^{79}Se(n,γ) measurement proposal

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and the n_TOF Collaboration

European Research Council

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n_TOF Collaboration Meeting, CERN, 9 th-10th June 2020

Outline

- **Introduction**
  - Motivations: s-process and nuclear waste
  - Status of the data and evaluations
  - Sample
  - Pros & cons of experimental set-ups and EARs: combined proposal

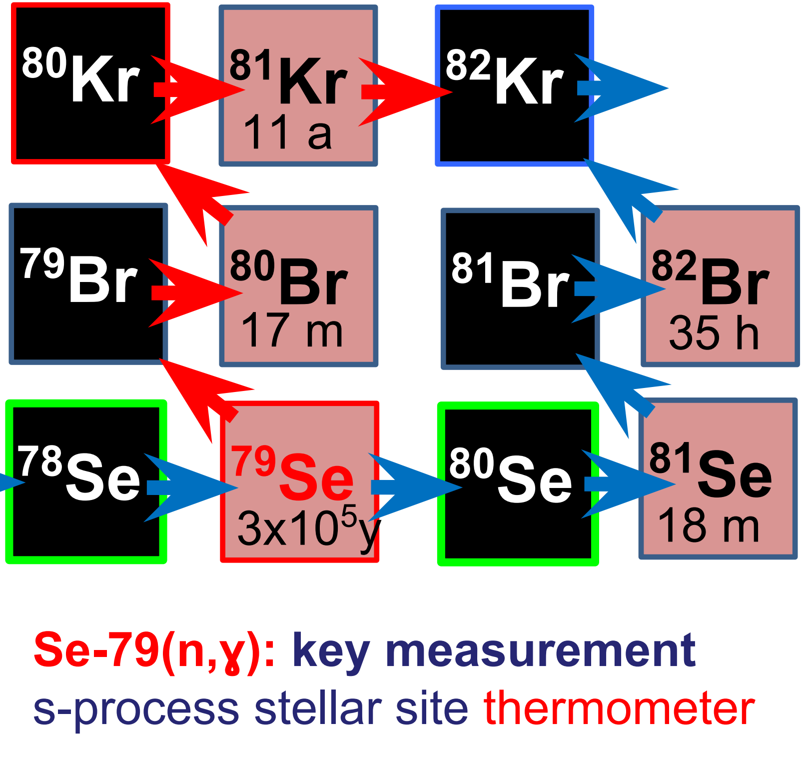
- **Counting rate estimates and expected accuracy**
  - Se-79(n,g) with i-TED @ EAR1
  - Se-79(n,g) with C6D6 @ EAR2

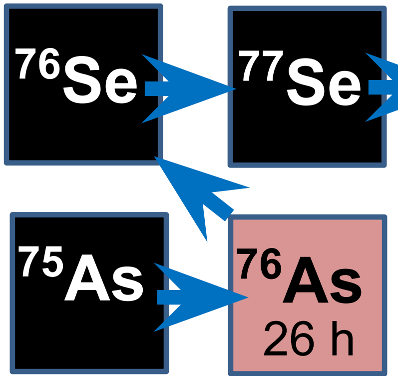
- **Summary**

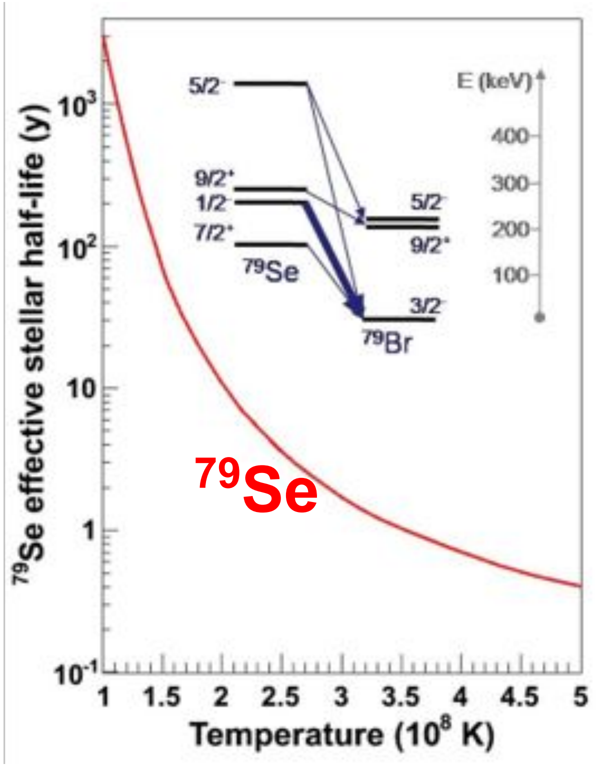
Motivation (I): s-process

s-process nucleosynthesis around A = 80

Se-79(n,ɣ) + s-only **80,82Kr** well characterized [Nature, 1988 Ott et al.]







Se-79(n,ɣ): key measurement

s-process stellar site thermometer

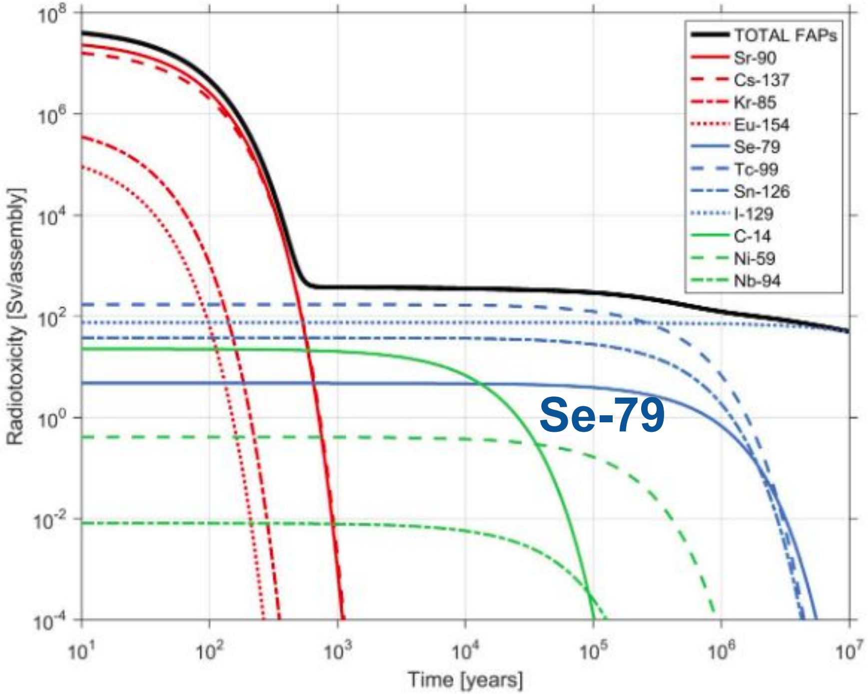
Motivation (II): nuclear waste

In terms of long-term radiotoxicity, however, long-lived fission products like Tc-99 and I-129, together with Se-79 and Cs-135, are the main contributors in addition to the above-mentioned actinides, and dominate the potential hazard in the case of HLW not containing actinides. Figure 13.2 compares

Handbook of advanced radioactive waste conditioning technologies

Se-79 is one of the main contributors to the long-term radiotoxicity among fission products

Se-79(n,ɣ): relevant for nuclear waste disposal and transmutation



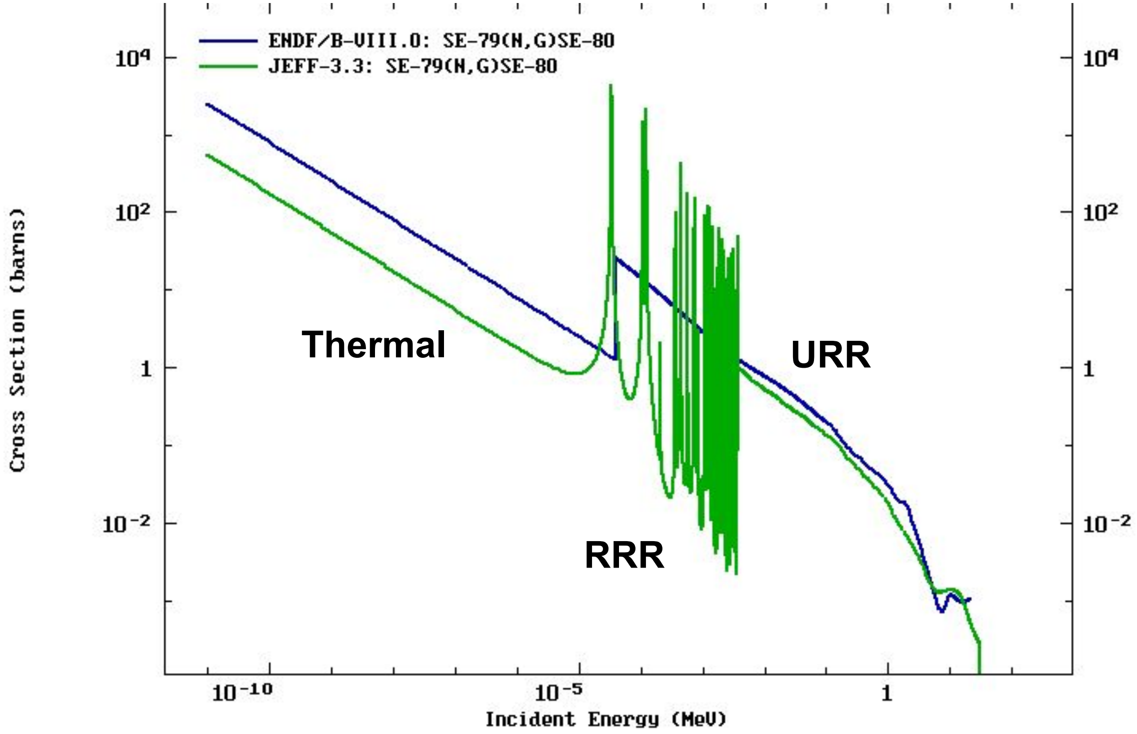
Status of the ^{79}Se(n,ɣ) data

EXPERIMENTAL DATA

- First measurement of this cross section at thermal, RRR and URR
- No data available in EXFOR:
- MACS via activation not possible (Se-80 stable)

EVALUATIONS

- **JEFF-3.3:** TALYS Calculation → Provides Resonance parameters
- **ENDF/B- VIII.0:** Systematics for the thermal point + 1/v dependence & OM for the URR



Additional calculations by A. Mengoni in Back-up

Se-79(n,ɣ): challenging measurement but **high impact.**
No data available → High accuracy is not mandatory.

^{79}Se Sample

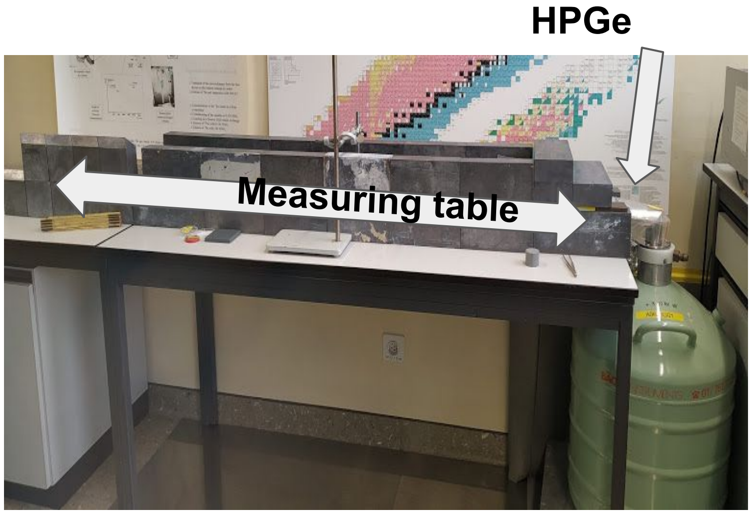
Se-78(n,ɣ) @ ILL

0.5 mm thick 6N Al casing (laser-welded)

PbSe alloy to avoid low melting point of pure Se

Sample properties

Isotope	Mass (g)	natoms_cm2
Se-78	0.77	4.01E+21
Se-79	0.003	1.53E+19
Pb-208	2.84	5.51E+21
Al-27	1.0244	5.90E+21



Gamma activity **characterization @ PSI**

Isotope	Activity (Bq) (Nov. 2021)	C.Rate C6D6 (Ethr = 250 keV)
Se-75	5.66E+06	2.82E+03
Ag-110m	2.04E+05	4.97E+03
Zn-65	2.33E+05	1.25E+03
Co-60	1.40E+06	2.75E+04
TOTAL	**7.50E+06**	**3.65E+04**

Detectors and EARs: pros & cons

Se-79(n,ɣ): EAR1 o EAR2?

- Small mass (3 mg Se-79 + 2.84 g Pb + 0.77 g Se-78)
- Radioactive sample
- **Measurement at EAR2** seems the best idea to achieve **good statistics in the URR and thermal point and optimize capture/activity.**

- RF EAR2: uncertain to resolve resonances in the keV range (& disentangle 78Se contribution)
- Performance of C6D6 and i-TED at "new" EAR2 is still uncertain: to be commissioned
- Feasibility of (n,ɣ) up to hundreds of keV @ EAR1 well known
- **High accuracy measurement at EAR1 required for validation/cross check in the RRR**

Se-79(n,ɣ): i-TED and/or C6D6?

- **Large contribution** of neutron scattering in Pb, Se-78 and Se-79 → **Case for i-TED**
- i-TED has shown good performance @ EAR1 (commissioning 2018)
- i-TED allows to extract spectroscopic information of the Se-79(n,ɣ) cascade
- **C6D6 better performance at high CR → Better suited for EAR2**

Combined proposal:
i-TED (+ C6D6?) @ EAR1 & C6D6 @ EAR2

Similar previous measurements:

- Tm-171(n,ɣ) @ EAR1 and EAR2
- Cm-244/246(n,ɣ)

$^{79}Se(n,\gamma)$:
Counting rate estimates

^{79}Se(n,ɣ) @ EAR1 with i-TED

XS: JEFF-3.3

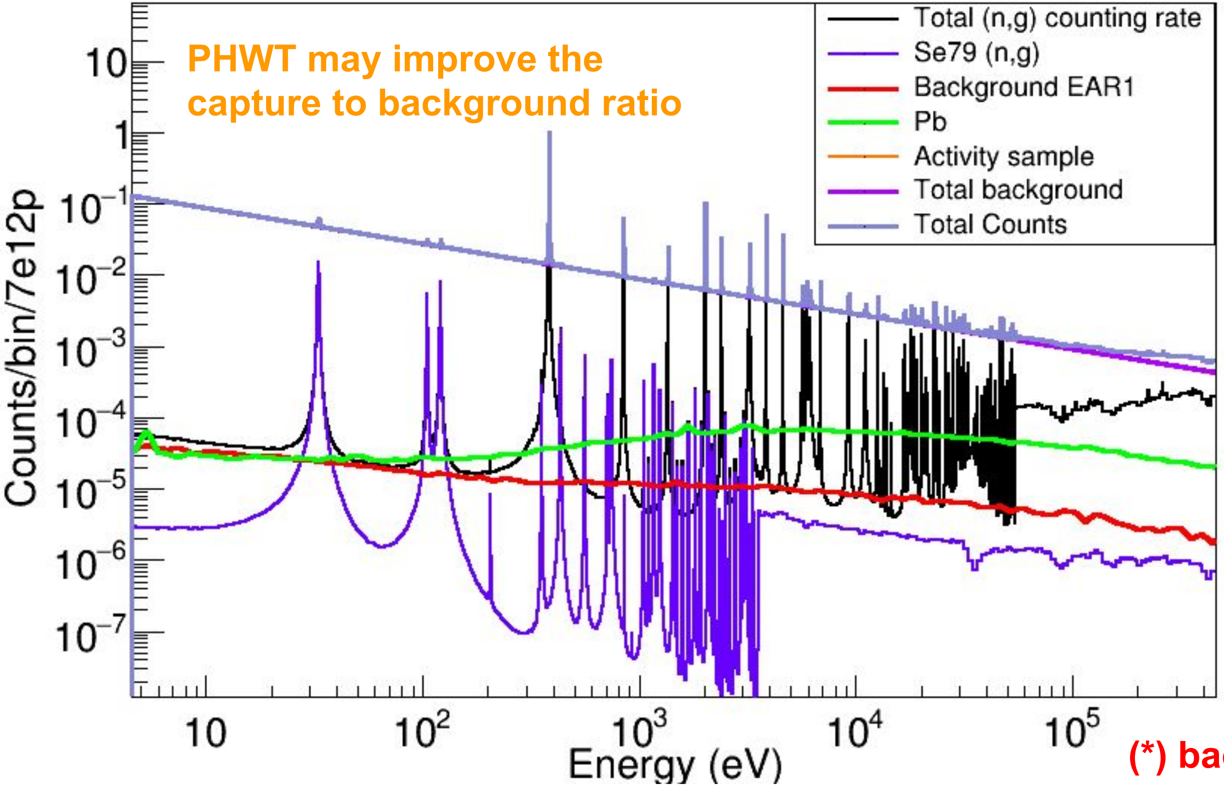
(n,g) efficiency: MC simulations

Empty and **Lead** from experimental C6D6 data.

