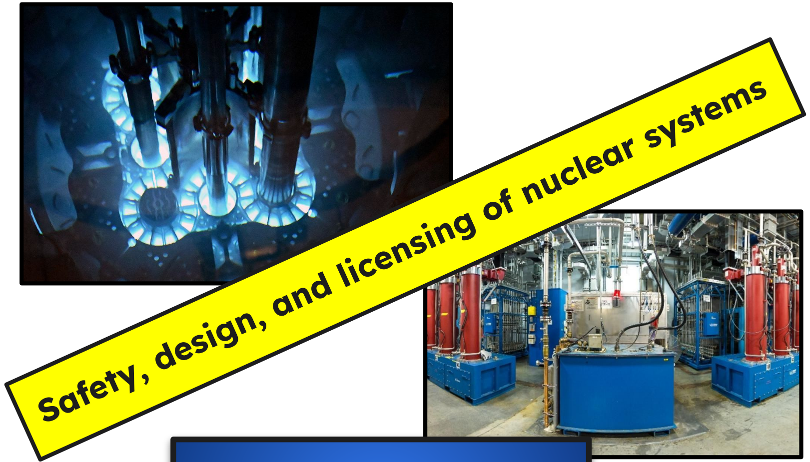
First high-resolution in-beam γ-ray spectroscopy of fast-neutron induced (n,xn) reactions with the EXOGAM array at Neutrons For Science (NFS)

Focus on: Nuclear data & cross-sections

24ème
COLLOQUE GANIL
21 au 25 septembre 2026
Bussang, France

Hemantika Sengar,
Emmanuel Clement and the e838 collaboration

GANIL cea



Benchmarking Codes

PHITS

mcnp

TALYS

GEANT4
A SIMULATION TOOLKIT

EMPIRE
Nuclear Reaction Model Code

Nuclear Data: Cross-section measurements

^{204}Pb ^{205}Pb ^{206}Pb ^{207}Pb ^{208}Pb

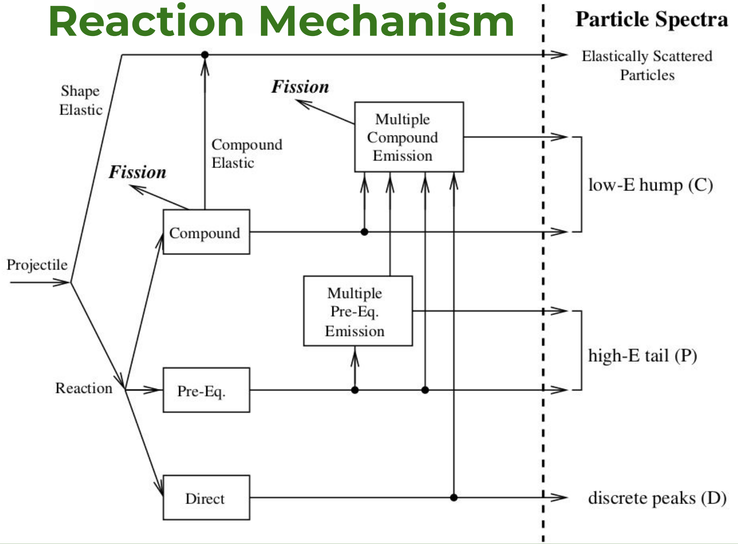
- ➢ Neutron-induced cross sections are interesting!
- ➢ Pb is important for nuclear reactors, accelerator & spallation facilities.
- ➢ Benchmarking Codes.
- ➢ Neutron-induced cross sections are difficult, especially (n, xn); where n>2 !
- ➢ Way to overcome → (n, xnγ) gamma cross-sections:
  - Nuclear model validation
  - Nuclear heating / dose rate in structural materials
  - Decay heat, shielding design, Fusion neutronics (ITER)

Nuclear Structure

Discrete levels	Masses
Level schemes	Level densities
Lifetimes	Resonances
Spin & Parities	Fission barrier
Branching ratios	Thermal XS
Abundancies	Microscopic LD
Deformations	Precision shapes

…

Reaction Mechanism

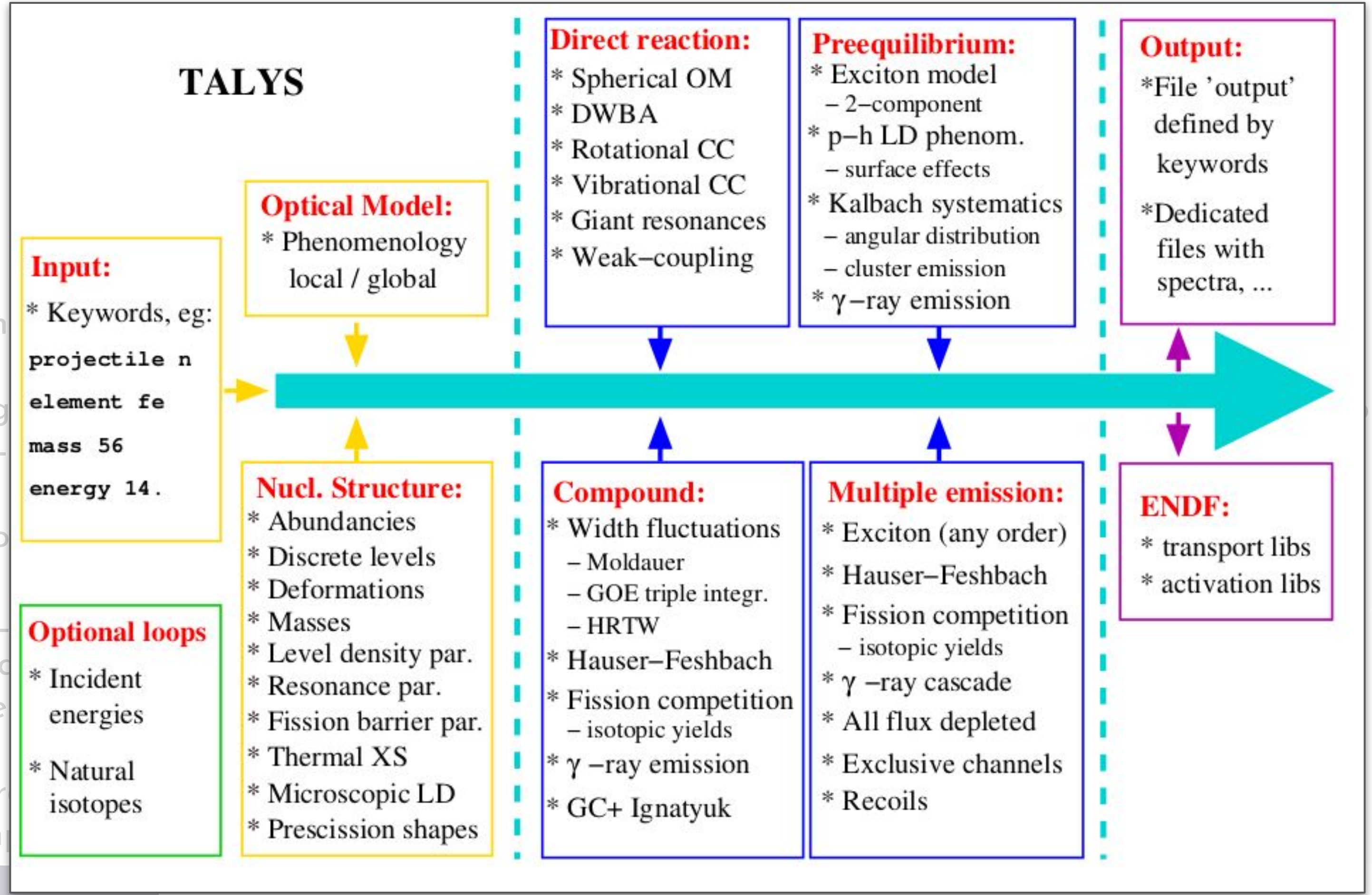


The correlation is obvious,
but combining nuclear structure properties and the reaction mechanism itself into a single framework is experimentally challenging and interesting…

TALYS-2.1

Nuclear Physics Tool Reaction Mechanism Code	Nuclear Data Prediction capabilities

- ➢ Continuing to develop… widely used in many fields.
- ➢ In general, an exact implementation of many of the latest nuclear models for direct, compound, pre-equilibrium and fission reactions.
- ➢ Reliable cross-section generator for well-established reactions
- ➢ TALYS combines optical model, compound, pre-equilibrium, and fission reaction theory into one predictive framework, spanning 0.001-200 MeV and A > 12, drawing structure inputs (masses, levels, level densities…) automatically from the IAEA Reference Input Parameter Library.
- ➢ A transparent source program.
  - Input/output communication that is easy to use and understand.



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TALYS-2.1

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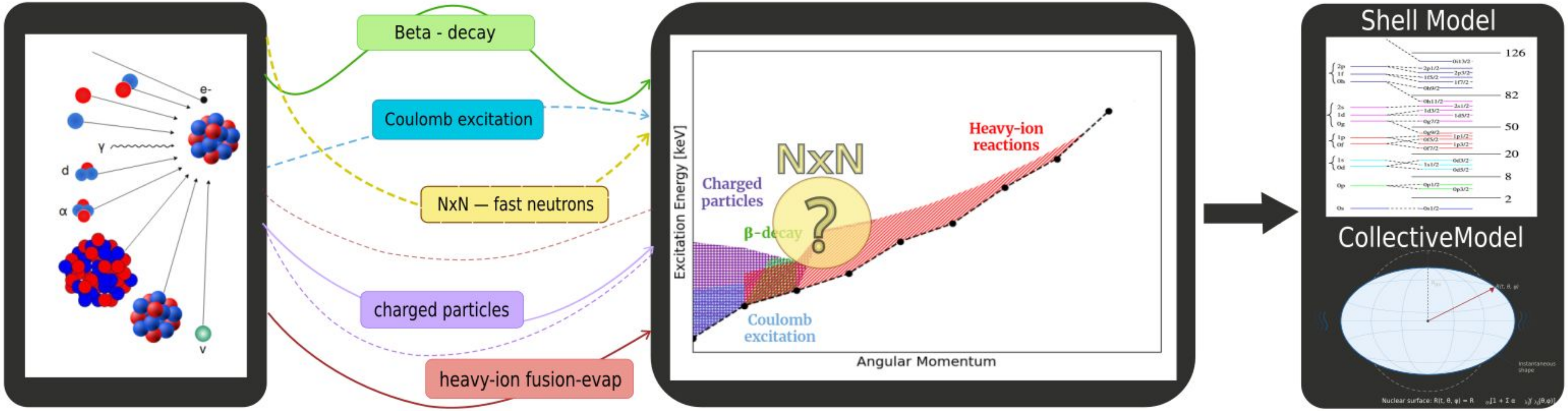


Goal : providing experimental insight using high resolution gamma ray spectroscopy of the populated states

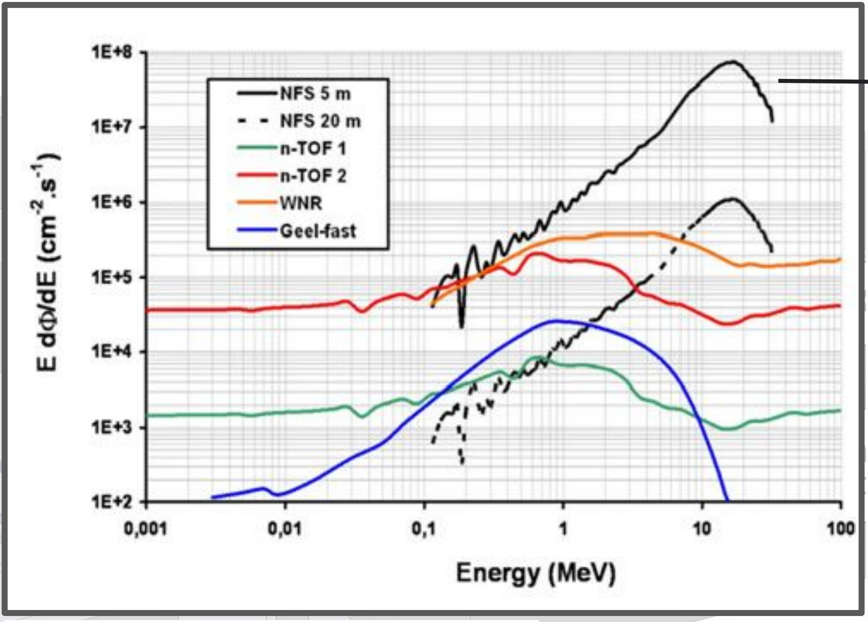
1. How do (n, xn) reactions differ from the conventional probes used to date?

2. Can this mechanism reveal aspects of nuclear structure that conventional probes leave untouched?

   Yrast / spin aspect **Compound vs direct reaction aspect** **Single particle vs collective states**

3. How accurately do nuclear reaction models decompose the contribution of nuclear structure, so as to arrive at a complete anatomy of the cross section?

Highest neutron flux beyond 10 MeV world-wide!



NFS (0-40 MeV)

Los Alamos, USA

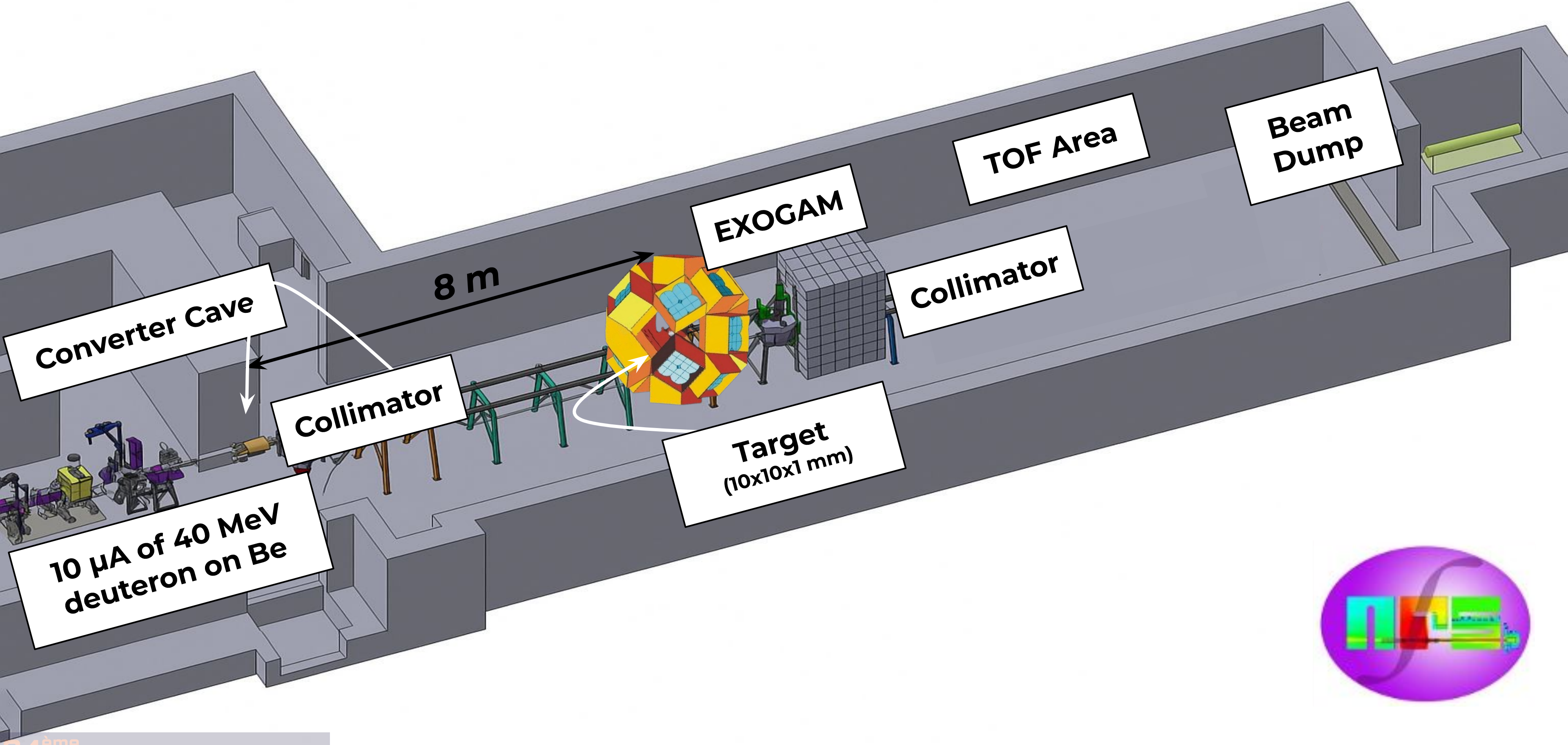
n_TOF (CERN, EAR1), Switzerland

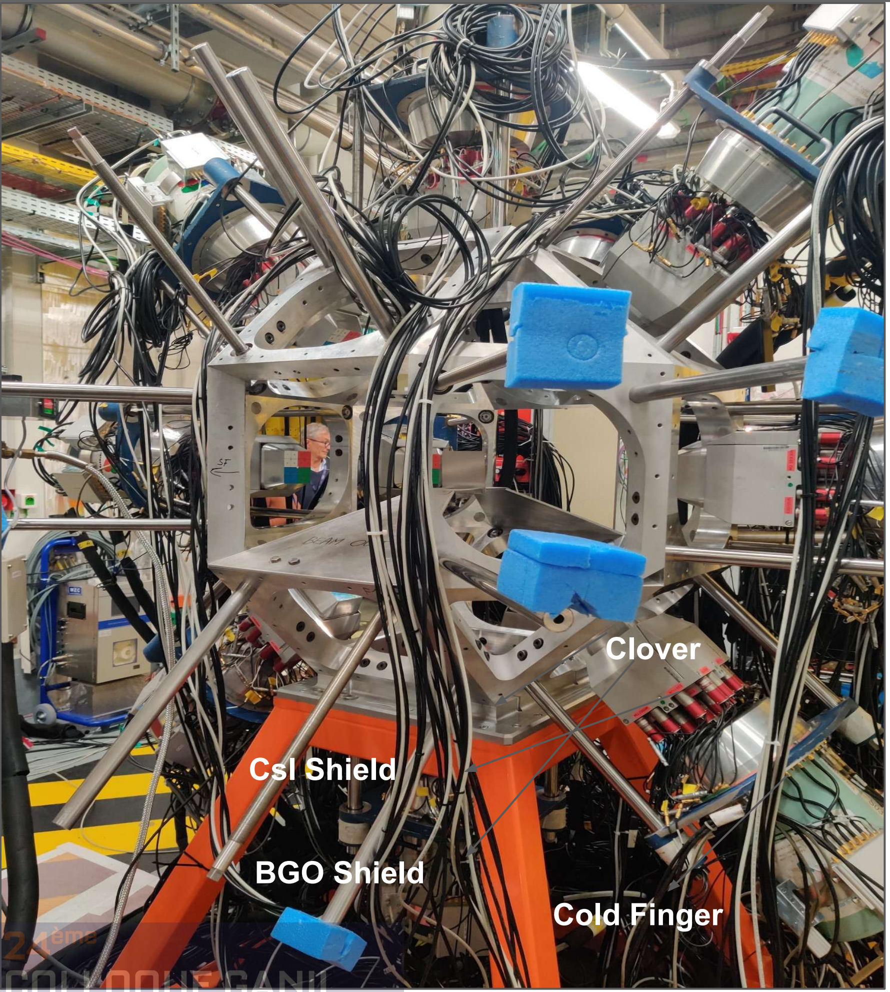
n_TOF (CERN, EAR2), Switzerland

GELINA (Belgium)

Courtesy: Xavier LEDOUX

Plus: Low gamma-flash background at NFS


Beam Dump
TOF Area
EXOGAM
Collimator
8 m
Converter Cave
Collimator
Target
(10x10x1 mm)
10 µA of 40 MeV deuteron on Be



High Resolution Measurement: EXOGAM

Prompt gamma-ray in-beam spectrometry

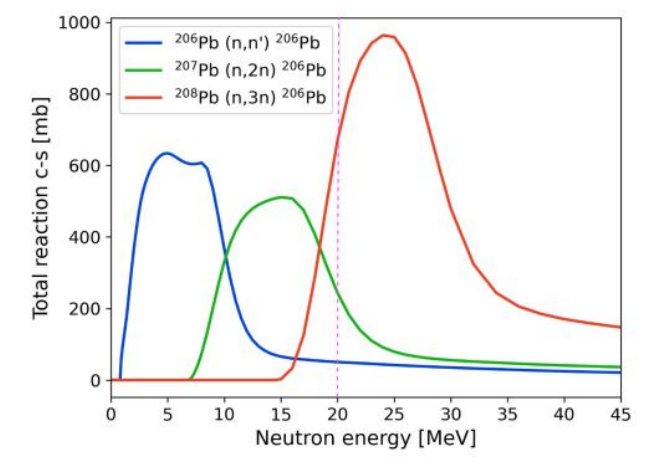
12*4 detectors at radius of 14.5 cm
31% of the solid angle
6% abs. efficiency at 1332 keV
Addback to improve P/T ratio

Neutron are damaging to HPGe detectors (expensive semiconductor devices)

How feasible it is to perform such experiments with EXOGAM at NFS?
Damage study and quantification performed.

EXOGAM@NFS campaign continues…
Second experiment in July (J. Wilson)
Another at the end of the year (C. Paxman)

Results with the Pb data

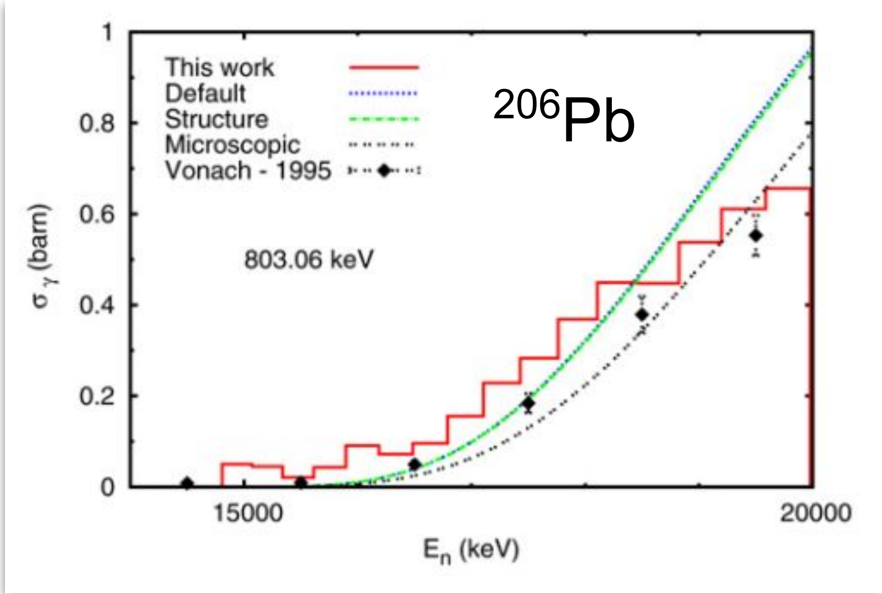


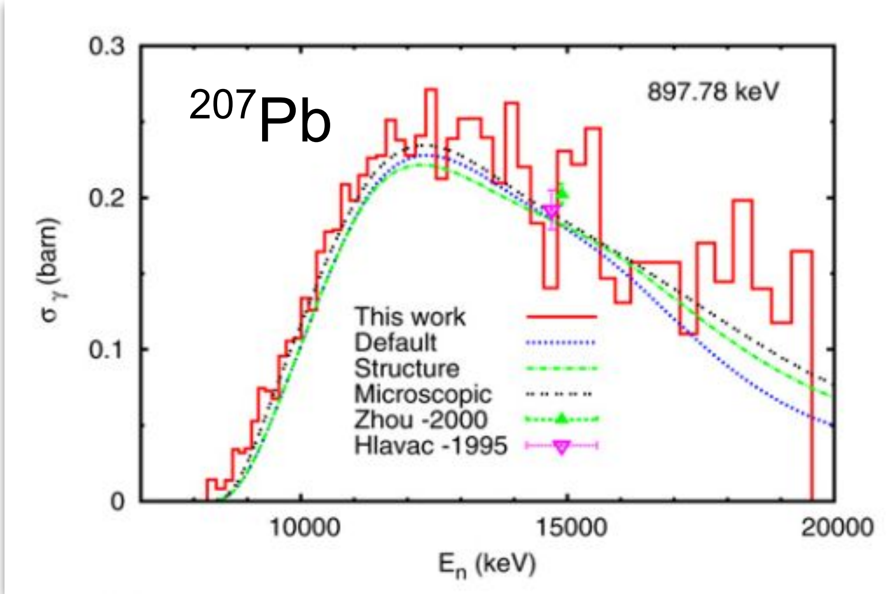
^{Nat}Pb target (60% ^{208}Pb, 20% ^{207}Pb, 20% ^{206}Pb)

$$^{206}\mathrm{Pb}(n,n')^{206}\mathrm{Pb} \qquad ^{207}\mathrm{Pb}(n,2n)^{206}\mathrm{Pb} \qquad ^{208}\mathrm{Pb}(n,3n)^{206}\mathrm{Pb}$$

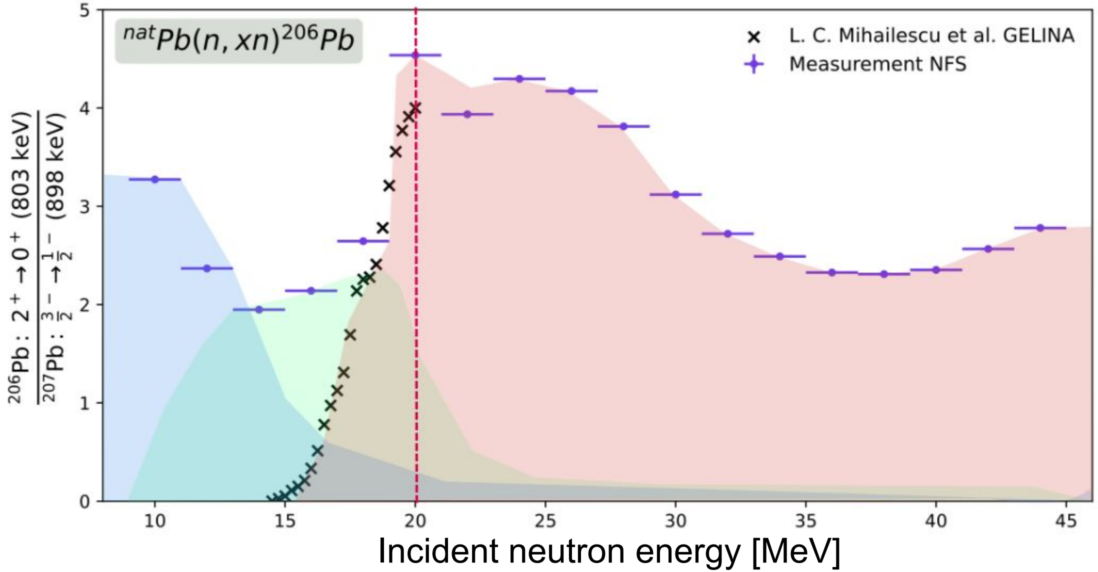
- ➢ Multi-isotopic natural target
- ➢ Different channels, same isotope.

