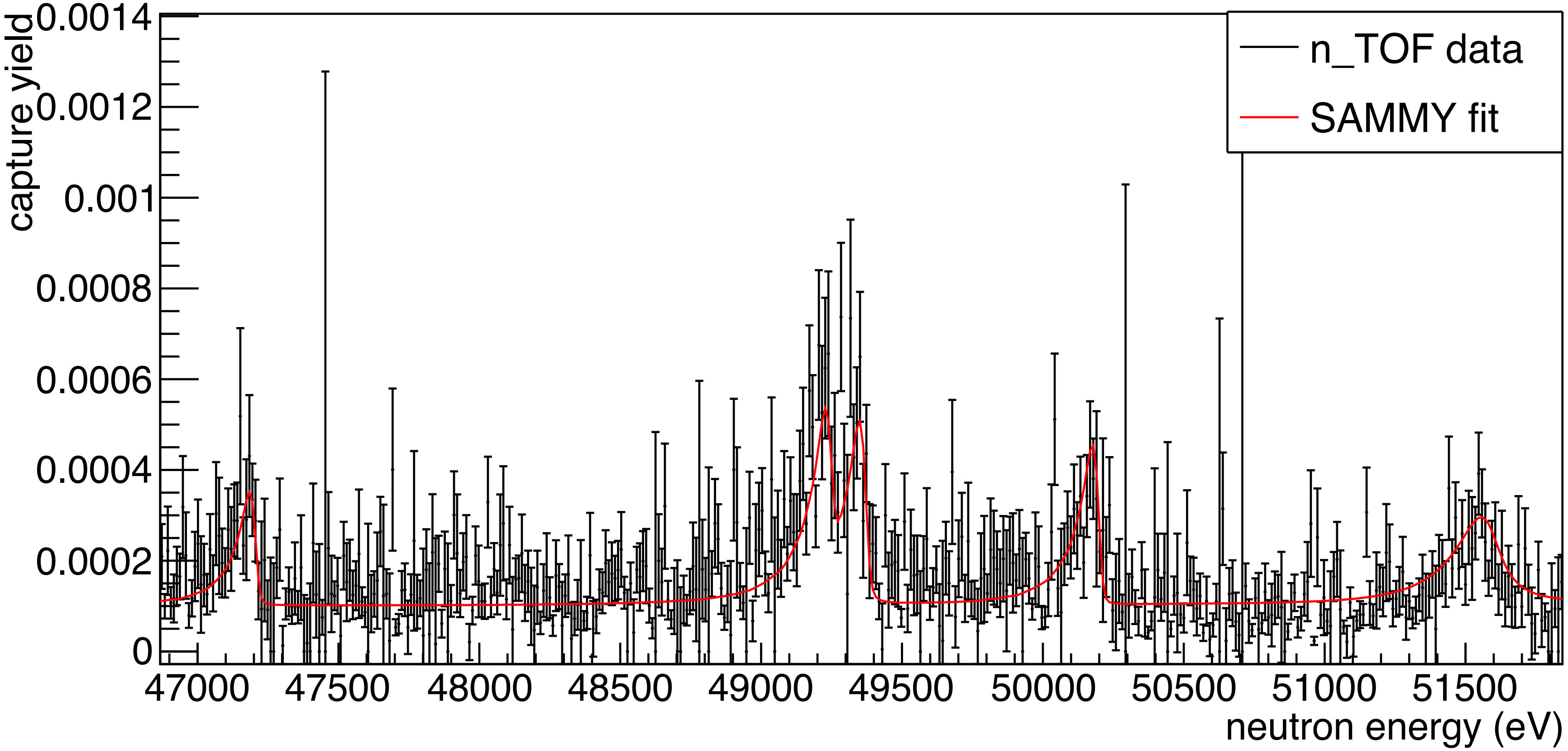
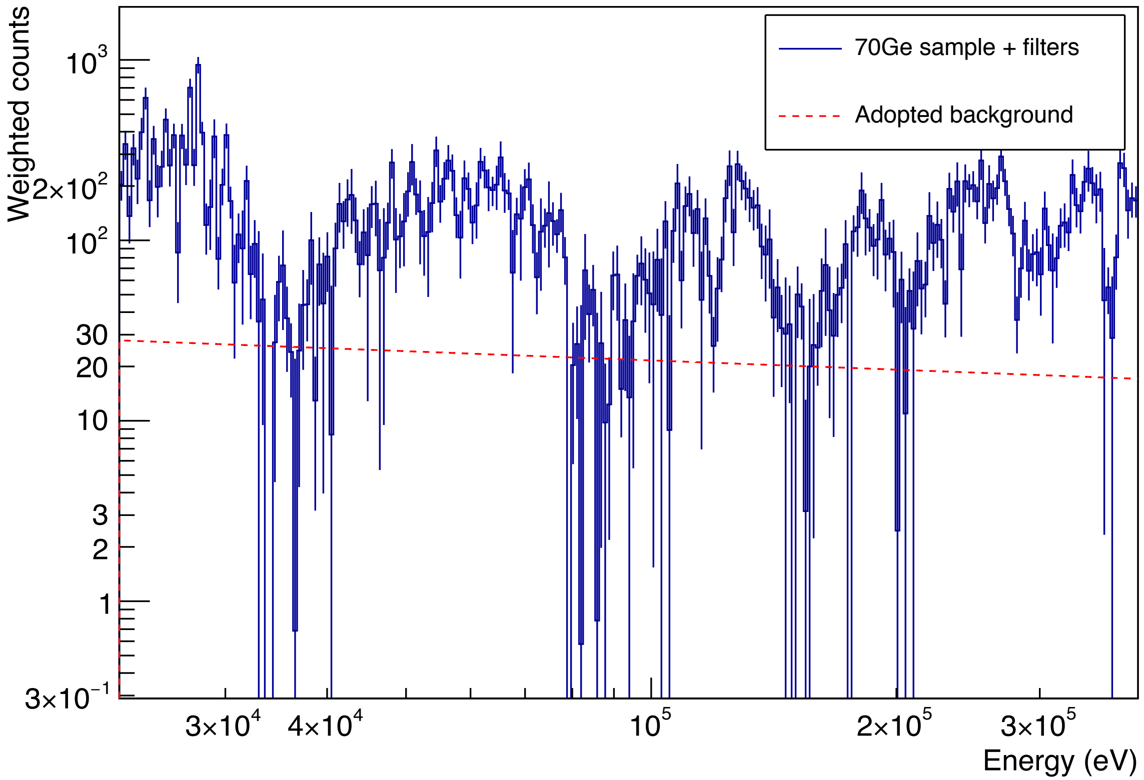
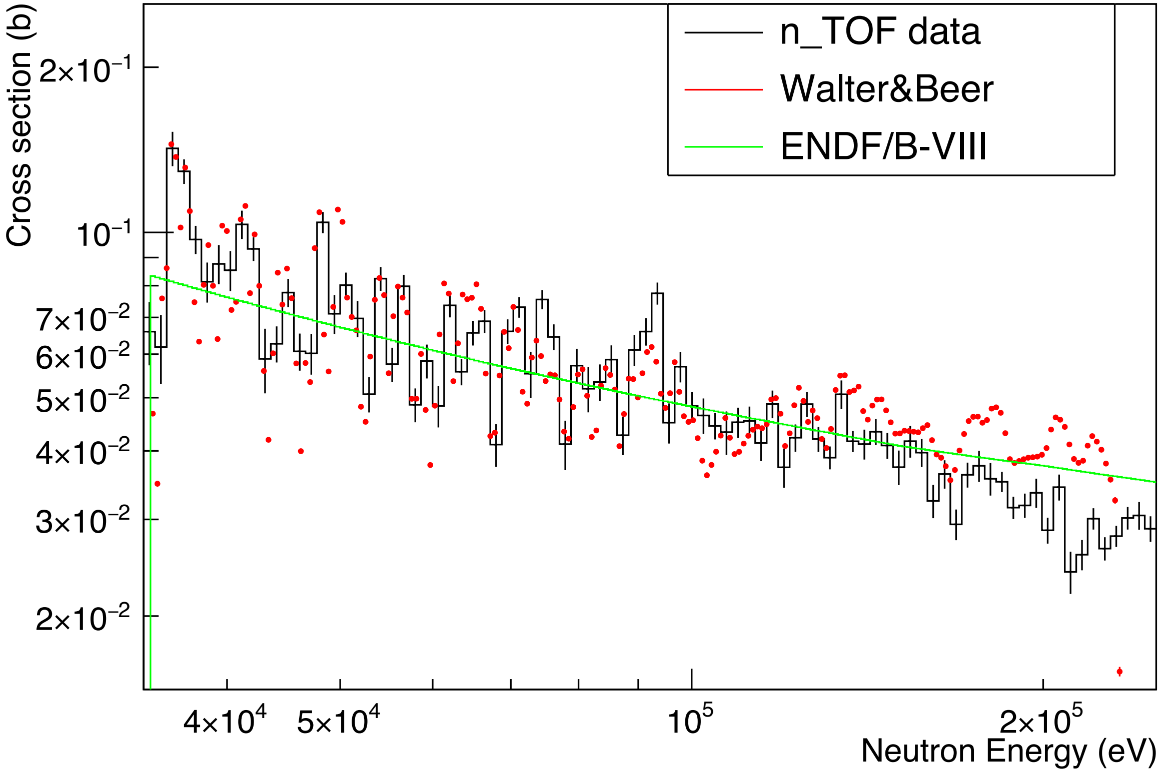