i-TED: Scaled assuming than (n,ɣ)/background can improve a factor 5**(*).**

Activity counting rate via MC simulations of the sample contaminants.

i-TED: Energy cuts -40% of the activity



(*) backup

Background dominated by sample activity: to be fitted and 1/v subtracted such as in previous measurements on highly active samples: Tm-171, Tl-204, …

$^{79}Se(n,\gamma)$ @ EAR1 i-TED: statistics

STATISTICS IN EAR1 FOR MC RESAMPLING

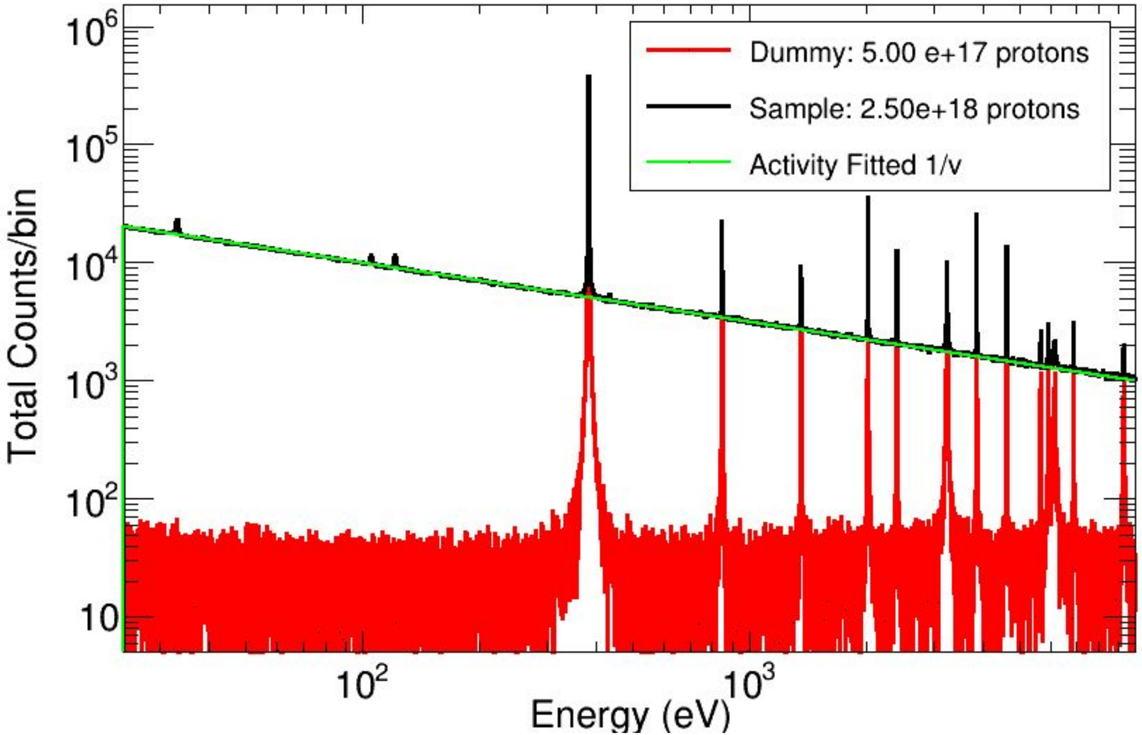
PbSe sample:
2.5e18 protons

Dummy:
0.5e18 protons

Dummy = Pb + Se-78 + Al + empty

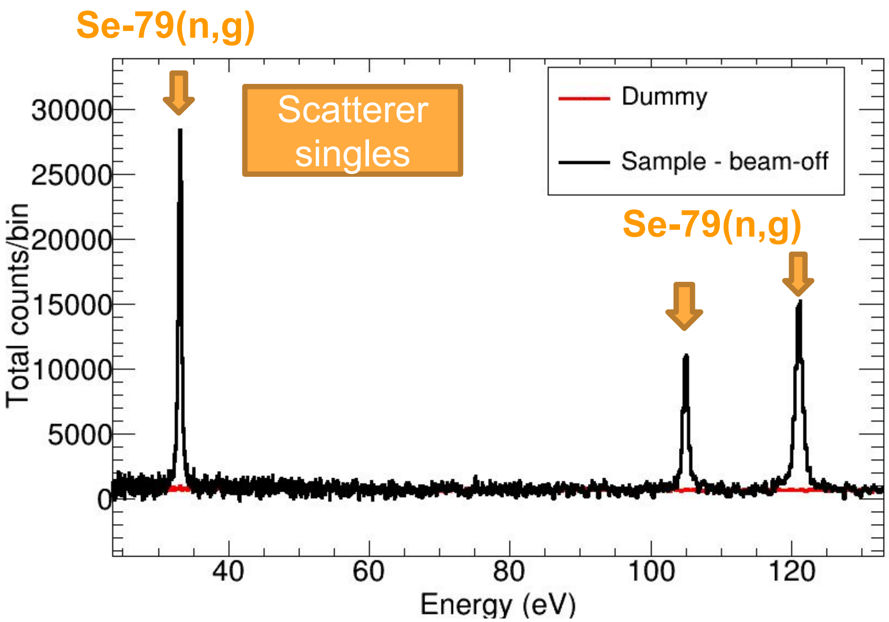
Activity (beam-off + sample-in)

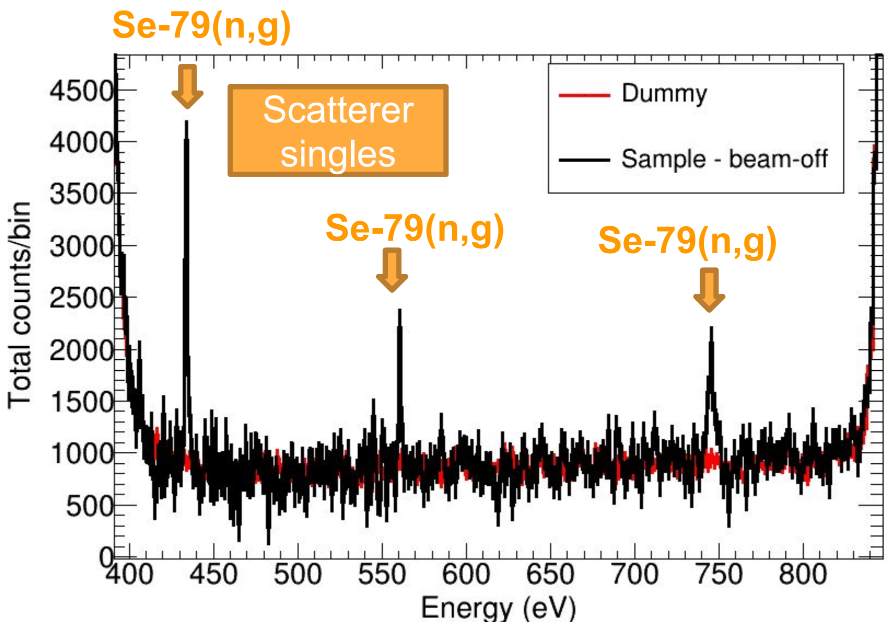
Sample = **Dummy** + **Activity** + Se-79



MC simulation of the experiment: Realistic counts and statistical uncertainties
i-TED: reduction of activity background in 40% and the dummy in a factor ~5 relative to capture (wrt to C6D6)

$^{79}Se(n,\gamma)$ @ EAR1 i-TED: RRR





Se-79 (n,g) @ EAR1:

- **RRR** (strongest resonances) of Se-79 below 1 keV with **high resolution (RF negligible)**
- **Cross-check/Validation** of Se-79(n,g) **@ EAR2**

PROTON REQUEST Se-79 @ EAR1

3.5 10^{18} protons

- **2.5 Se-79 sample +**
- **0.5 dummy (Se-78 + Pb) +**
- **0.5 backgrounds/normalization)**

$^{79}Se(n,\gamma)$ @ EAR2 with C6D6

STATISTICS IN EAR2
FOR MC RESAMPLING

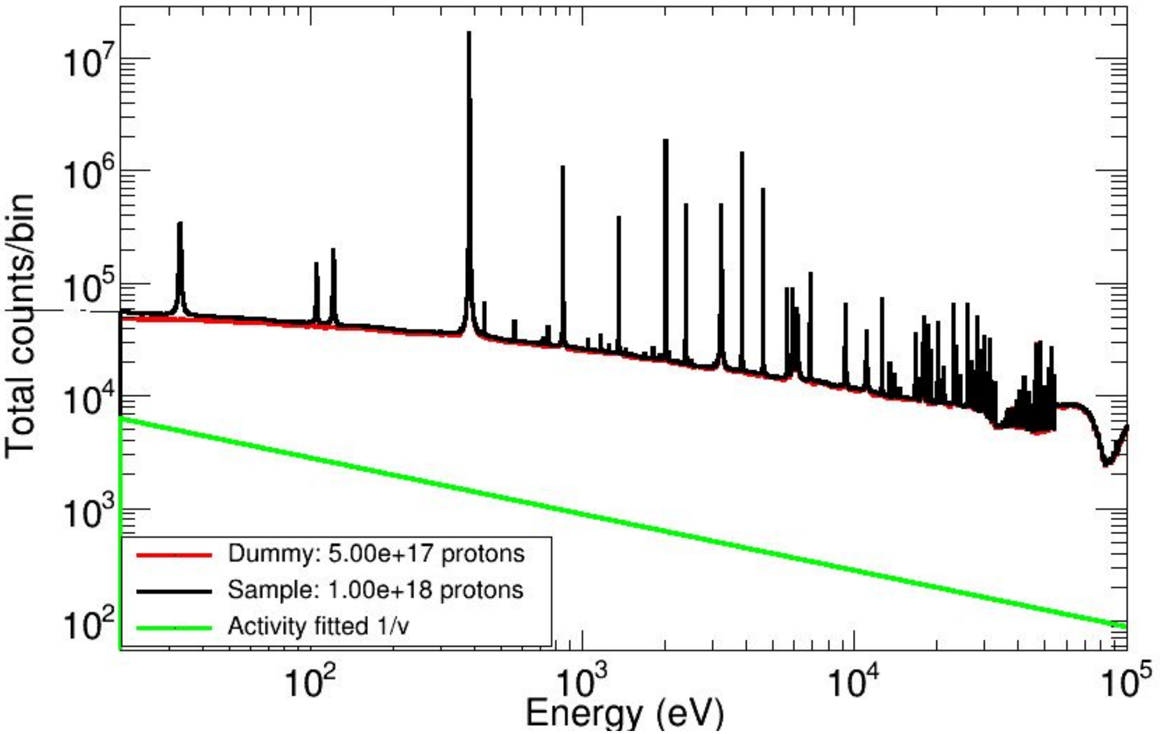
PbSe sample:
1.0e18 protons

Dummy:
0.5e18 protons

Dummy = Pb + Se-78 + Al + empty

Activity (beam-off + sample-in)

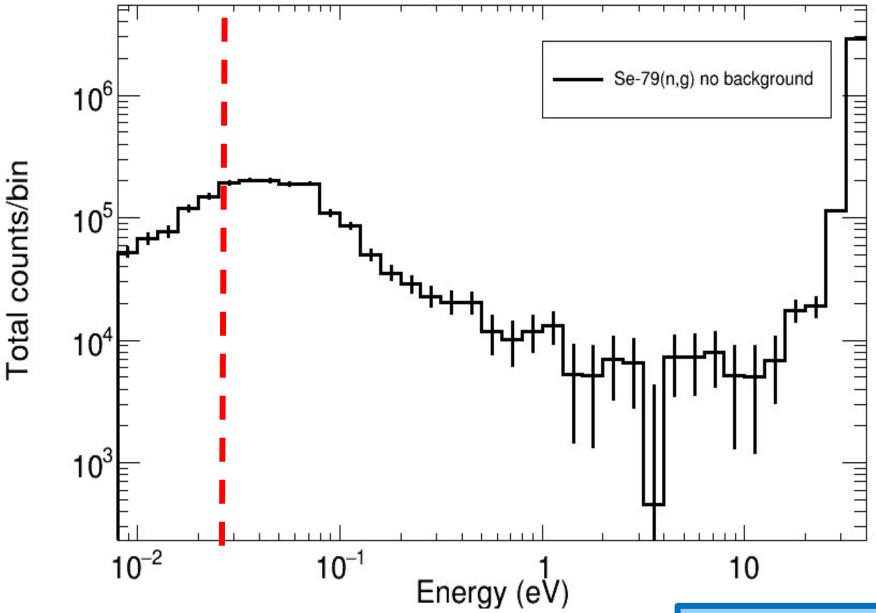
Sample = Dummy + Activity + Se-79



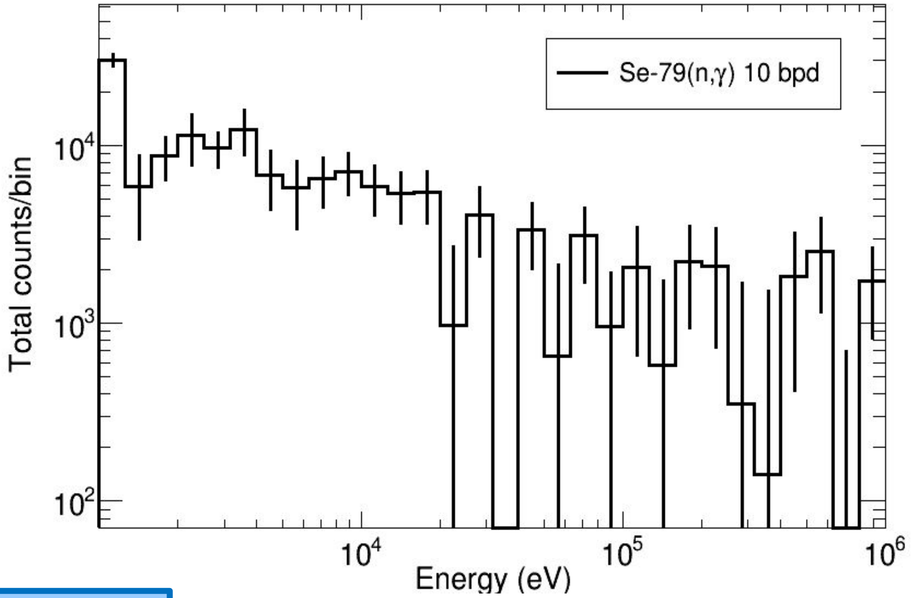
MC simulation of the experiment: Realistic counts and statistical uncertainties
Activity does not dominate Overall (n,g)/background better

$^{79}Se(n,\gamma)$ @ EAR2 C6D6: Thermal & URR

THERMAL



URR



Se-79(n,g) @ EAR2:

Thermal point: large deviation between evaluations and other calculations
Measurement @ EAR2 required for this point

