Probing nuclear structures with fast neutrons at NFS

EuNPC 2025

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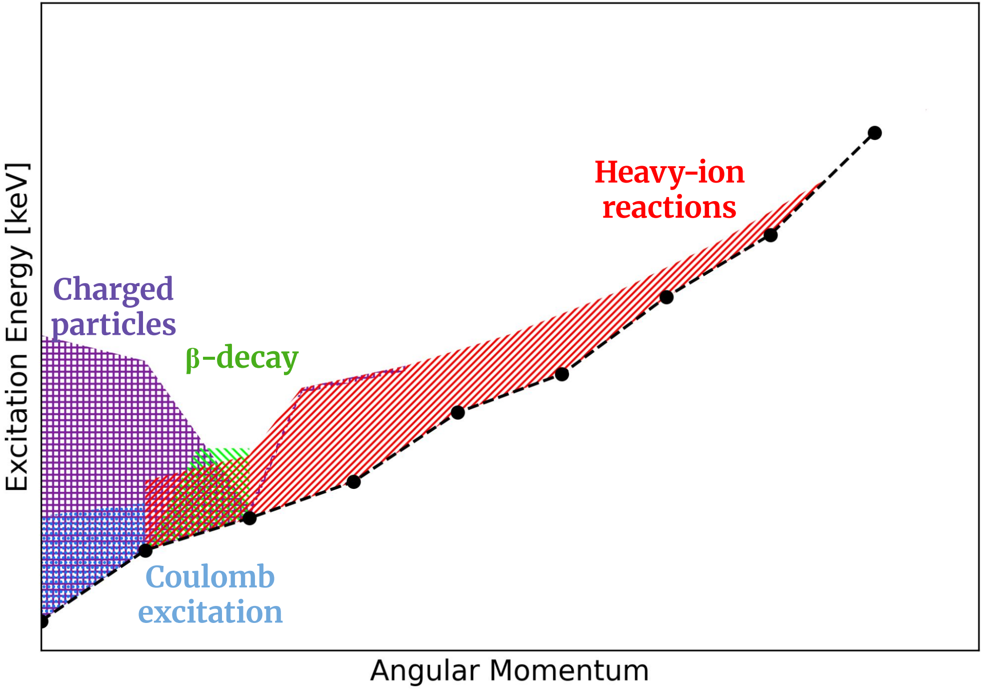
Emmanuel CLÉMENT, e838 collaboration

CONTENTS

Motivation

Unlocking new nuclear frontiers with fast neutron probes.

Beyond cross-sections: What can nxn reactions reveal about nuclear structures?



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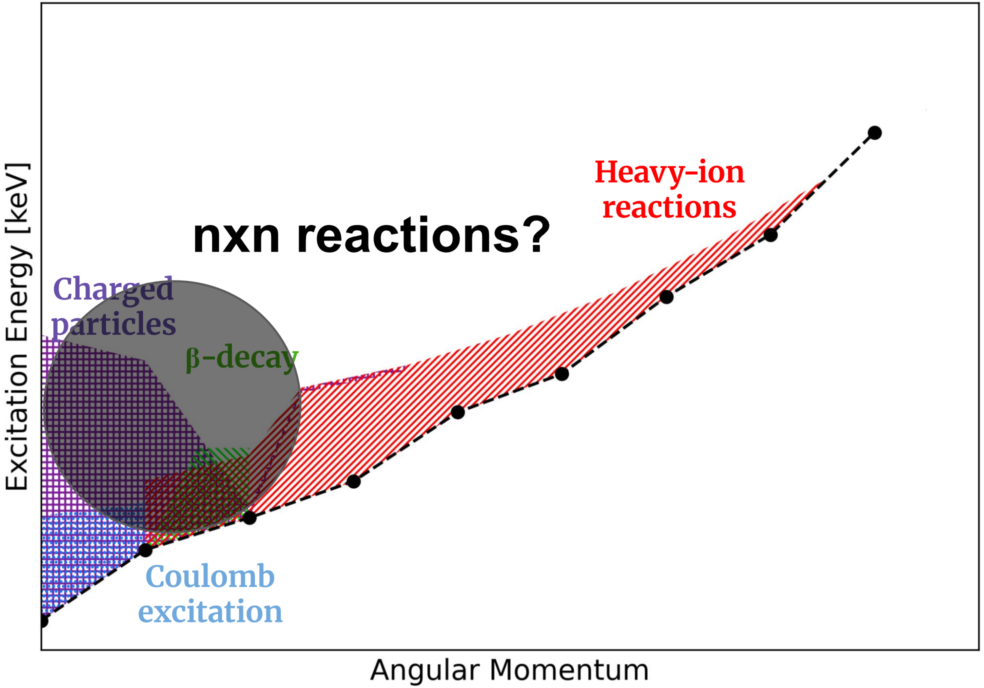


Motivation

Unlocking new nuclear frontiers with fast neutron probes.

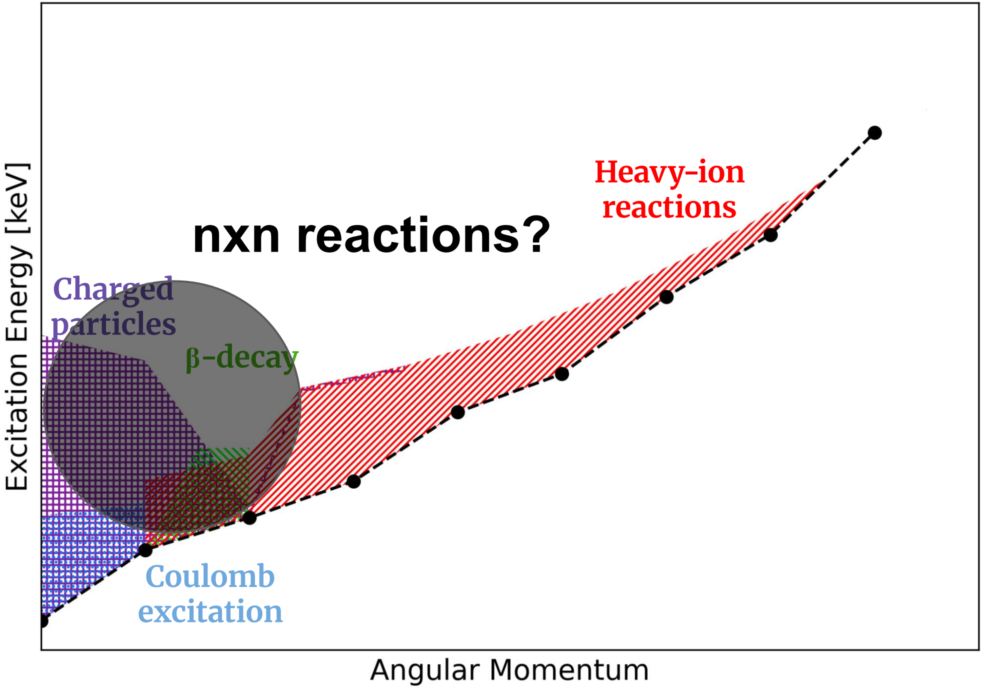
Beyond cross-sections: What can nxn reactions reveal about nuclear structures?