Analysis in progress

Cross section in the unresolved resonance region

In the continuum region where resonances are no longer isolated, capture cross section can be calculated with following equation: $\sigma_\gamma(E_\mathrm{n}) = \frac{Y(E_\mathrm{n})}{n}$.





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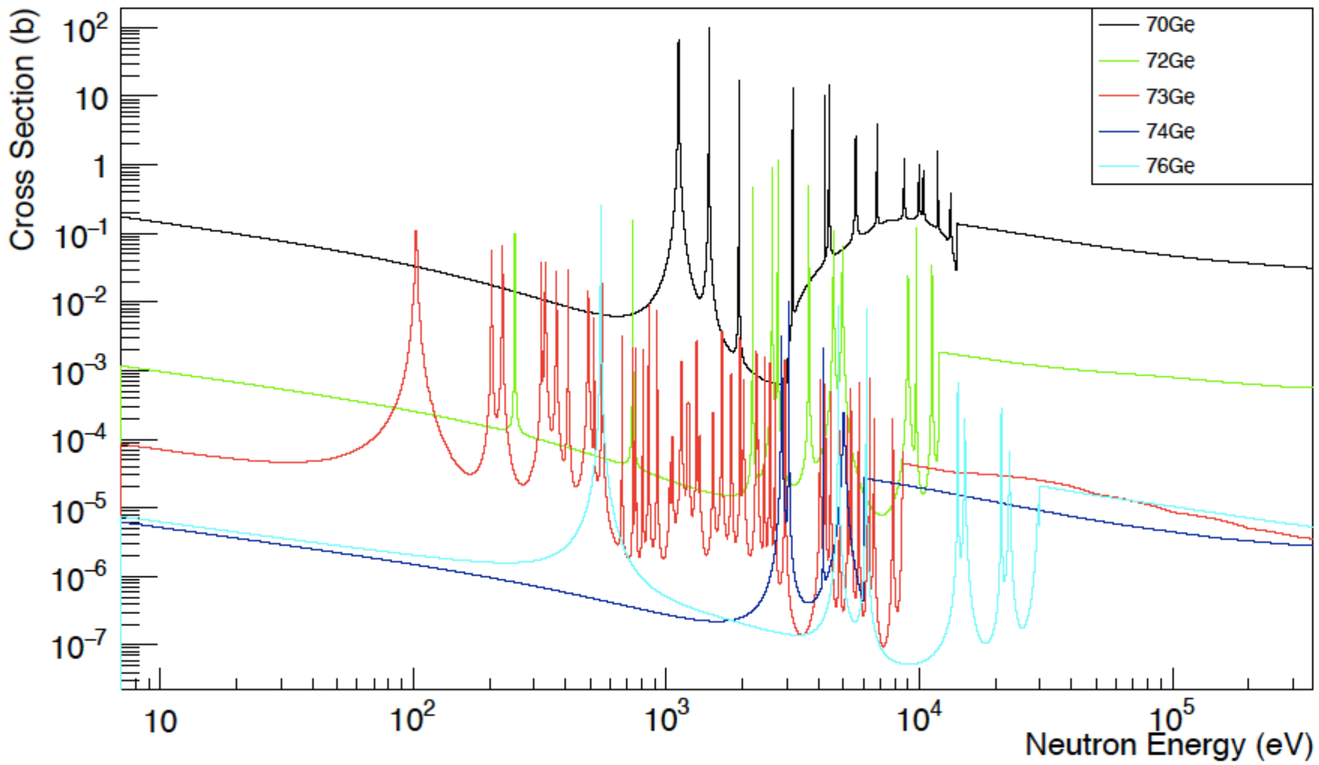