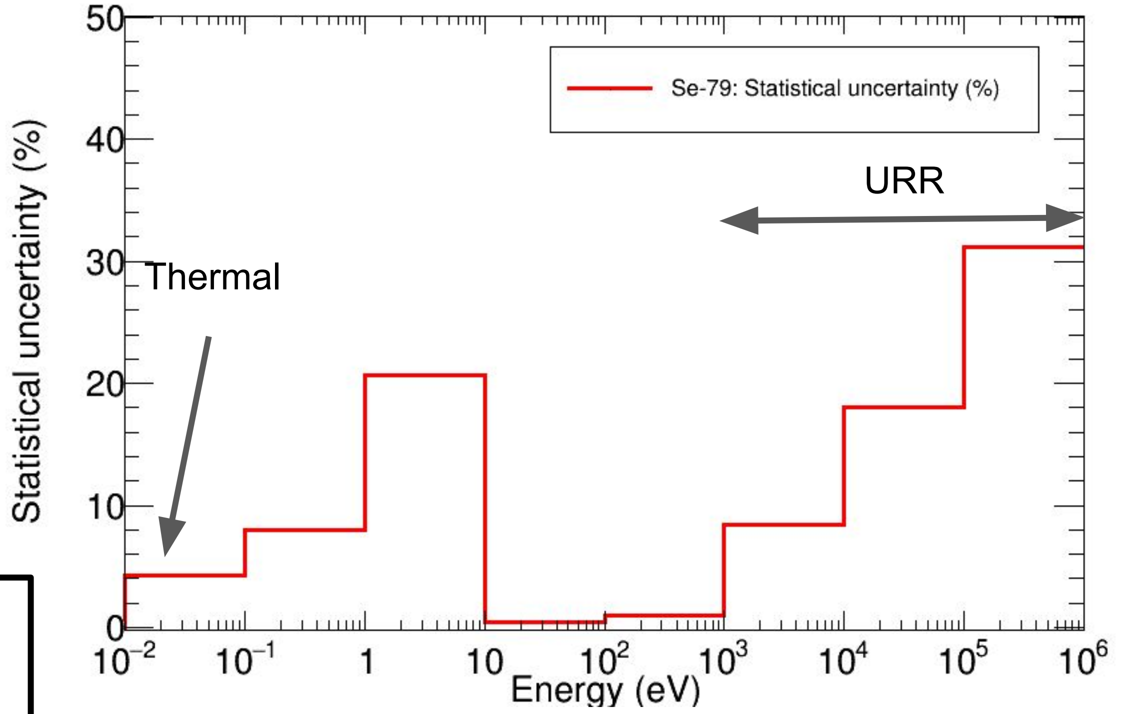
URR: Very relevant for the stellar capture rates (MACS)
Feasible @ EAR2 with 5-10 bpd

^{79}Se(n,ɣ) @ EAR2 C6D6: uncertainty

Statistical uncertainties in the Se-79(n,ɣ) yield (1 bpd)

- Integral cross section **URR** (useful for MACS) with **statistical unc. < 20 % up to 100 keV**

- Measurement at EAR2 provides also the **thermal point: 5% unc. (Integral 10-100 meV))**



PROTON REQUEST Se-79 @ EAR2

2.0 10^{18} protons

- **1.0 Se-79 sample +**
- **0.5 dummy (Se-78 + Pb) +**
- **0.5 backgrounds/normalization)**

Summary

- **Motivation for Se-79(n,g):**
  - Key s-process branching point isotope: Constrain thermal conditions of massive stars
  - One of the largest contributions to the long-term radiotoxicity among FP in the nuclear waste

- **Goal of the proposal:**
  - **First measurement of this cross section** at thermal, RRR and URR
  - Get the most comprehensive knowledge of Se-79(n,g) in the 3 energy regions.

- **Se-79 sample ready and characterized @ PSI**

- **Realistic counting rate estimates of Se-79(n,g) @ EAR1 and EAR2:**
  - Realistic efficiencies from MC simulations
  - Evaluated cross sections JEFF-3.3 (TALYS for Se-79)
  - Impact of statistical uncertainties in background subtraction and RF **(see Back-up for details)**

- **A combined proposal would be ideal for a successful measurement of this key isotope**
  - **Se-79(n,ɣ) @ EAR1** with i-TED (& C6D6): RRR with high resolution and validation
    3.5 10^{18} protons (2.5 sample + 0.5 dummy + 0.5 backgrounds normalization)
  - **Se-79(n,ɣ) @ EAR2** with C6D6: good statistics for the URR and thermal point
    2.0 10^{18} protons (1.0 sample + 0.5 dummy + 0.5 backgrounds normalization)

Summary: proton request

SAMPLE	Se-79(n,g) @ EAR1 i-TED (& C6D6)	Se-79(n,g) @ EAR2 C6D6
Se-79 (PbSe sample)	$2{,}5.10^{18}$ p	1.10^{18} p
Dummy (Se-78 + Pb + Al)	5.10^{17} p	5.10^{17} p
Au, C, Pb, Filters	~5.10^{17} p (*)	~5.10^{17} p (*)
TOTAL	**$3{,}5.10^{18}$ p**	**$2{,}5.10^{18}$ p**

(*) Might be shared with other measurements

Watch Recorded presentation
or see back-up slides
for more details!

EXTRA SLIDES
LONG VERSION

Outlook

Possible sample improvement:

- Under discussion with PSI's colleagues: Chemical purification of the PbSe sample to reduce the sample activity and make a Se Oxide sample. →Specially relevant for the measurement @ EAR1

i-TED development & characterization:

- Results of the i-TED 5.3 prototype look promising and proof the good perfomance in EAR1 **(V. Babiano's talk)**
- Optimization of the position reconstruction & imaging algorithms to improve background suppression capabilities: Machine learning looks promising **(J. Balibrea & J. Lerendegui's talks)**
- On-going tests @ IFIC-lab to characterize the CRT and the counting rate limit.
- Before measurement: i-TED 4 pi commissioning in EAR1 and EAR2 during target commissioning **(Cesar's talk)**

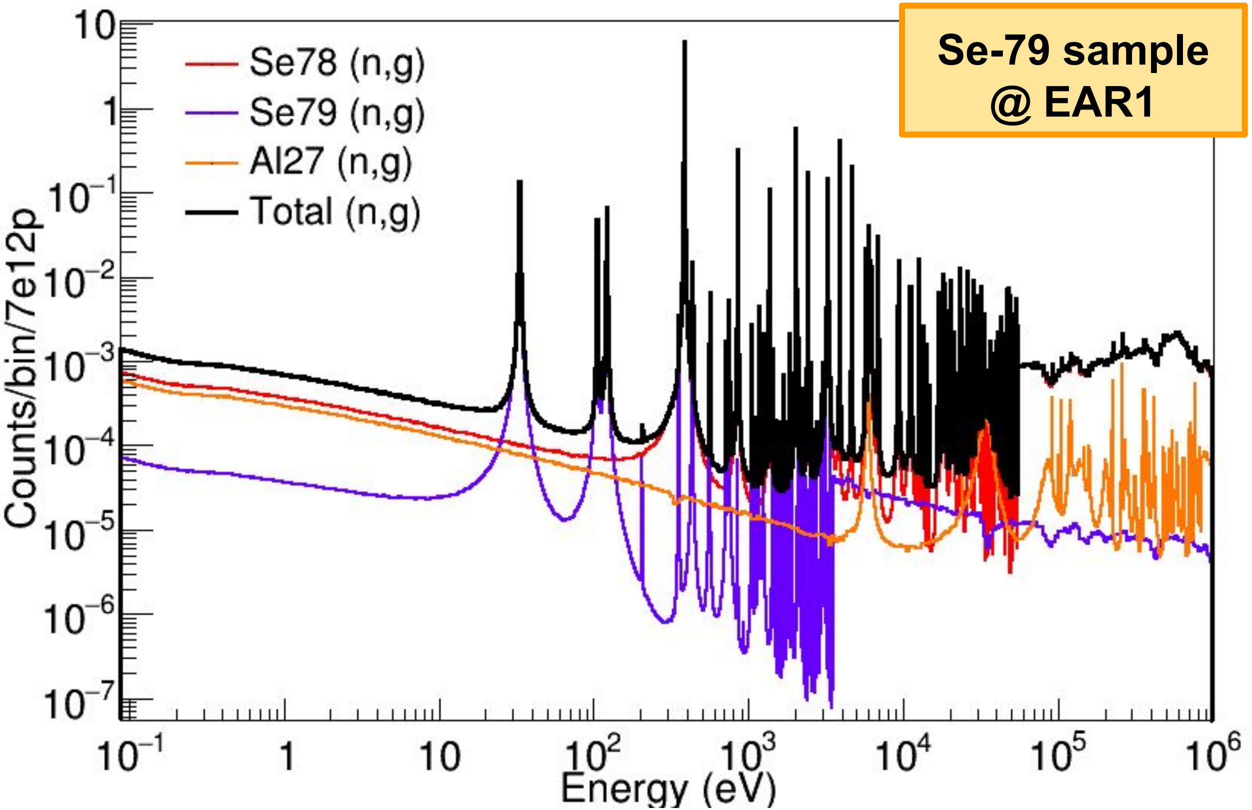
Proposal timeline:

- Presentation to INTC in November
- Measurement: End 2021, early 2022 → **ERC Project ends May 2022**

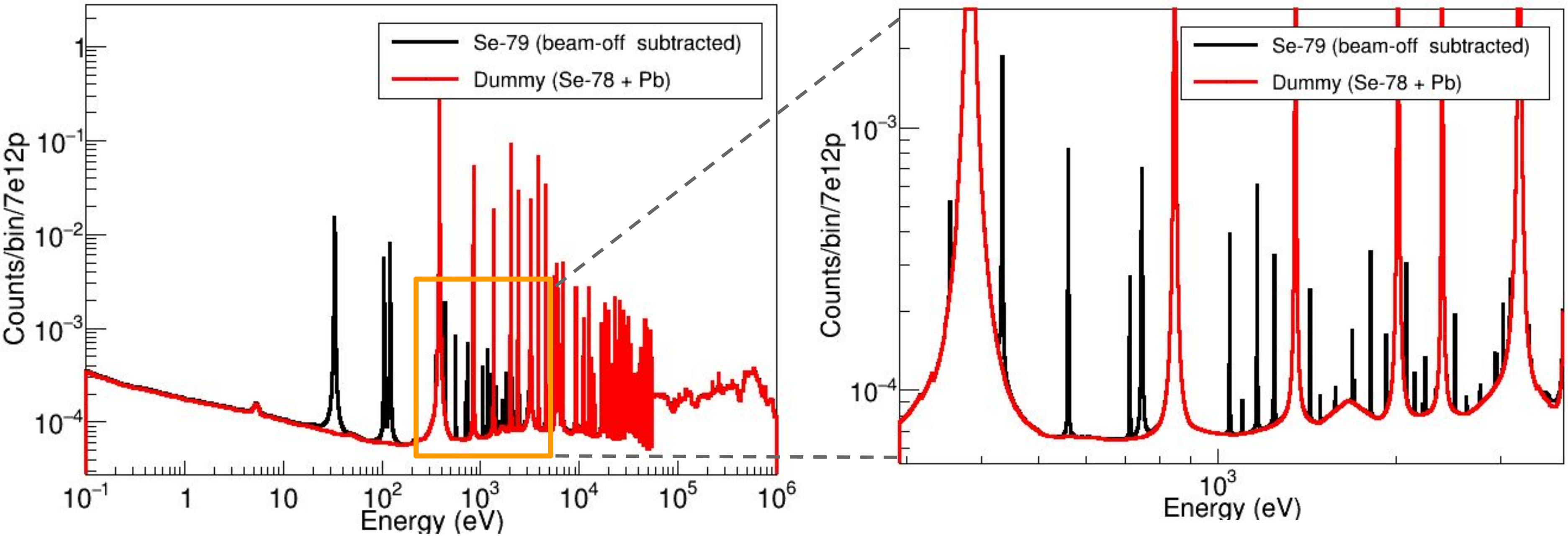
^{79}Se(n,ɣ): Counting rate estimates

COUNTING RATES: Ingredients

- Cross sections from JEFF-3.3
- Evaluated Flux EAR1/2 phase 3
- BIF: Geant4 spallation target
- (n,ɣ) efficiency from MC assuming Au-197 cascade
- Ethr = 200 keV for C6D6 & i-TED (coinc.)



$^{79}Se(n,\gamma)$ @ EAR1: expected results



Theoretical estimation: After 1/v activity subtracted → Total counts vs “dummy”

ASTROPHYSICS: keV-to-100keV region is the most important one.

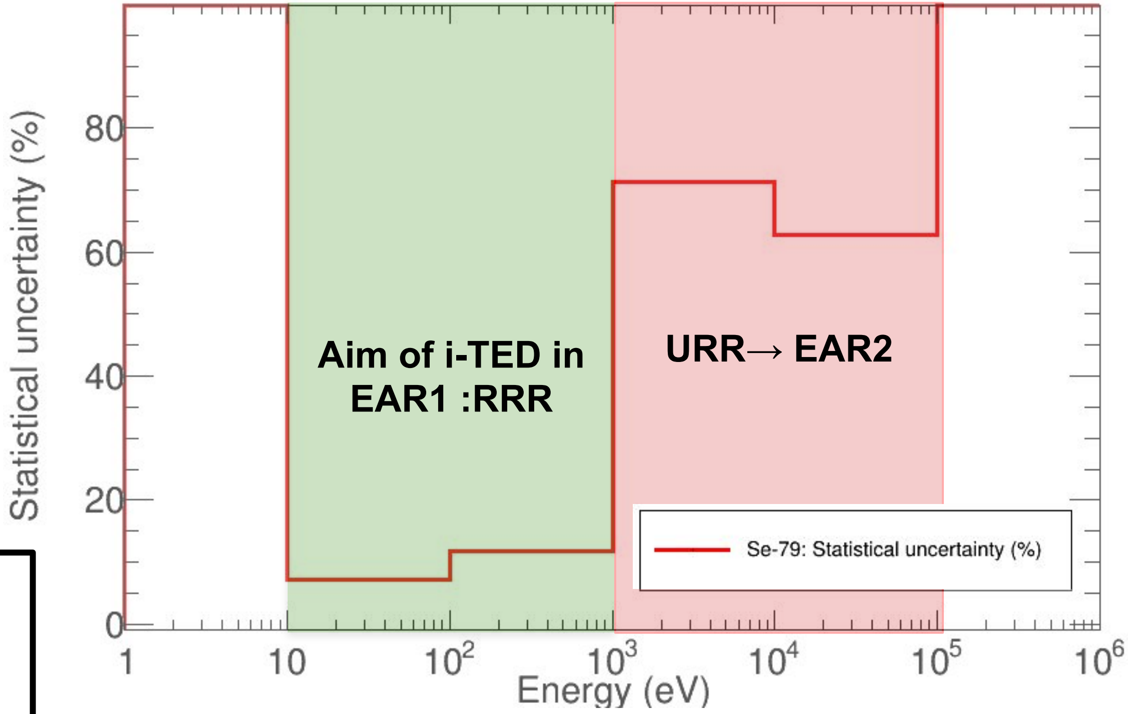
High-resolution of EAR1 is required here to resolve 79Se capture levels between Se-78 resonances

Strength and level density of Se-79 may change (BASED IN TALYS)

$^{79}Se(n,\gamma)$ @ EAR1 i-TED: uncertainty

Statistical uncertainties in the Se-79(n,ɣ) yield (1 bpd)

- RRR; Uncertainty < 15% up to 1 keV **AIM OF EAR1**
- URR and thermal: Motivation for EAR2



PROTON REQUEST Se-79 @ EAR1

3.5 10^{18} protons

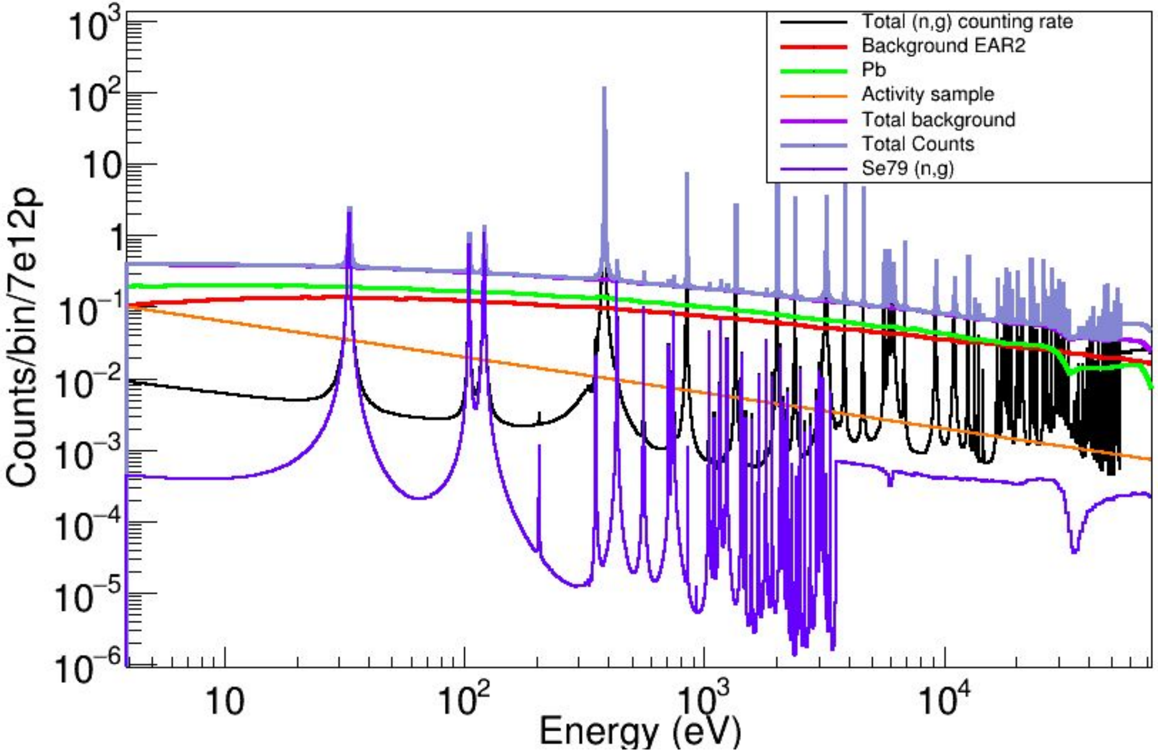
- **2.5 Se-79 sample +**
- **0.5 dummy (Se-78 + Pb) +**
- **0.5 backgrounds/normalization)**

$^{79}Se(n,\gamma)$ @ EAR2 with C6D6

Empty and **Lead** experimental data with C6D6 @ EAR2

Activity counting rate calculated with MC simulations of the sample contaminants.