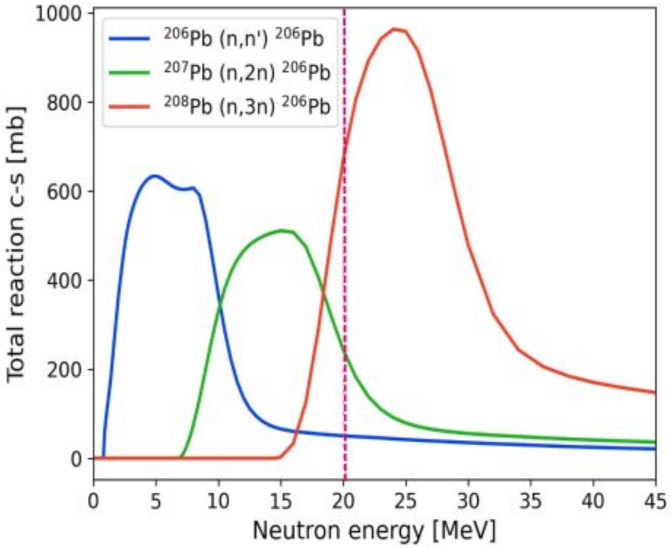
L.C. Mihailescu et al. / Nuclear Physics A 811 (2008)





Earlier measurements exist with an enriched ^{208}Pb target (GELINA) until 20 MeV.





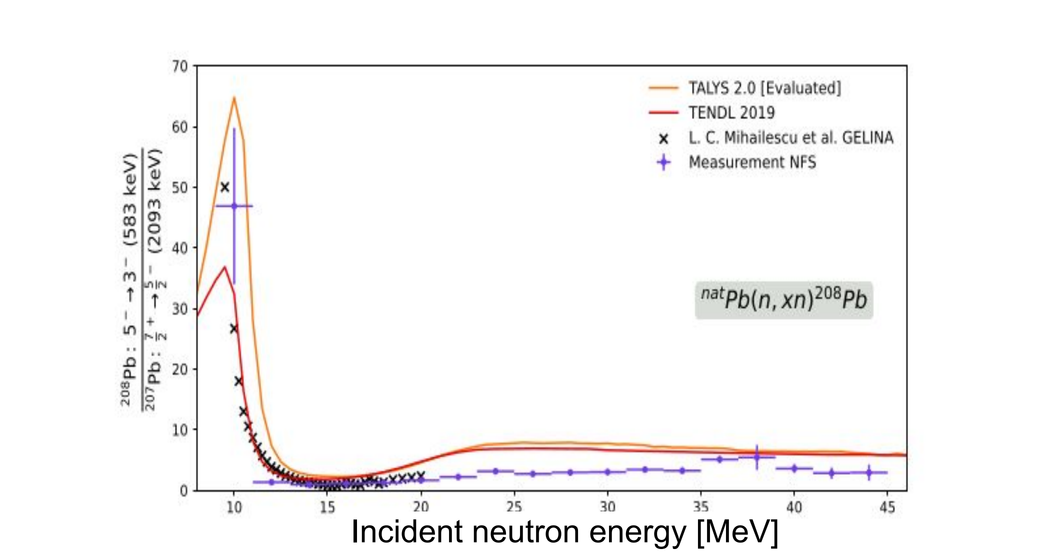
Earlier measurements exist with an enriched ^{208}Pb target (GELINA) until 20 MeV.

Comparison with that highlights the contamination from the (n,2n) and (n,n′) channel

With NFS we can extend these measurements upto 44 MeVs

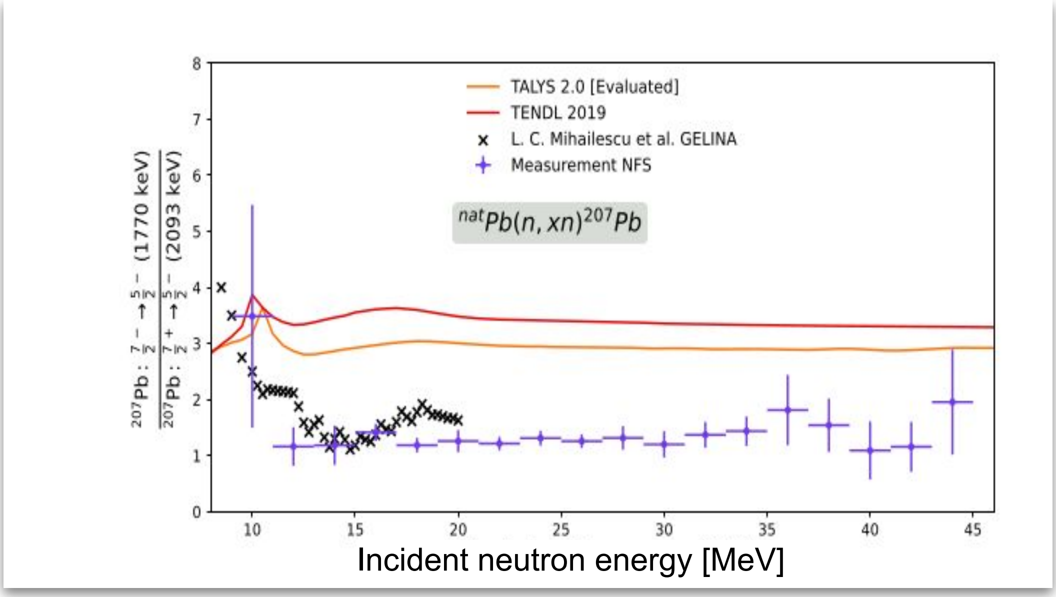
Anatomy of gamma cross-section

$^{208}Pb(n, n')^{208}Pb$



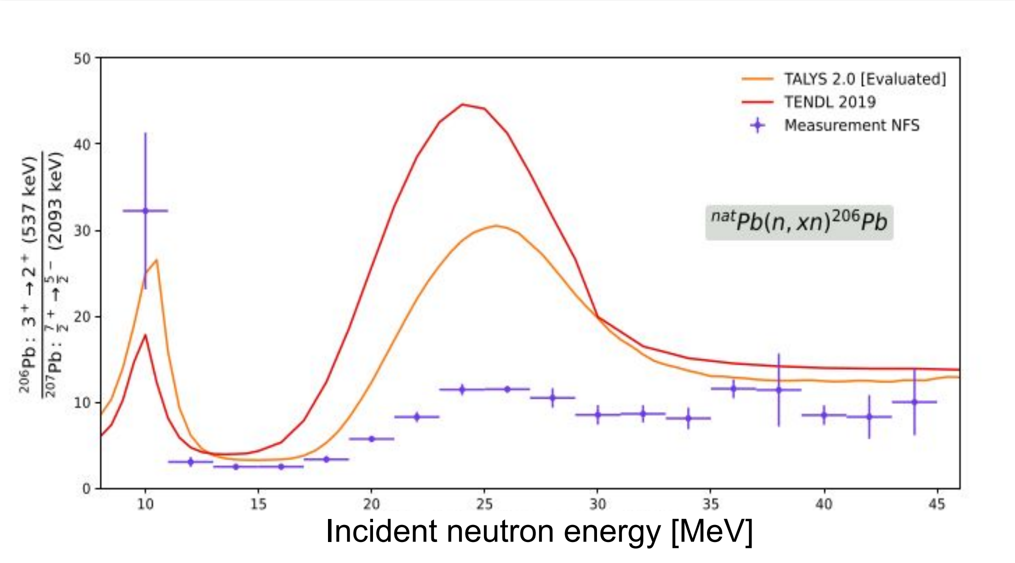
- ➢ Measured cross-section matches previous data below 20 MeV
- ➢ Extended measurement beyond previous limit, up to 44 MeV
- ➢ TENDL (red) and TALYS (orange) predictions for the same gamma line overlaid
- ➢ Both models agree well with the measured data
- ➢ Demonstrates model reliability specifically for the (n,n') channel

$^{208}Pb(n, 2n)^{207}Pb$



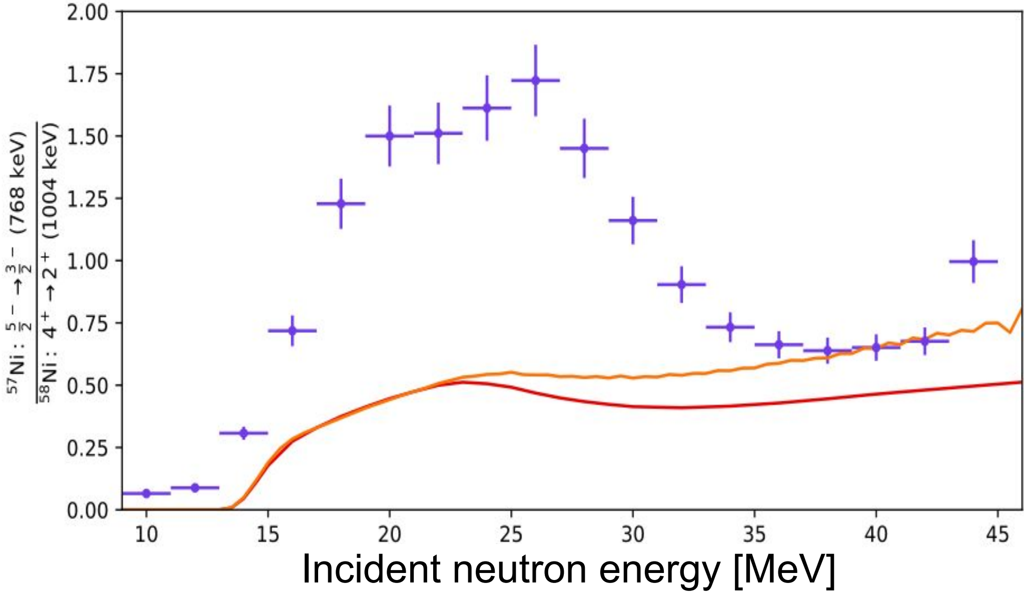
- ^{207}Pb produced via two channels: (n,n') on ^{207}Pb itself, and (n,2n) on ^{208}Pb
- Good agreement with previous (GELINA) data in the overlapping energy range
- New measurement extends the dataset to higher energy
- Beyond this, TALYS/TENDL predictions start to diverge from the measured cross-sections

$^{208}Pb(n, 3n)^{206}Pb$

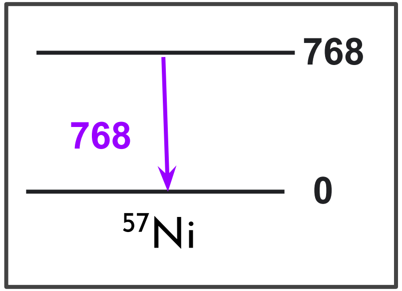


- ^{206}Pb: measured cross-sections for gamma lines not previously explored
- These correspond mainly to the (n,3n) channel
- Discrepancies with model predictions are even larger here than for 207Pb
- Better tuning is needed at higher energies

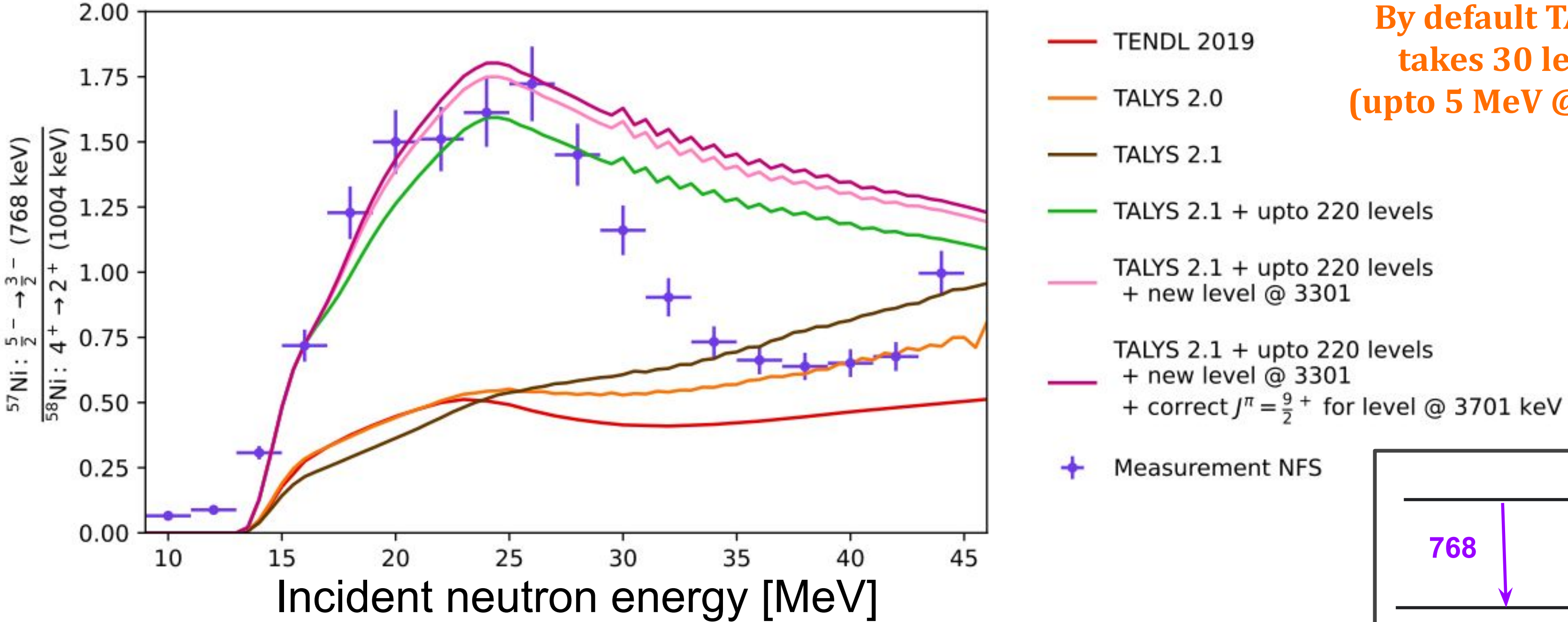
Another interesting observation from Ni data…



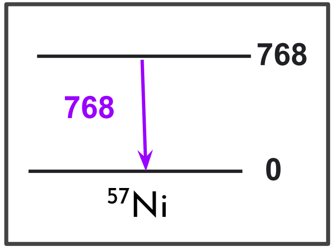
$^{58}Ni(n, 2n)^{57}Ni$



- Measured cross-section (cs) for $5/2^{-} \rightarrow 3/2^{-}$ in ^{57}Ni.
- The measured cs is larger that the TENDL evaluation.



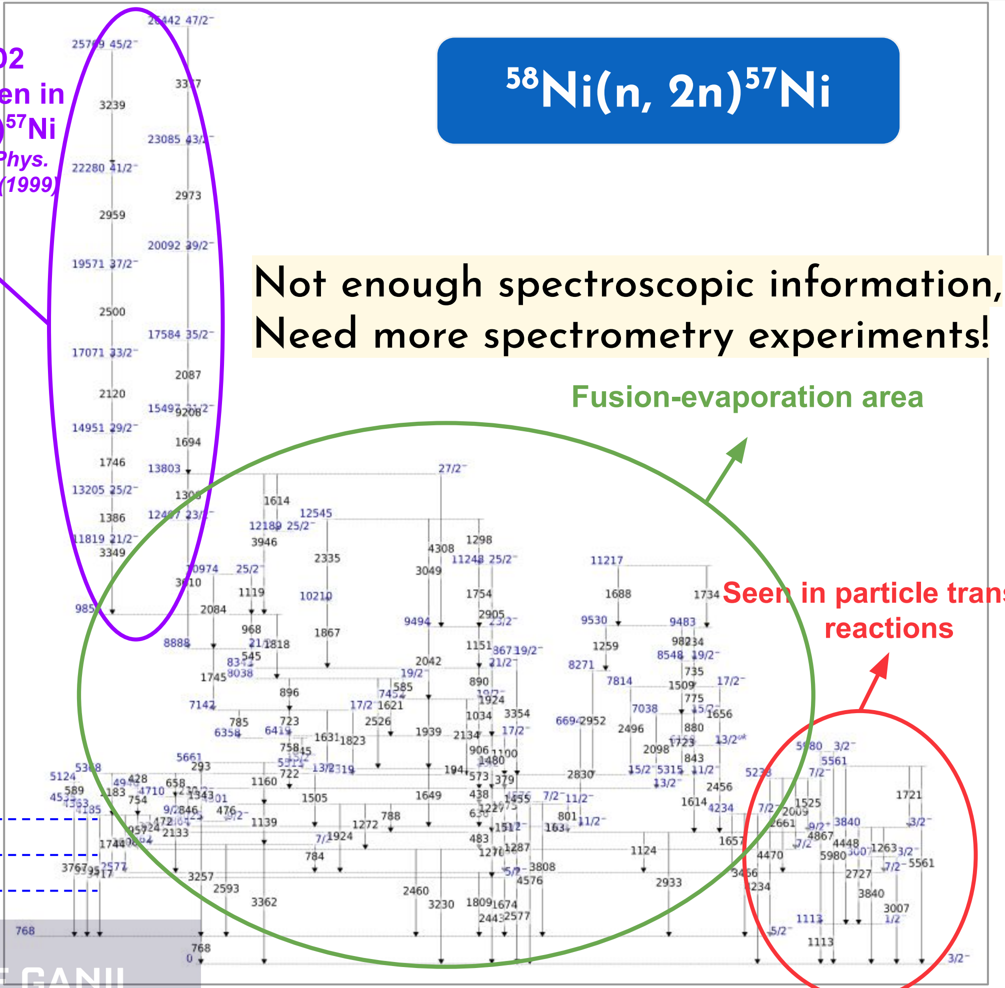
By default TALYS takes 30 level (upto 5 MeV @ ^{57}Ni)



➢ Better agreement until 25 MeV when including higher levels not used by default TALYS and TENDL libraries, still not the best at higher energies

$^{58}Ni(n, 2n)^{57}Ni$

SD1 and SD2 bands only seen in $^{28}Si(^{32}S, 2p1n)^{57}Ni$
D. Rudolph et al, Phys. Rev. Lett. 82, 3763 (1999)



4216
4183
3301

Not enough spectroscopic information,
Need more spectrometry experiments!

Fusion-evaporation area

Seen in particle transfer reactions

- ➢ We are not seeing states seen exclusively in particle transfer reactions
- ➢ Overall (n,2n) seems to be quite like the heavy ion fusion evaporation
- ➢ Alignment seen for the first time after angular studies.
- ➢ BUT… it is not a subset, we have new states from (n,2n) for this very well characterized nuclei.

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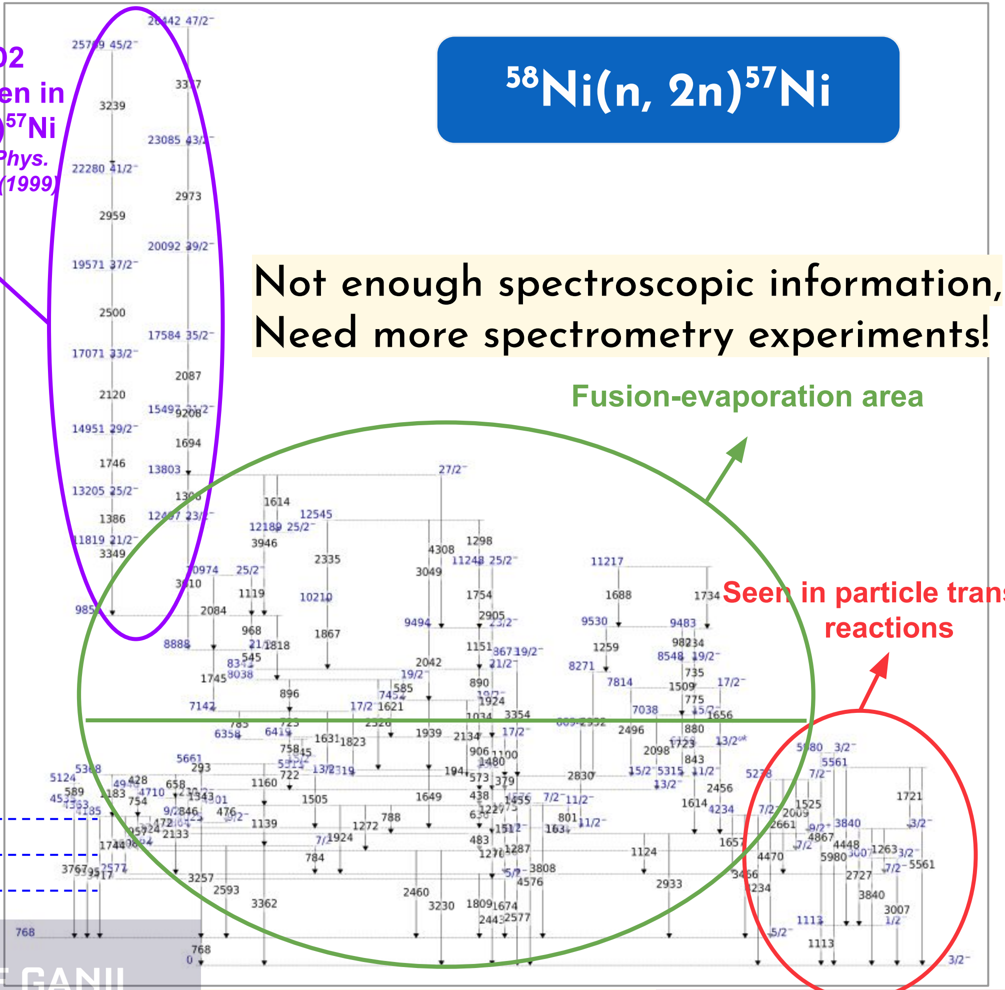

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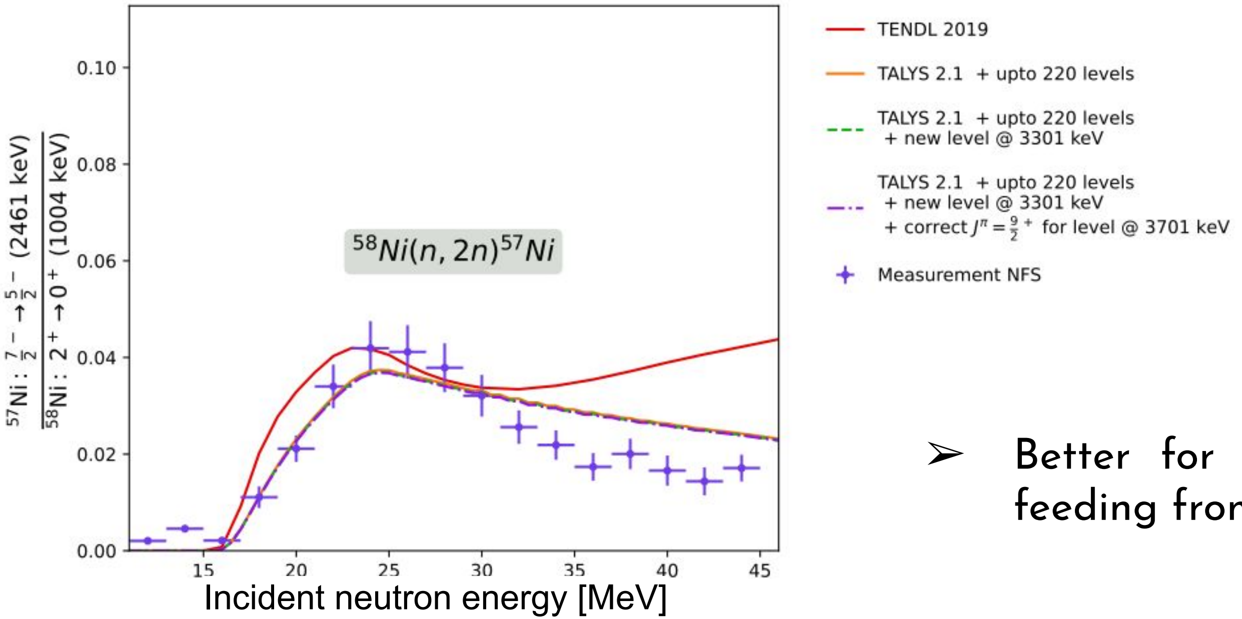
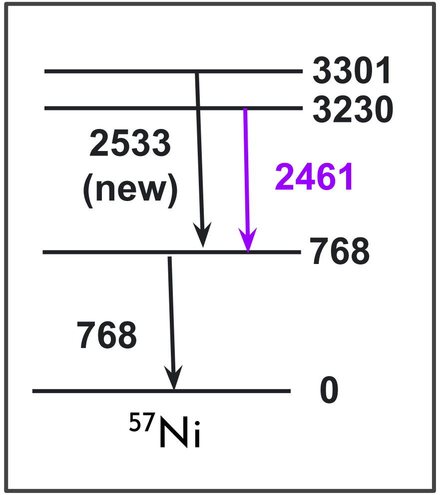




➢ Better for gammas without significant feeding from new and higher levels

➢ More accurate spectroscopy on the decay of these states is needed, branching ratios could explain this... better modelling could help as well.