Can detailed studies of populated excited states help improve nuclear reaction codes (e.g., TALYS)?

Now possible at NFS:

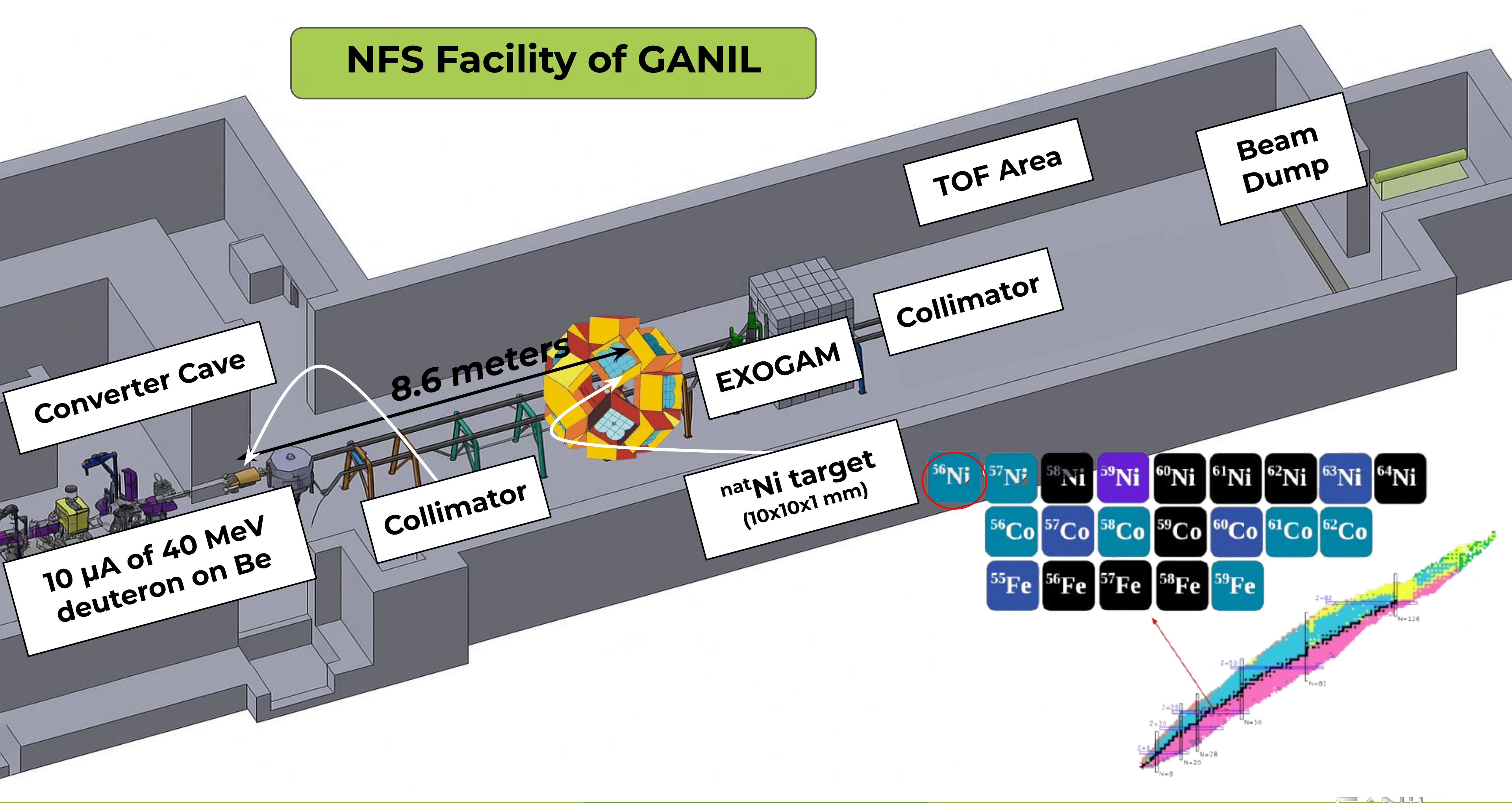
nxn reactions have high energy thresholds

⇒ need large flux at high neutron energies.