PHWT not applied:
It may improve the capture to background ratio



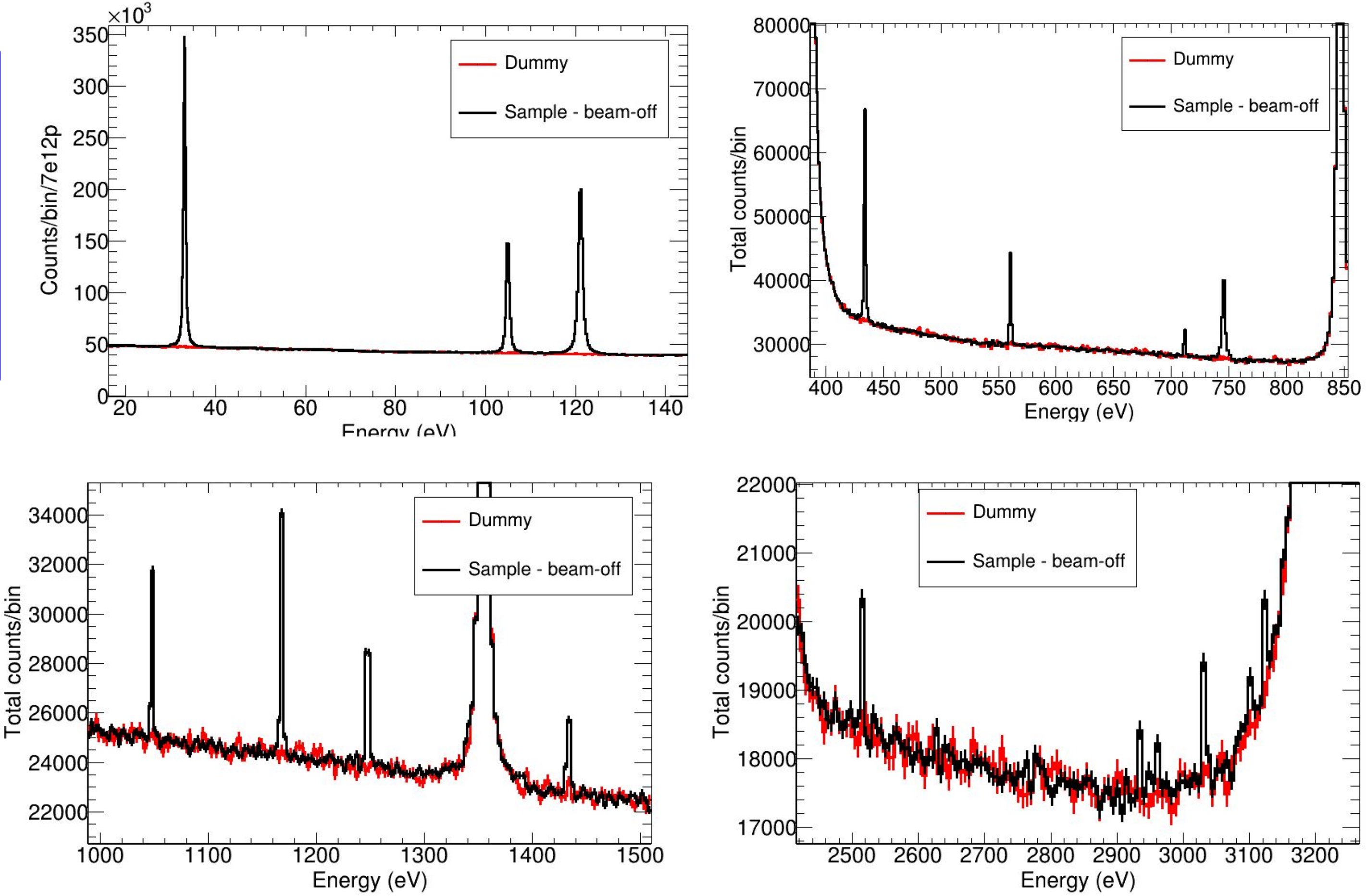
Activity background does not dominate like in EAR1
Overall (n,γ)/background better than in EAR1

$^{79}Se(n,\gamma)$ @ EAR2 C6D6: RRR

Very good statistics in the resolved resonances of Se-79 below 1 keV

GOAL: Validation/normalization with EAR1 data

RF @EAR2 NOT INCLUDED: Impact RF from target #2 (Back-up slides)
Improvement with Target #3 expected



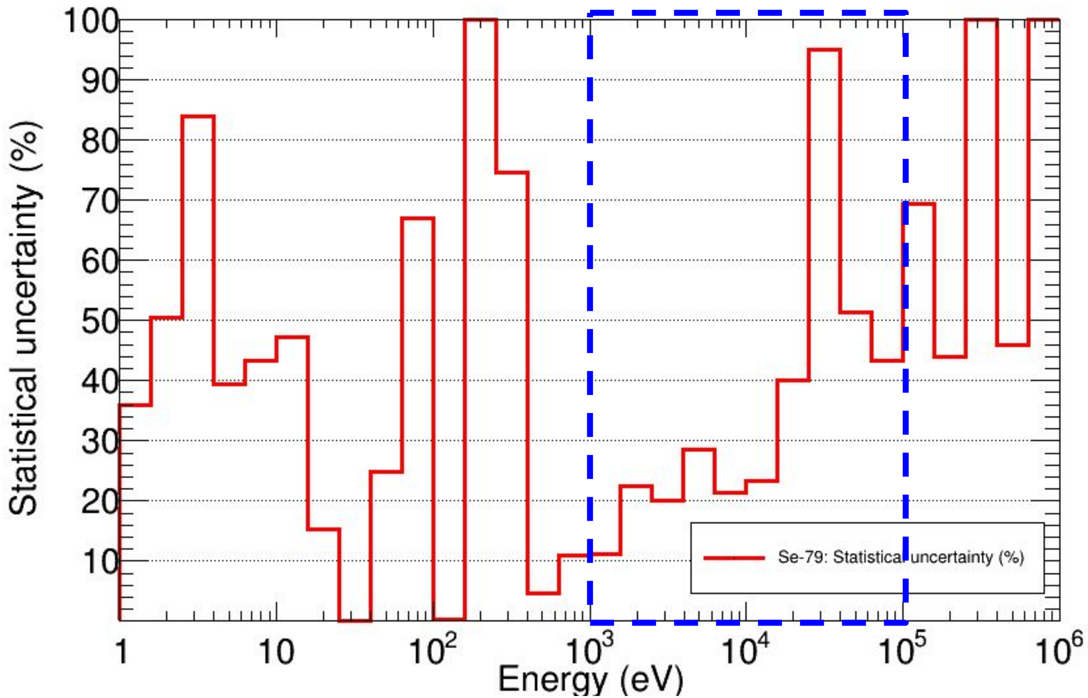
$^{79}Se(n,\gamma)$ @ EAR2 C6D6: uncertainty

Statistical uncertainties in the Se-79(n,γ) yield (5 bpd)

- Very small < 1% in the resonances below 200 eV
- Between 5 and 10% in the 500-2 keV range (RRR)

- **URR: 20-25% up to 2-20 keV**
- **URR: Larger than 40% above 30 keV**

AIM OF EAR2



BACK-UP SLIDES

$^{79}Se(n,\gamma)$

Motivation

Key reactions s-process nucleosynthesis

Progress in Particle and Nuclear Physics 66 (2011) 390–399

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

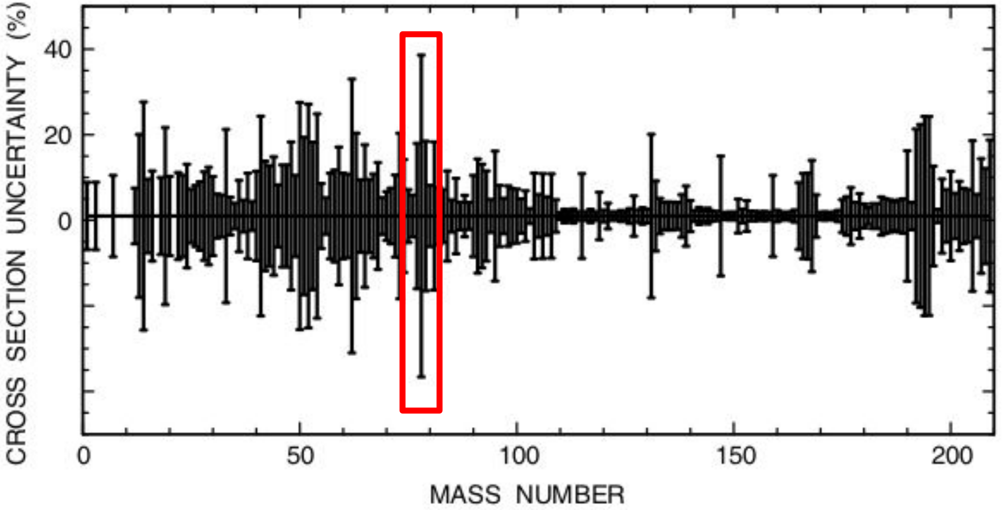
ELSEVIER

Review

Reaction cross sections for the *s*, *r*, and *p* process

F. Käppeler

Karlsruhe Institute of Technology, Campus Nord, Institut für Kernphysik, Karlsruhe, Germany



- Last, but not least, enhanced efforts should be directed to measurements on unstable nuclei. In addition to the activation technique, the very high neutron fluxes available at spallation neutron sources appear to be promising options for such studies. Priority should be given to the important branch points ^{79}Se, ^{147}Pm, ^{151}Sm, ^{163}Ho, ^{170}Tm, ^{171}Tm, ^{179}Ta, ^{204}Tl, and ^{205}Pb.

$^{79}Se(n,\gamma)$
Cross section calculations
(A. Mengoni)

Thermal value: ENDF, JEFF and TALYS

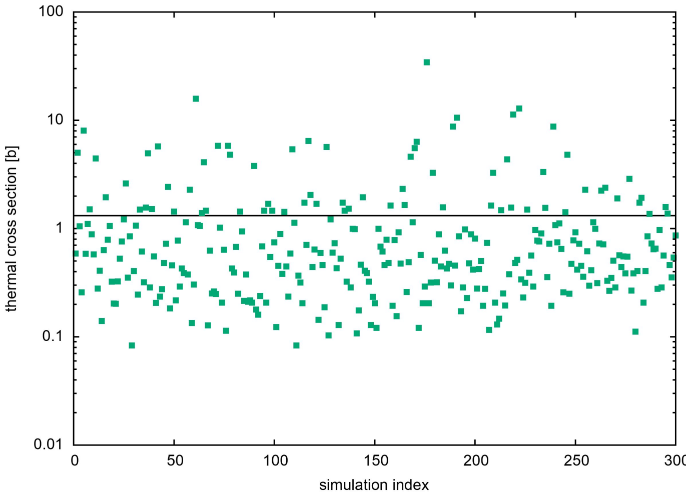
A. Mengoni's calculations:

300 sets of resonance using average parameters in TALYS:

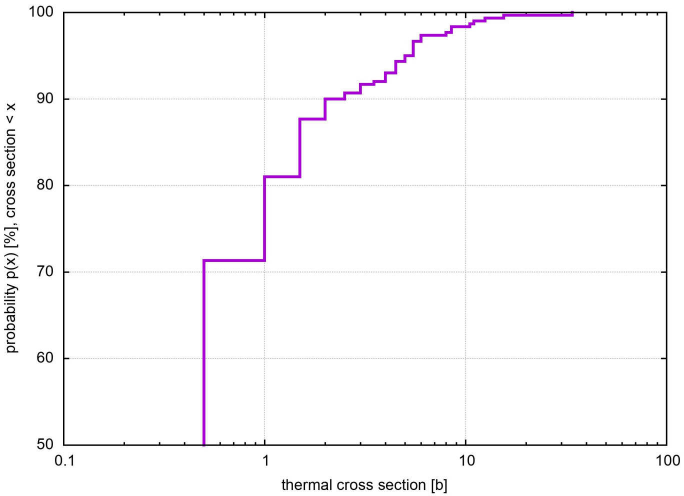
- <D0> = 56.8 eV
- S0 = 0.98 x 10^{-4}
- <Gamma_g(0)> = 0.078 (+-10%)

JEFF-3.3 (TENDL 2019) uses <Gamma_g(0)> = 0.100 meV

CALCULATED THERMAL XS



PROBABILITY SIGMA_TH



Calculation at thermal shows remarkable differences with evaluations

- Calculation: P(sigma_th <1b)= 80% + P (sigma_th <10 b) = 98%
- sigma_th = 50 b In ENDF/B-VIII.0

  sigma_th = 11.8 b in TENDL-2019

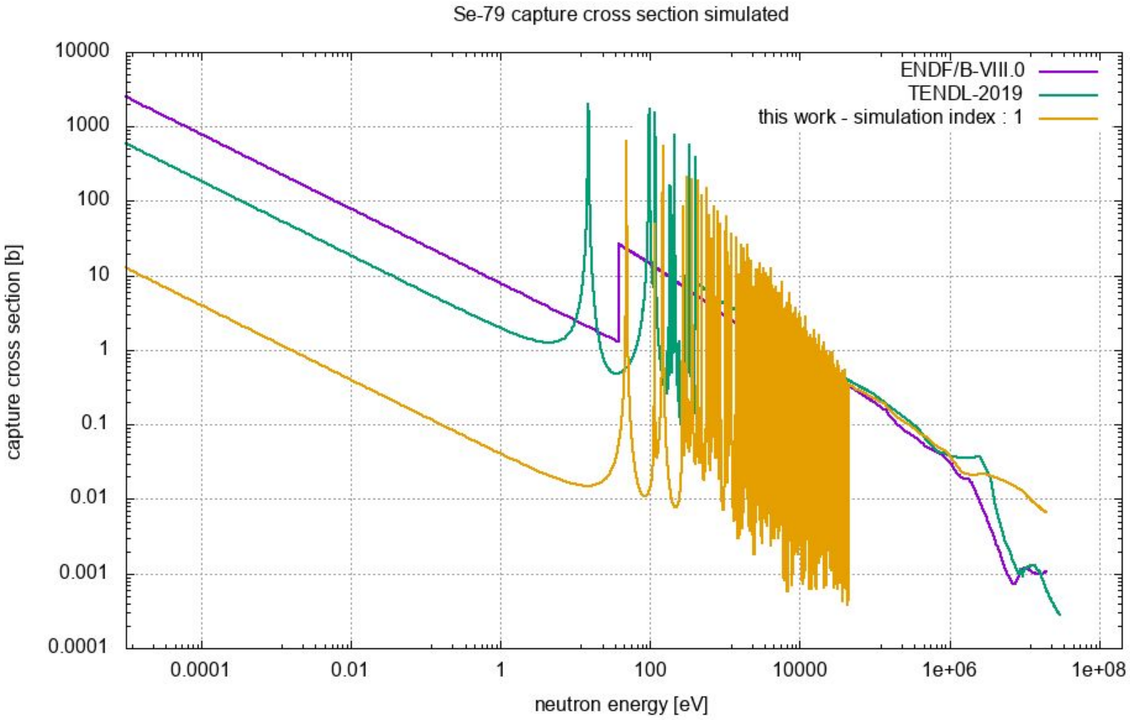
RRR and URR: ENDF, JEFF and TALYS

A. Mengoni's calculations:

300 sets of resonance using average parameters in TALYS:

- <D0> = 56.8 eV
- S0 = 0.98 x 10^{-4}
- <Gamma_g(0)> = 0.078 (+-10%)

JEFF-3.3 (TENDL 2019) uses <Gamma_g(0)> = 0.100 meV



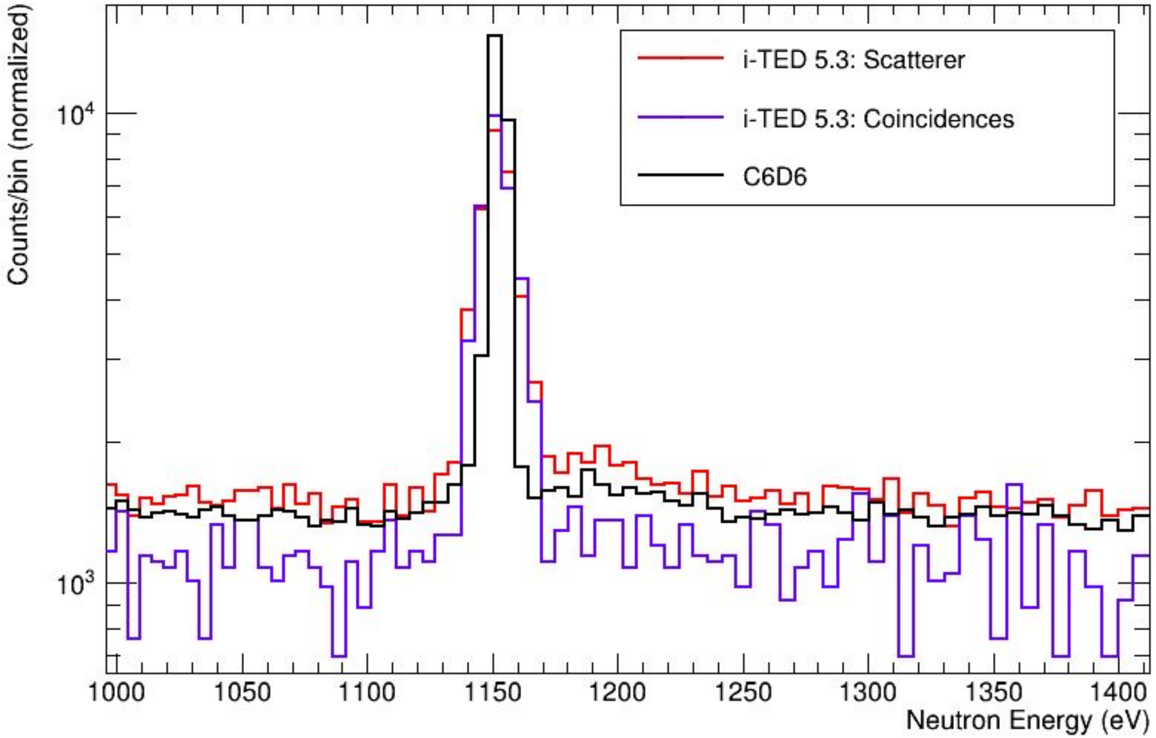
Calculation RRR: some realizations are compatible to JEFF-3.3 (used for the estimates). In some cases the strength of resonances is smaller
Calculation URR: Above 55 keV, TALYS Statistical model

^{79}Se(n,γ) @ EAR1:
i-TED imaging capabilities

i-TED5.3 vs C6D6 @ EAR1: Fe-56(n,g)

Spectra normalized to integral (1140-1160 keV)

Resonance is wider in i-TED due to non-perfect trigger timing correction



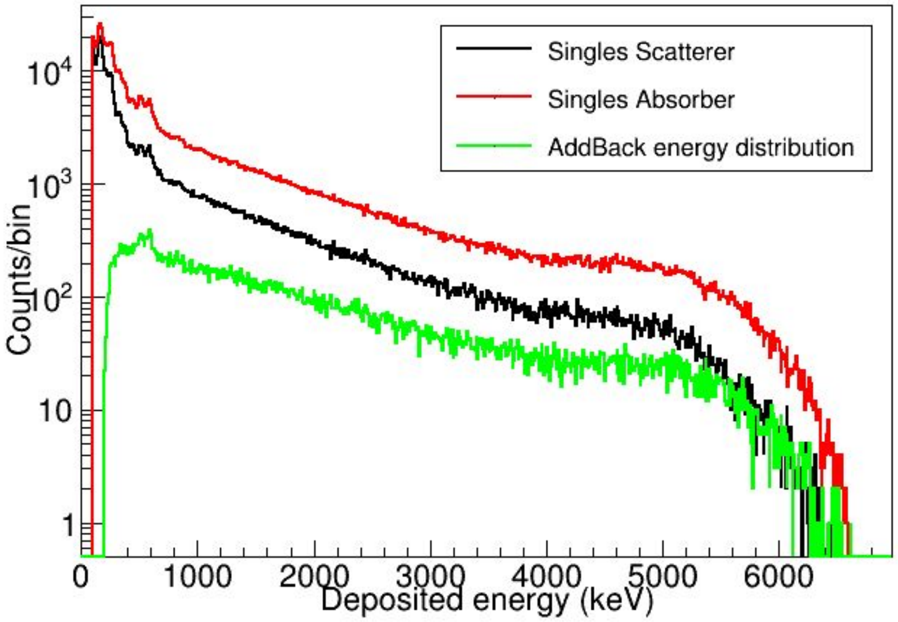
NORMALIZATION TO 1.15 KeV Resoannce to proof gain in (n,g) background in the keV range

i-TED Spectra : singles & add-back

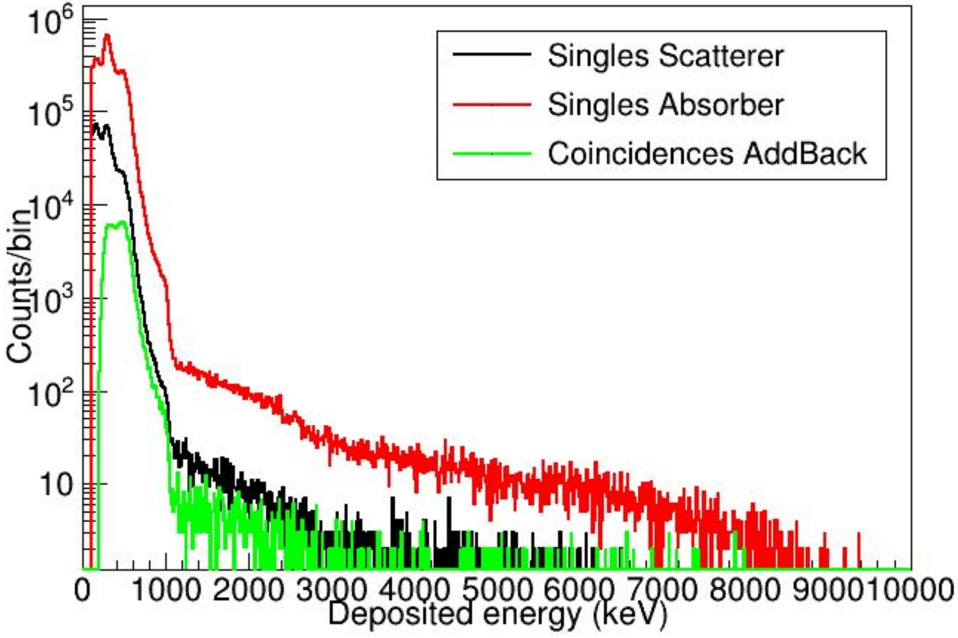
(n,g) and background

Det #2
D = 50 mm

Au-197(n,g)



Background EAR1



i-TED: Experimental bckg suppression

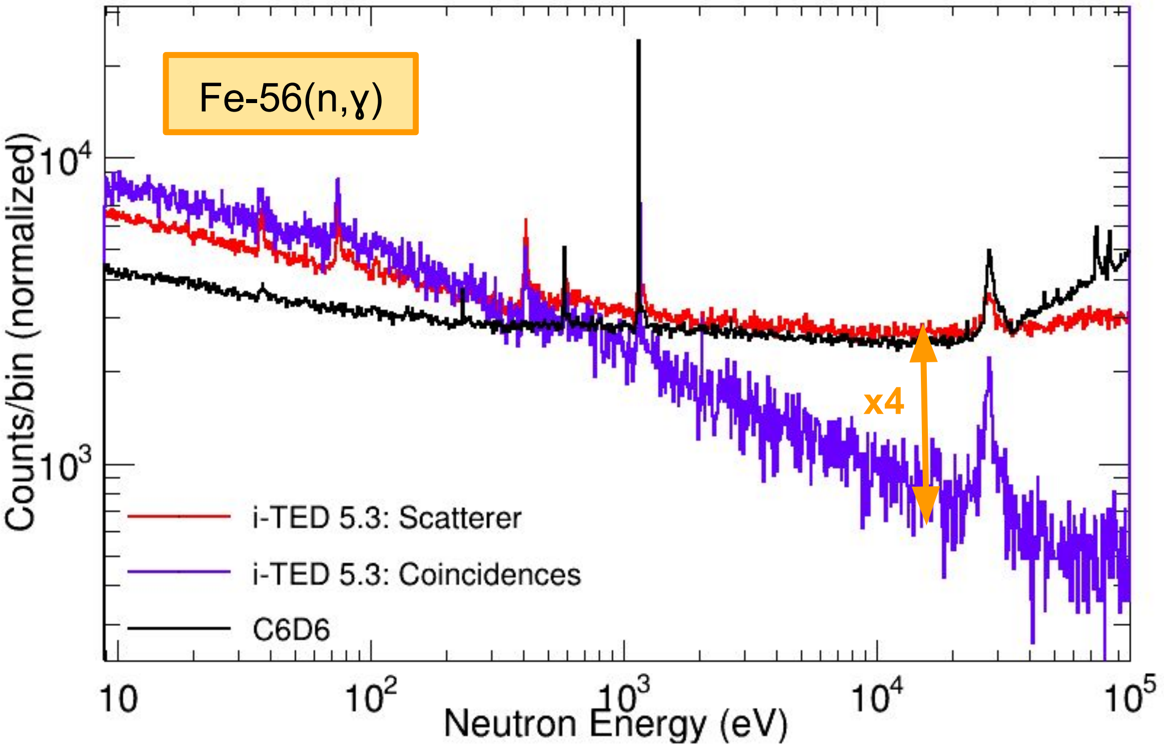
i-TED 5.3 (n,ɣ)/background gain vs C6D6: Scatterer-Absorber coincidences

Scatterer alone very similar counting rate that **C6D6** but:

- + Higher resolution
- + Spectroscopic

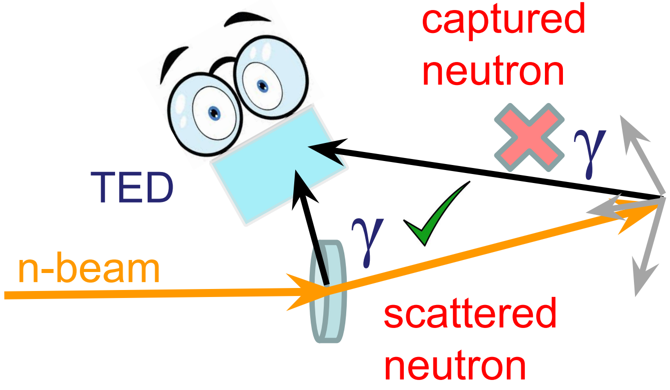
Before imaging: i-TED improves (n,ɣ)/background ratio in the keV range after **coincidences** between absorber-scatterer

See V. Babiano's talk for more details on the i-TED prototype commissioning



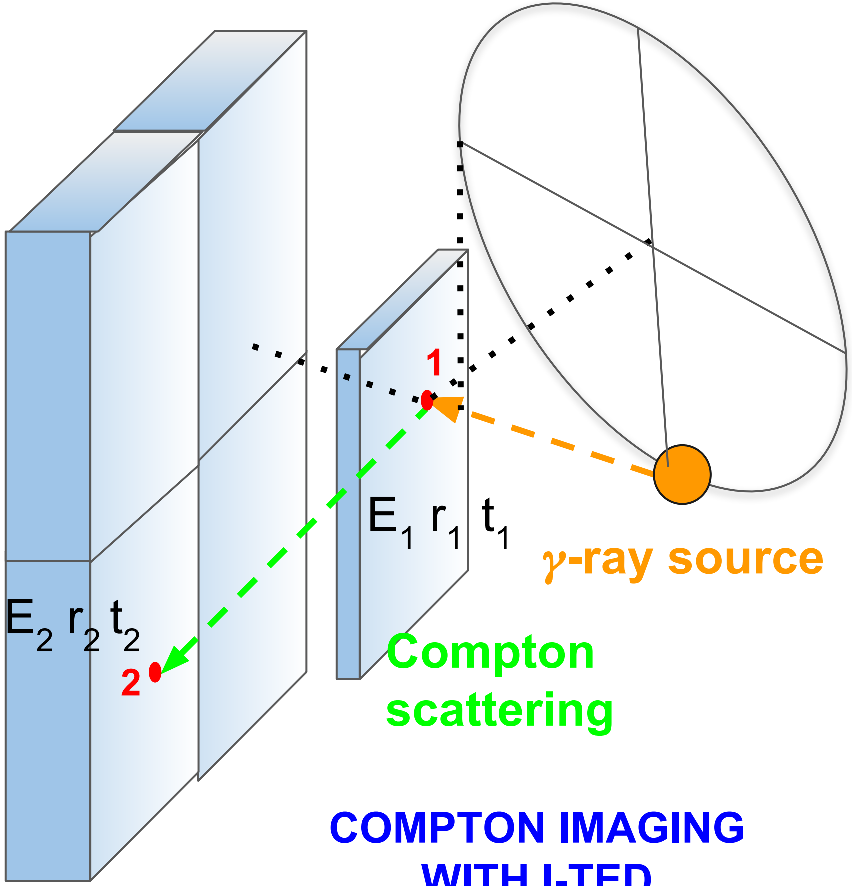
Background suppression i-TED

i-TED CONCEPT



$$\theta = arcos\left(1 - m_e c^2\left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right)\right)$$

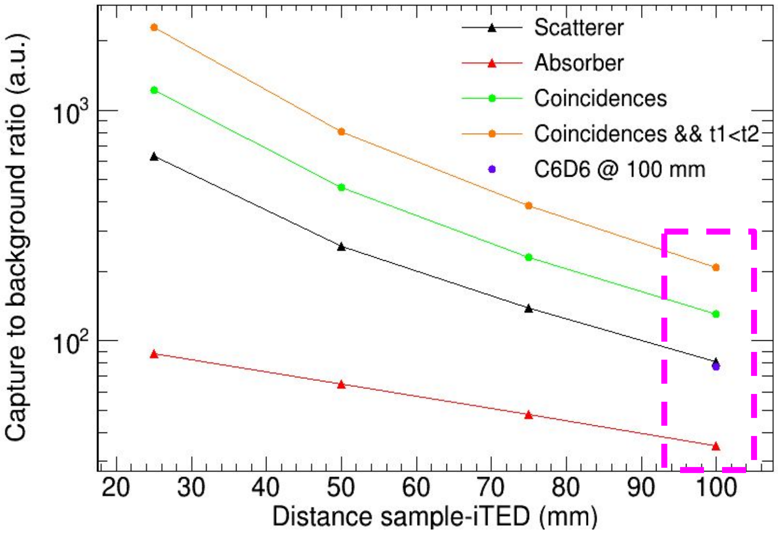
$$\Delta\theta = \frac{E_1 + E_2}{sen\,\theta}\left(\frac{1}{E_1^2}\left(\frac{\Delta E_1}{E_1}\right)^2 + 2\,sen^2\theta\left(\frac{\Delta r}{r}\right)^2\right)^{1/2}$$