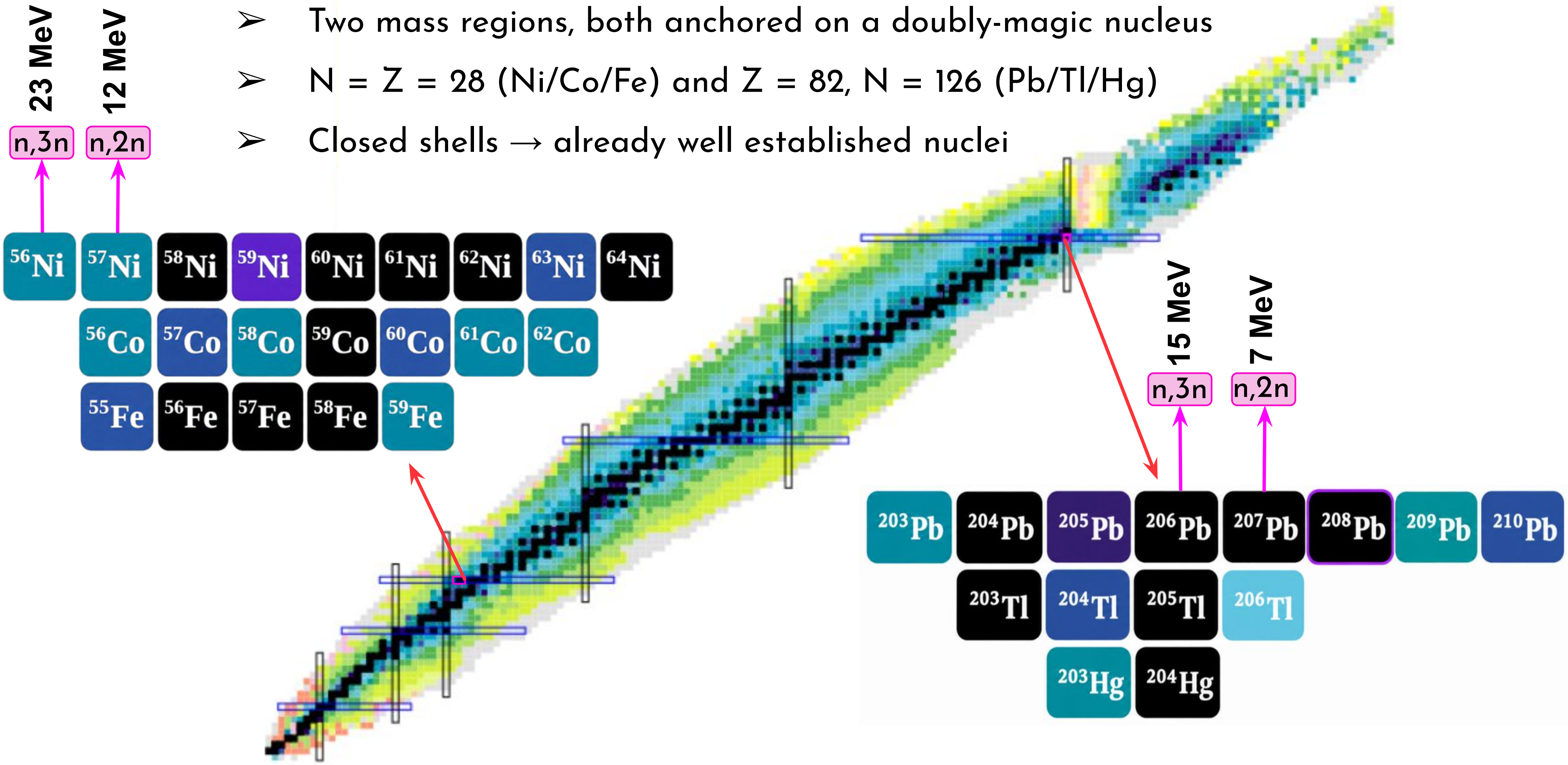
Summary

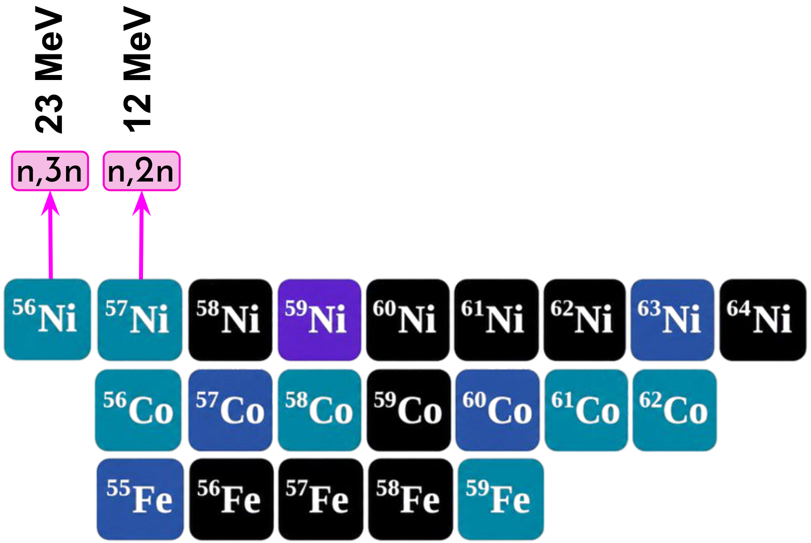
- EXOGAM at NFS validated for gamma cross-section measurements, extending Pb/Ni data to 44 MeV (vs 20 MeV prior GELINA measurements) providing first benchmarks at high energies.
- TALYS seems to agree well for simple (n,n') but diverge more with complex multi-nucleon emission channels
- Detailed gamma cross-section (Pb/Ni/Co) decomposition for TALYS validation
- New intruder multiple structure seen for ^{57}Ni in the (n, 2n) reaction
- Cross-sections predictions and nuclear structure physics go hand in hand.

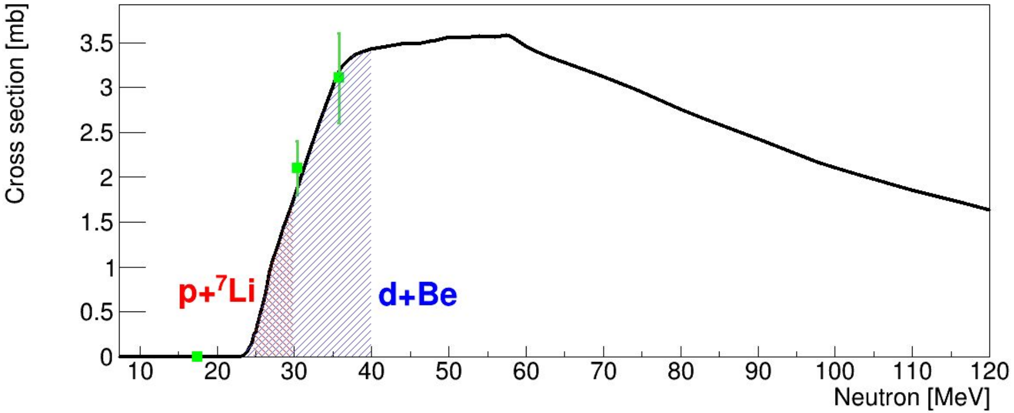
Thanks!

Back-up

- Two mass regions, both anchored on a doubly-magic nucleus
- N = Z = 28 (Ni/Co/Fe) and Z = 82, N = 126 (Pb/Tl/Hg)
- Closed shells → already well established nuclei





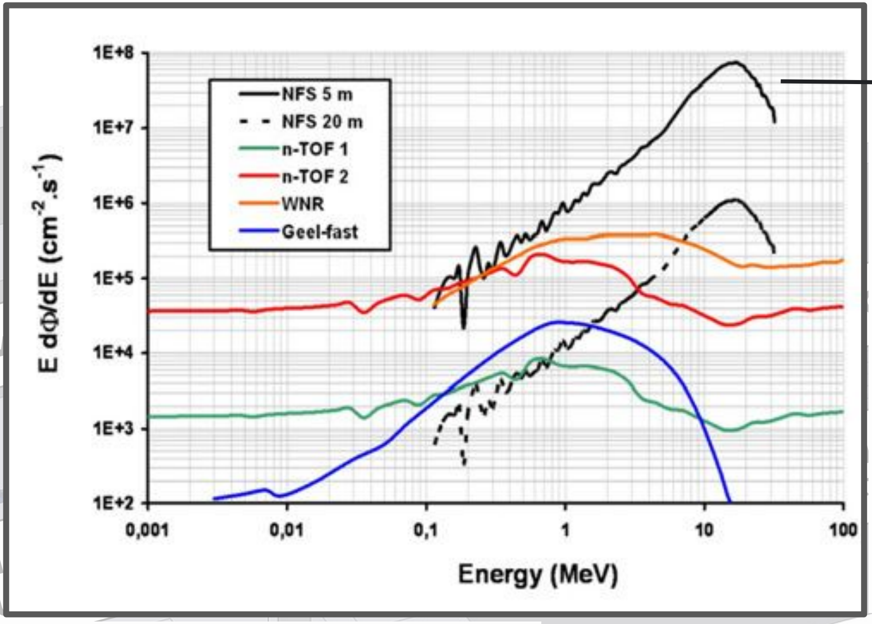


Scarce existing data for (n,3n) cross-section.

Why NxN is so difficult?

NxN reactions: high energy thresholds, low c-s
⇒ need large flux at high neutron energies.

Highest neutron flux beyond 10 MeV world-wide!



NFS (0-40 MeV)

Los Alamos, USA

n_TOF (CERN, EAR1), Switzerland

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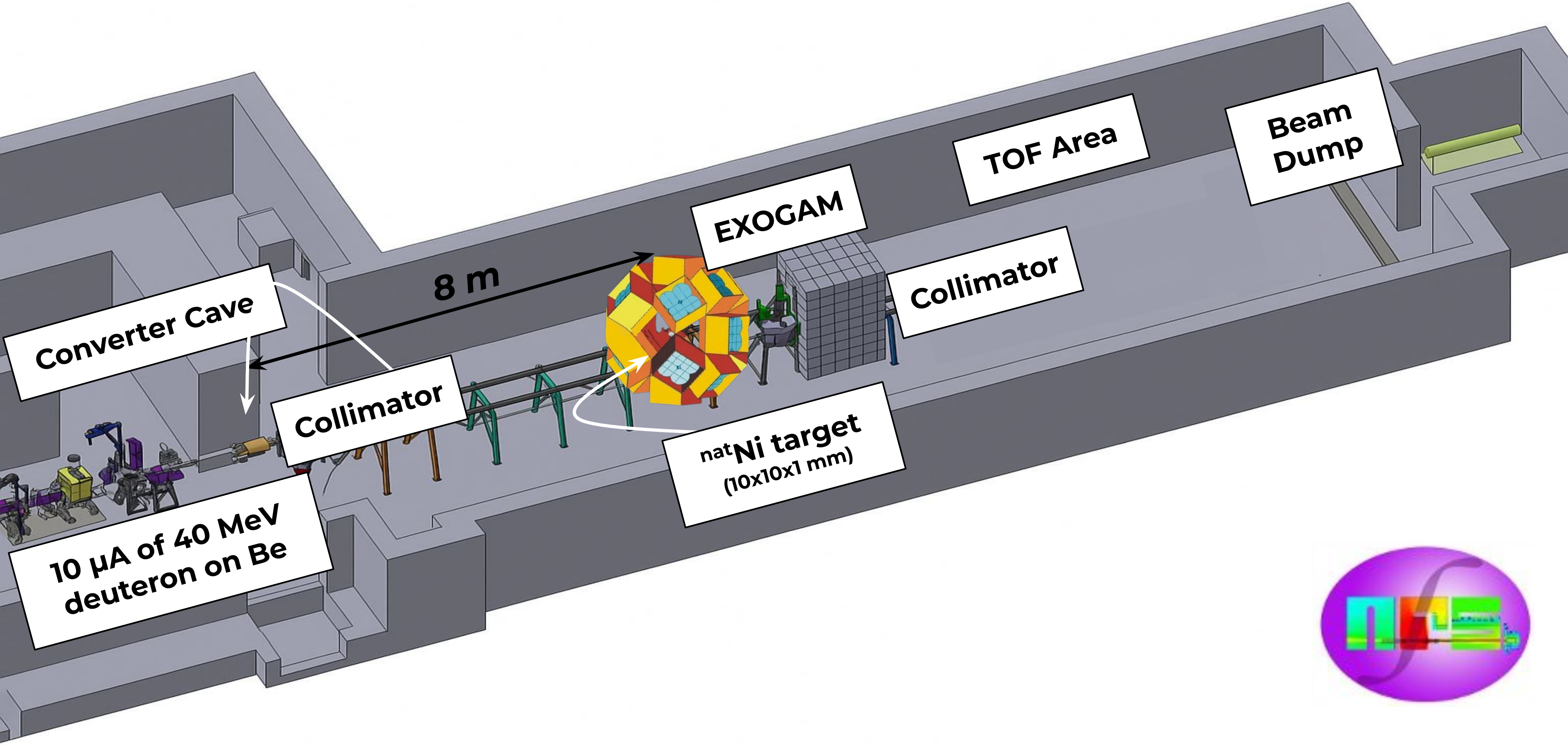
GELINA (Belgium)

Courtesy: Xavier LEDOUX

Plus: Low gamma-flash background at NFS


Converter Cave
8 m
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TOF Area
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Collimator
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natNi target
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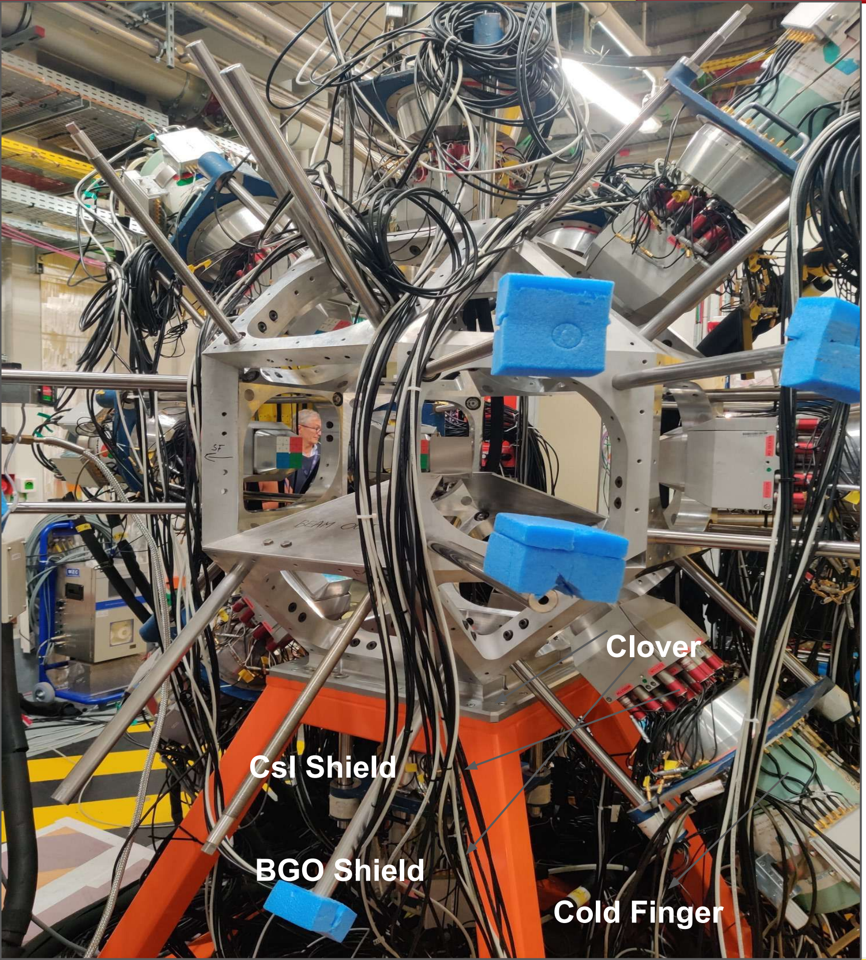
10 µA of 40 MeV deuteron on Be



High Resolution Measurement: EXOGAM

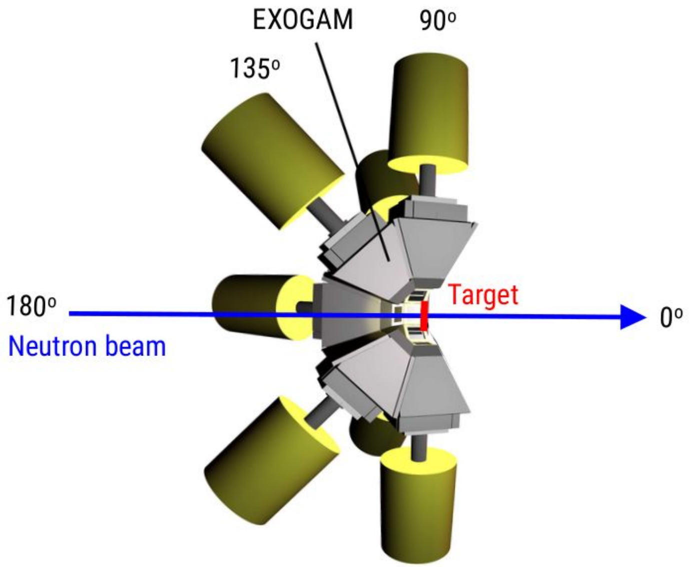
Prompt gamma-ray in-beam spectrometry

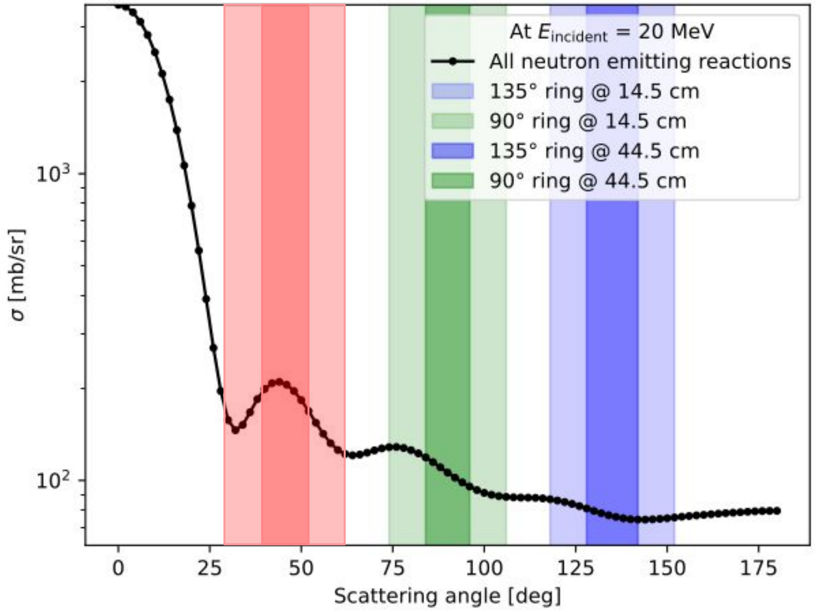
12*4 detectors at radius of 14.5 cm
31% of the solid angle
6% abs. efficiency at 1332 keV
Addback to improve P/T ratio

Neutron are damaging to HPGe detectors (expensive semiconductor devices)

How feasible it is to perform such experiments with EXOGAM at NFS?

➢ Only 12 out of 16 available clovers used to avoid the large forward secondary neutron flux (red)



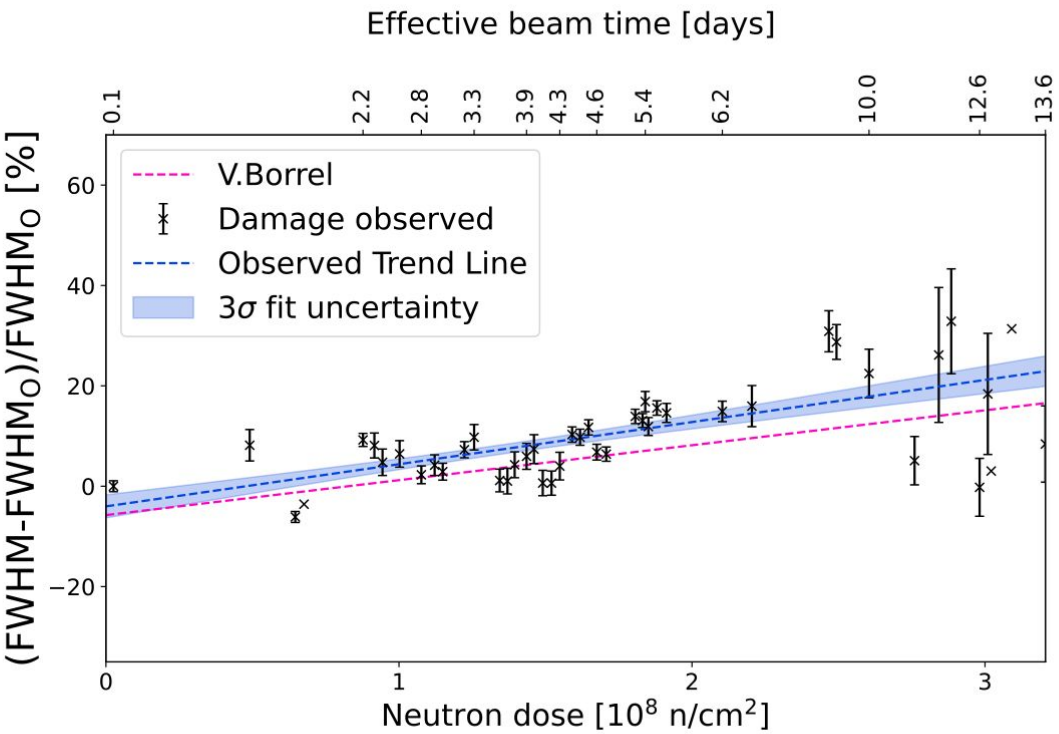


➢ Two different detector configurations are indicated (dark and light shaded area), corresponding to detector radii of 14.5 cm and 44.5 cm from the target.

Full in-situ dosimetry simulation performed using double differential cross-sections from TALYS, accounting for changes in experimental conditions.

Using a reference gammas from ^{58}Ni and ^{207}Pb quantitative damage study is performed.

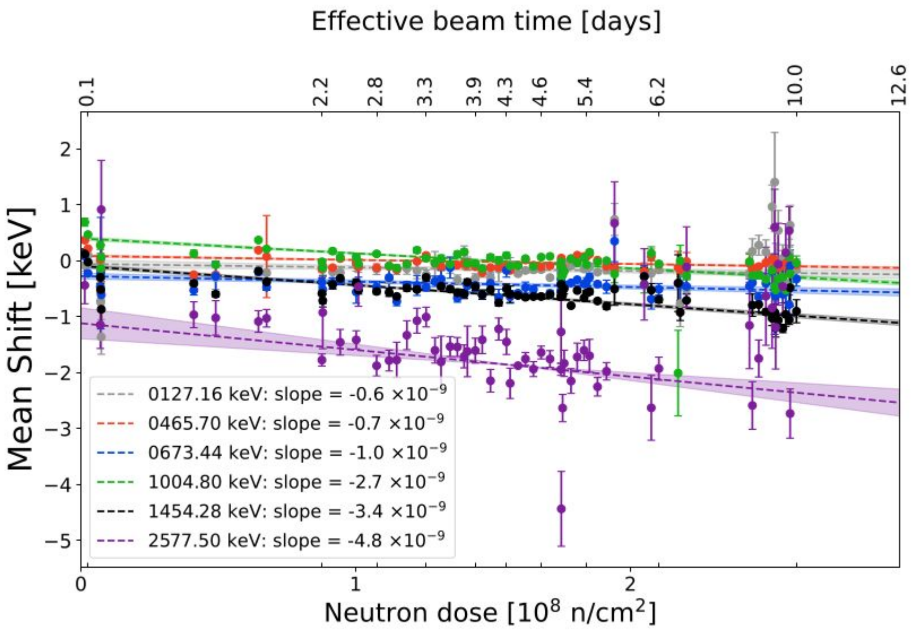
The measured degradation rate is in good agreement with previous systematic study by V.Borrel et al. (extrapolation based on 2 points and single-crystal, closed-end coaxial n-type detector)

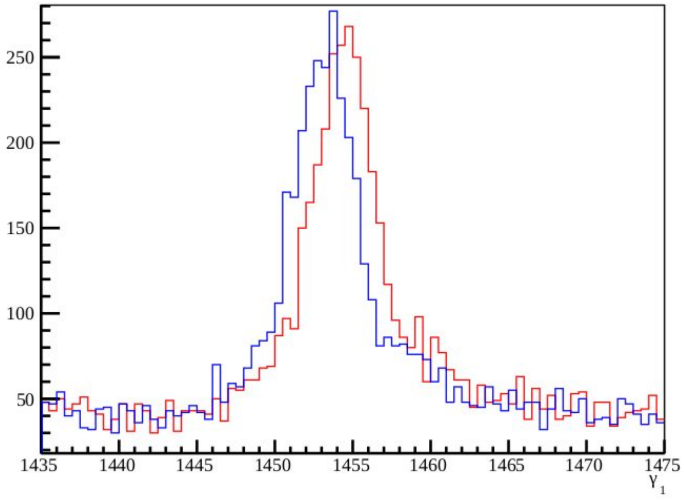


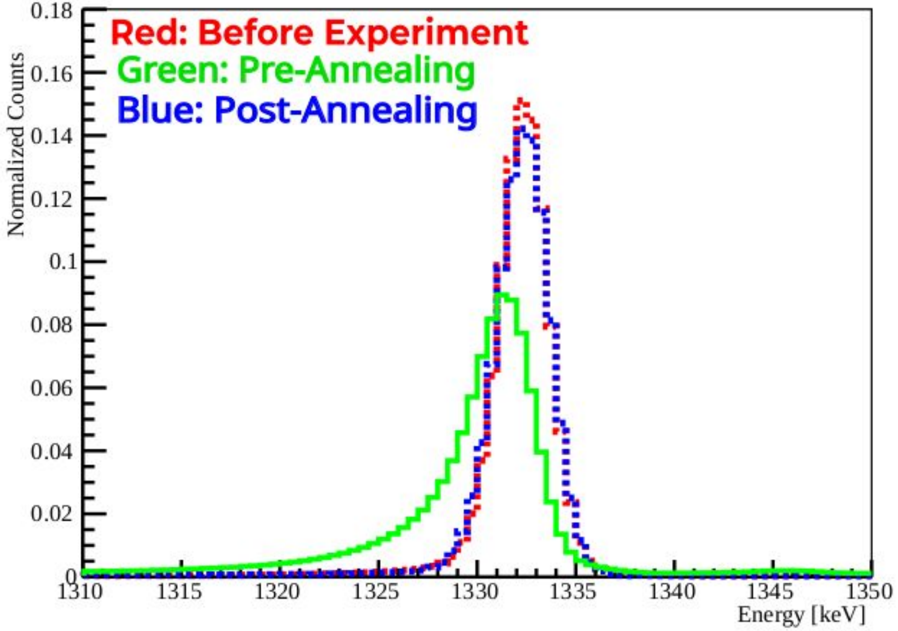
First neutron-damage characterization of a segmented clover type detector.