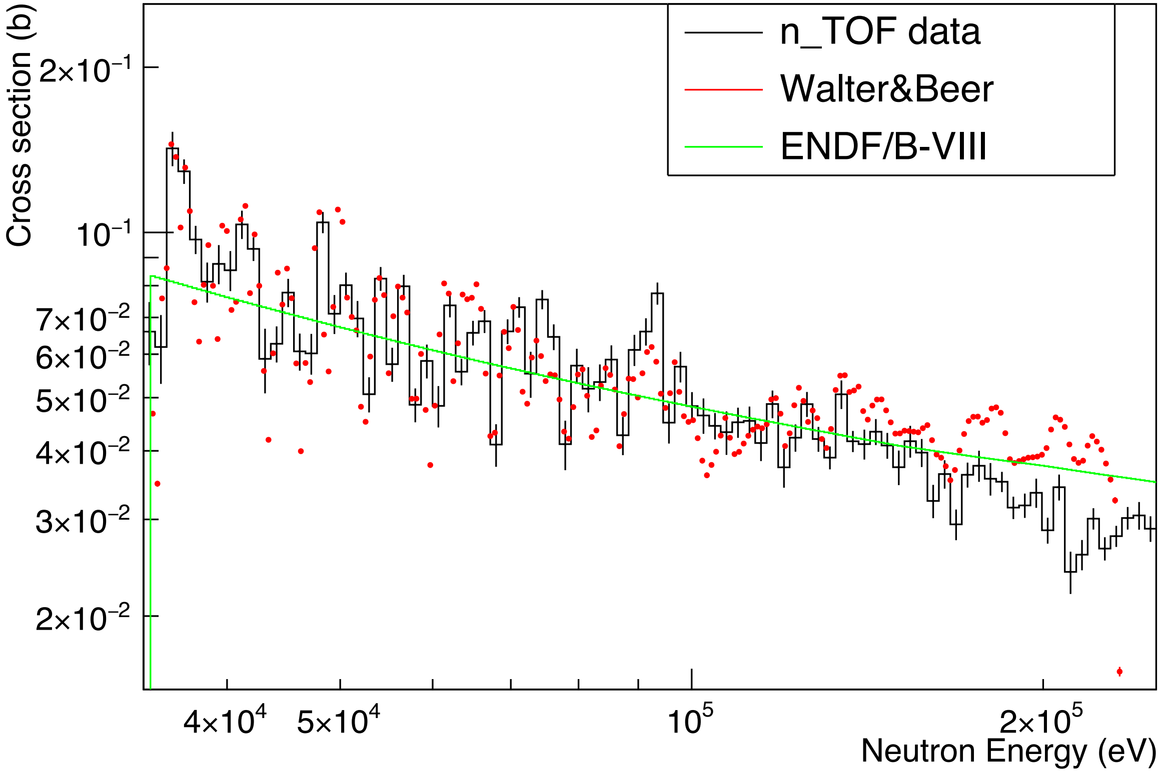

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