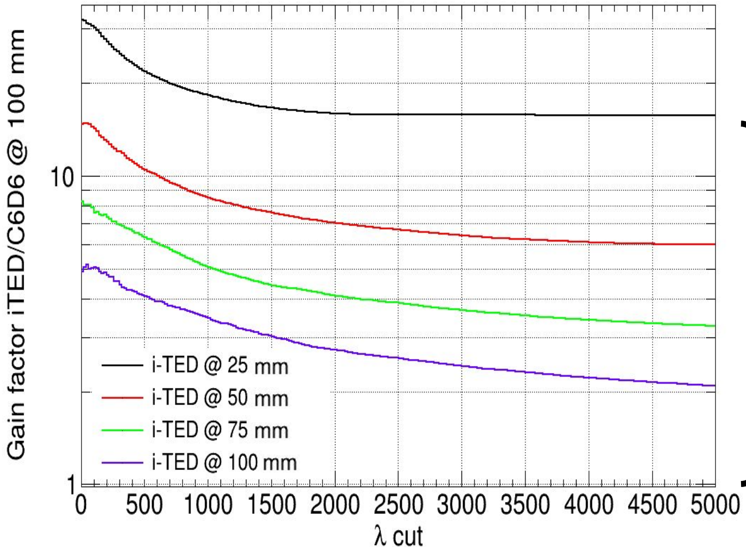
COMPTON IMAGING WITH I-TED

Background suppression i-TED

MC :C6D6 & i-TED to capture & background



Best gain factors (n, ɣ)/bckg ratio wrt to C6D6



Values with no imaging cut

Coincidences and time resolution make a factor 2-3 in (n,ɣ)/background gain

Feasible (n,ɣ)/background gain:
Factor 4-10 depending of the sample-i-TED distance

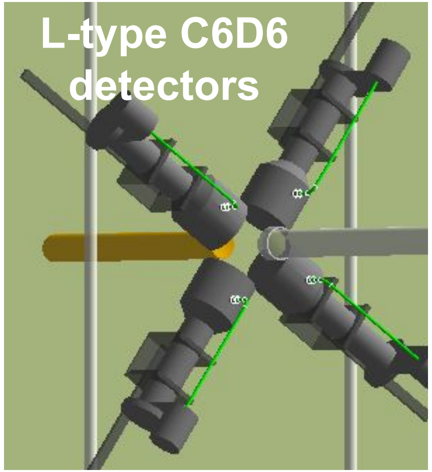
Optimization of the background rejection capabilities still on-going

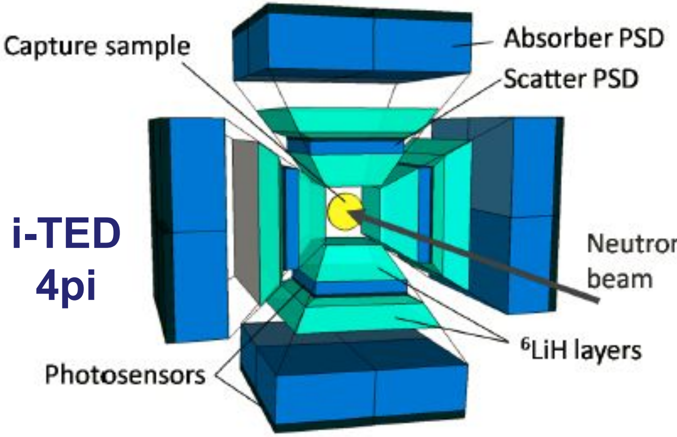
^{79}Se(n,γ) @ EAR1:
i-TED vs C6D6

Detectors and EARs: summary

DETECTOR / EAR	EAR1	EAR2
C6D6	Higher efficiency, Worse background rejection (large neutron scattering)	**Better Performance @ high CR** **More statistics** **Activity not an issue**
I-TED	**~ 5-10 x Better (n, γ)/background in the keV range.** **C. Rate is not an issue.**	Performance in EAR2 is still uncertain, probably too high CR

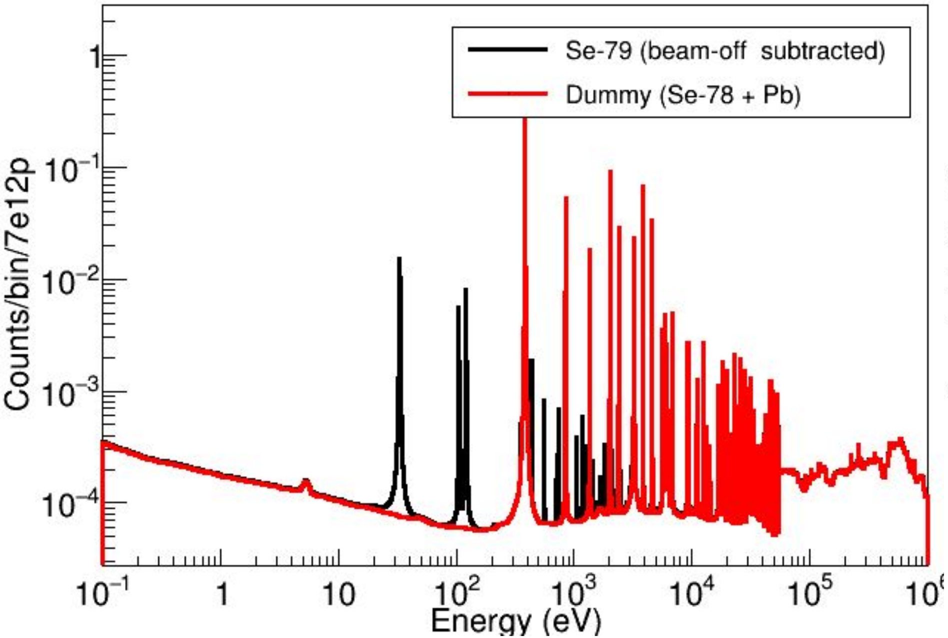
Combined proposal:
i-TED (+ C6D6?) @ EAR1 & C6D6 @ EAR2



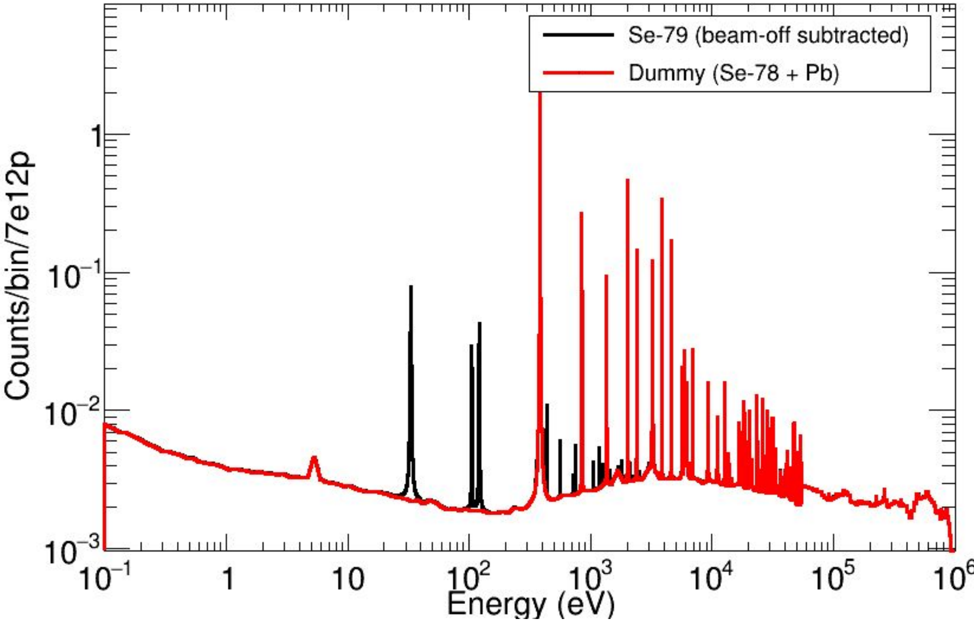


$^{79}Se(n,\gamma)$ @ EAR1: i-TED vs C6D6

i-TED (coinc.)



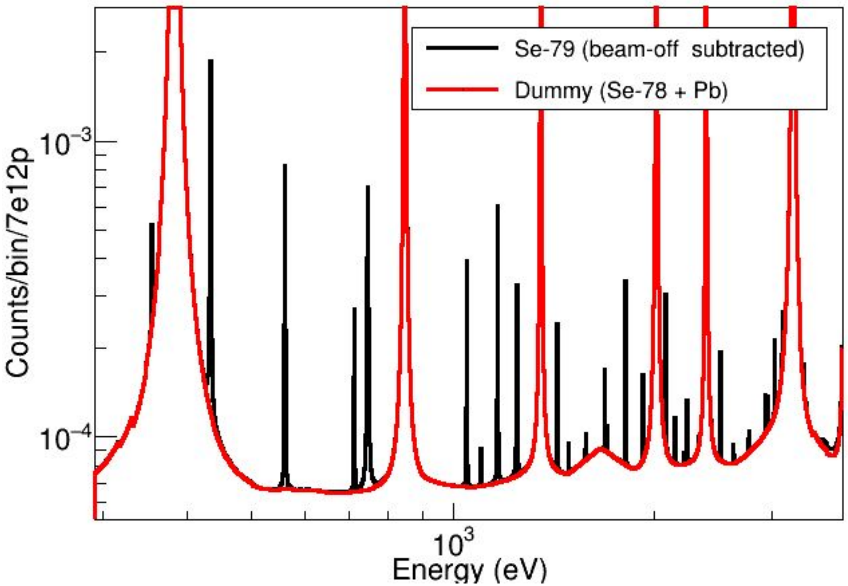
C6D6 (or i-TED scatterer)



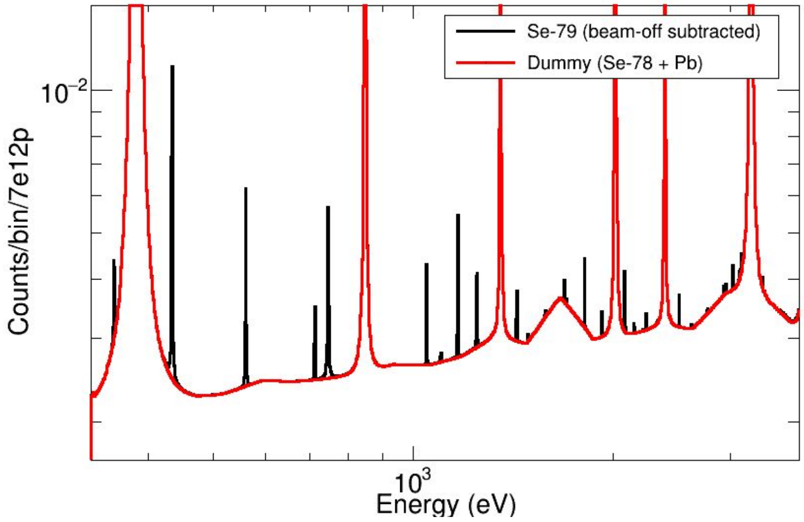
Theoretical estimation: After 1/v activity subtracted → Total counts vs "dummy" sample
i-TED: improved Se-79(n,ɣ)/background above 100 eV
Background due to Se-78(n,n) and Se-79(n,n) not included and also suppressed with i-TED

$^{79}Se(n,\gamma)$ @ EAR1: i-TED vs C6D6

i-TED (coinc.)



C6D6 (or i-TED scatterer)

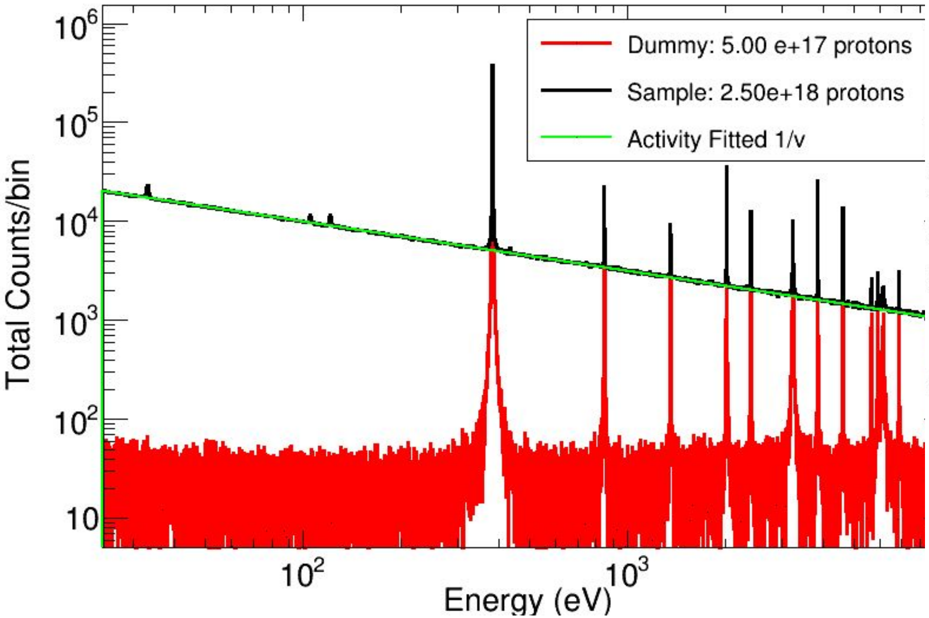


Theoretical estimation: After 1/v activity subtracted → Total counts vs “dummy” sample
Reduction of the background in i-TED seems critical to observe Se-79 resonances,
Strength and level density may change (BASED IN TALYS)

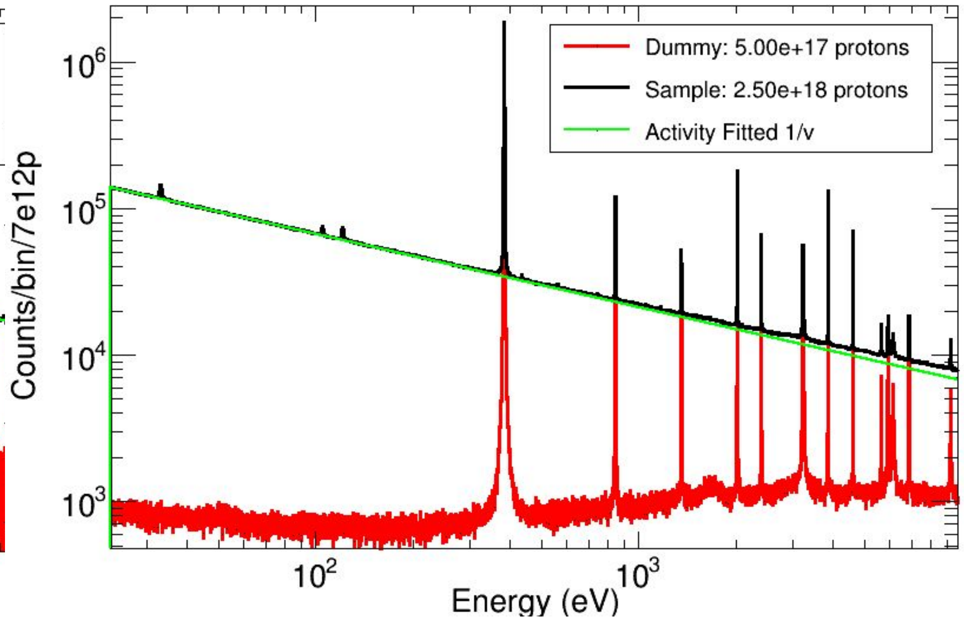
$^{79}Se(n,\gamma)$ @ EAR1 i-TED vs C6D6

PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

i-TED (coinc.)