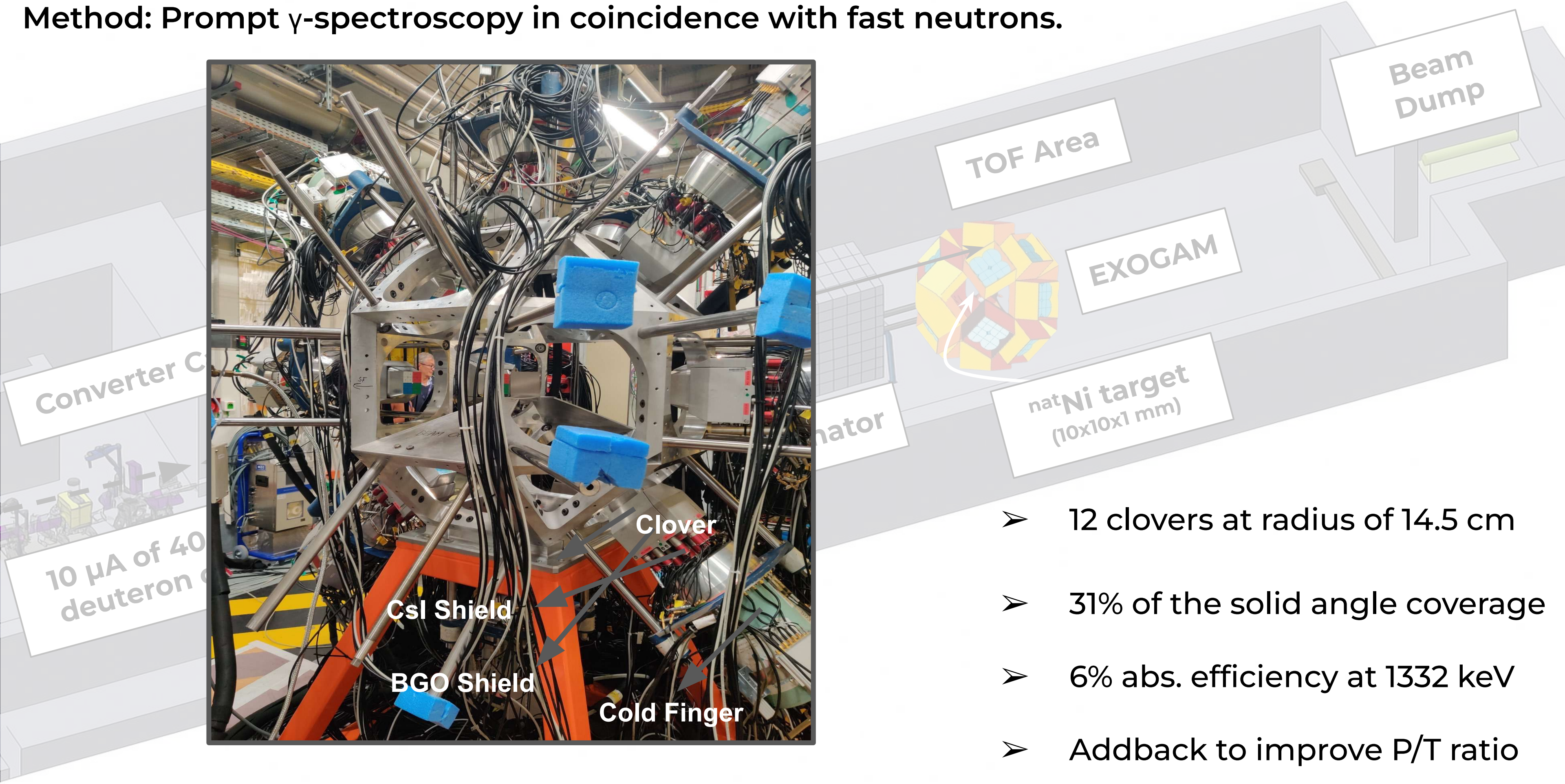


First test case, the ^{58}Ni region. Also, charged particle channels (Co and Fe isotopes). Data also collected with a Pb target.