To be published...

- Similarly mean-shift was studied and corrected later run by run







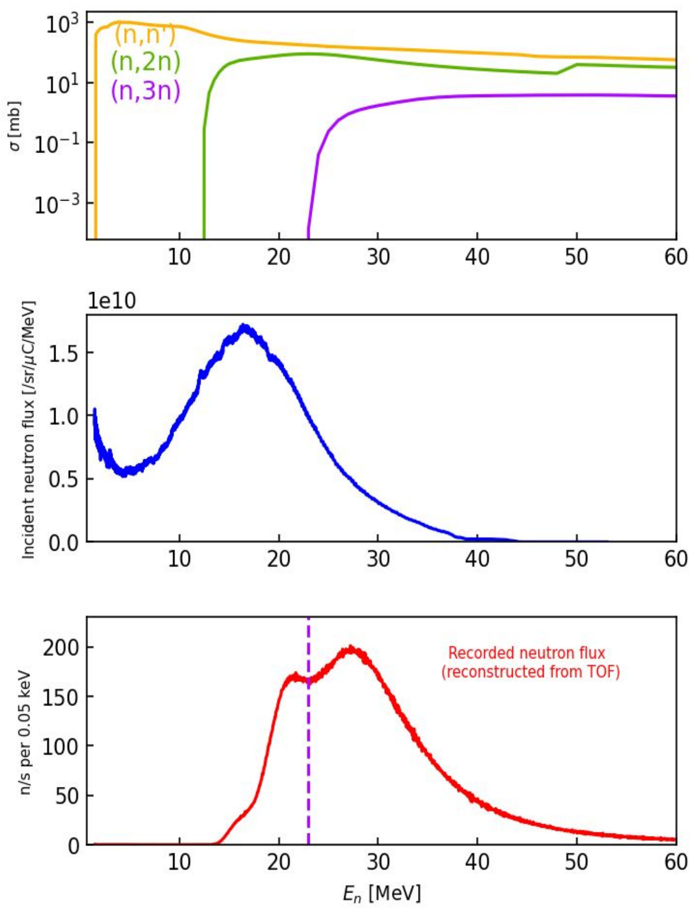
- ➢ Annealing was performed and was shown to recover the performance

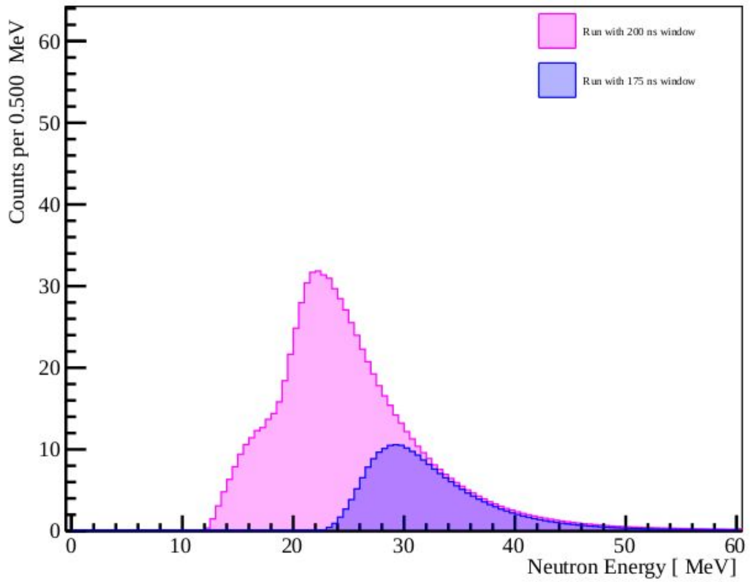
Can you run a modern Compton-suppressed clover array (like EXOGAM) for nuclear structure spectroscopy inside an intense white fast-neutron beam at a facility like NFS, and recover it by annealing ?

EXOGAM@NFS campaign continues…

Second experiment in July (J. Wilson)

Another at the end of the year (C. Paxman)



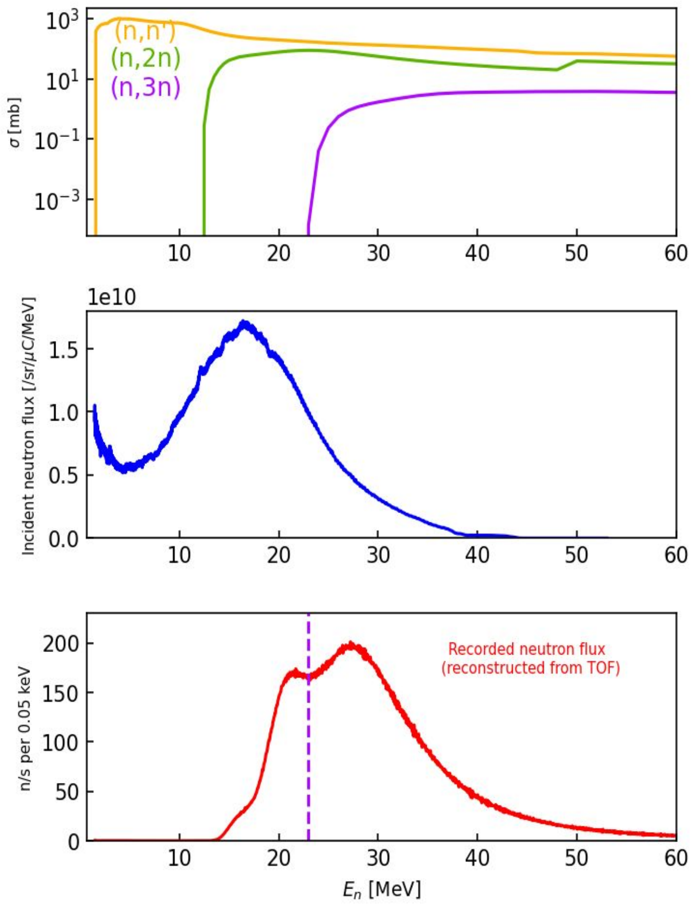


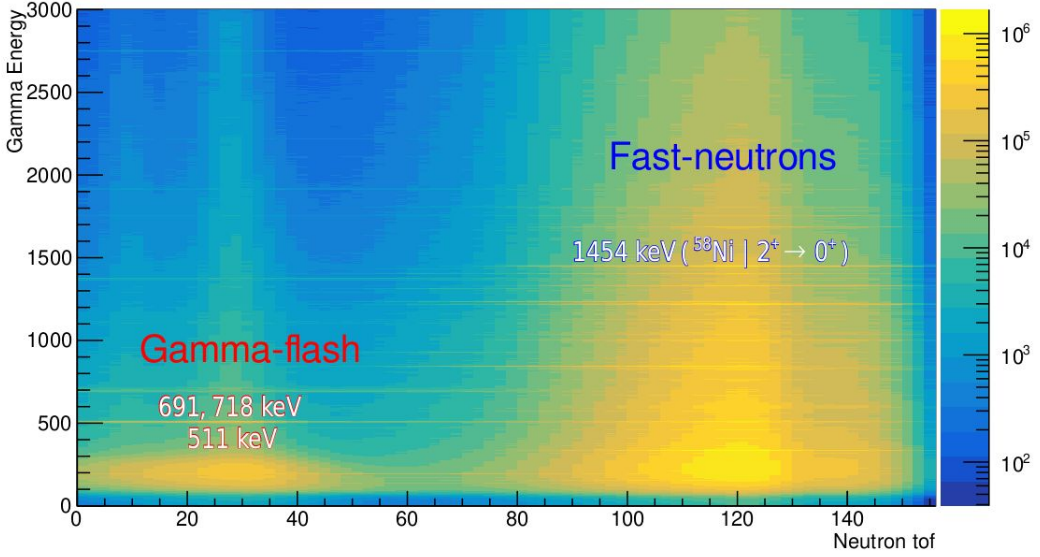
DAQ challenge: Data stored with a cut on neutron energy (10 - 40 MeV)

Distinguish the γ-flash region and the gammas coming from the interaction of neutrons on the Ni target.

Event by event neutron tof measurement.

TOF MEASUREMENT





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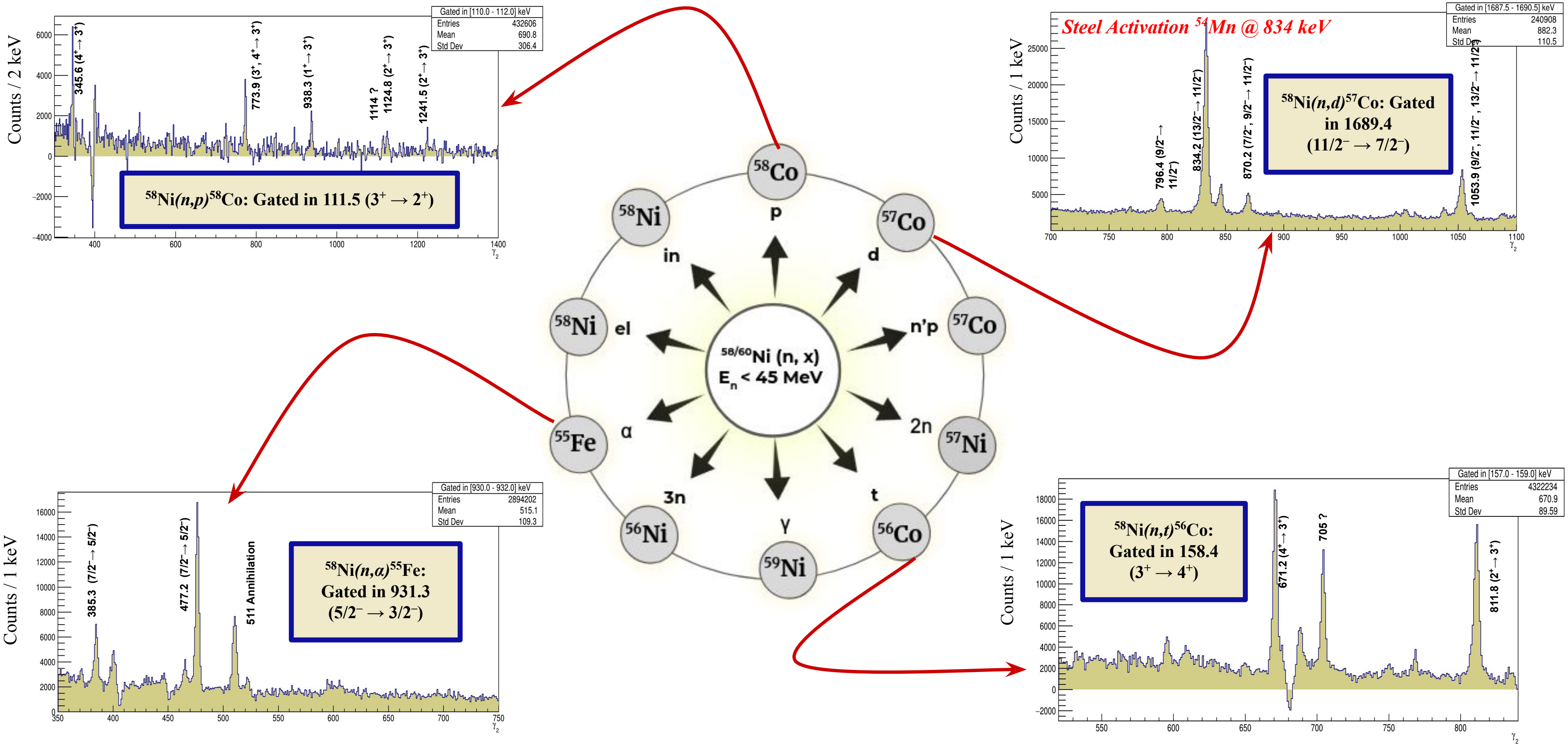
Distinguish the γ-flash region and the gammas coming from the interaction of neutrons on the Ni target.

Event by event neutron tof measurement.

10^{10} γγ coincidences (within a time window of 100ns) recorded after addback



We are opening up many channels
No veto detectors
⇒ Many isotopes!
⇒ We populate extensively!
⇒ Many projected γ in each gate!
Odd mass nuclei: high density of states.

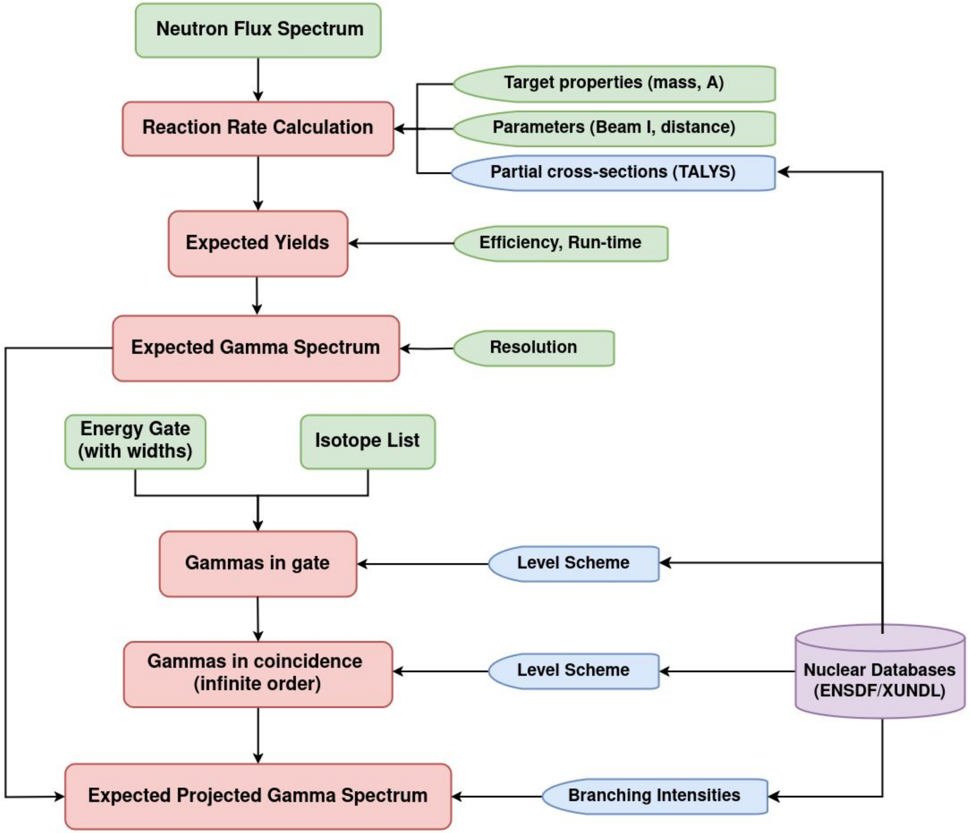
In total we could be producing 2500+ different transitions in our experiment!

Verifying them all is a huge task.
New gammas can only be identified after verifying.

GitHub

Hemantika1122 / GammaSPY Public

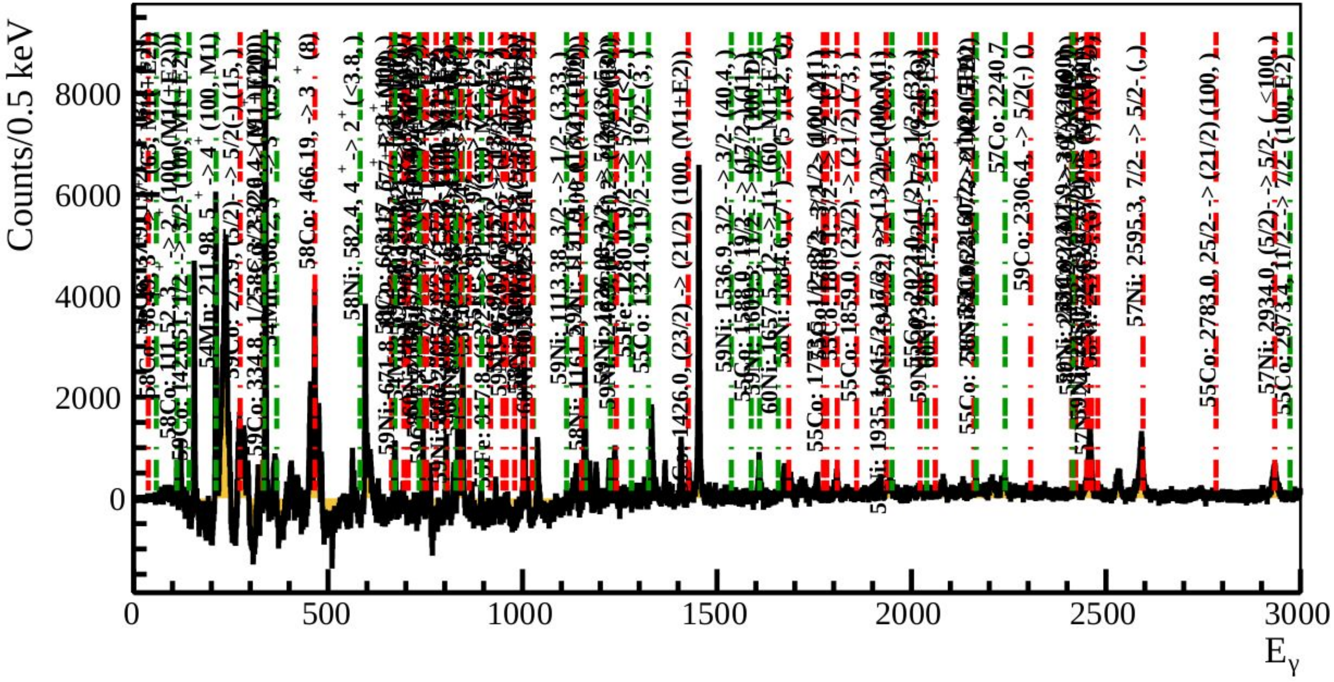
Software tool development: GammaSPY

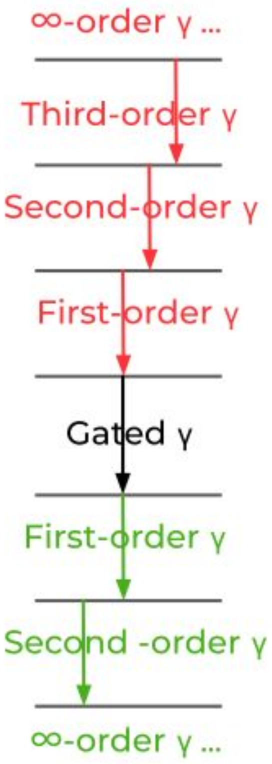


INPUTS

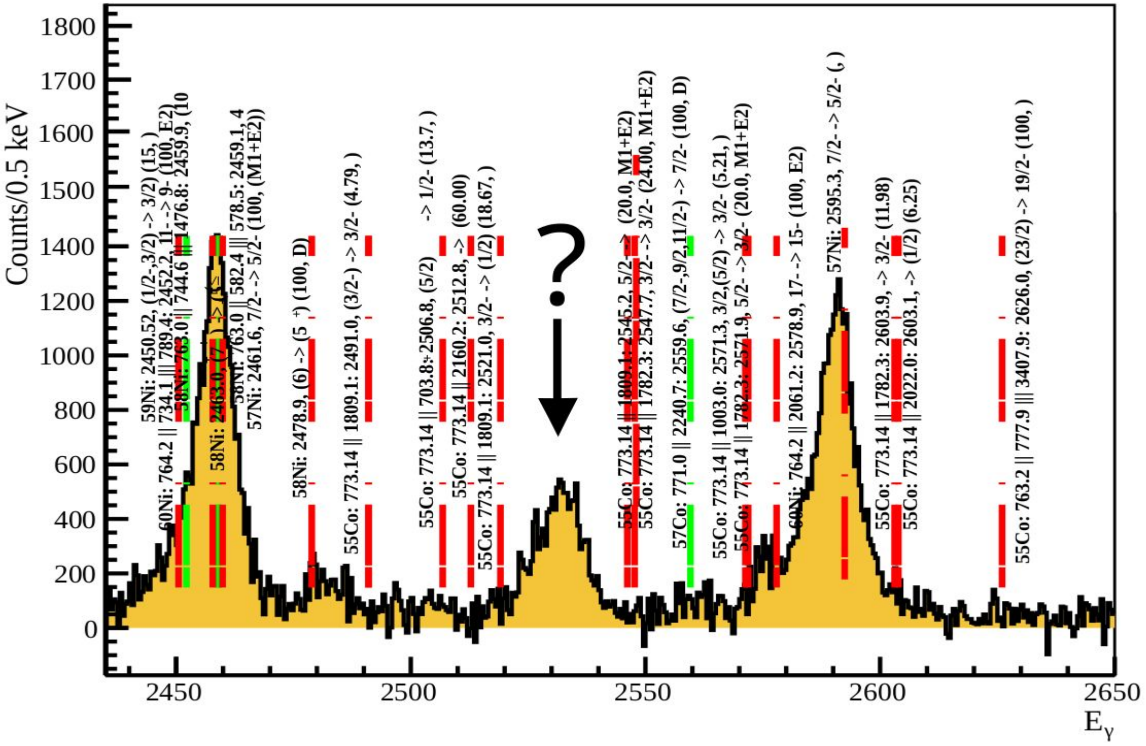
NuDat 3.0

OUTPUT



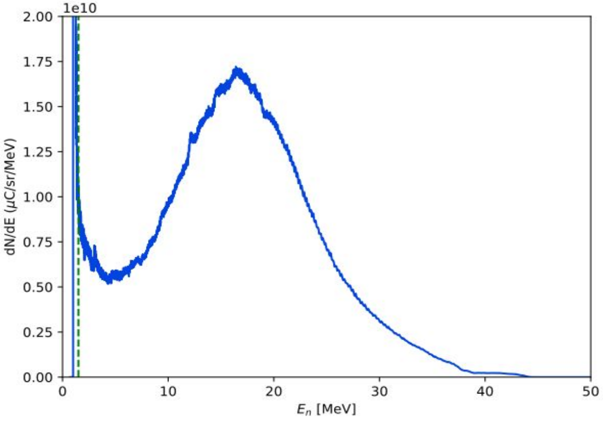


GammaSPY: OUTPUTS

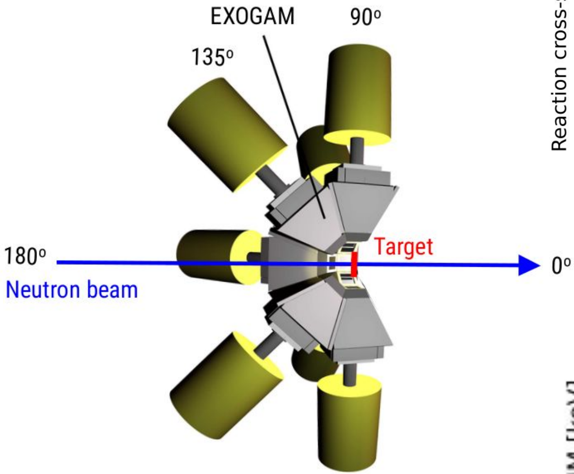


- ➢ Zoomed GammaSPY output, 2450–2650 keV region.
- ➢ Colored ticks = predicted transitions from known isotopes (60Ni, 58Ni, 57Ni, 55Co).
- ➢ Unmatched peak: no prediction from any populated isotope.
- ➢ Some ticks show no visible peak, limitation of this stage (no intensity info).