C6D6 (or i-TED scatterer)

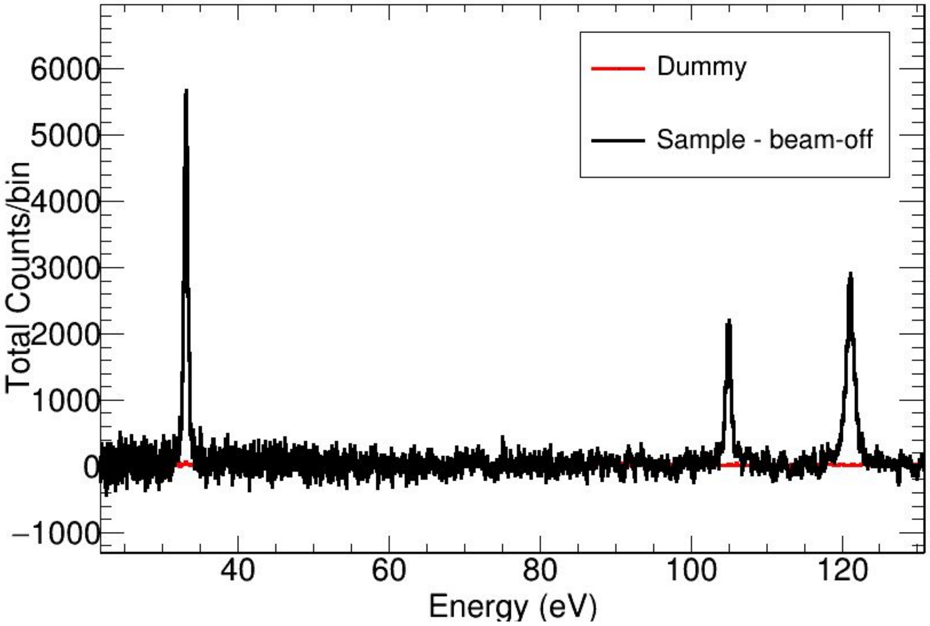


MC simulation of the experiment: Realistic counts and statistical uncertainties
i-TED vs C6D6: reduction of activity background in 50% and the dummy in a factor ~5 relative to capture

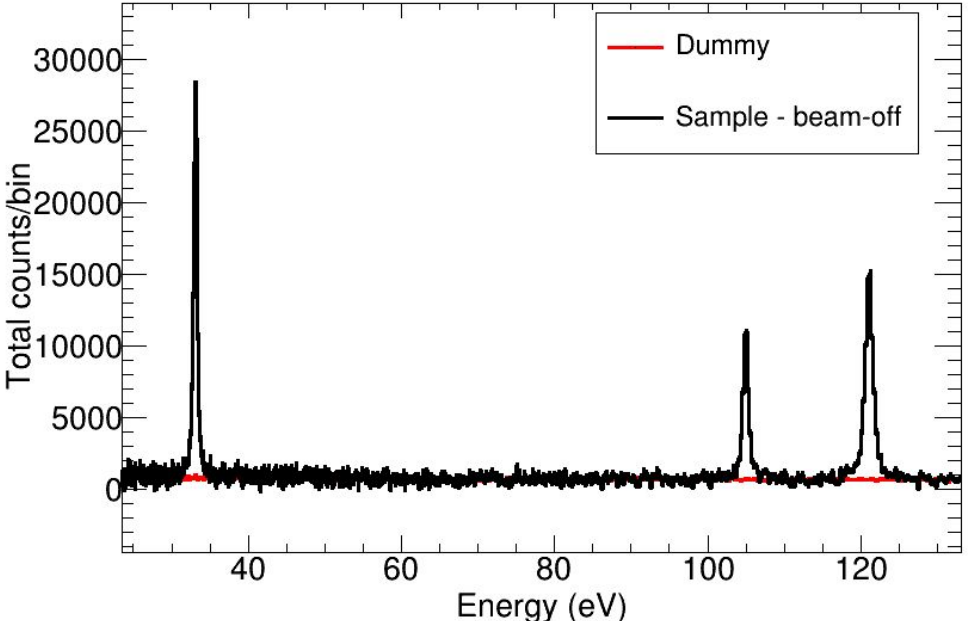
$^{79}Se(n,\gamma)$ @ EAR1 i-TED vs C6D6: RRR

PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

i-TED (coinc.)



C6D6 (or i-TED scatterer)

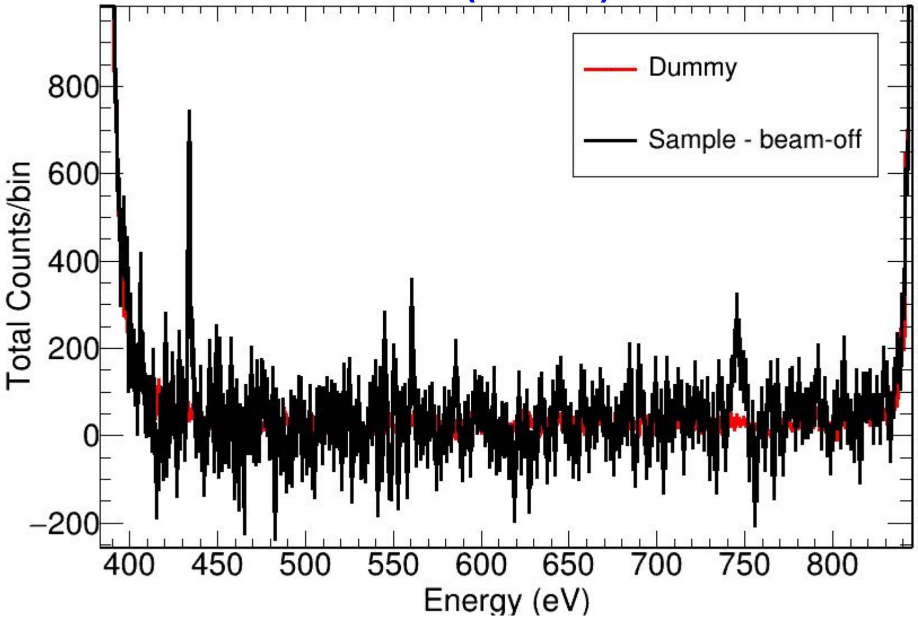


Largest resonances of Se-79 below 200 eV clearly observed

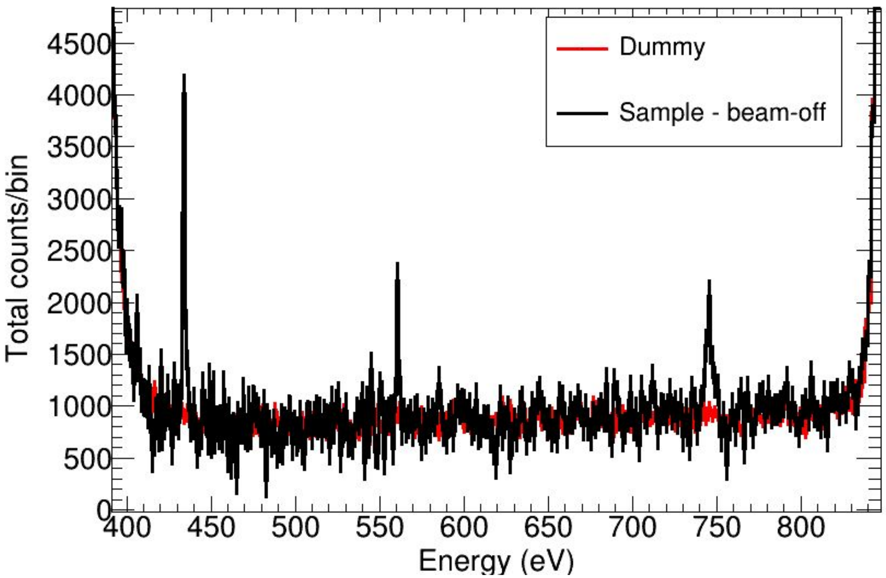
$^{79}Se(n,\gamma)$ @ EAR1 i-TED vs C6D6: RRR

PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

i-TED (coinc.)



C6D6 (or i-TED scatterer)



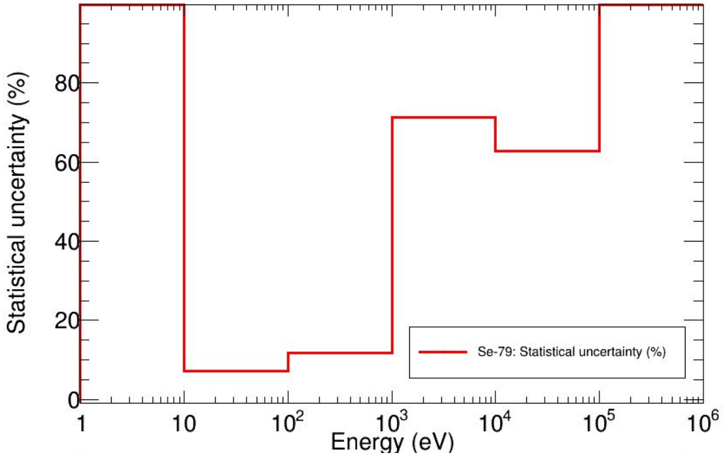
Possible to measure @ EAR1 the RRR below 1 keV
URR: complementary measurement at EAR2

^{79}Se(n,ɣ) @ EAR1: uncertainty

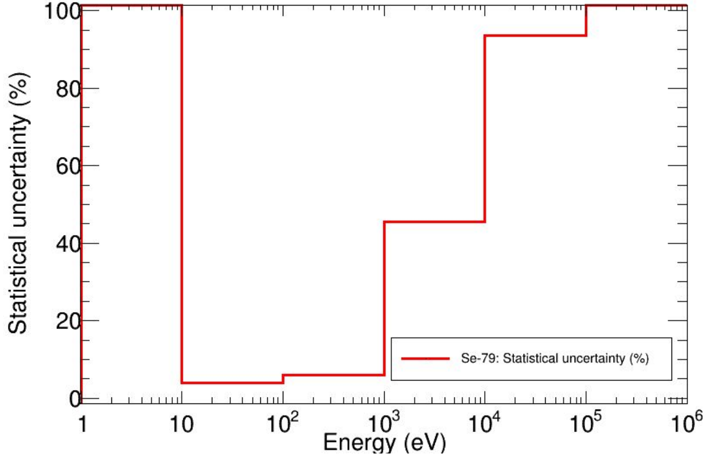
PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

Statistical uncertainties in the Se-79(n,ɣ) integral yield (1 bpd)

- Below 15% up to 1 keV (both setups)
- At higher energies: Uncertainty 50-70%. Very challenging to extract any cross section
- i-TED provides better uncertainty in above 10 keV→ better Se-79(n,ɣ)/ background



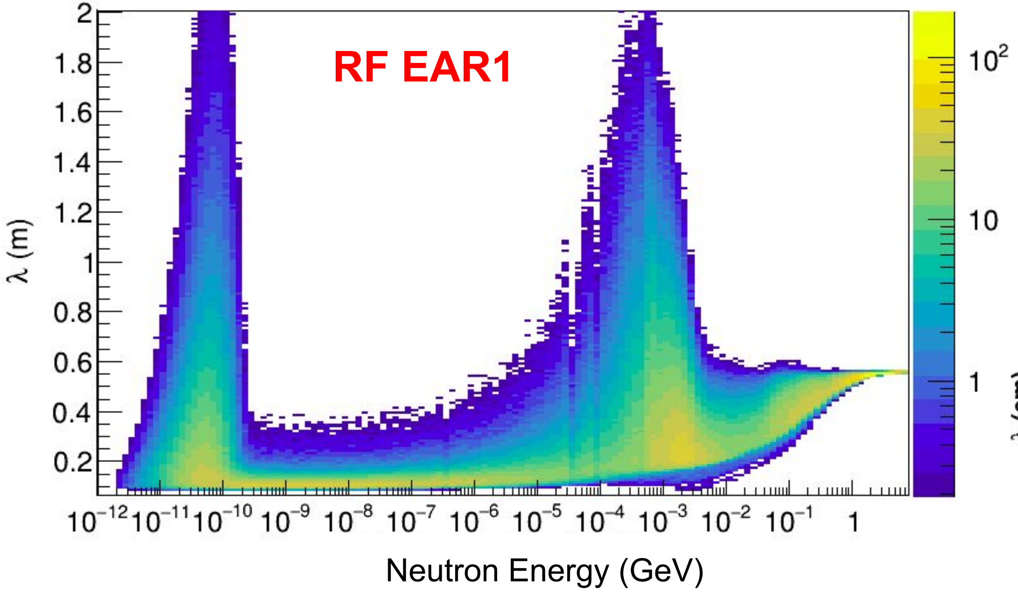
i-TED (coinc.)

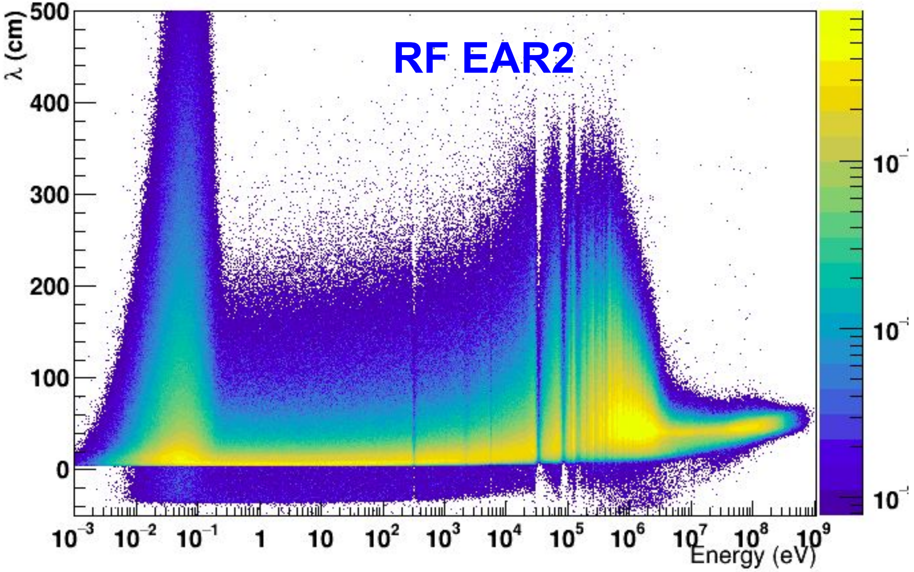


C6D6

^{79}Se(n,γ) @ n_TOF:
Including RF

Resolution Function





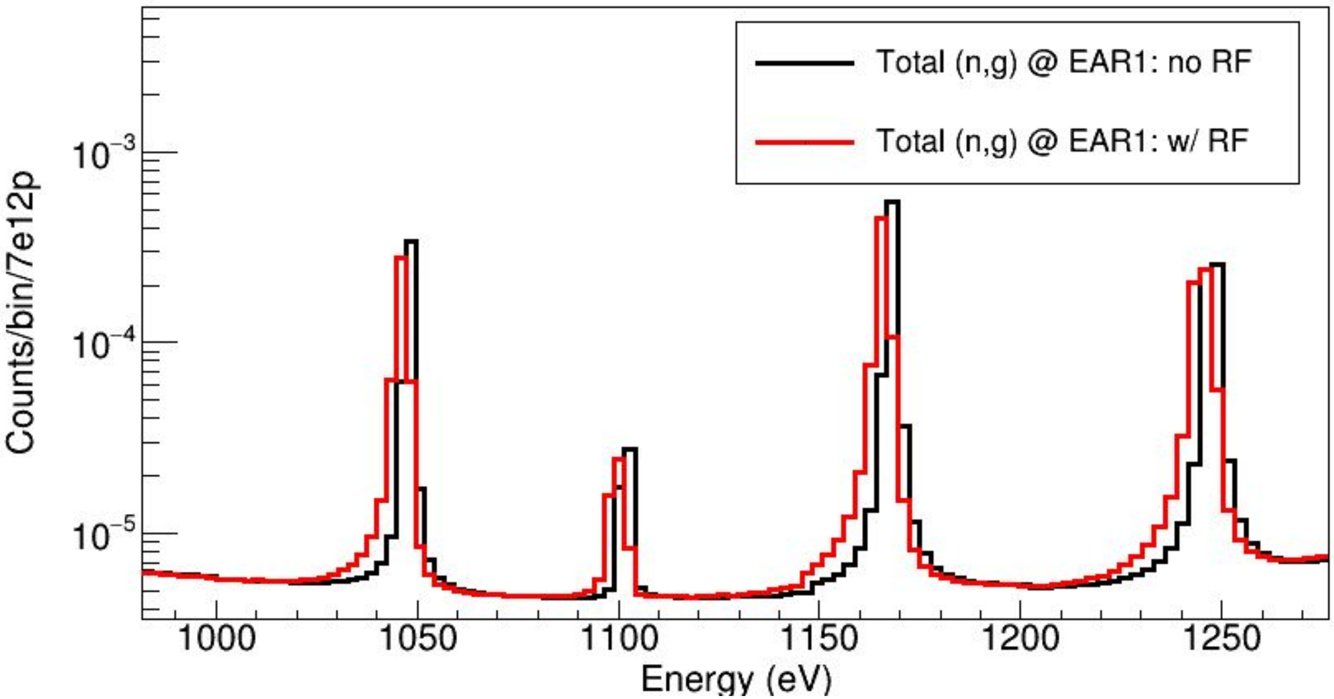
For a given real neutron Energy (En):