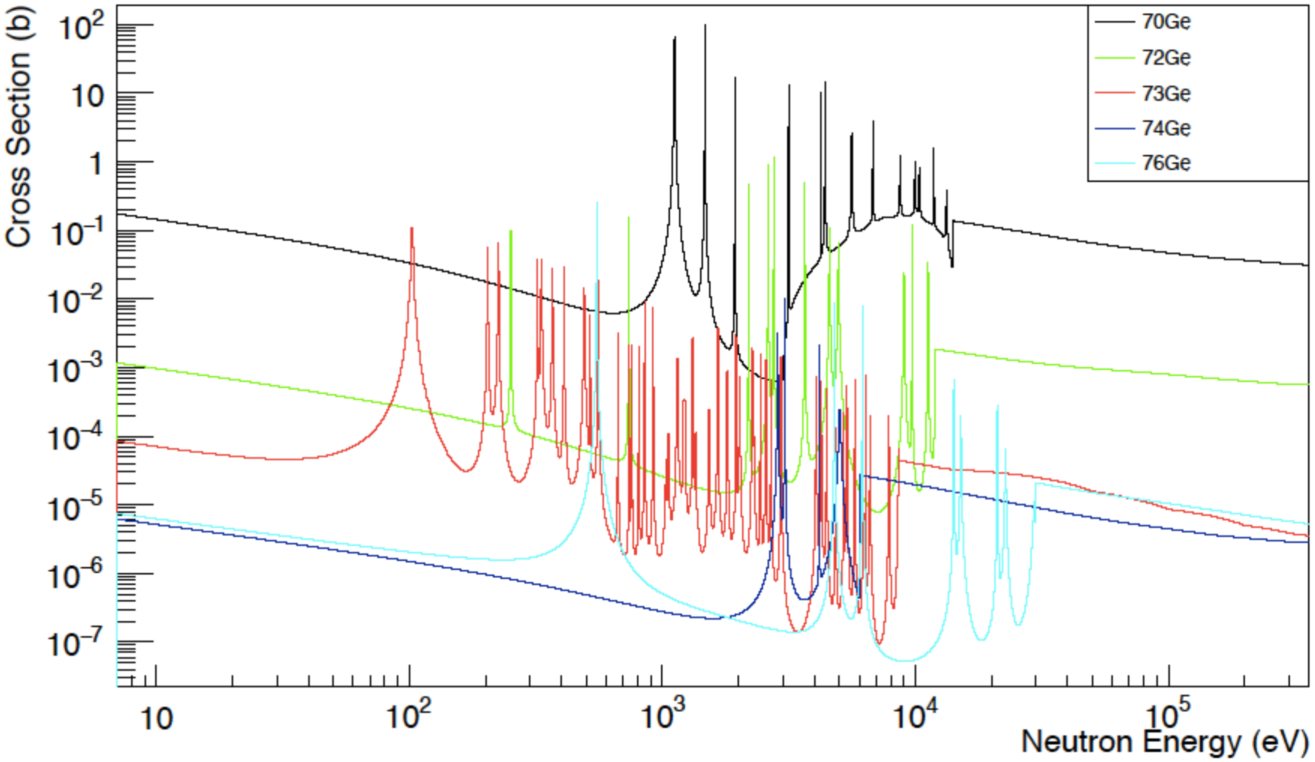
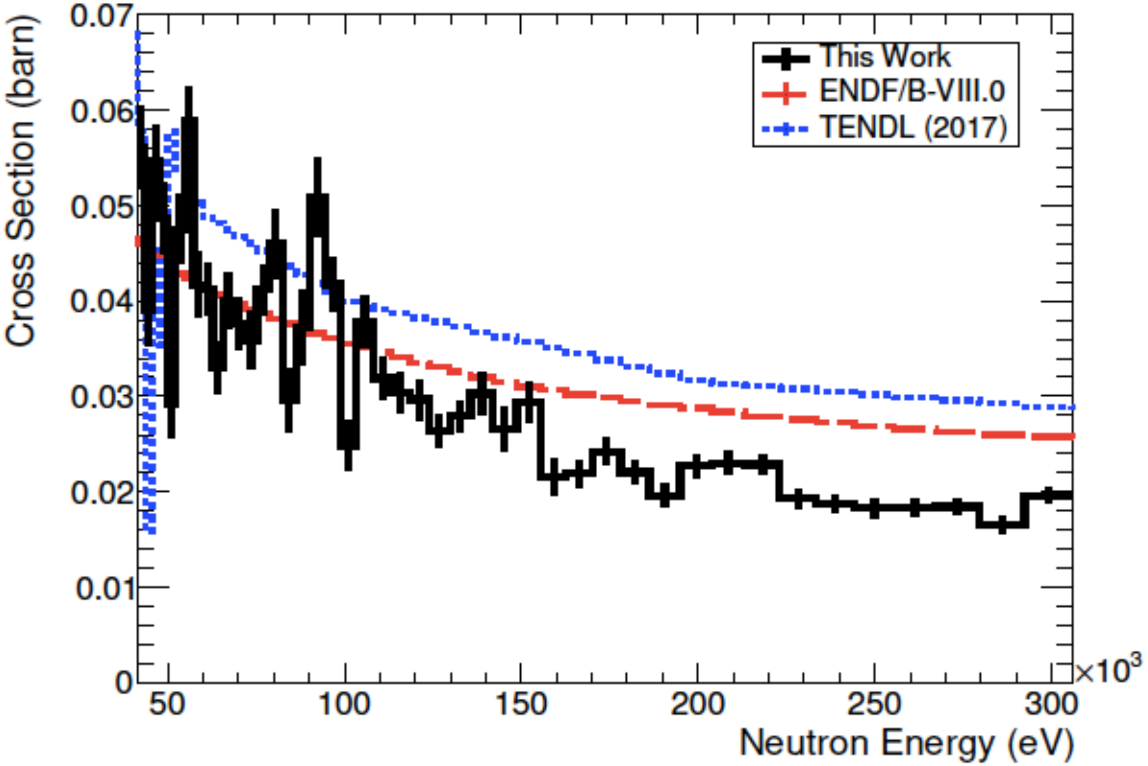
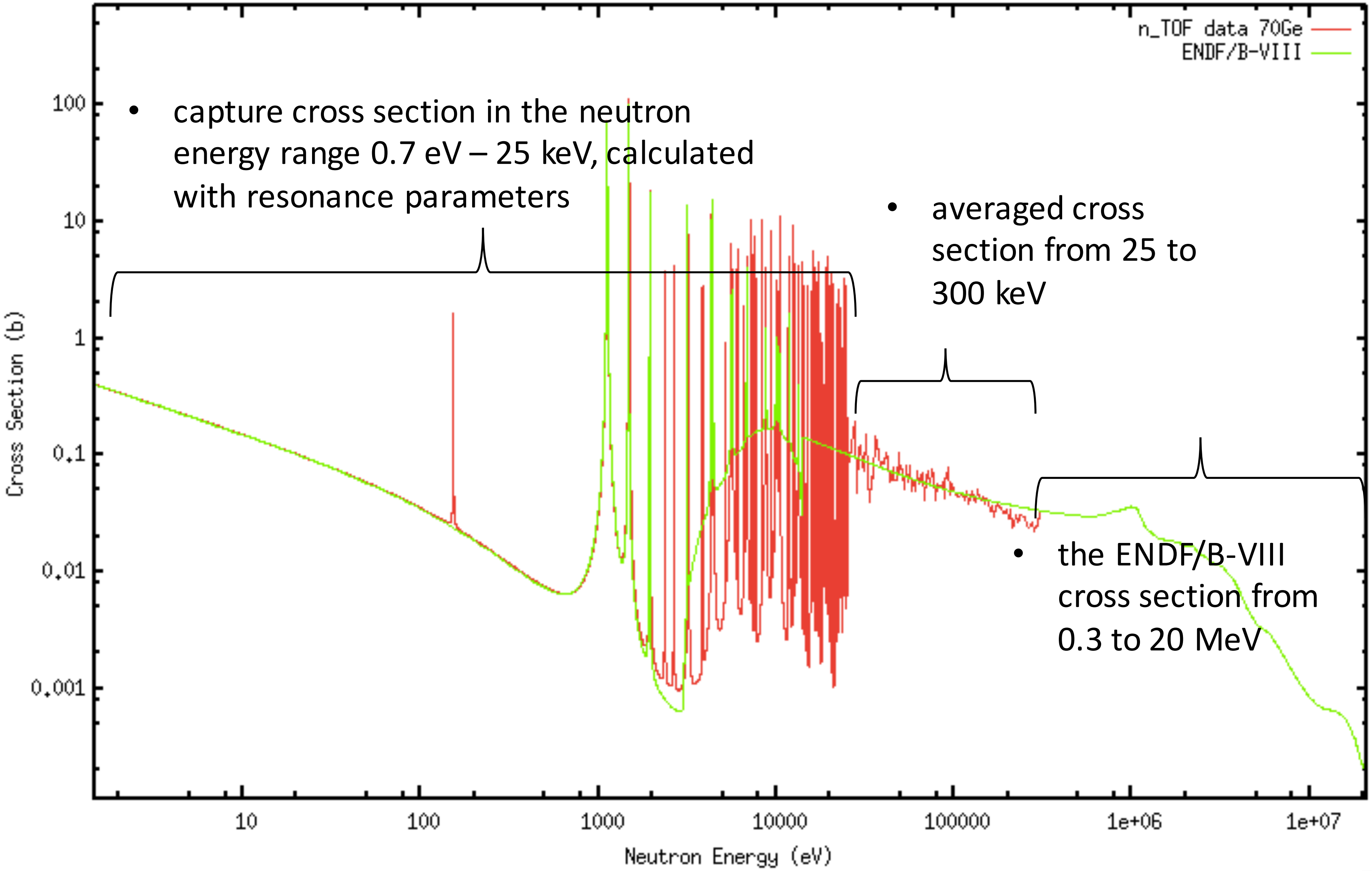