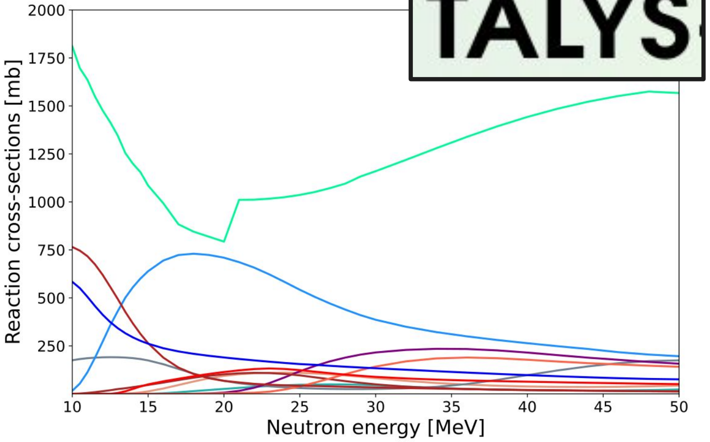
GammaSPY: INPUTS

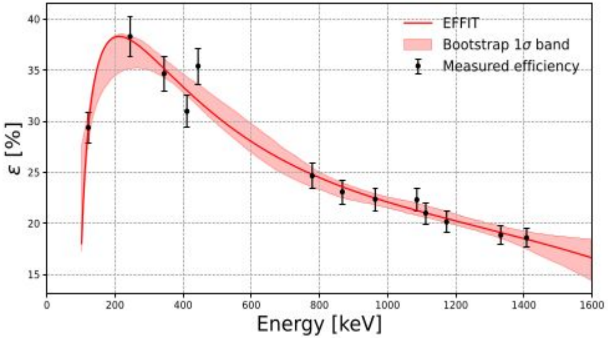


INPUTS

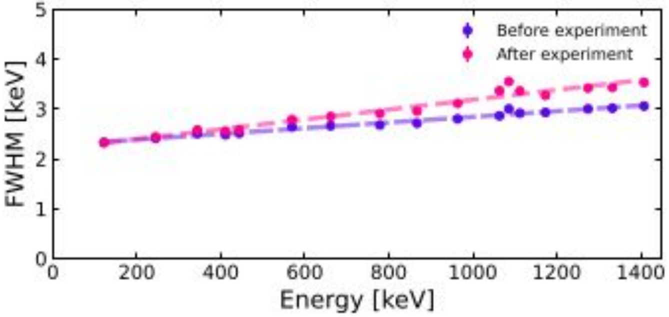


TALYS

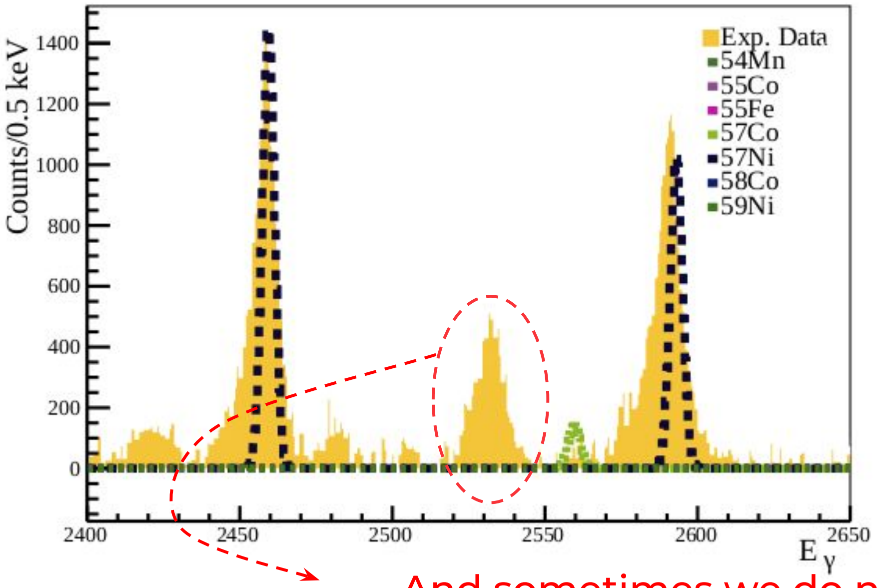


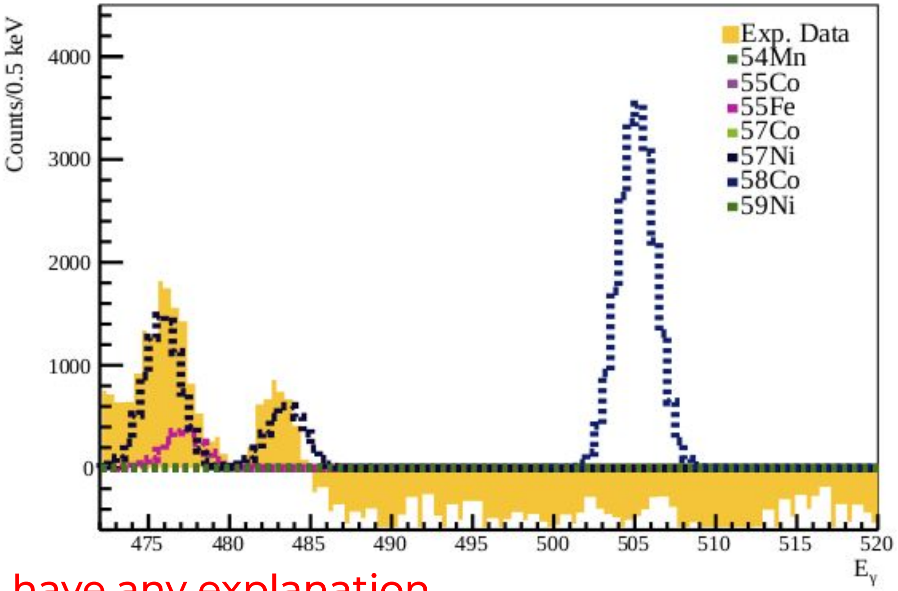


NuDat 3.0



OUTPUT



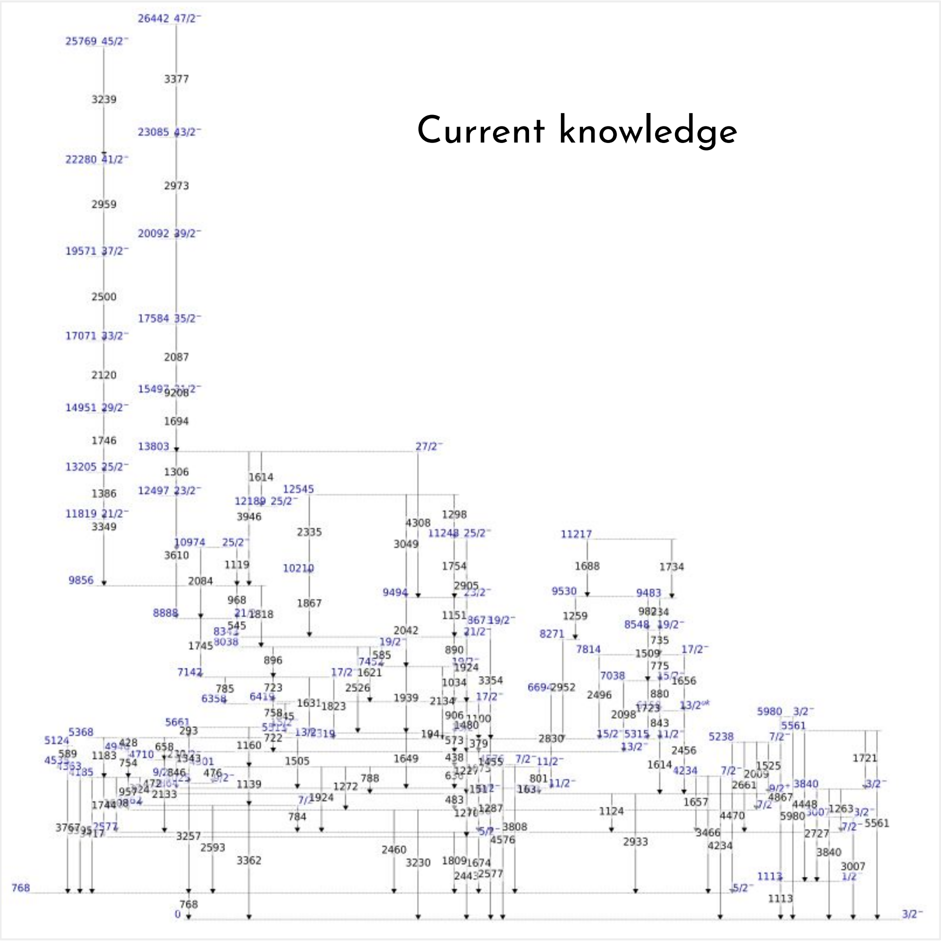


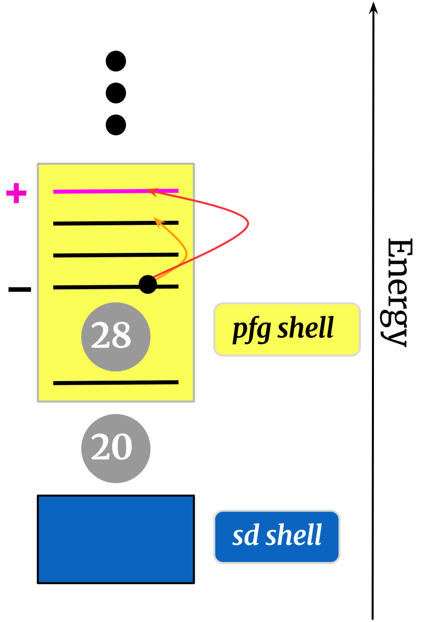
And sometimes we do not have any explanation

GammaSPY = Experimental Response + Nuclear Database + Cross-sections generator

$^{58}Ni(n,2n)^{57}Ni$

Current knowledge

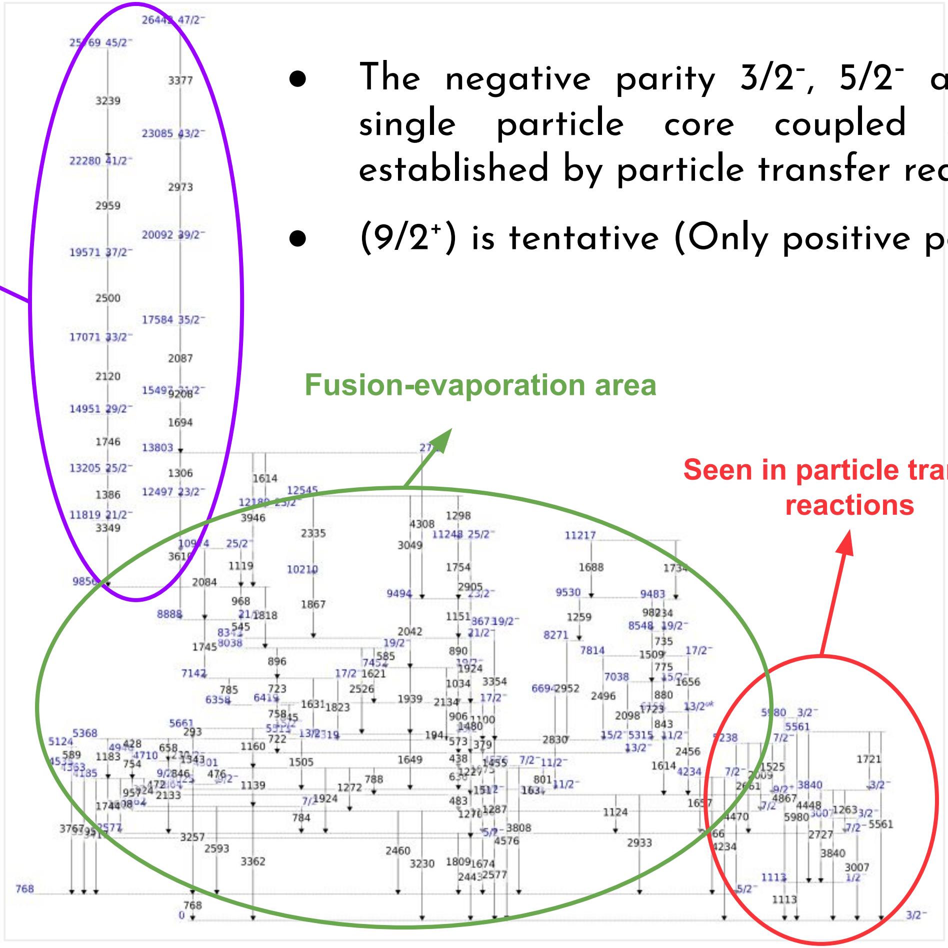




$^{58}Ni(n,2n)^{57}Ni$

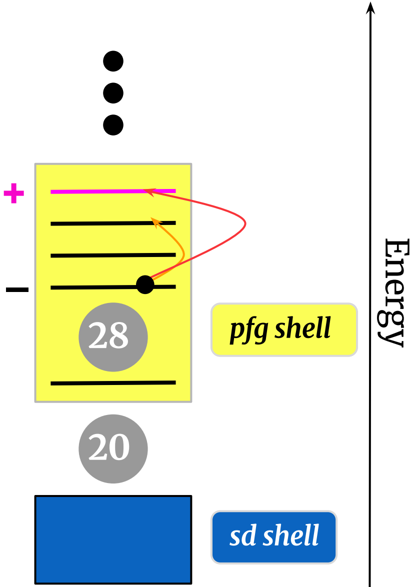
SD1 and SD2 bands only seen in $^{28}Si(^{32}S, 2p1n)^{57}Ni$
D. Rudolph et al, Phys. Rev. Lett. 82, 3763 (1999)

- The negative parity $3/2^-$, $5/2^-$ and $7/2^-$ neutron single particle core coupled states are well established by particle transfer reactions.
- $(9/2^+)$ is tentative (Only positive parity state)



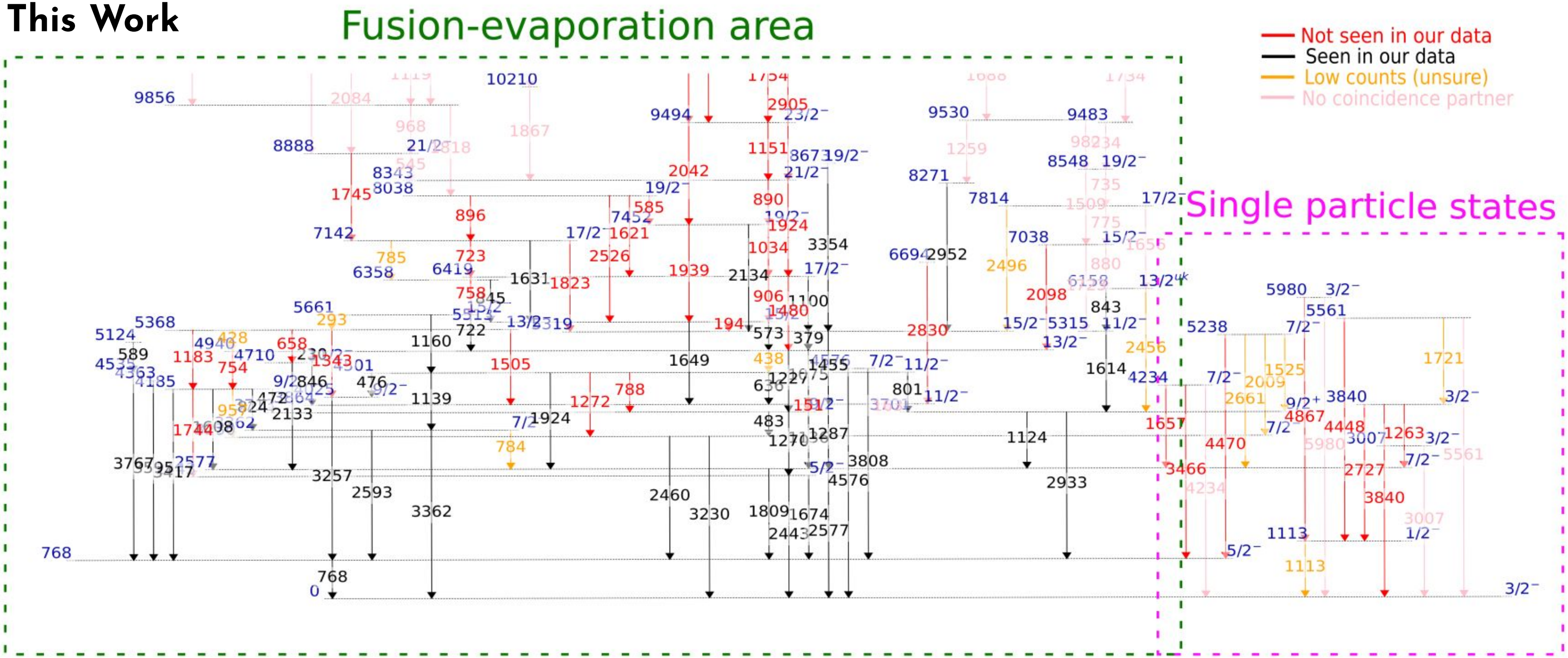
Fusion-evaporation area

Seen in particle transfer reactions



- We are not seeing states seen exclusively in particle transfer reactions
- Overall (n,2n) seems to be quite *like the heavy ion fusion evaporation*

This Work



- We are not seeing states seen exclusively in particle transfer reactions
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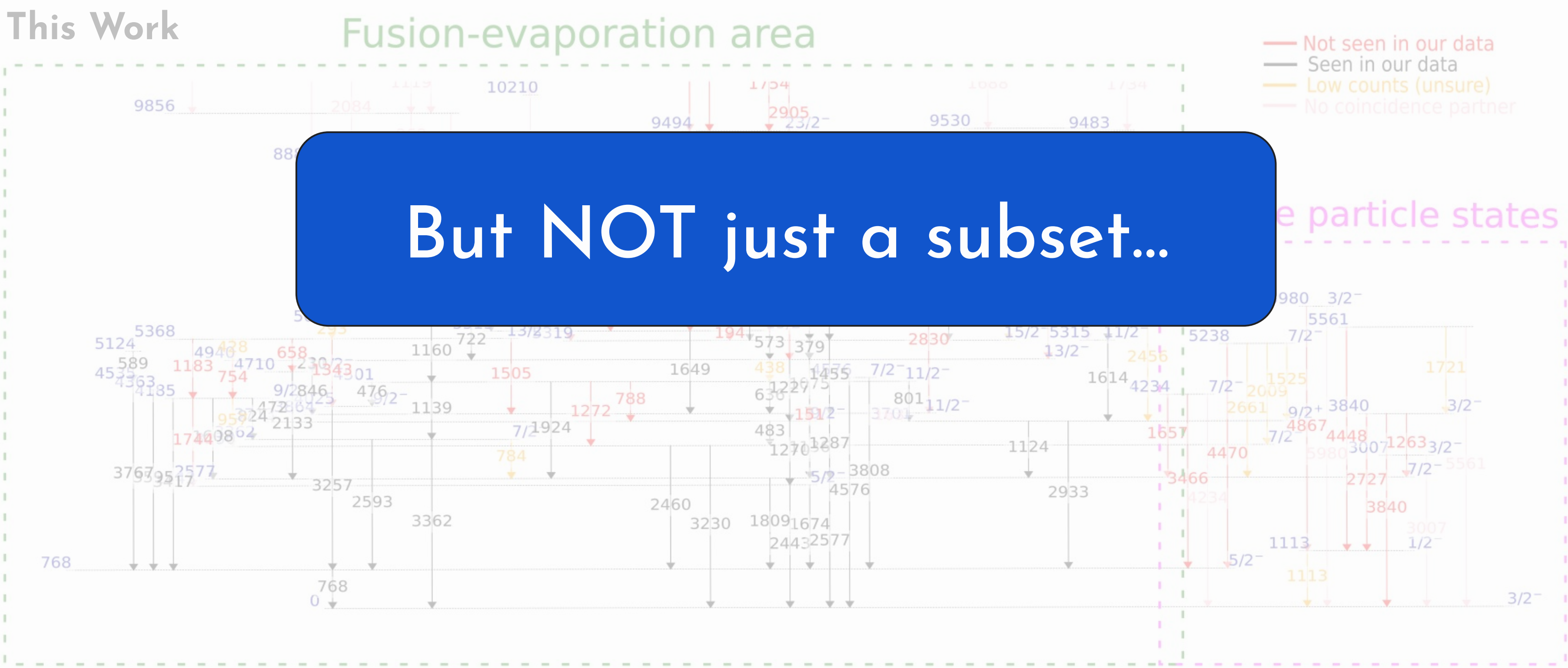
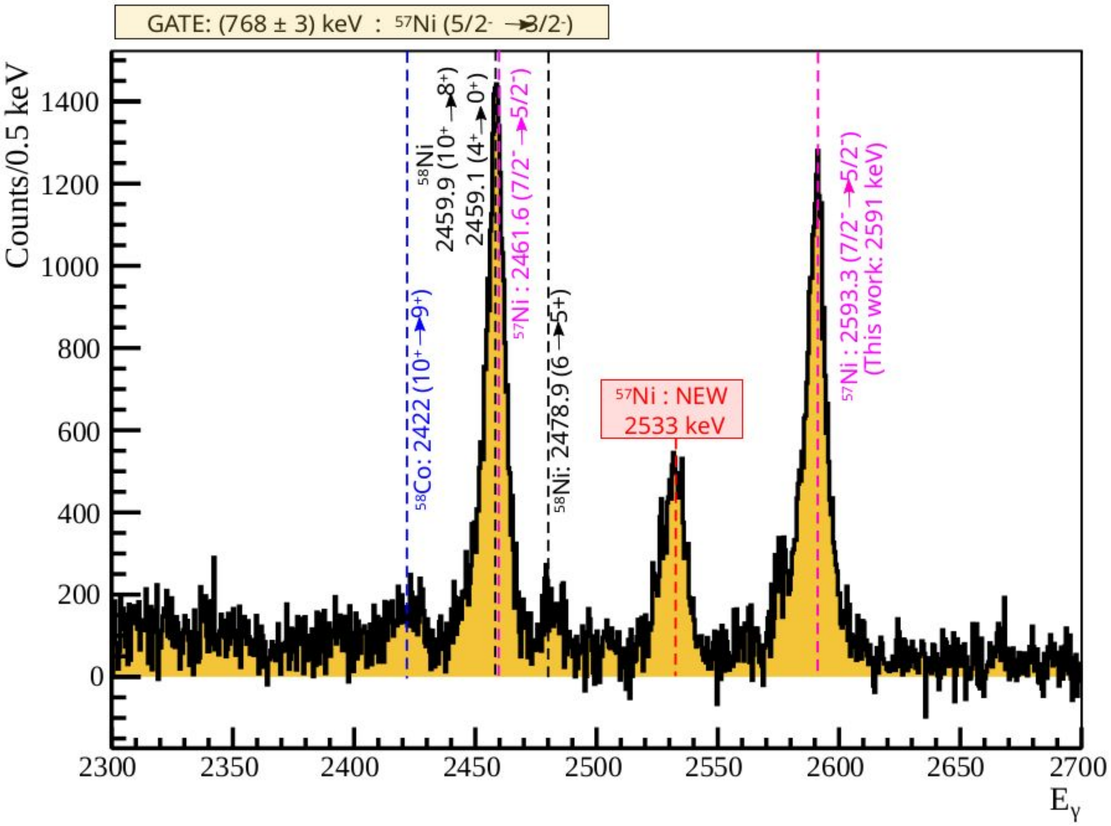
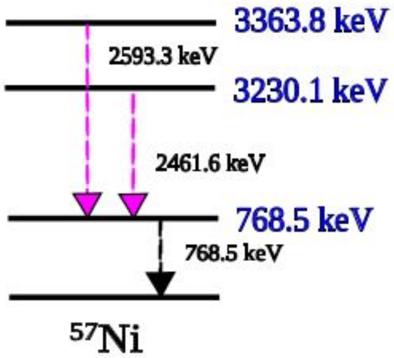


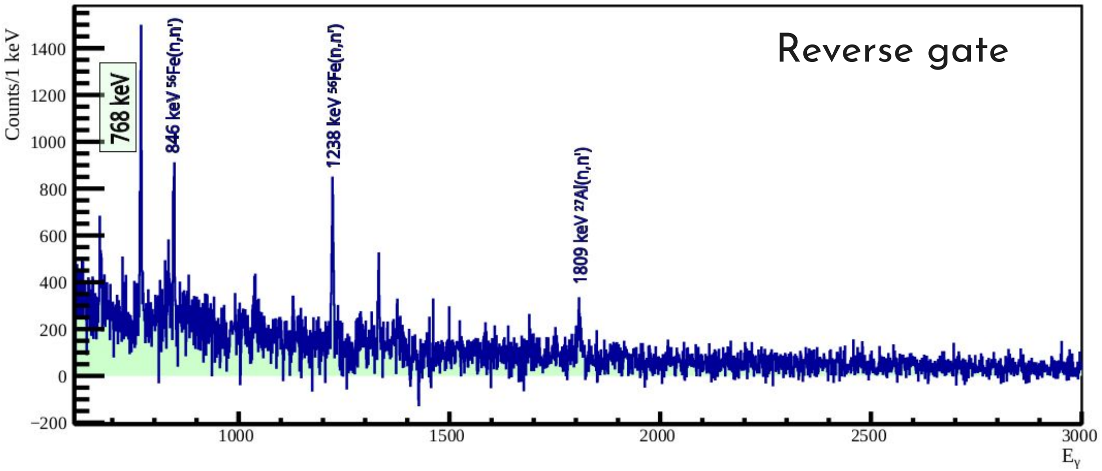
But NOT just a subset…

Evidence for new levels: the 2533 keV transition

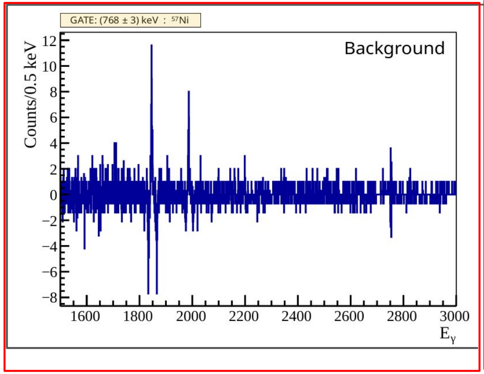


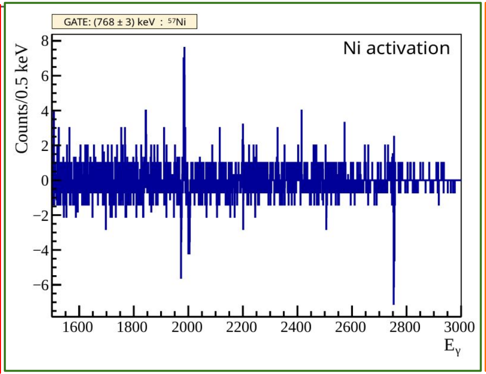


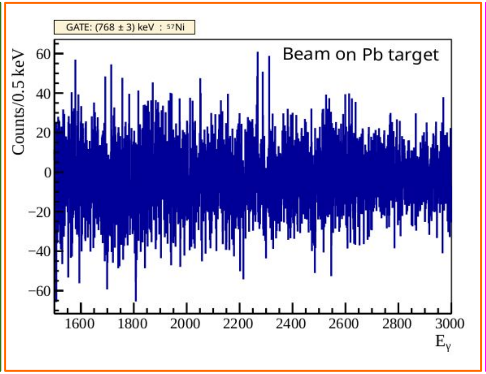
Multi-step verification with a series of independent control measurement