NFS Facility of GANIL

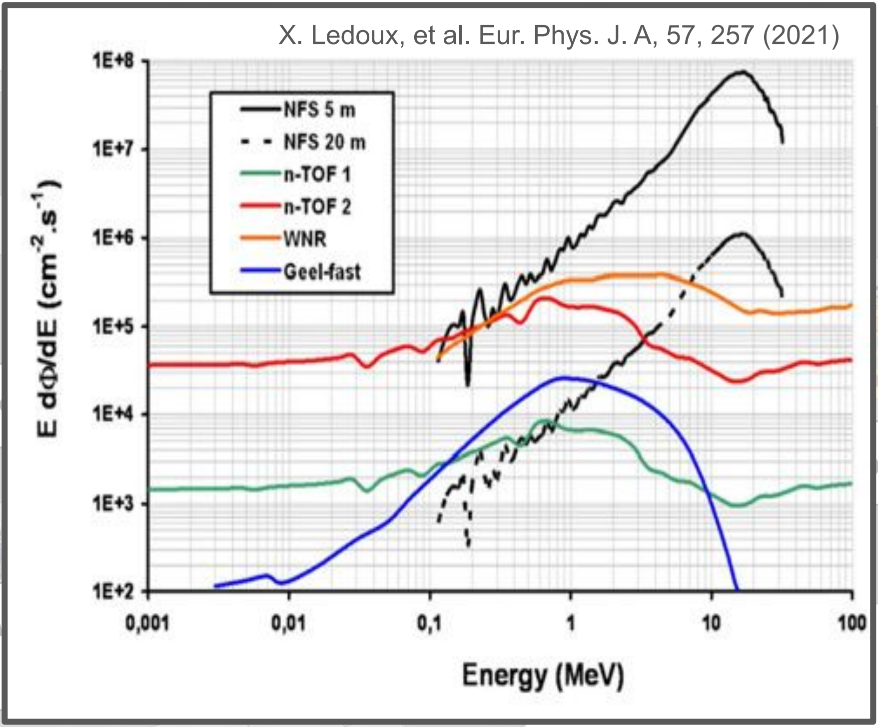


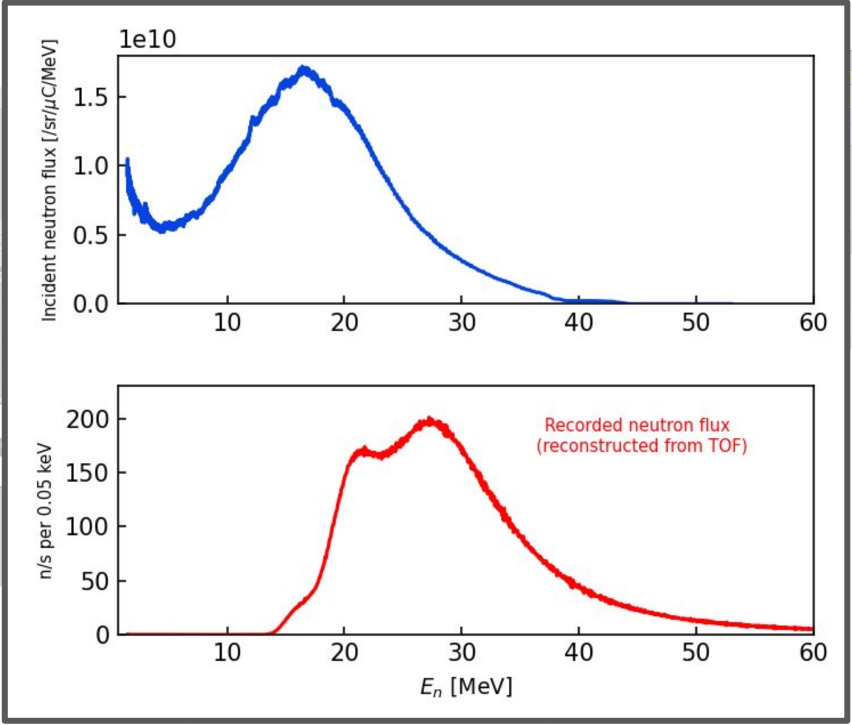
Method: Prompt γ-spectroscopy in coincidence with fast neutrons.



- ➢ 12 clovers at radius of 14.5 cm
- ➢ 31% of the solid angle coverage
- ➢ 6% abs. efficiency at 1332 keV
- ➢ Addback to improve P/T ratio

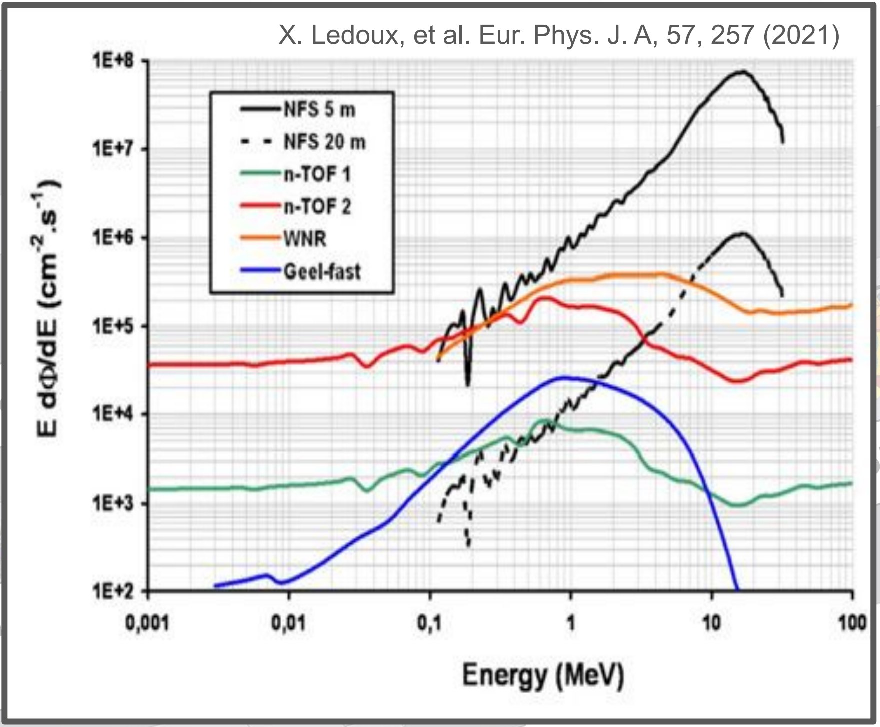
Highest neutron flux beyond 10 MeV world-wide!