Maxwellian averaged cross section

The stellar or Maxwellian-averaged cross section calculated using following data:



- capture cross section in the neutron energy range 0.7 eV – 25 keV, calculated with resonance parameters
- averaged cross section from 25 to 300 keV
- the ENDF/B-VIII cross section from 0.3 to 20 MeV

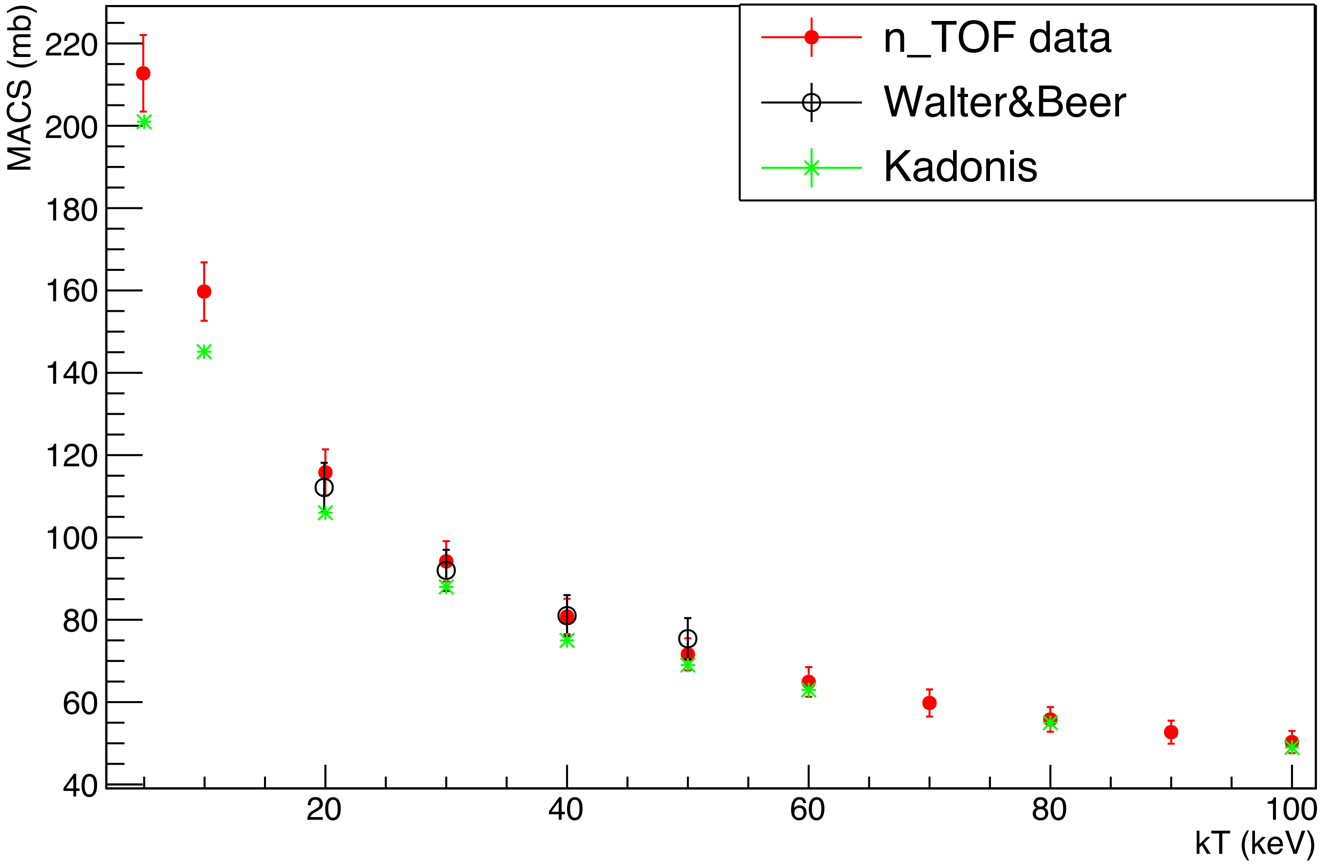
Maxwellian averaged cross section

KADoNiS (Karlsruhe Astrophysical Database of Nucleosynthesis in Stars) is widely used as reference for reaction rates in astrophysical calculations.

Agreement with Walter and Beer values is very good, and there is also good agreement with Kadonis-1.0, considering uncertainties.