1. **L(En) = L0 + λ(En)** → Flight path distribution

1. **TOF (En) = TOF(L(En))** → TOF distribution

1. **E'(En) = E'(TOF(En))** →Exp. Energy distribution

$^{79}Se(n,\gamma)$: Resolution Function



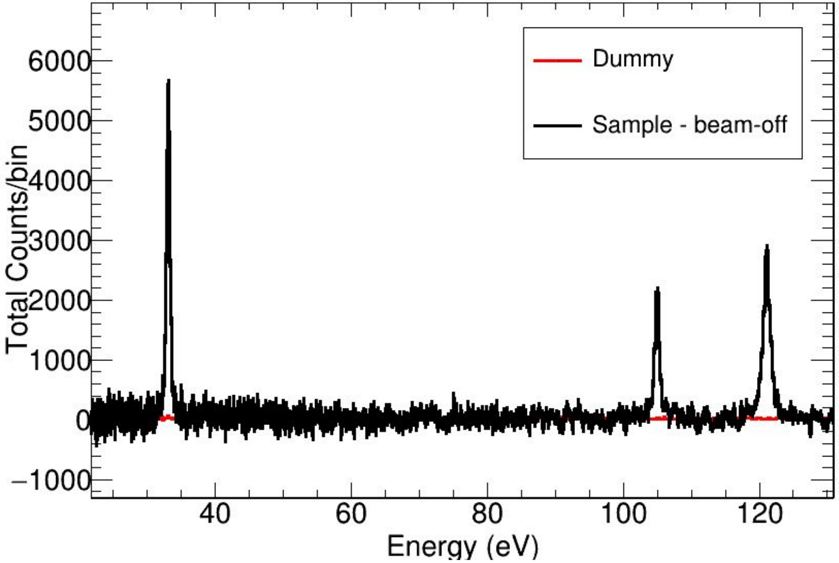
Shift resonance energy + broadening + asymmetry (low energy tail)

$^{79}Se(n,\gamma)$ @ EAR1 i-TED: Impact RF

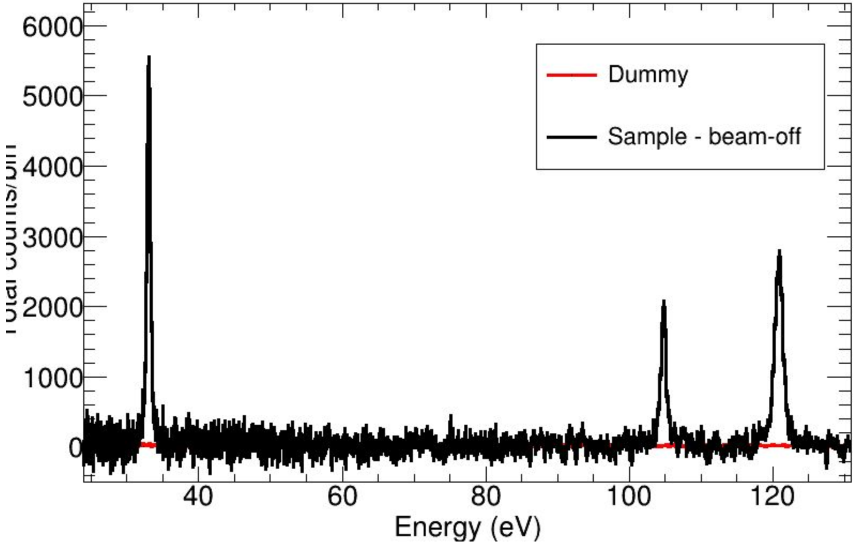
MC simulation
Experiment

PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

NO RF



WITH RF



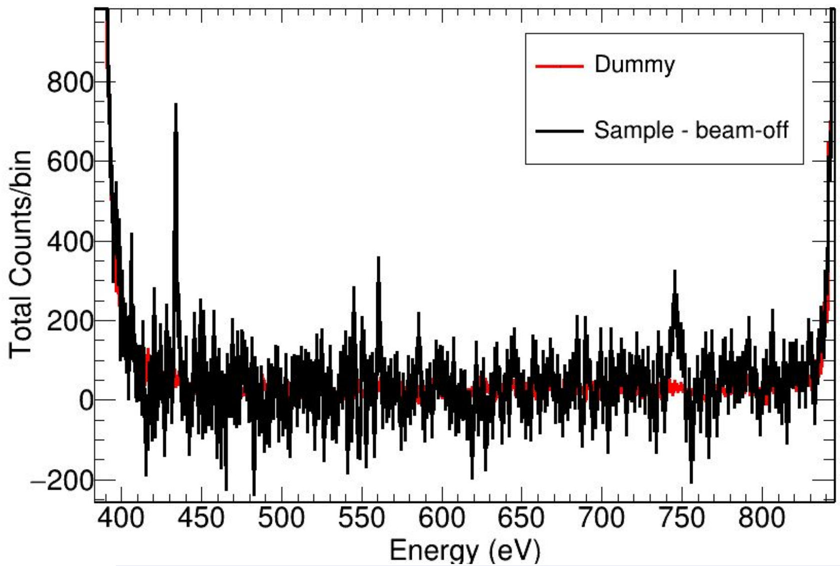
Resolution function at EAR1 not sizable below 1 keV
Target #3 should not worsen the RF @ EAR1

$^{79}Se(n,\gamma)$ @ EAR1 i-TED: Impact RF

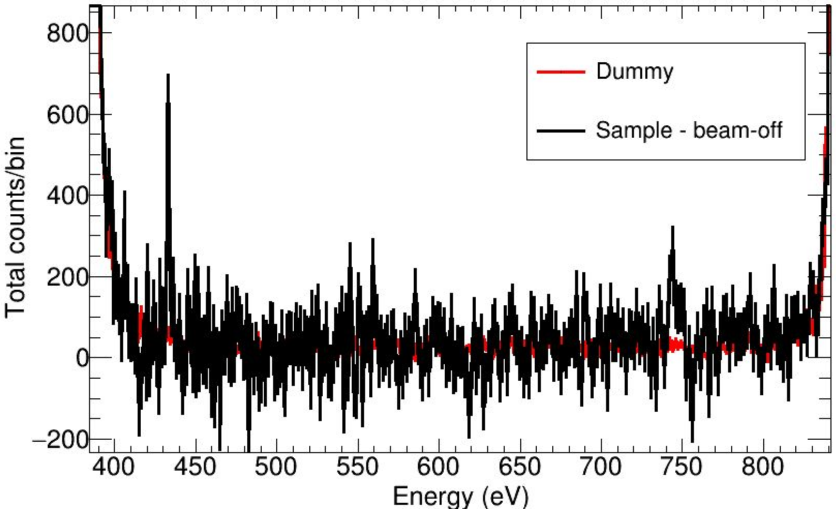
MC simulation
Experiment

PbSe sample: 2.5e18 protons
Dummy: 0.5e18 protons

NO RF



WITH RF

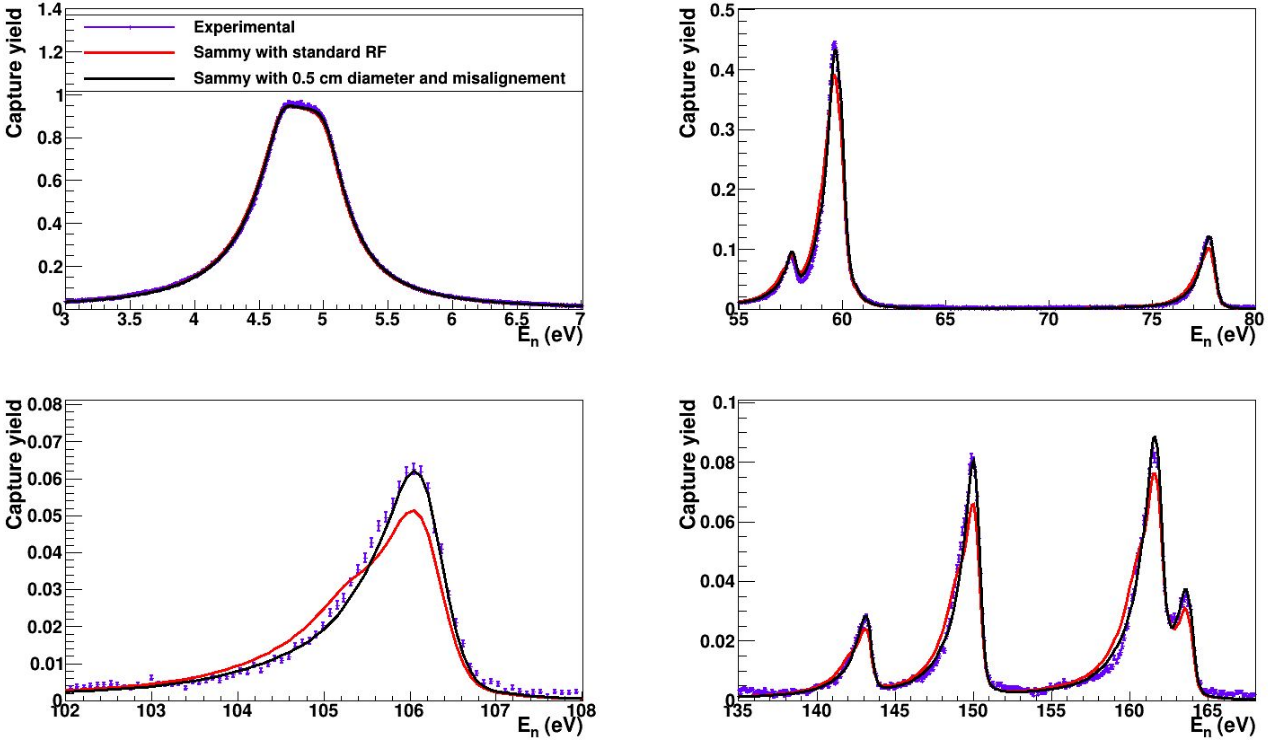


Resolution function at EAR1 negligible below 1 keV
Target #3 should not worsen the RF @ EAR1

RF @ EAR2: Difficult to estimate

Exp vs SAMMY
With different RF

(See V. Alcayne's RF talk)



RF depends on sample dimension → Standard RF overestimates → V. Alcayne 's Talk)

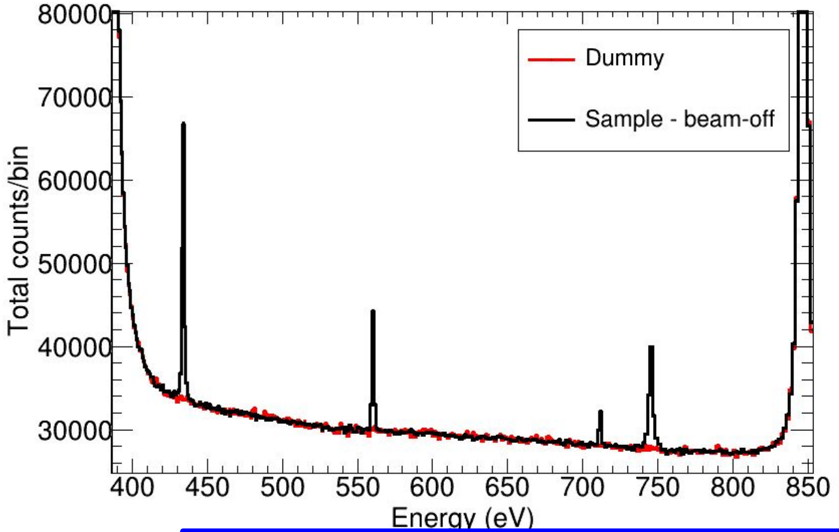
Target #3 should significantly improve the RF @ EAR2

$^{79}Se(n,\gamma)$ @ EAR2 C6D6: Impact RF

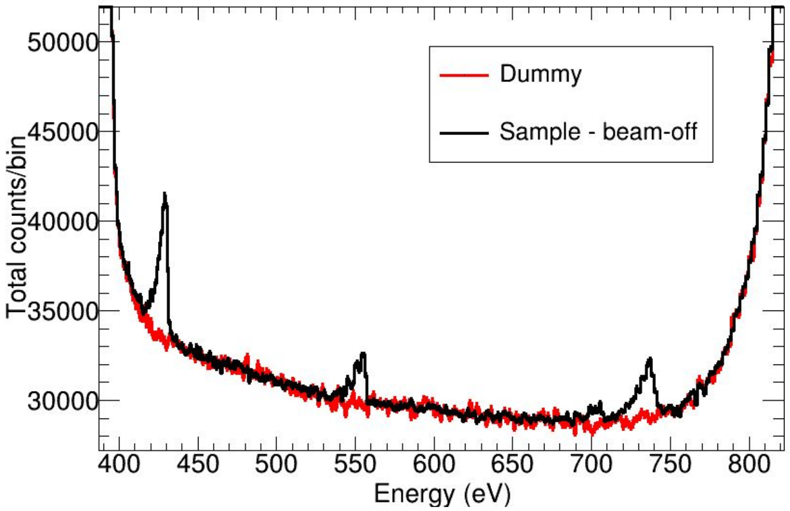
MC simulation
Experiment

PbSe sample: 1e18 protons
Dummy: 0.5e18 protons

NO RF



WITH RF

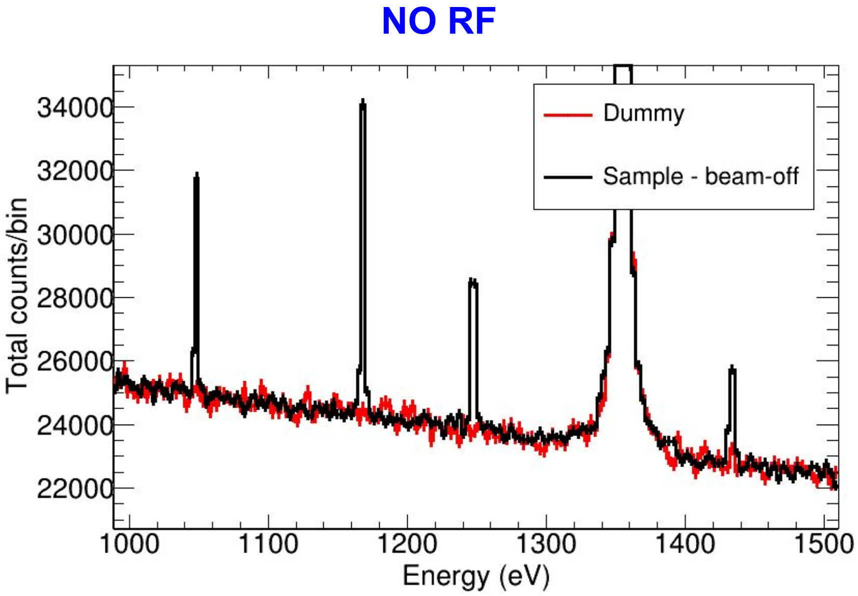


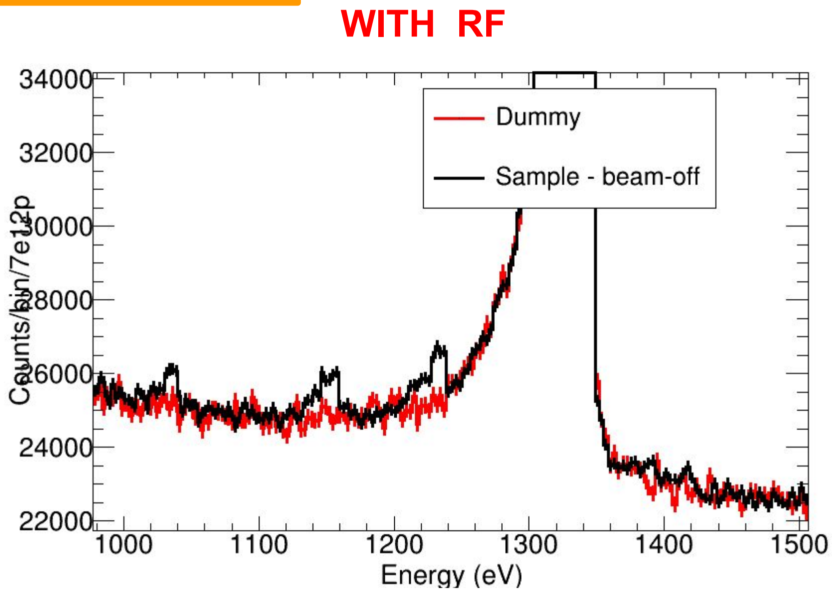
Measurement at EAR2 can observe resonances up to 1 keV even with Standard RF (overestimates → V. Alcayne 's Talk)
Target #3 should improve the RF @ EAR2

$^{79}Se(n,\gamma)$ @ EAR2 C6D6: Impact RF

MC simulation
Experiment

PbSe sample: 1e18 protons
Dummy: 0.5e18 protons





Challenging to analyze individual Se-79 resonances @ EAR2 above 1 keV
Standard RF (overestimates → V. Alcayne 's Talk)
Target #3 should improve the RF @ EAR2