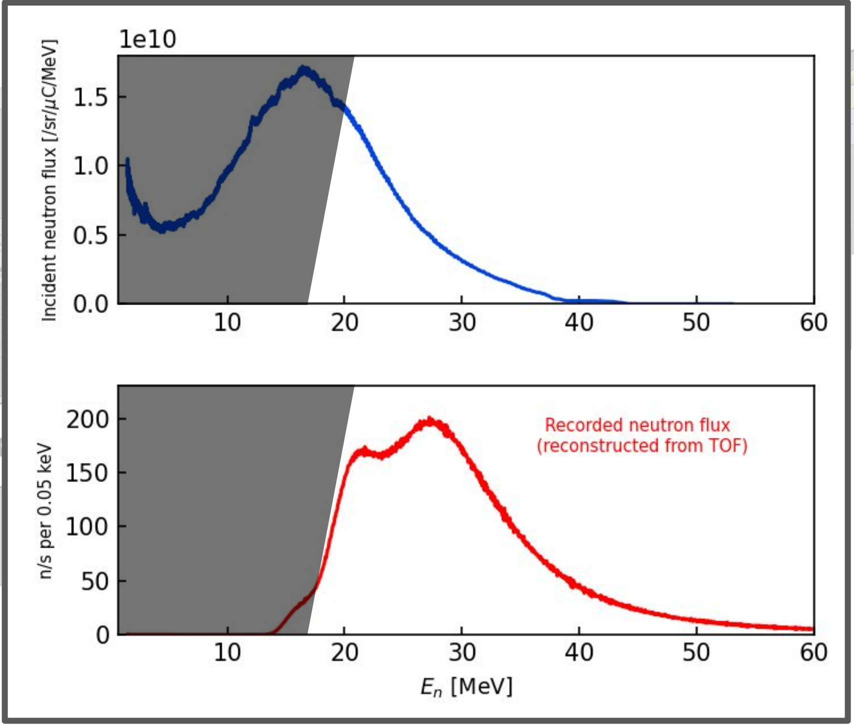




Reconstructed neutron flux from TOF

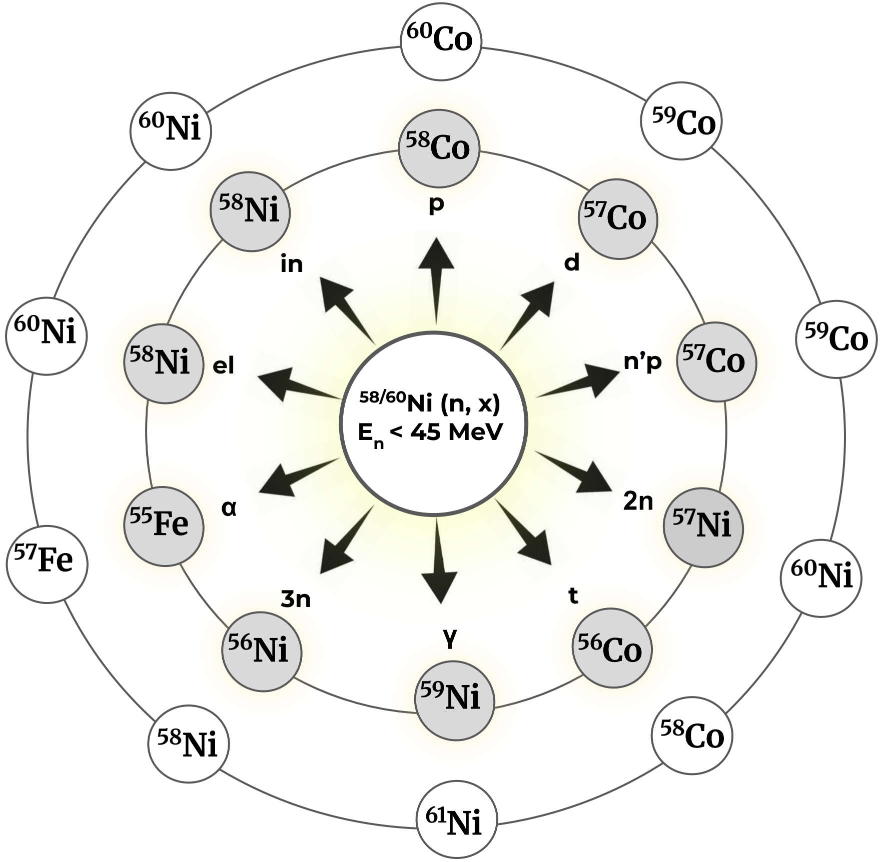
Highest neutron flux beyond 10 MeV world-wide!



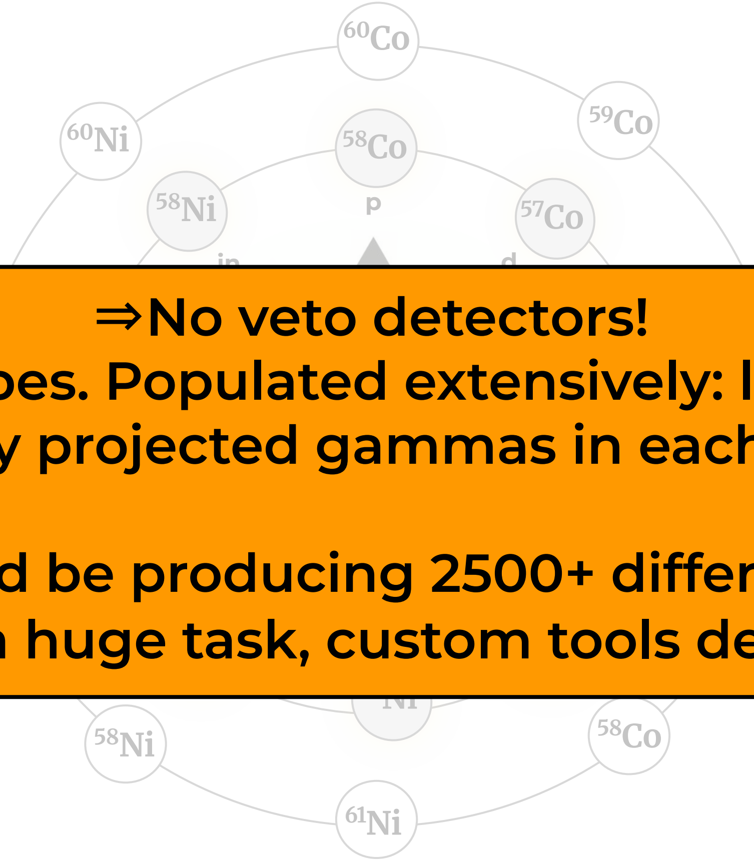


Reconstructed neutron flux from TOF

Method: γ-γ analysis



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



⇒No veto detectors!
⇒Many isotopes. Populated extensively: low selection.
⇒Many projected gammas in each gate!

In total we could be producing 2500+ different transitions!
Verifying is a huge task, custom tools developed! 😅