^{70}Ge

kT (keV)	MACS (mb)		
	This work	Kadonis-1.0 [38]	Walter and Beer [14]
5	212.4 ± 9.3	207.3	
10	159.7 ± 7.1	154.8	
20	115.8 ± 5.6	109.8	112 ± 6
30	94.2 ± 4.9	89.1 ± 5.0	92 ± 5
40	80.8 ± 4.3	77.1	81 ± 5
50	71.6 ± 3.9	69.3	75 ± 4
60	64.9 ± 3.6	63.7	
70	59.8 ± 3.3		
80	55.8 ± 3.1	56.2	
90	52.7 ± 2.9		
100	50.3 ± 2.9	51.4	



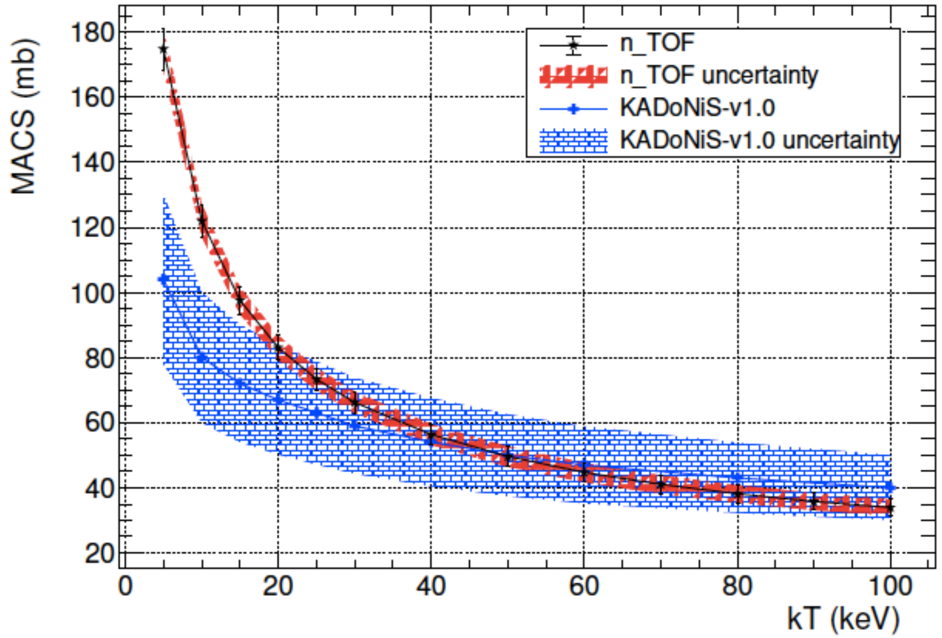
A. Gawlik, C. Lederer-Woods et al., Measurement of the ^{70}Ge(n, γ) cross section up to 300 keV at the CERN n_TOF facility, Phys. Rev. C 100, 045804 (2019).

Maxwellian averaged cross section

^{72}Ge

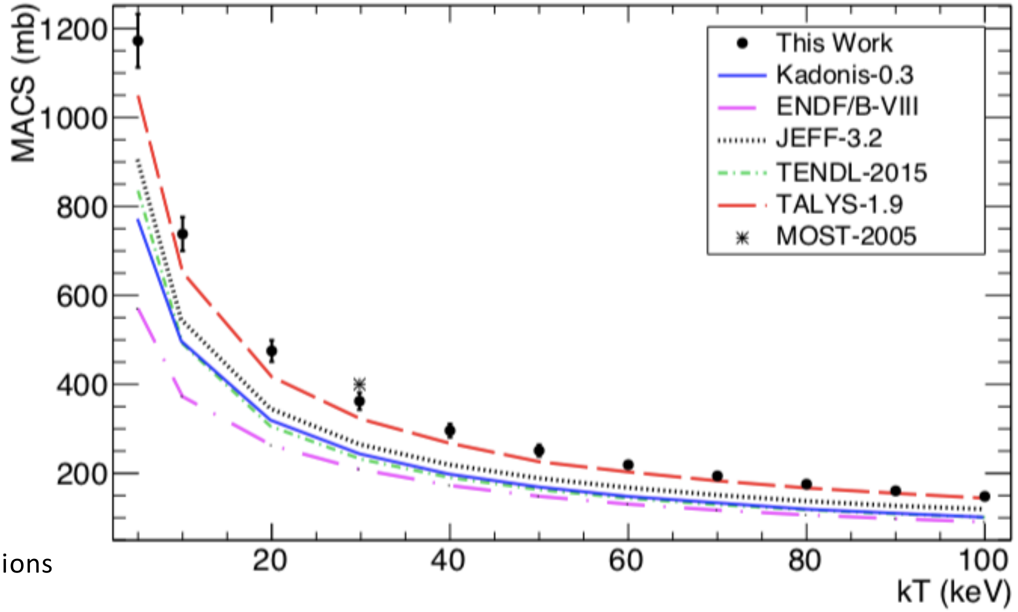
kT (keV)	MACS (mb)	
	This work	KADoNiS-v1.0 [13]
5	174.9 ± 6.5	104 ± 26
10	122.0 ± 4.9	80 ± 20
20	83.1 ± 3.7	67 ± 17
30	66.2 ± 3.3	59 ± 15
40	56.3 ± 3.2	54 ± 14
50	49.6 ± 3.1	50 ± 13
60	44.7 ± 3.0	47 ± 12
70	41.0 ± 2.9	
80	38.1 ± 2.7	43 ± 11
90	35.7 ± 2.6	
100	33.9 ± 2.5	40 ± 10

M. Dietz,, C. Lederer-Woods, A. Gawlik et al., Measurement of the ^{72}Ge(n,γ) cross section over a wide energy range at the CERN n TOF facility, submitted to PL B