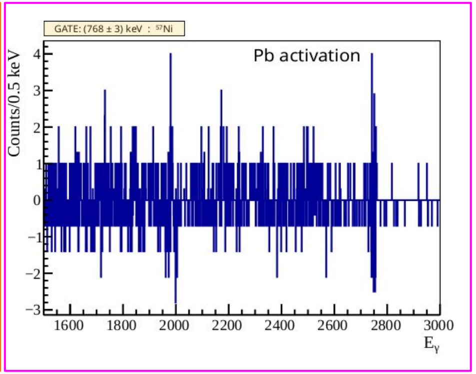


- ➢ Reverse gate
- ➢ Background run
- ➢ Activation run
- ➢ Lead target beam runs
- ➢ Lead target activation runs









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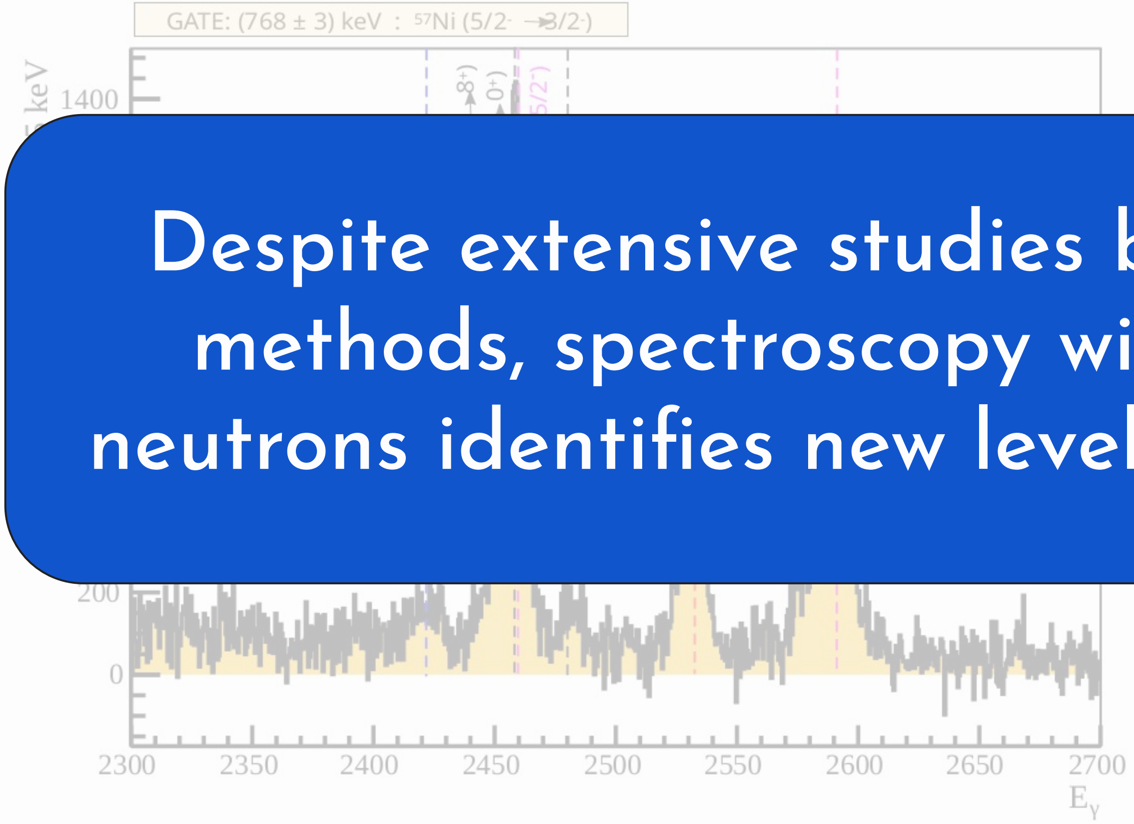
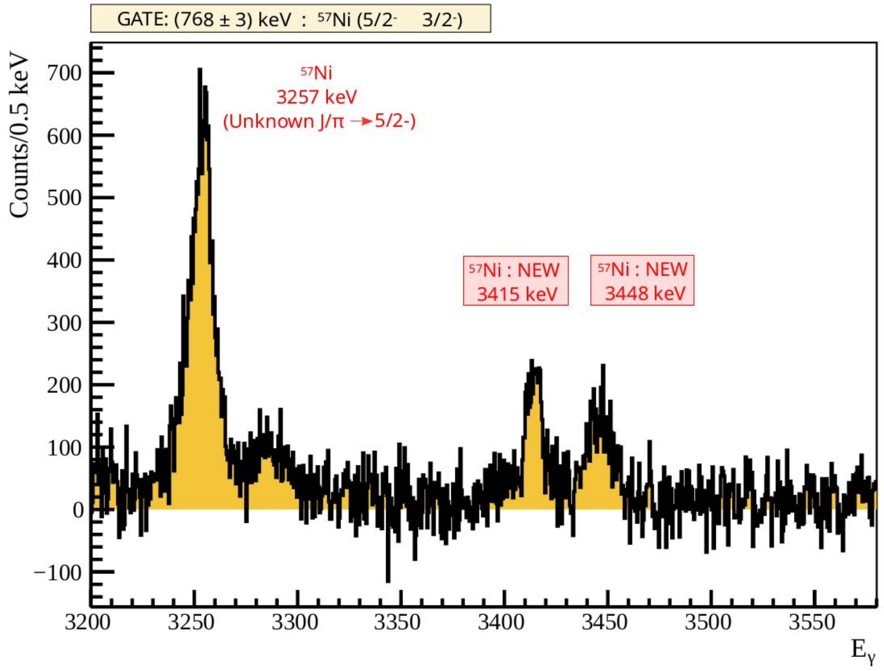
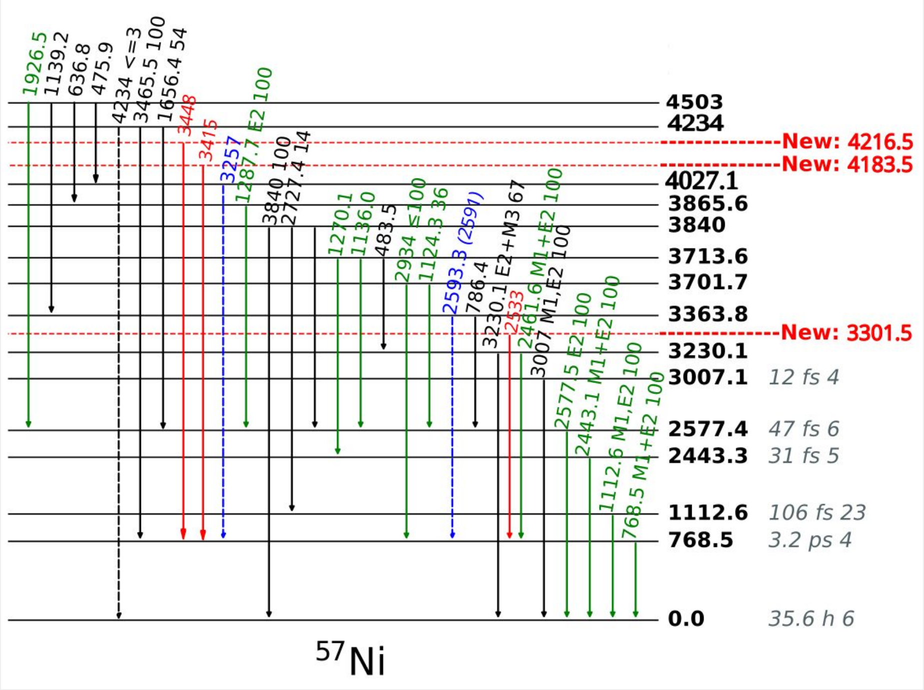


Despite extensive studies by other methods, spectroscopy with fast neutrons identifies new levels in 57Ni.

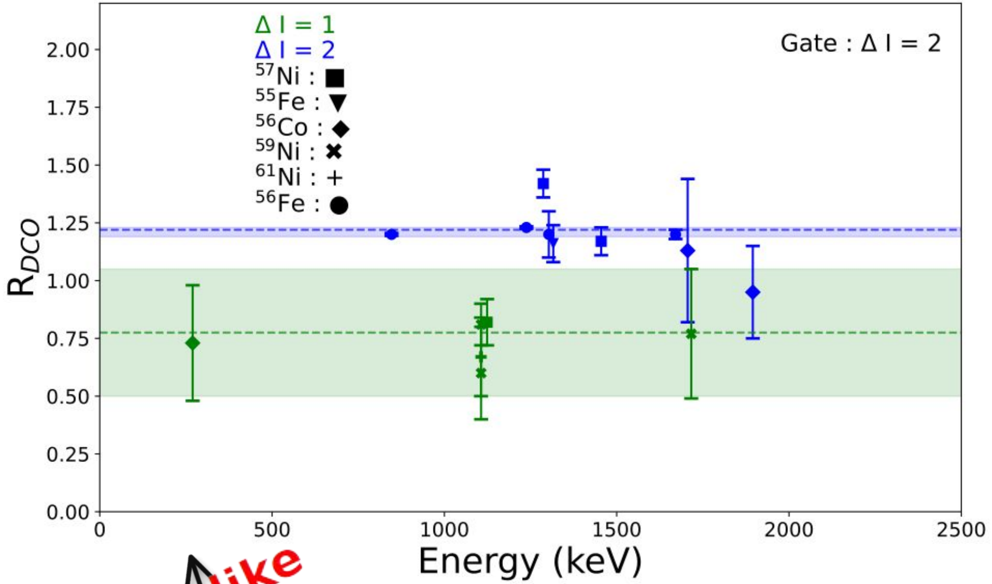
Two more new transitions observed

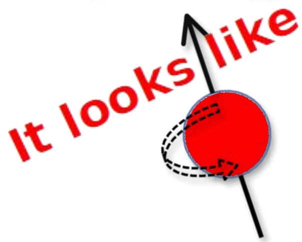




Three new levels for ^{57}Ni

Do fast neutrons align the nucleus?





Explain what is Rdco:
focus on beam axis
asymmetry in definition

Sensitive to assigning multipolarities to unknown and new transitions

⇒ can infer spin and parity of new levels.

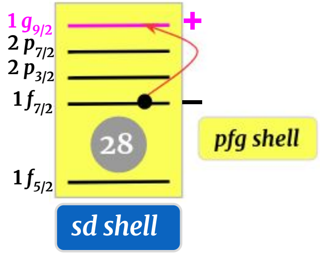
Do fast neutrons align the nucleus?

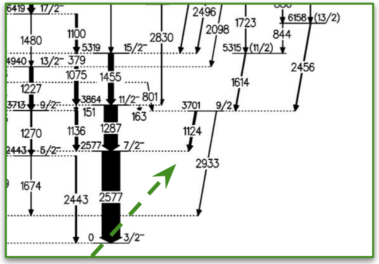
A 3701 keV state in ^{57}Ni was first identified as $(5/2)^-$ in pick-up reaction

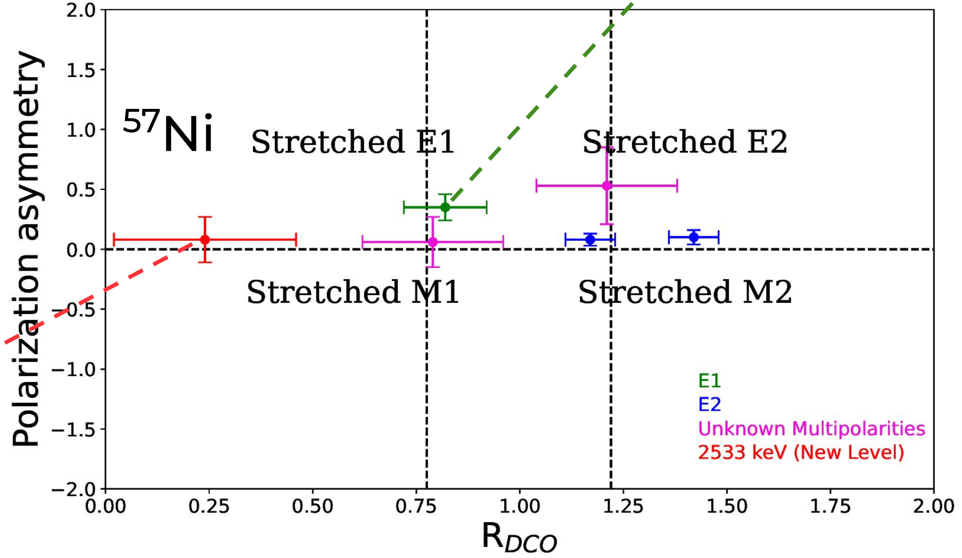
Rudolph et al. later reassigned it as $(9/2^+)$ based on the ^{28}Si(^{32}S, 2pn)^{57}Ni reaction as first observation of single particle excitation into the $g_{9/2}$

The E1 character of its decay validated using our independent (n,2n) data set!

Newly observed level (3301) seems to be of E1 character







The intruder multiplet and the N = 28 shell

^{57}Ni is the closest odd-mass nucleus to the doubly-magic ^{56}Ni core
gap

Promoting one neutron from the pf shell across the N = 28 gap into the $g_{9/2}$ orbital creates a ν $(pf)^{-1}(g_{9/2})$ particle-hole configuration

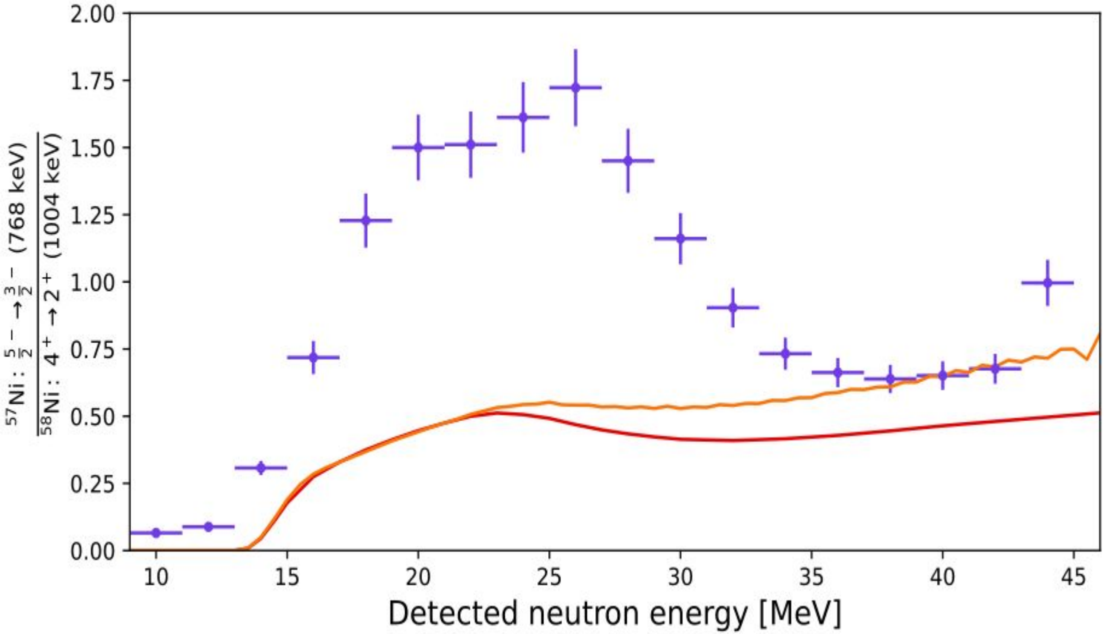
The neutron-hole can occupy the $2p_{3/2}$ (hole spin $3/2^-$) or $1f_{5/2}$ (hole spin $5/2^-$) orbitals, while the particle occupies the $g_{9/2}$ (spin $9/2^+$).
⇒ Coupling these positive-parity states spanning spins from $3/2^+$ to $15/2^+$

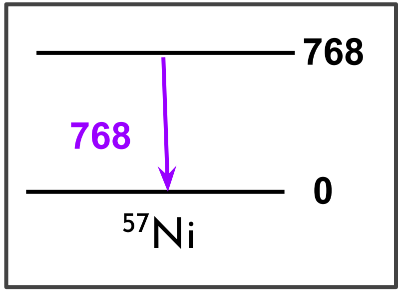
<u>Conclusion</u>: tentative spin-parity assignment of $3/2^+$ or $7/2^+$ for the new 3301 keV

Together with the known $9/2^+$ at 3701 keV it maps the $\nu(pf)^{-1}g_{9/2}$ multiplet structure and provides a new experimental constraint on the cross-shell particle-hole interaction near the Z = N = 28 doubly-magic core.

Until now no existing shell-model interaction predicts the $\nu(pf)^{-1}g_{9/2}$ intruder multiplet in ^{57}Ni

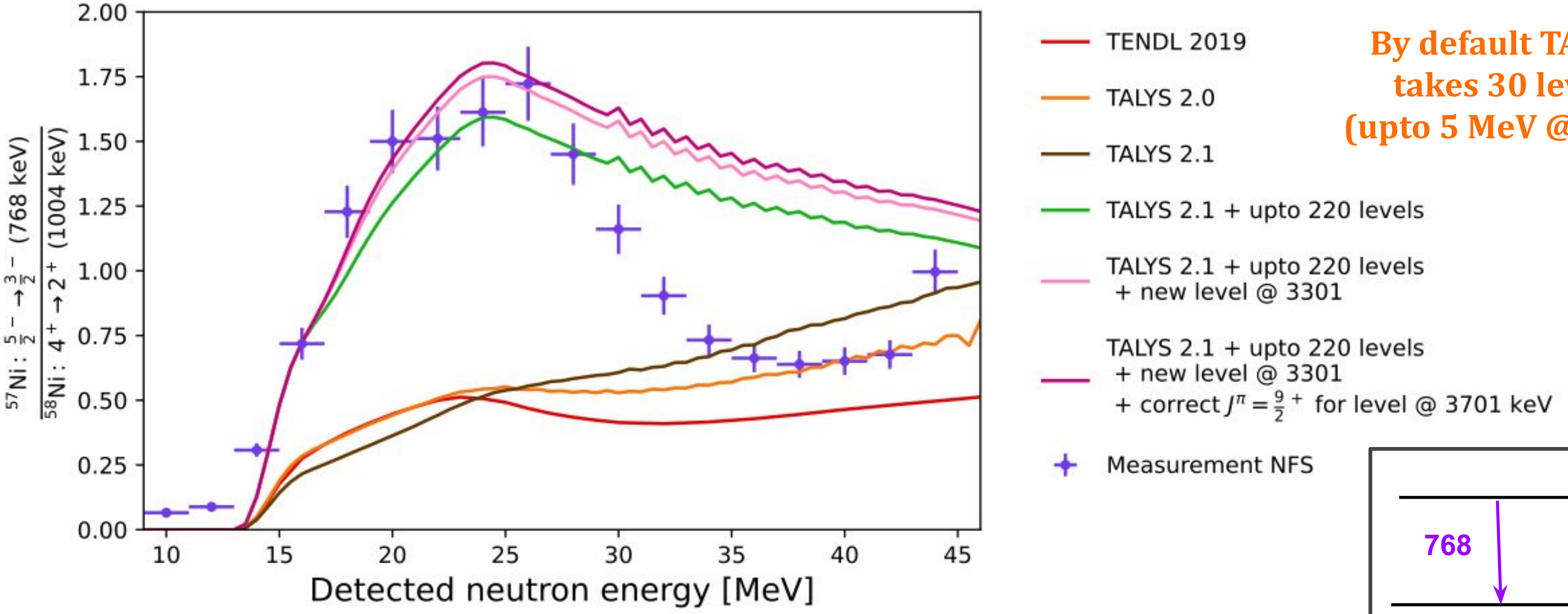
Gamma cross-section measurement: Nuclear Data Libraries and C



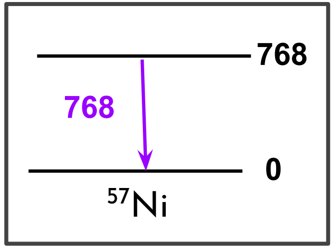


- ➢ Verified the measured cross-section (cs) for 5/2$^-$ in ^{57}Ni.
- ➢ Beyond 21 MeV the measured cs is larger that the TENDL evaluation.
- ➢ Cross-section data is only as complete as the structure data behind it.

Gamma cross-sections

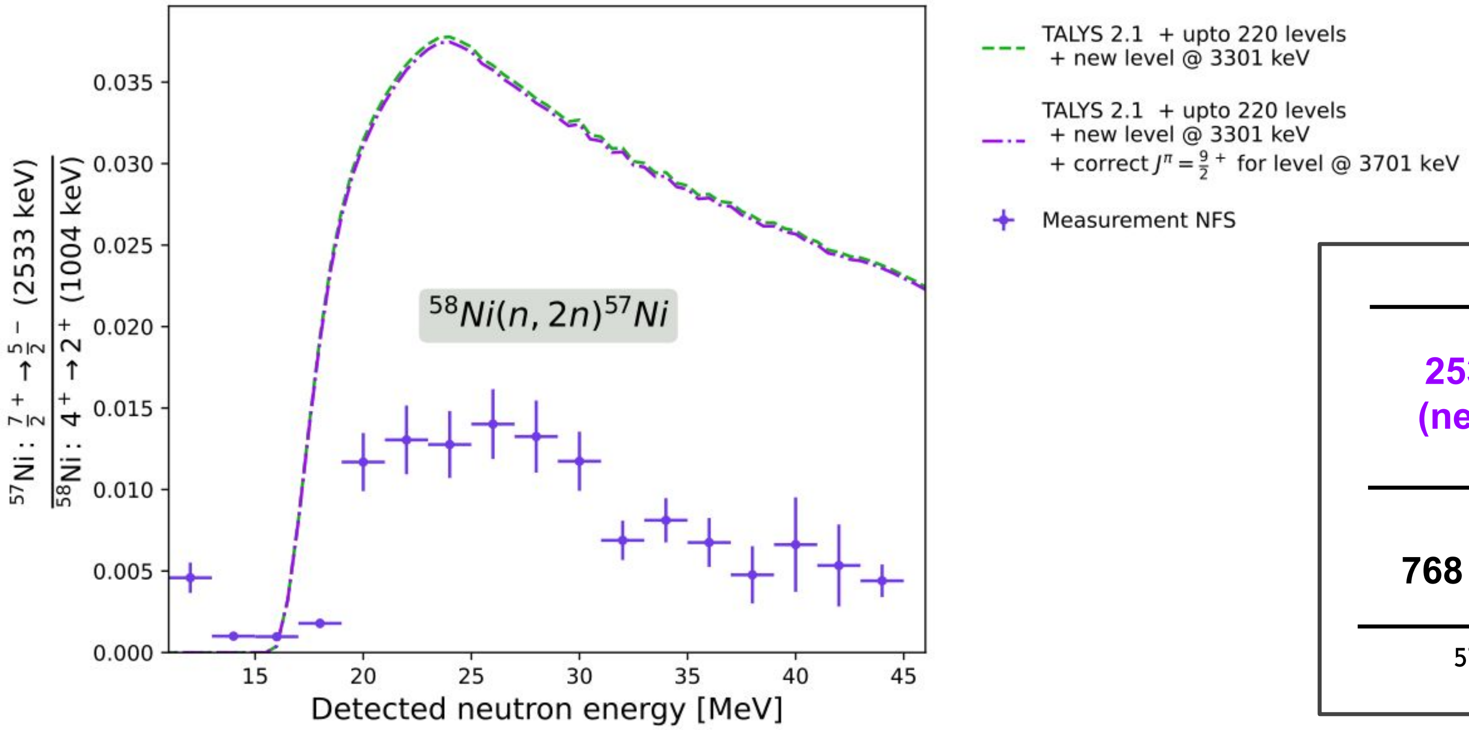


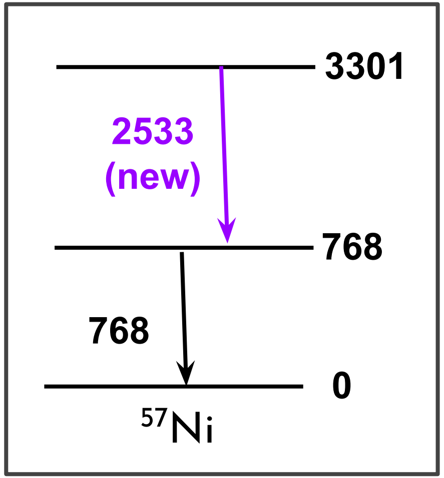
By default TALYS takes 30 level (upto 5 MeV @ ^{57}Ni)