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

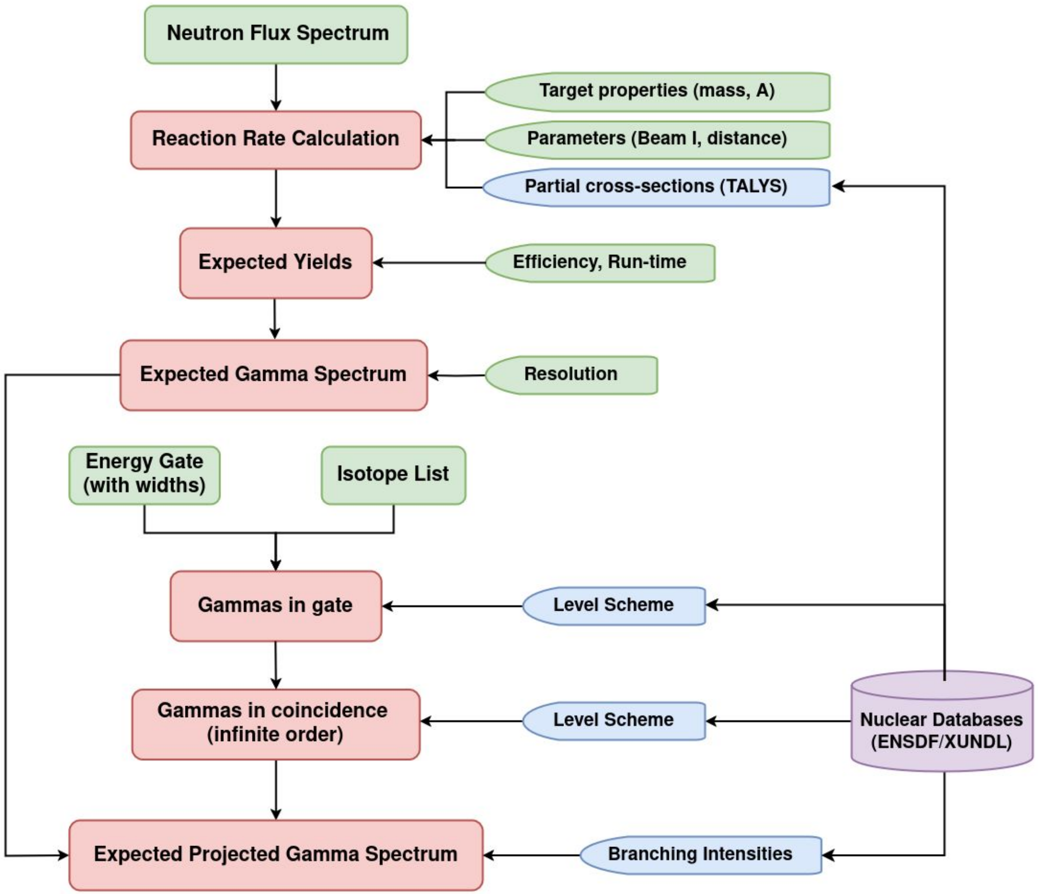
CUSTOM TOOLS

Built custom tools inspired by:

cubix RadWare

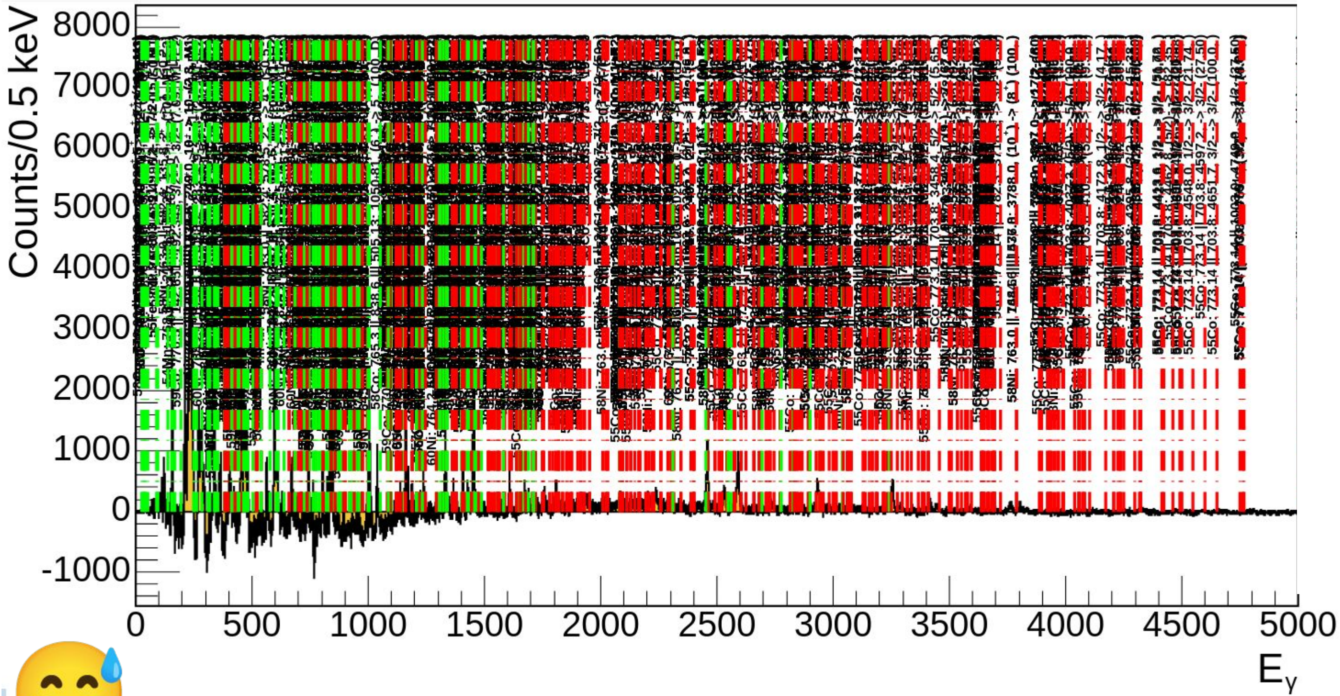
With additional features including:

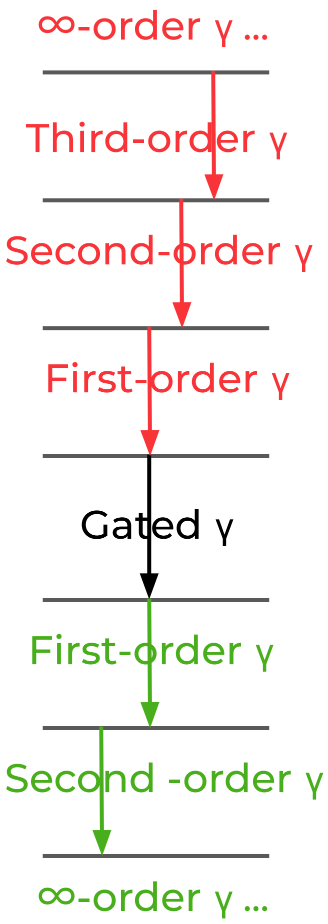
- ➢ Draws identifiers for coincident γ for all orders
- ➢ Calculates simulated coincident gamma spectrum using experiment-specific cross sections and parameters (e.g., Talys).