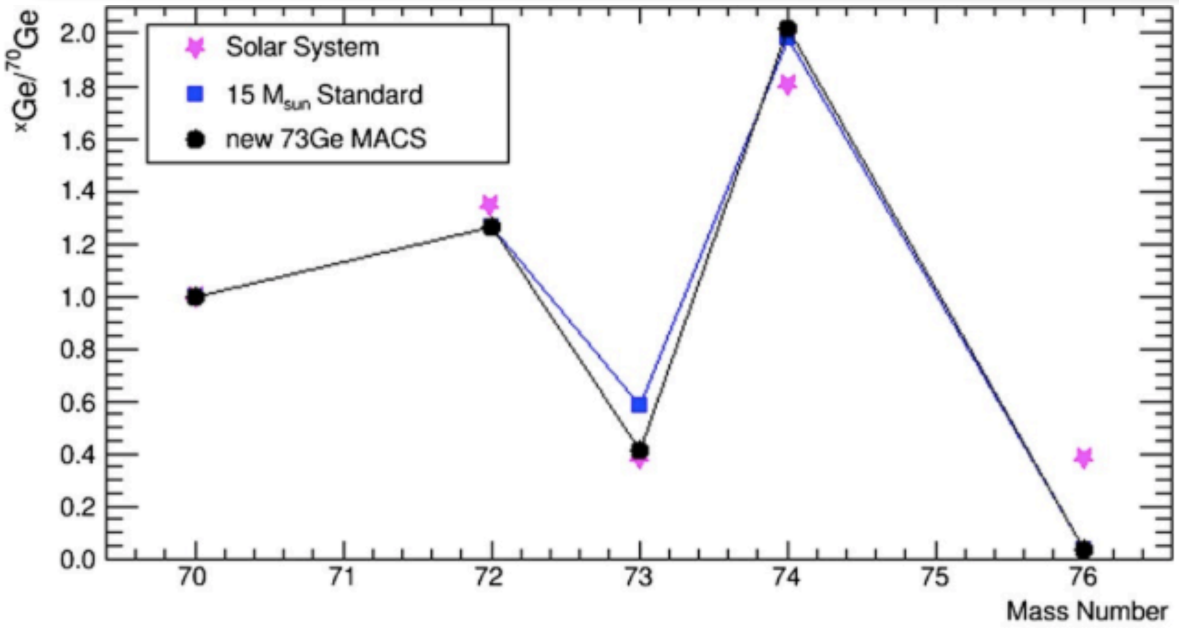
^{73}Ge

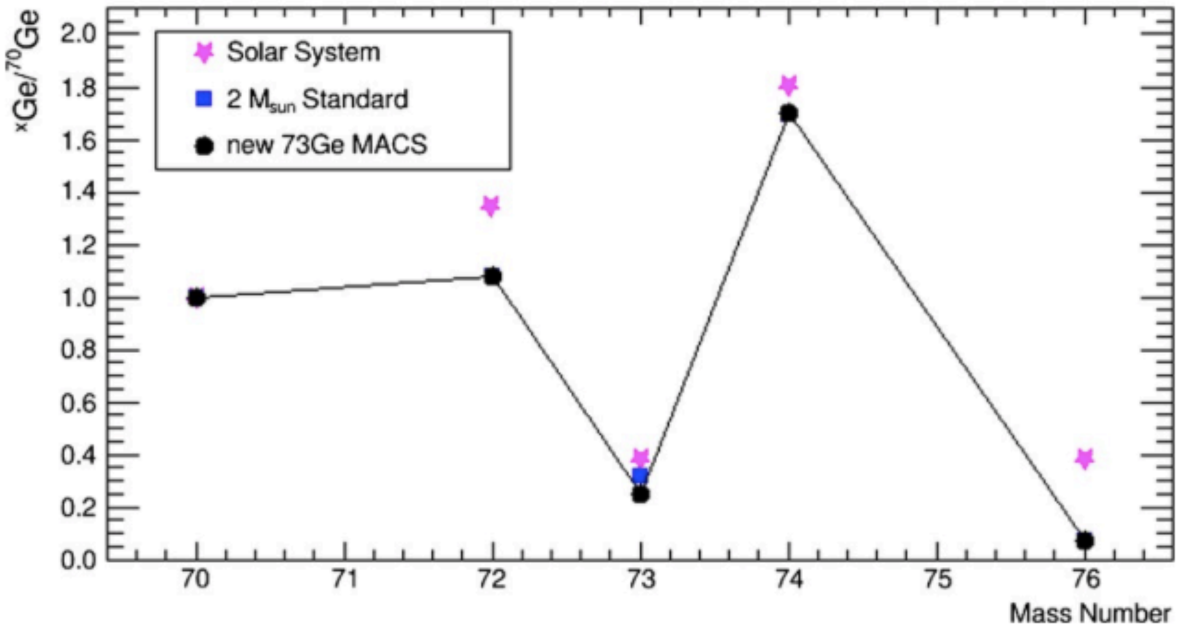
kT (keV)	MACS (mb)
5	1170 ± 60
10	738 ± 38
20	475 ± 24
30	362 ± 19
40	296 ± 15
50	251 ± 13
60	219 ± 11
70	194 ± 10
80	175.5 ± 8.9
90	160.4 ± 8.2
100	148.0 ± 7.6



C. Lederer-Woods, A. Gawlik et al., "Measurement of ^{73}Ge(n, γ) cross sections and implications for stellar nucleosynthesis", Physics Letters B 790, 458, (2019).

Astrophysical impact





- The neutron capture network consisted of rates recommended by Kadonis, the new $^{70,\ 73}$Ge(n, γ) MACSs
- It is estimated that the bulk of germanium in the solar system is produced in massive stars, while a small contribution of about 10-20% comes from the main s process in AGB stars.