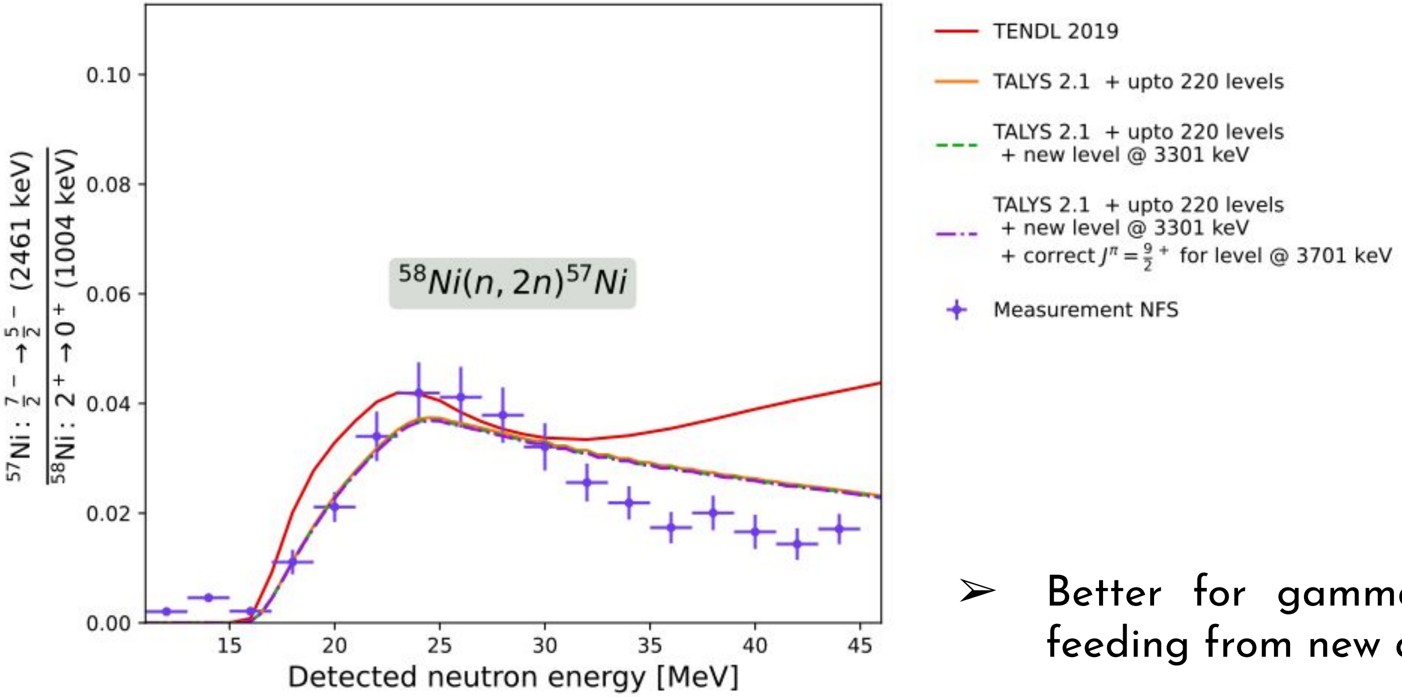
➢ Better agreement until 25 MeV when including higher levels not used by default TALYS and TENDL libraries, still not the best at higher energies

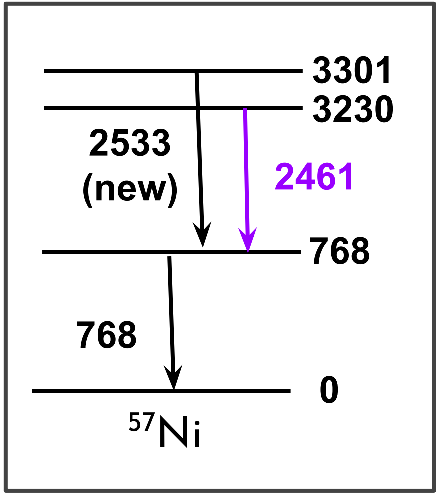
Gamma cross-sections





➢ Better tuning needed

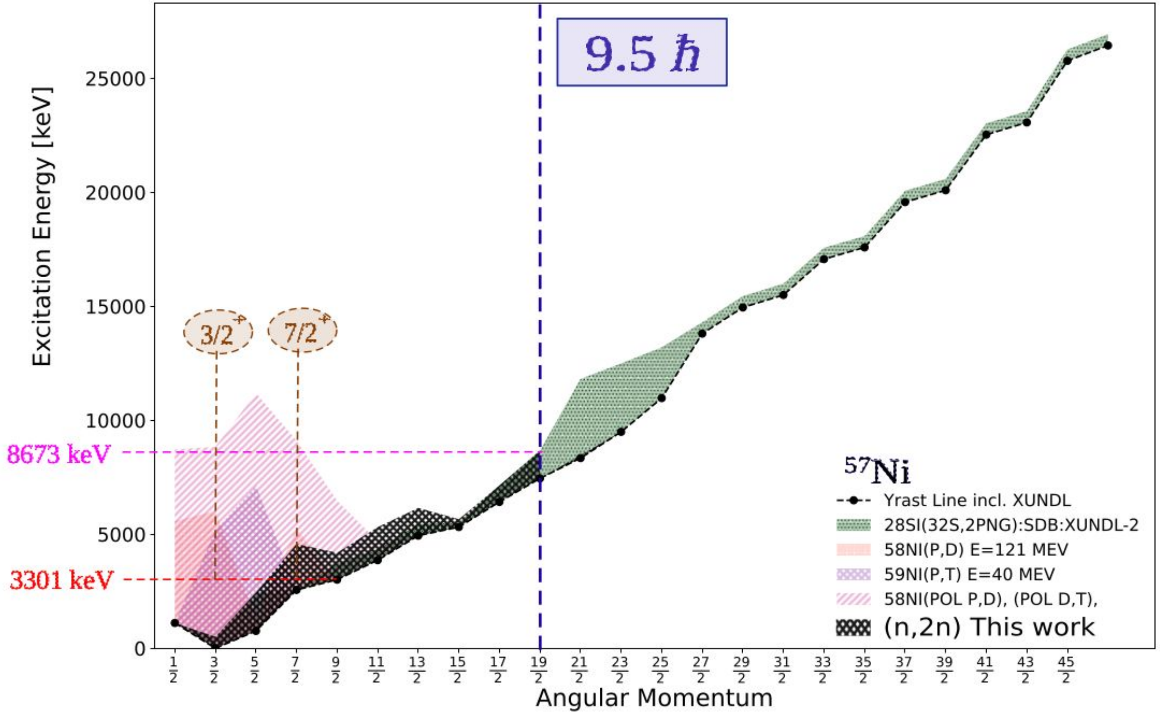




➢ Better for gammas without significant feeding from new and higher levels

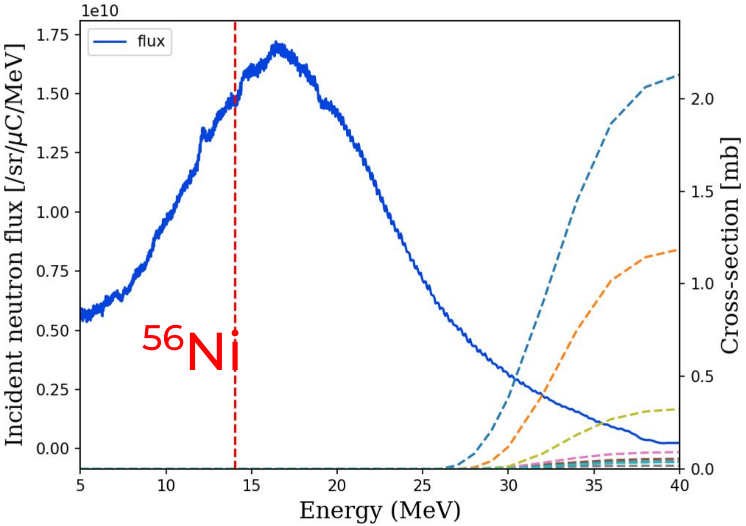
➢ More accurate spectroscopy on the decay of these states is needed, branching ratios could explain this… better modelling could help as well.

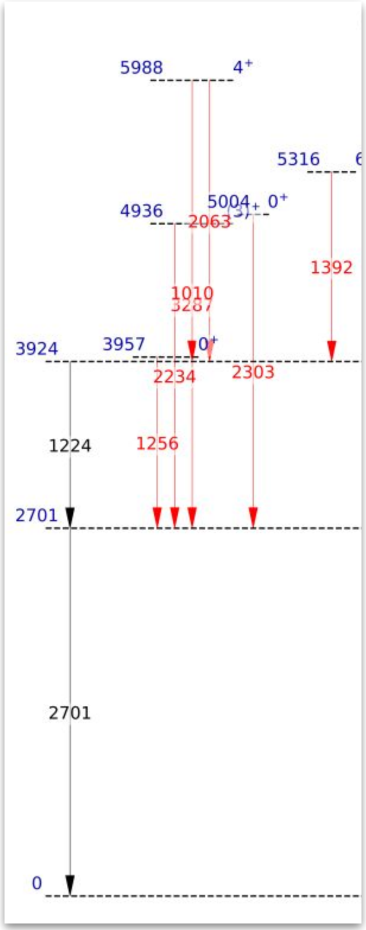
Characterizing (n, 2n) reaction on the yrast



- ➢ Overall (n,2n) behavior resembles heavy-ion fusion-evaporation
- ➢ High-energy levels not observed at low angular momentum
- ➢ Observed spin cut-off: 21/2
- ➢ NFS flux limitation at high neutron energy ($E_n \approx$ 40 MeV)

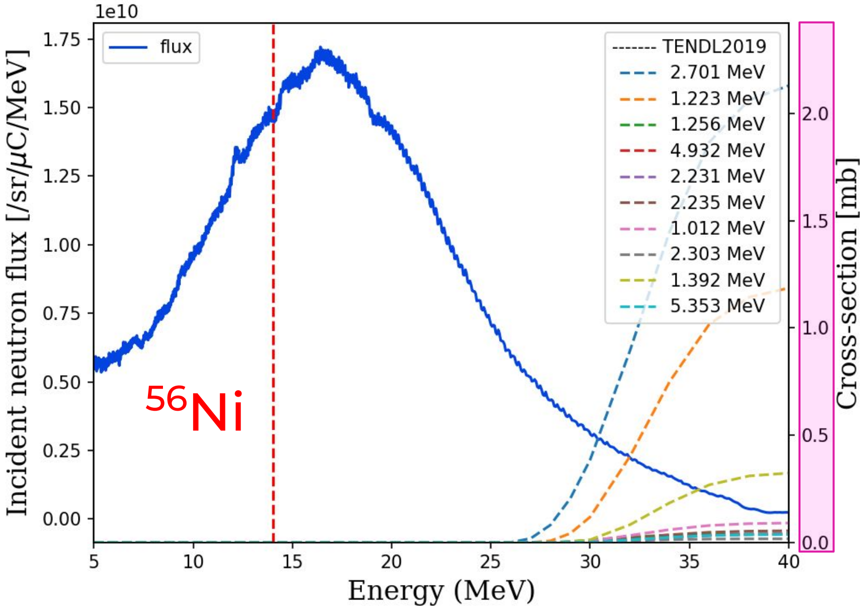
$^{58}Ni(n, 3n)^{56}Ni$



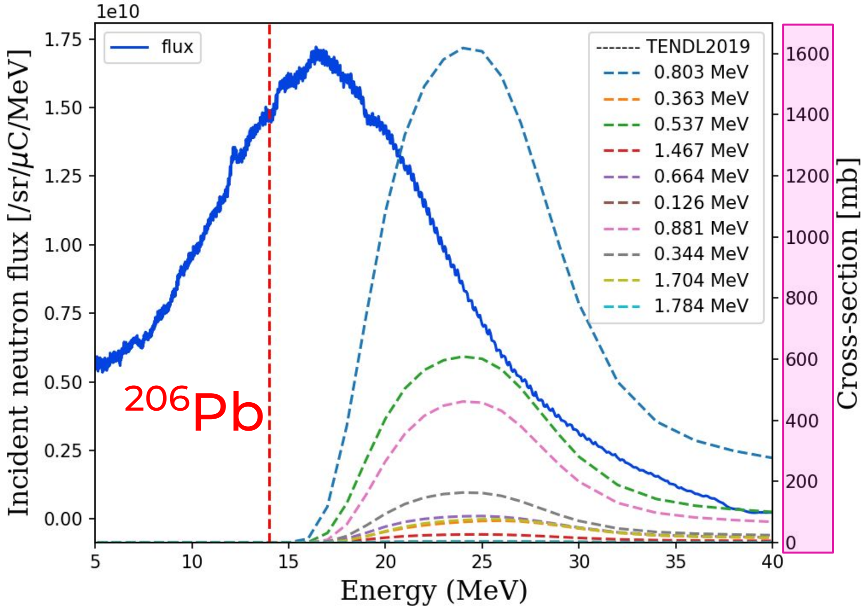


- ➢ Higher threshold and lower c-s for $^{58}Ni(n,3n)^{56}Ni$
- ➢ 2303 keV, 1256 keV, and γ-rays from higher-lying levels are not observed
- ➢ Two states at low spin is however observed
- ➢ Improved sensitivity is needed

Data: 10 days EBT



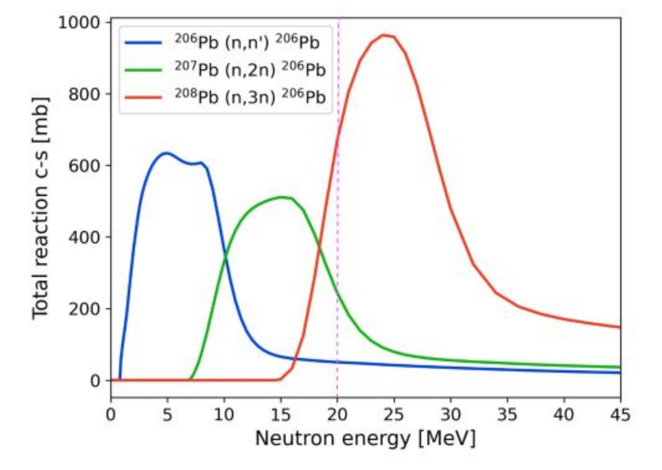
Data: 4 days EBT



- Much lower thresholds and relatively higher c-s for $^{208}Pb(n,3n)^{206}Pb$
- Also, the acceptance and beam intensity changed effectively reducing the statistics for lead.

Lead Target

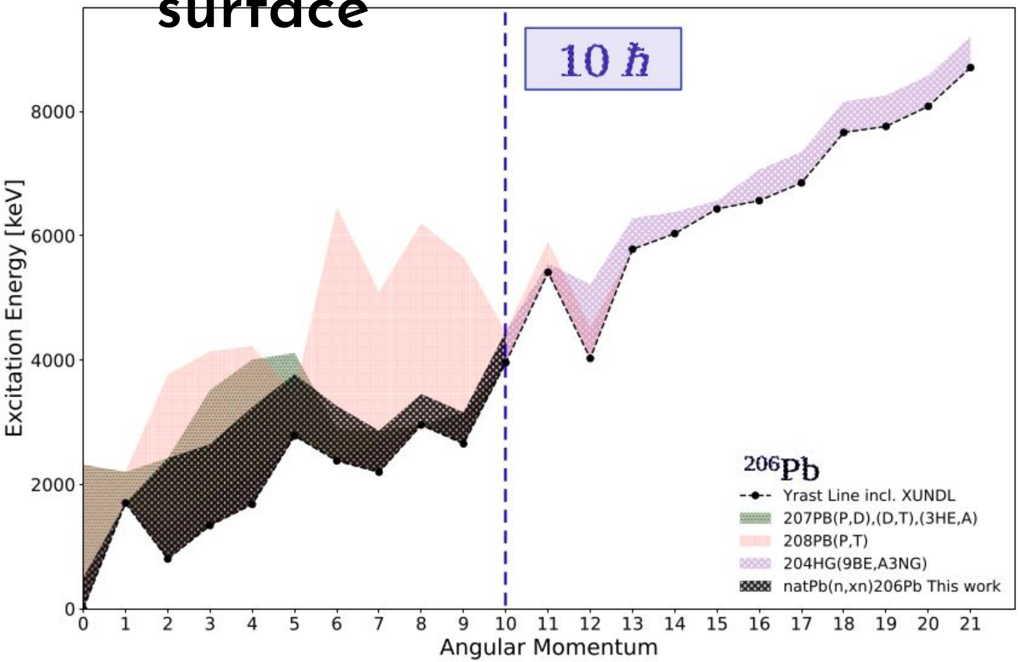
^{Nat}Pb target (60% ^{208}Pb, 20% ^{207}Pb, 20% ^{206}Pb)



$^{206}\mathrm{Pb}(n,n')^{206}\mathrm{Pb}$ $\quad$ $^{207}\mathrm{Pb}(n,2n)^{206}\mathrm{Pb}$ $\quad$ $^{208}\mathrm{Pb}(n,3n)^{206}\mathrm{Pb}$

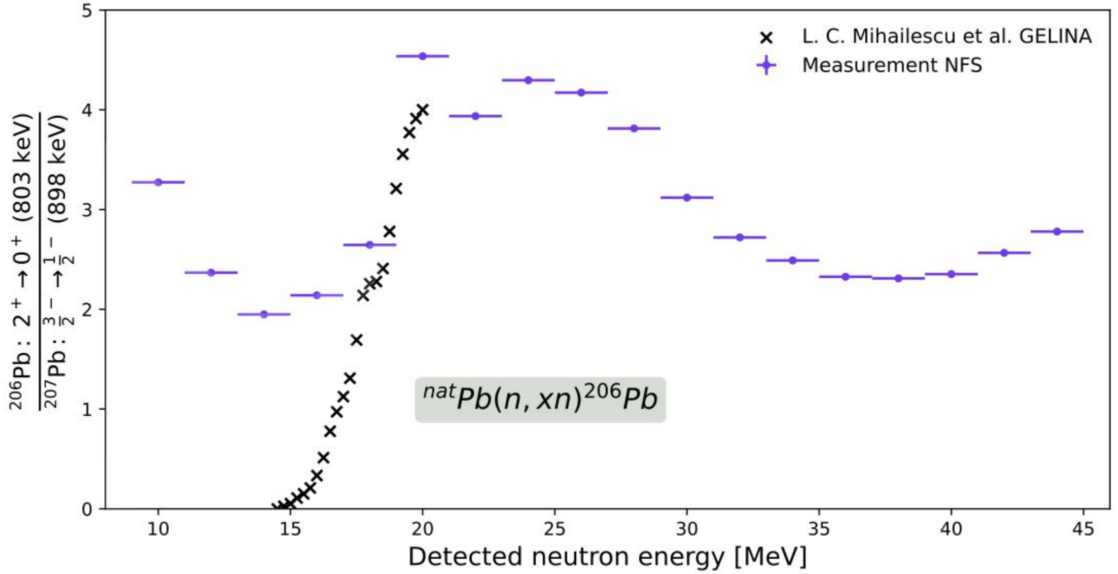
- ➢ Multi-isotopic natural target
- ➢ Different channels, same isotope.

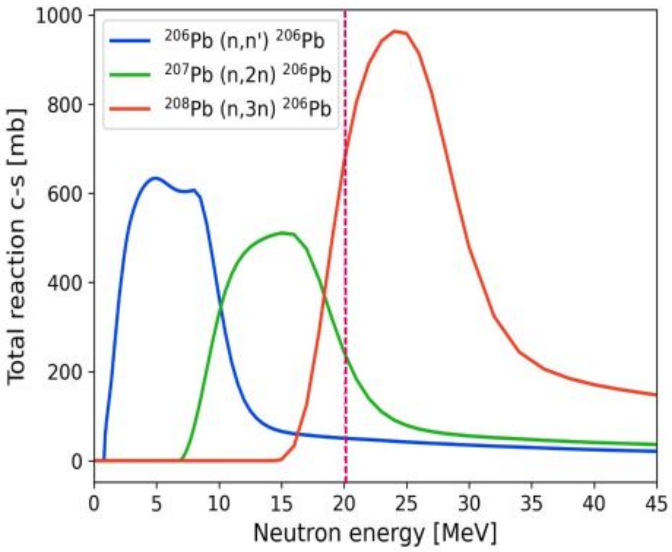
Characterizing (n, 3n) reaction on the yrast surface



- ^{206}Pb yrast diagram from $^{nat}Pb(n,xn)$ compared to particle-transfer reactions
- Observed spin cut-off: ~10 ħ
- Excited 0^+ state (363 keV) not observed, not sensitive, most go to E0

Gamma cross-sections



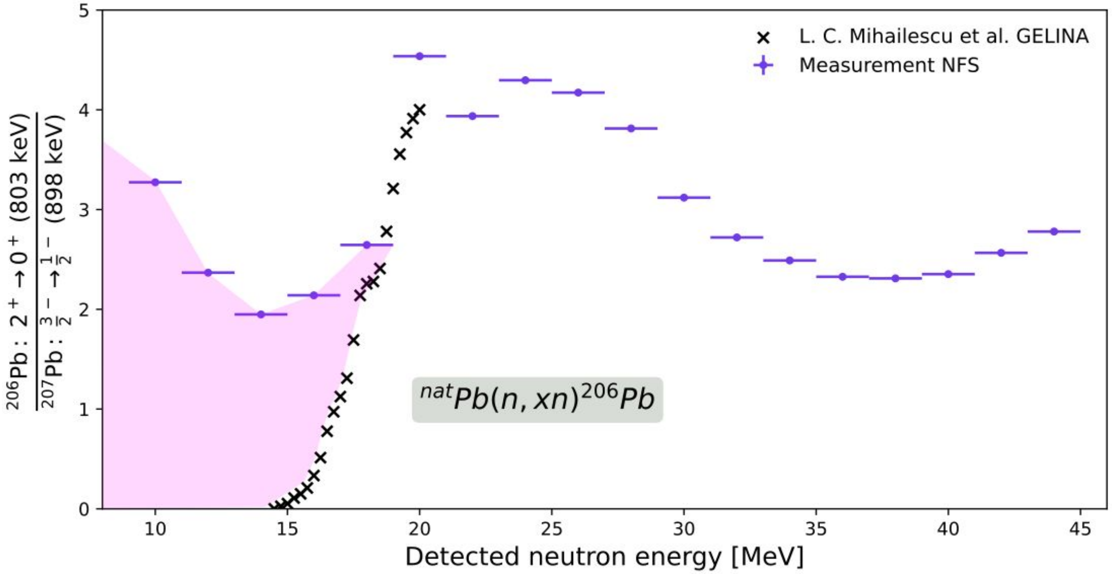


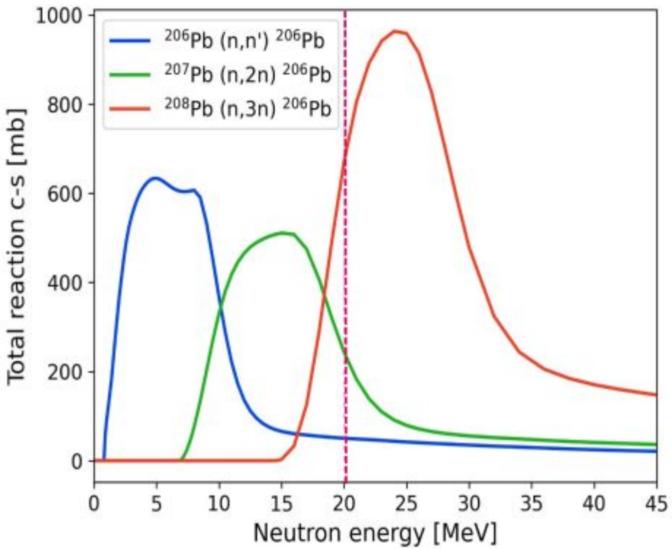
Earlier measurements exist with an enriched ^{208}Pb target (GELINA) until 20 MeV.