Custom Tools : The coincidence finder

Gating on 5/2⁻ → 3/2⁻ of ^{57}Ni : 768 keV, ±3 keV *(shown up to 3rd order)*

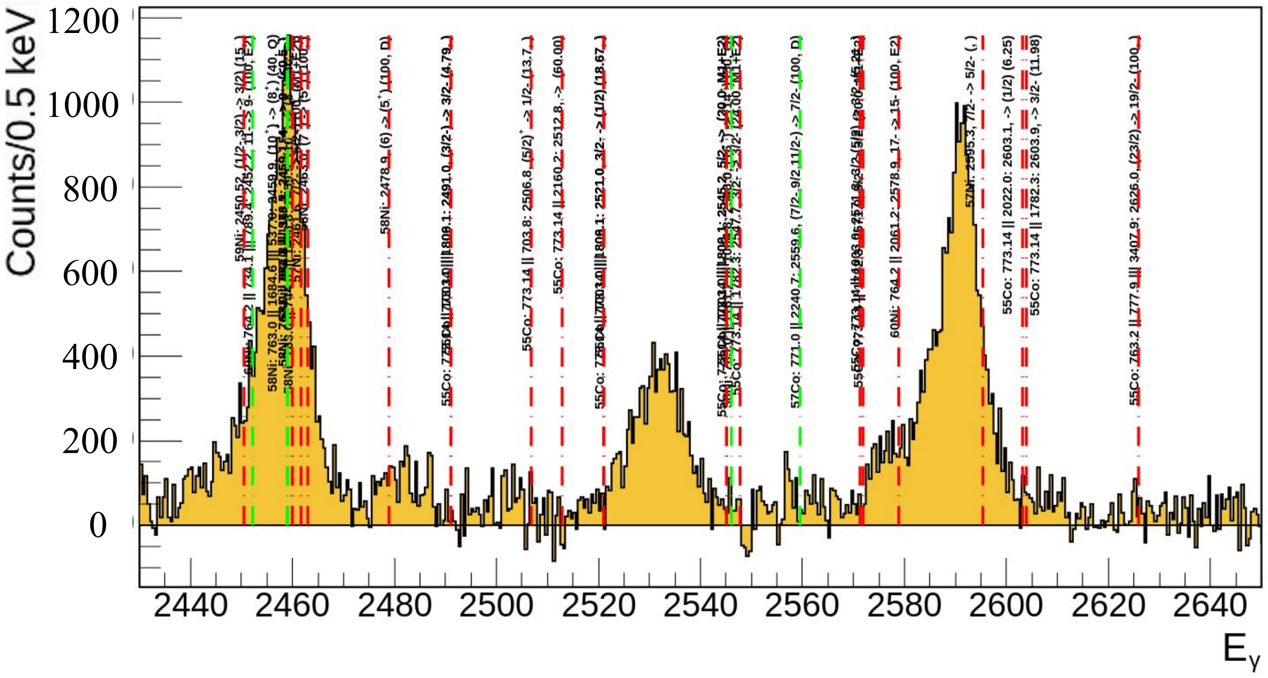




The plots are interactable (easy to zoom in)

Custom Tools : The coincidence finder

Gating on 5/2⁻ → 3/2⁻ of ^{57}Ni (768 keV, ±3 keV)

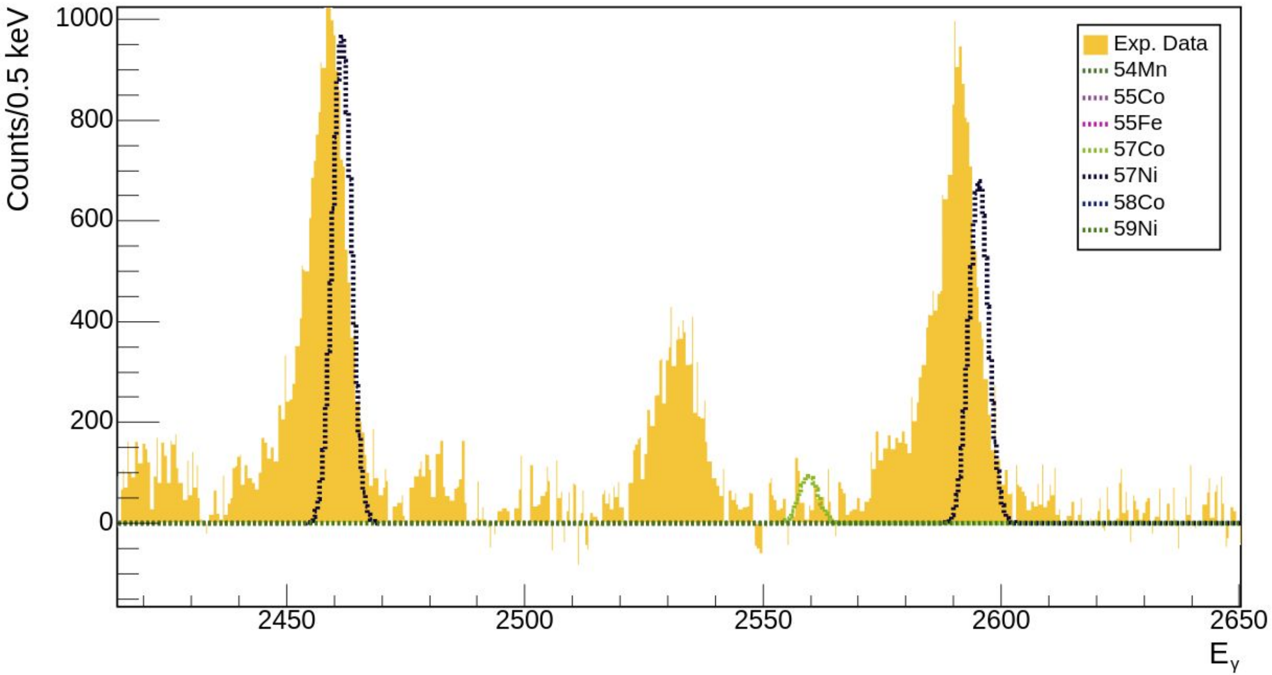


Can go up to infinite order (here shown up to 3rd order).

While these guiding lines make the verification simpler, they are limited.