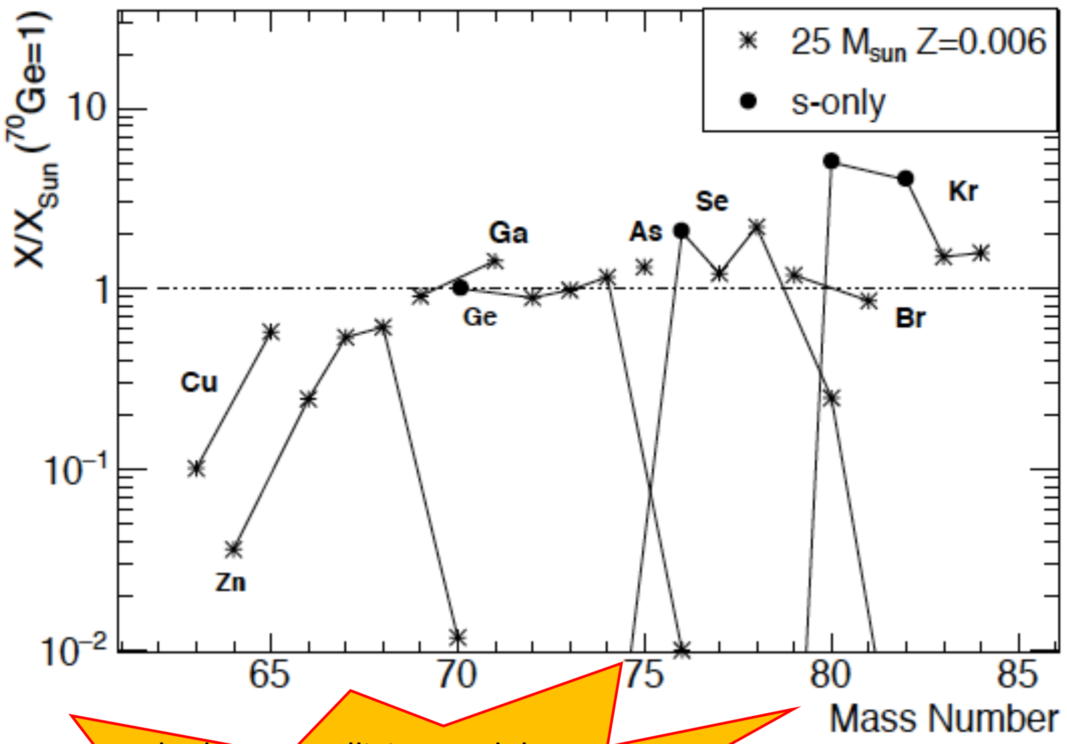
simulation of germanium abundances produced in weak s process prior to supernova explosion vs. solar abundances

simulation of germanium abundances produced in 2 $M_\odot$ AGB star

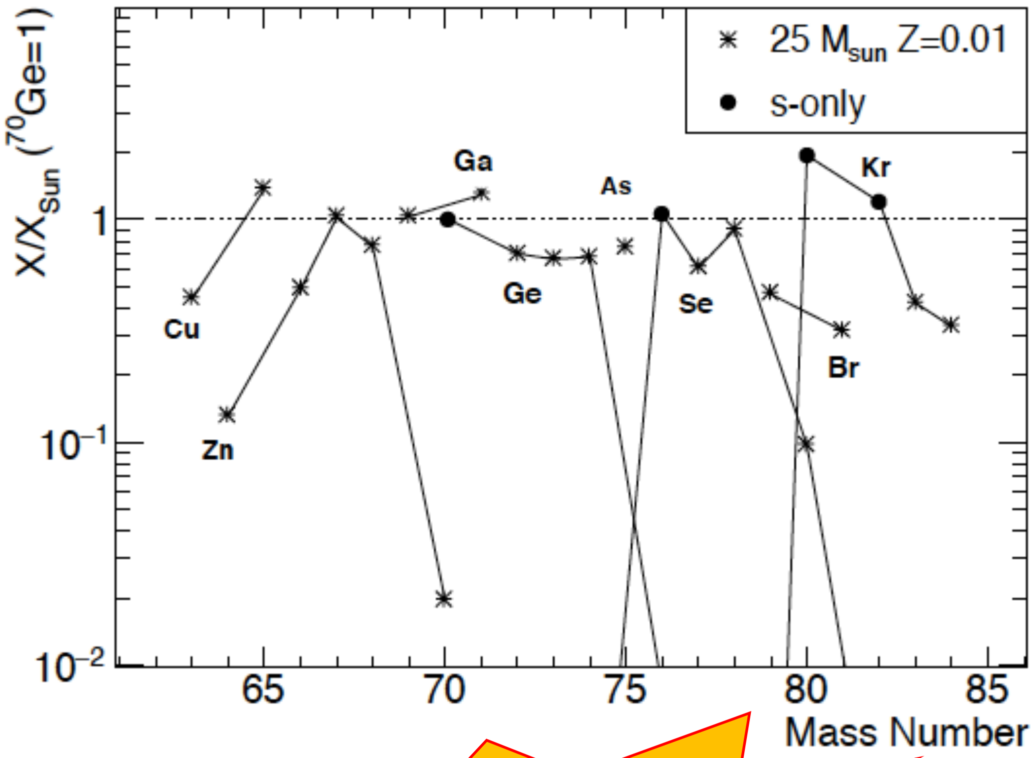
C. Lederer-Woods, A. Gawlik et al., “Measurement of 73Ge(n, γ) cross sections and implications for stellar nucleosynthesis”, Physics Letters B 790, 458, (2019).

Astrophysical impact

- The neutron capture network consisted of rates recommended by Kadonis, the new $^{70,\,73}$Ge(n, γ) MACSs
- Contributions to the solar system abundances due to the main s process and the p process have been subtracted using results by Arlandini et al.



the low metallicity model reproduces best the solar isotopic abundance pattern of germanium isotopes



the model close to solar metallicity provides a better global t to the other s-only isotopes

A. Gawlik, C. Lederer-Woods et al., Measurement of the ^{70}Ge(n, γ) cross section up to 300 keV at the CERN n_TOF facility, Phys. Rev. C 100, 045804 (2019).

Conclusion

1. Measurement of the (n, γ) cross sections of the stable germanium isotopes were performed in 2015/2016 at n_TOF facility.
2. Detailed analysis allowed to parameterize many new resonances, most of them not existed in the databases.
3. Precision in the data analysis allowed to obtain MACSs with 5/6% uncertainty.
4. MACS calculated for energies from 5 to 100 keV. For ^{72,73}Ge(n, γ) measurement provided first experimental data.
5. In case of ^{70}Ge, new data, in the wide neutron energy region, provides an important independent confirmation of stellar cross sections used in astrophysical calculations.
6. Additionally, very good agreement with previous measurement from Karlsruhe (1985) proofs that the resonance parameters obtained at n_TOF are correct.