Comparison with that highlights the contamination from the (n,2n) and (n,n′) channel

With NFS we can extend these measurements upto 44 MeVs

Gamma cross-sections





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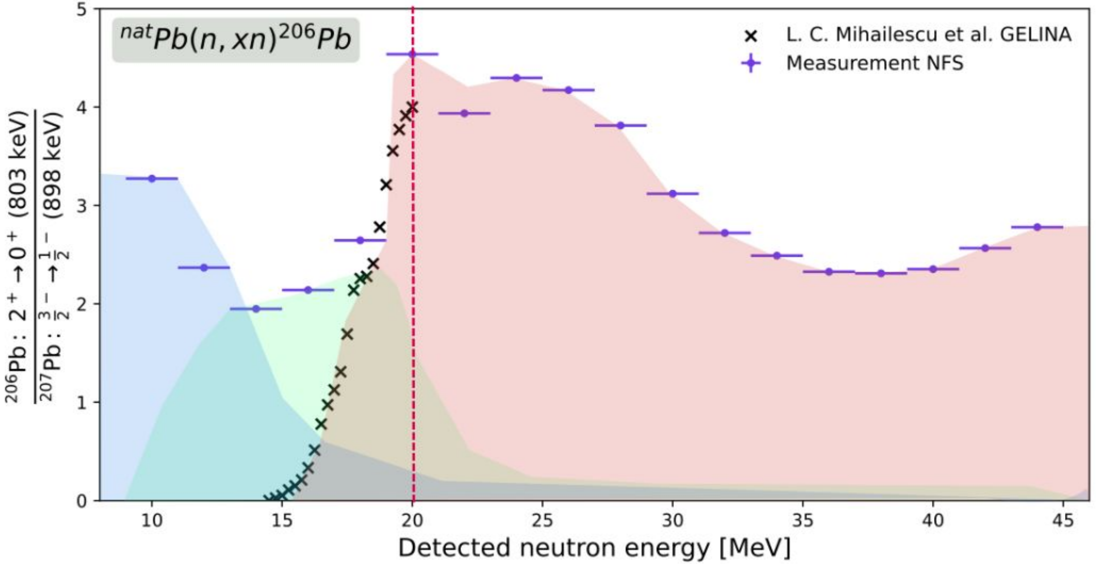

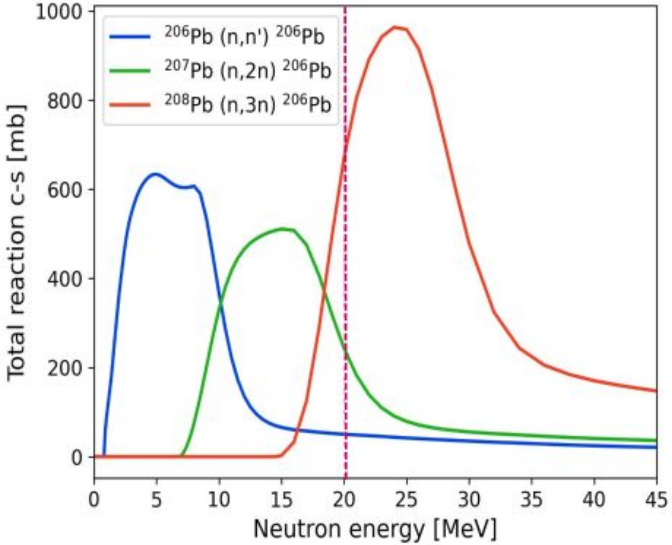

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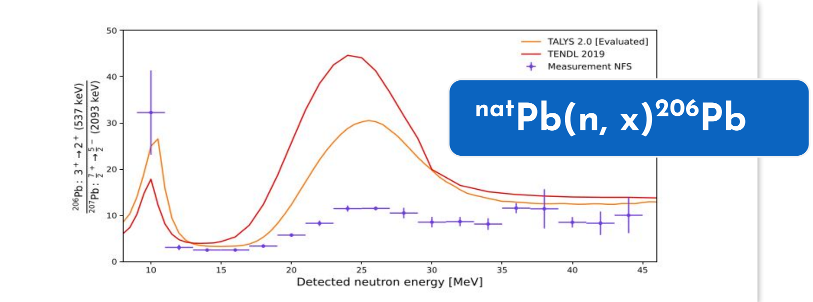
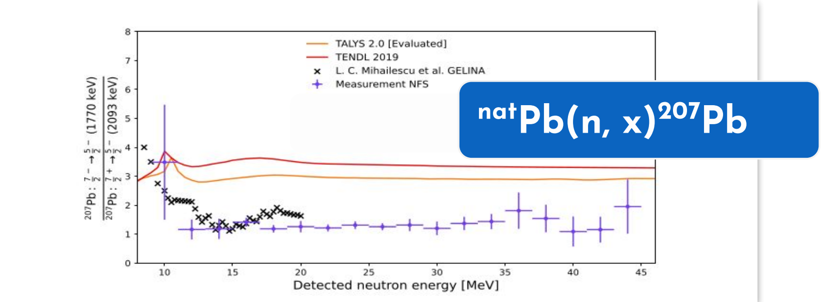
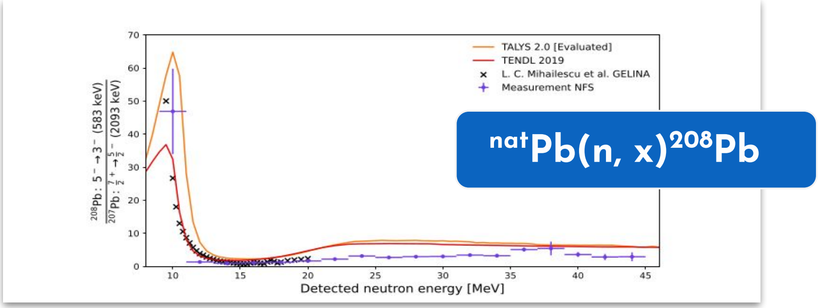


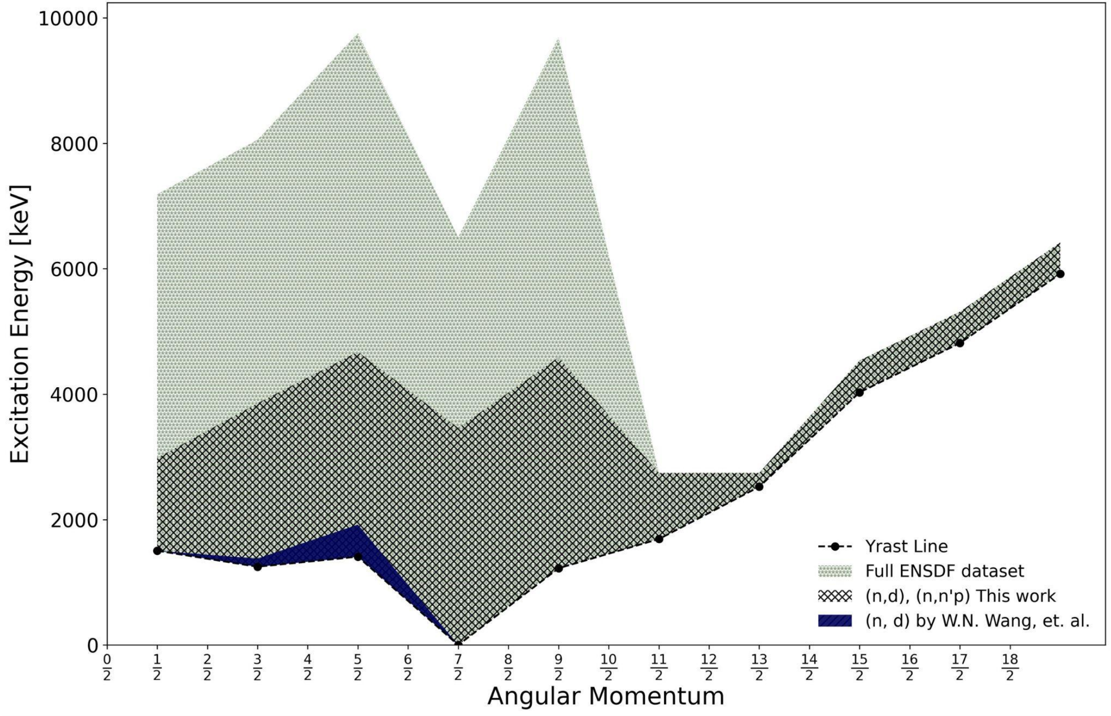




Cross-section (Anatomy)

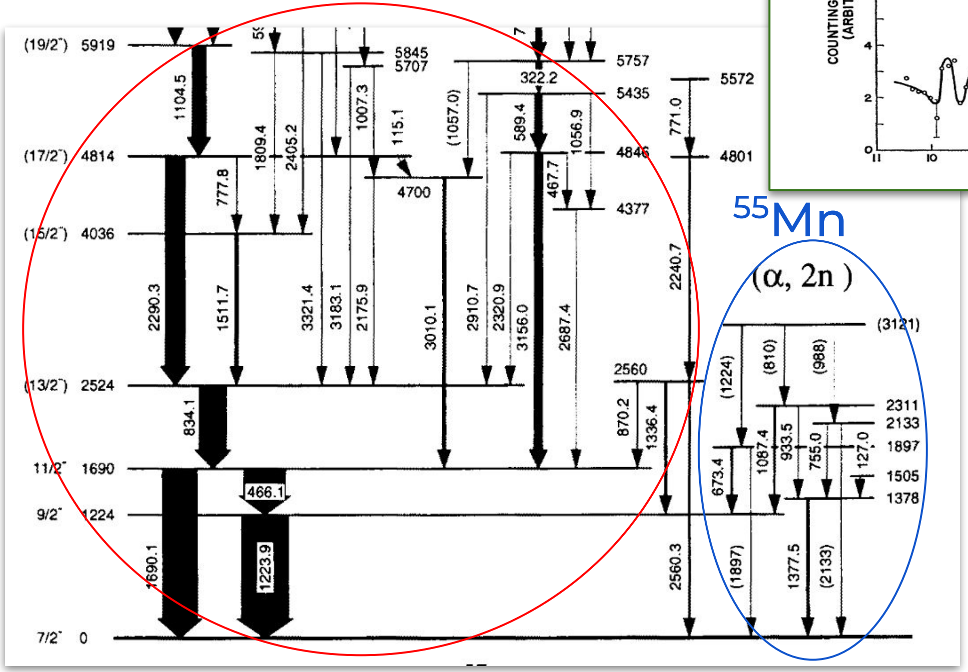
- We also decompose this down further by measuring new gamma-ray cross sections that feed into the 803 keV line.
- These give tuning benchmarks for TALYS calculations at higher neutron energies.
- A future measurement using enriched ^{208}Pb will let us isolate the (n,3n) reaction.
- We also extended the gamma-ray cross sections for ^{207}Pb and ^{208}Pb to higher neutron energies than GELINA covered, and added new measurements.

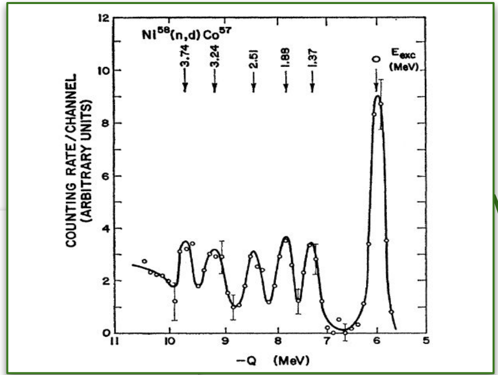
^{57}Co: (n,d) vs (n,n′p)



- ➢ ^{57}Co produced by (n, d) and (n, n′p) channels
- ➢ Extensively populating this isotope
- ➢ Very low selection rules

Heavy-ion: ^{40}Ca (^{20}Ne, 3pγ)





^{58}Ni(n, d)

W. N. Wang et al.

(n,d) populates only single particle states.

We see both collective and single particle states in our data.

Goal: Identify which reactions lead to which nuclear states

Challenge: No charged-particle detectors in our setup

Solution: Use TALYS simulations to disentangle contributions

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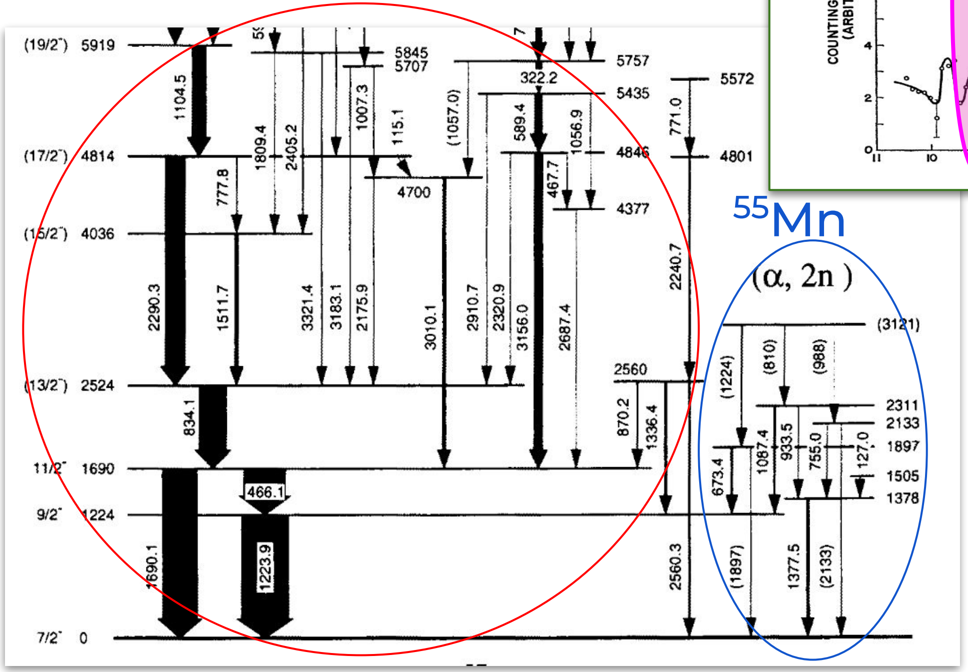

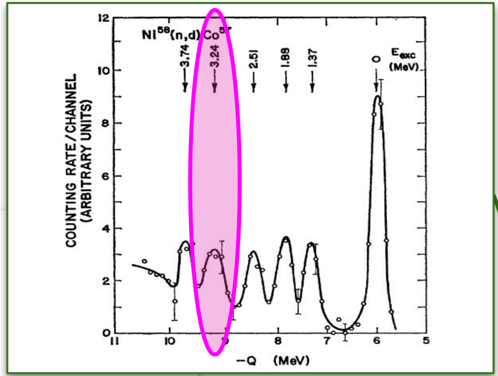

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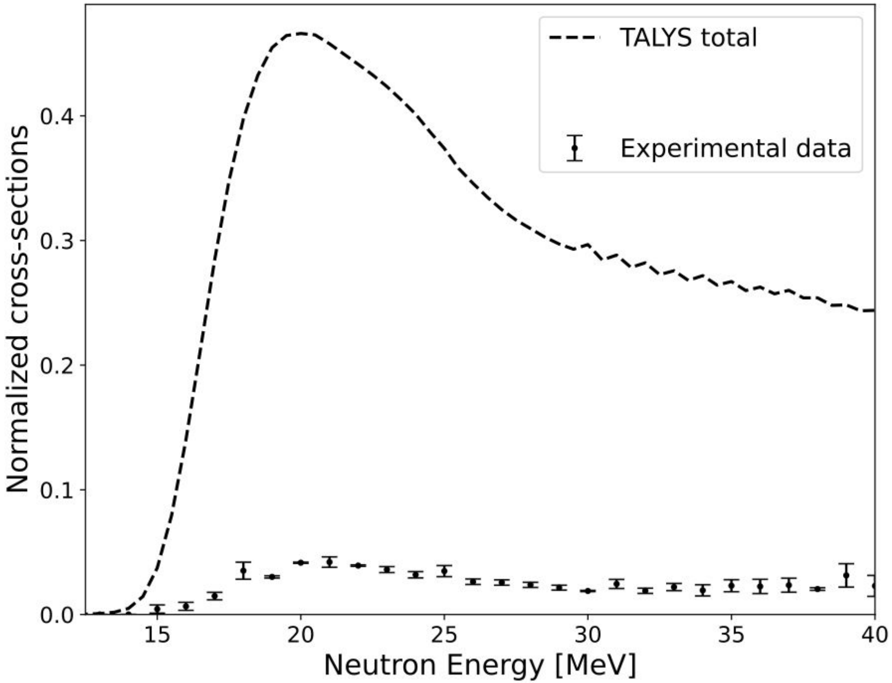
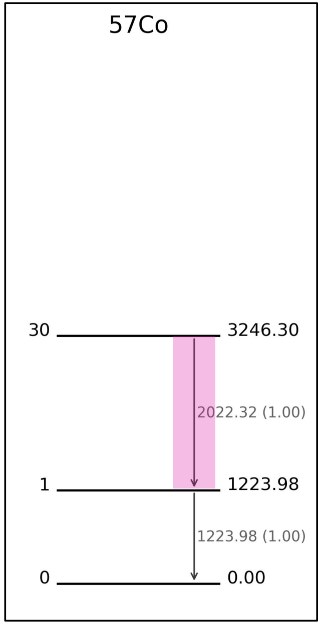
Solution: Use TALYS simulations to disentangle contributions

^{57}Co: 57Co: (n,d) vs (n,n'p)





- ➢ Note: We measure a specific gamma-ray transition cross-section
- ➢ TALYS overestimates the cs of this transition

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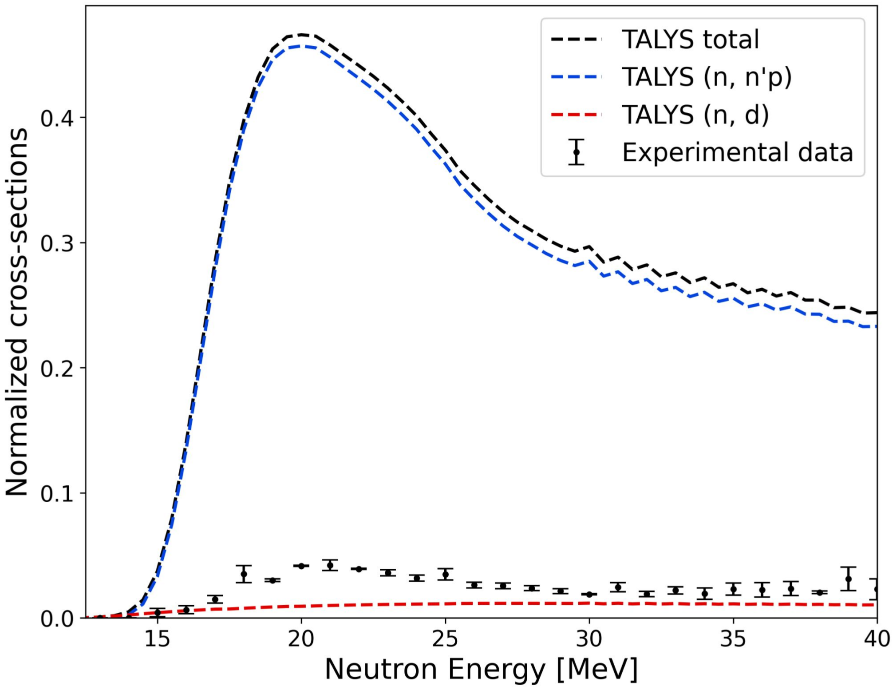

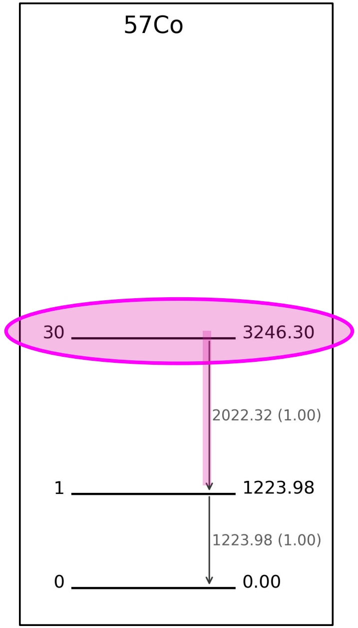

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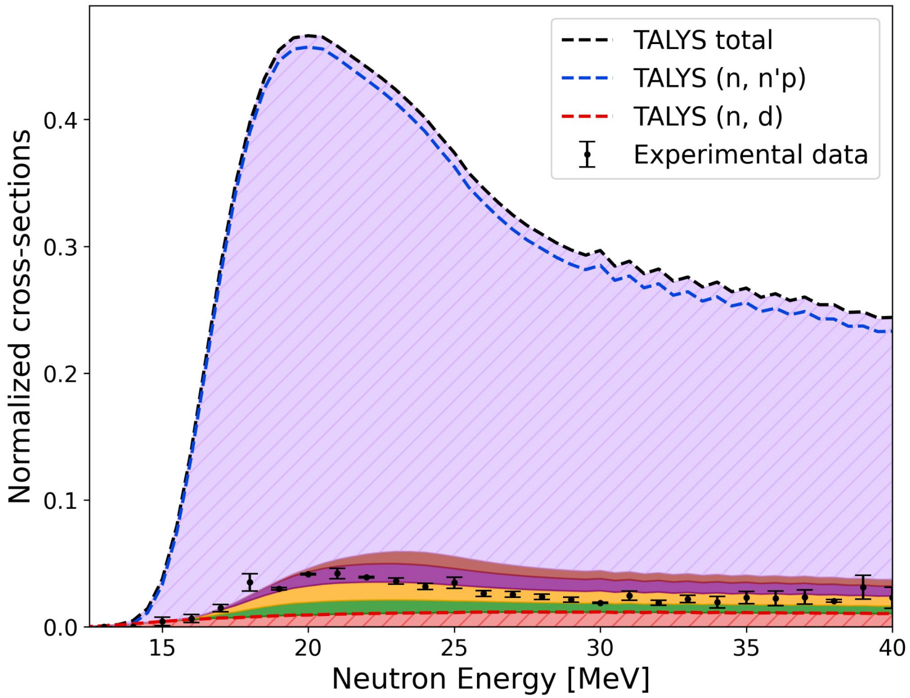
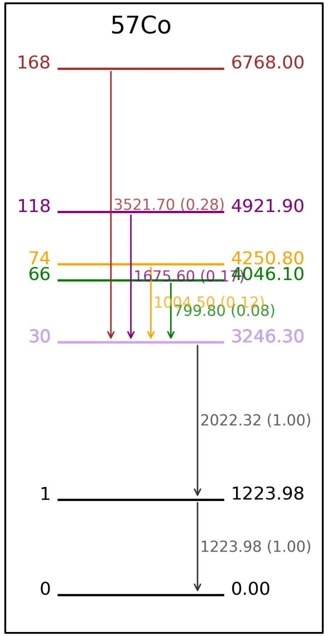
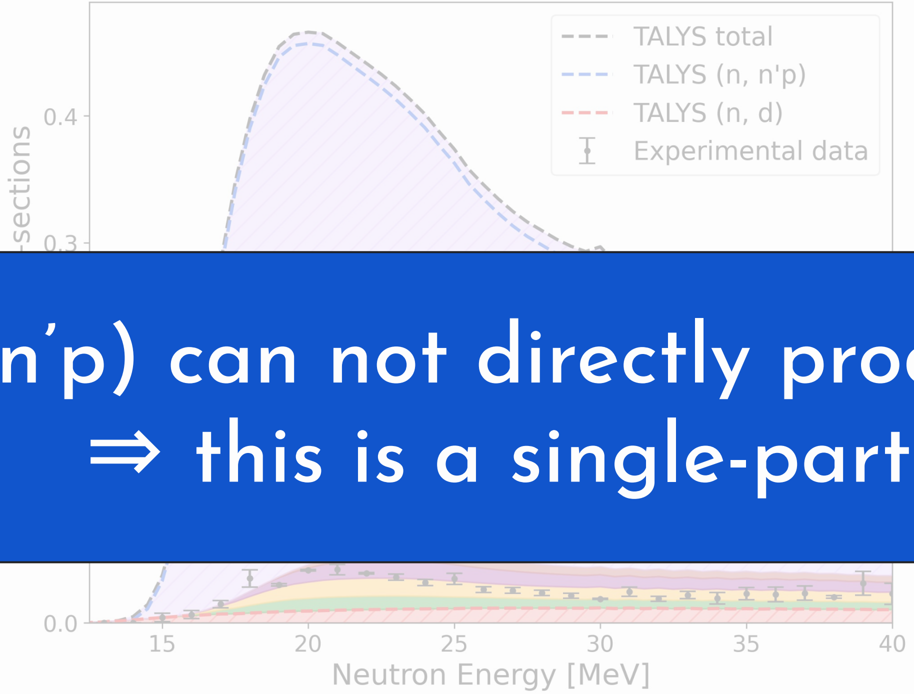




- Modified TALYS source-code for obtaining reaction specific level cs
- TALYS says 3.2 MeV state is directly populated via (n, n′p) → likely incorrect.



(n,n'p) can not directly produce this level
⇒ this is a single-particle state

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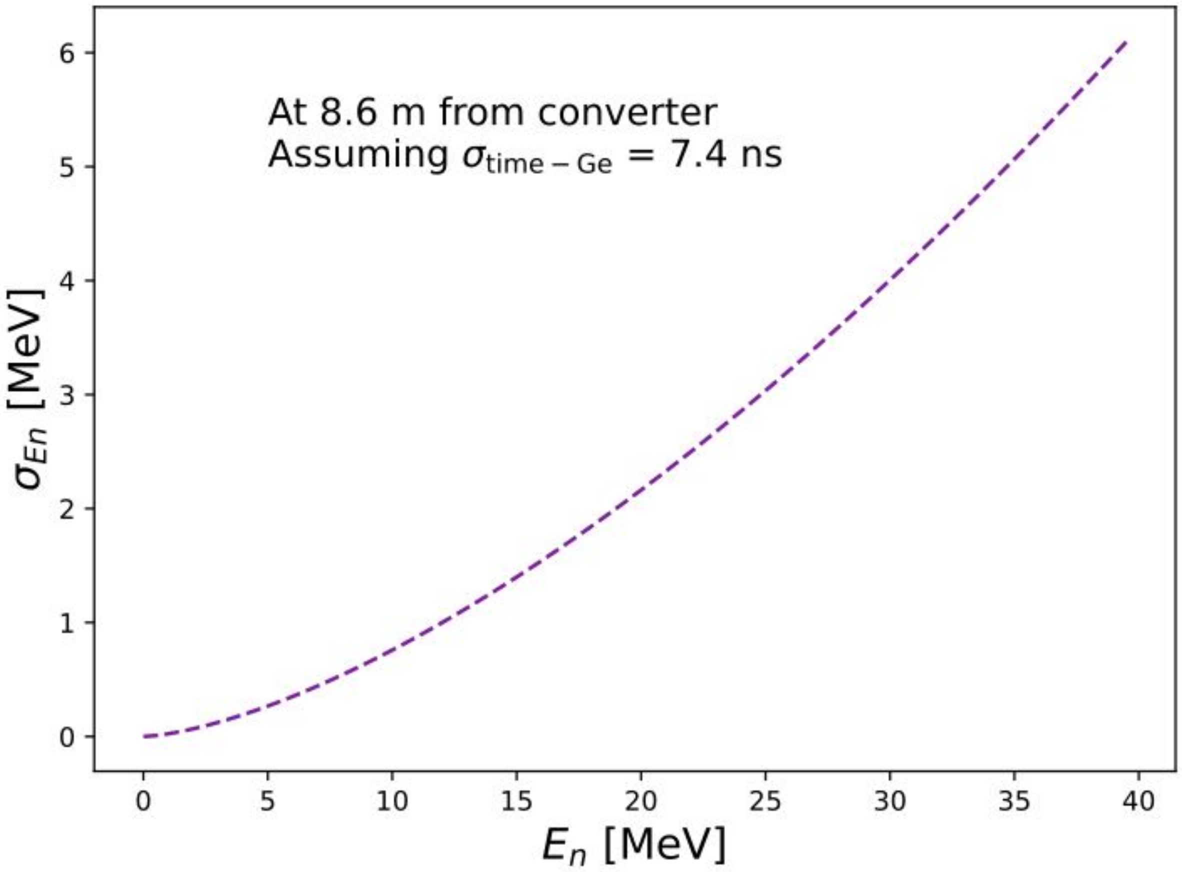
At 8.6 m from converter
Assuming $\sigma_{time-Ge}$ = 7.4 ns
σ_{En} [MeV]
E_n [MeV]
0 1 2 3 4 5 6
0 5 10 15 20 25 30 35 40