Custom Tools: Simulated Coincidence Spectrum

Can overlay the simulated spectrum on the experimental spectrum, one example shown here for :

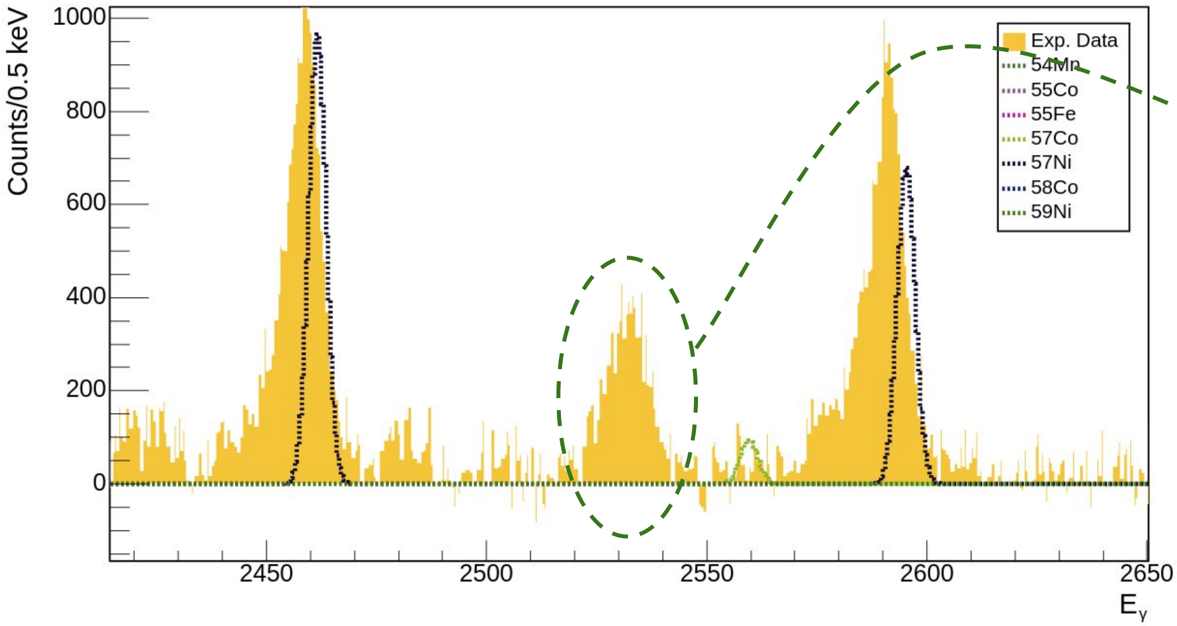


Since the plot is more readable, we go upto infinite order here.

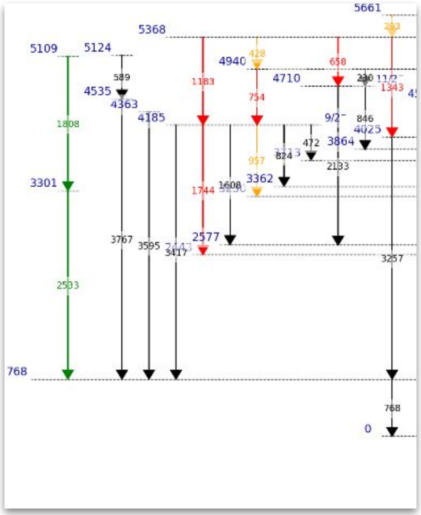
Current limitations of the tool:

- Normalization is needed
- Fraction of peak in gate window not considered
- More realistic FWHM

New Light on ^{57}Ni with (n,2n)



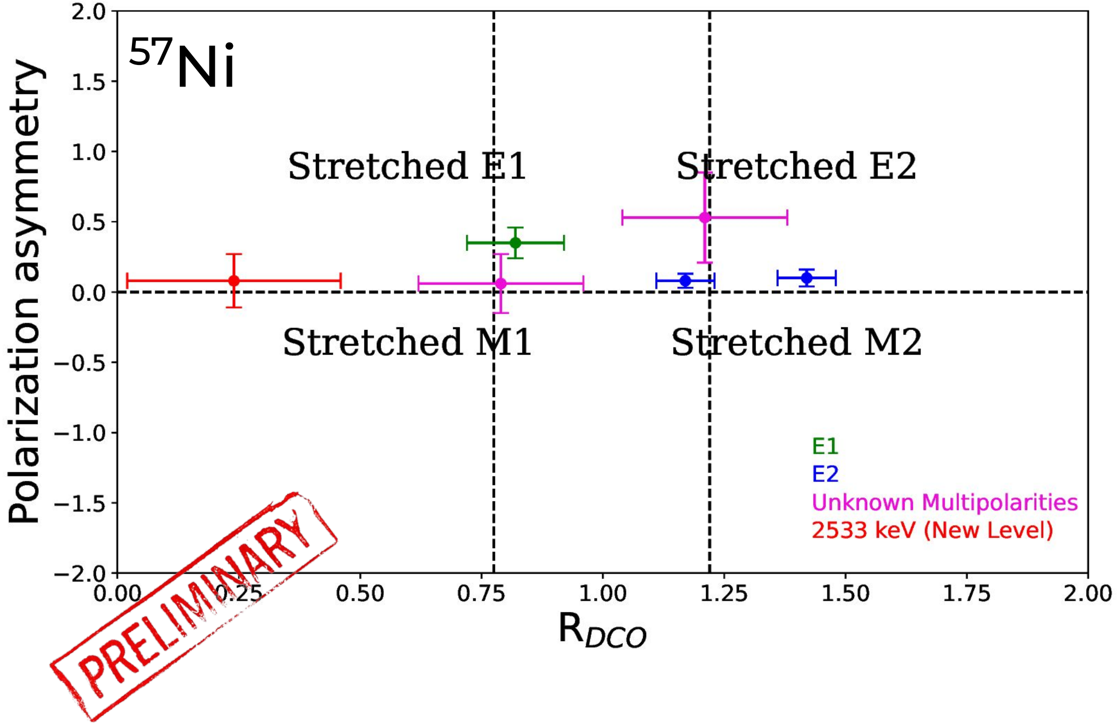
Despite extensive studies by conventional methods, spectroscopy with fast neutrons sheds new light on ^{57}Ni.



- ➢ No evidence of states populated only via particle transfer reactions
- ➢ Overall (n,2n) resembles heavy-ion fusion–evaporation
- ➢ But it’s not simply a subset—it provides new information

https://doi.org/10.1051/epjconf/202532400020

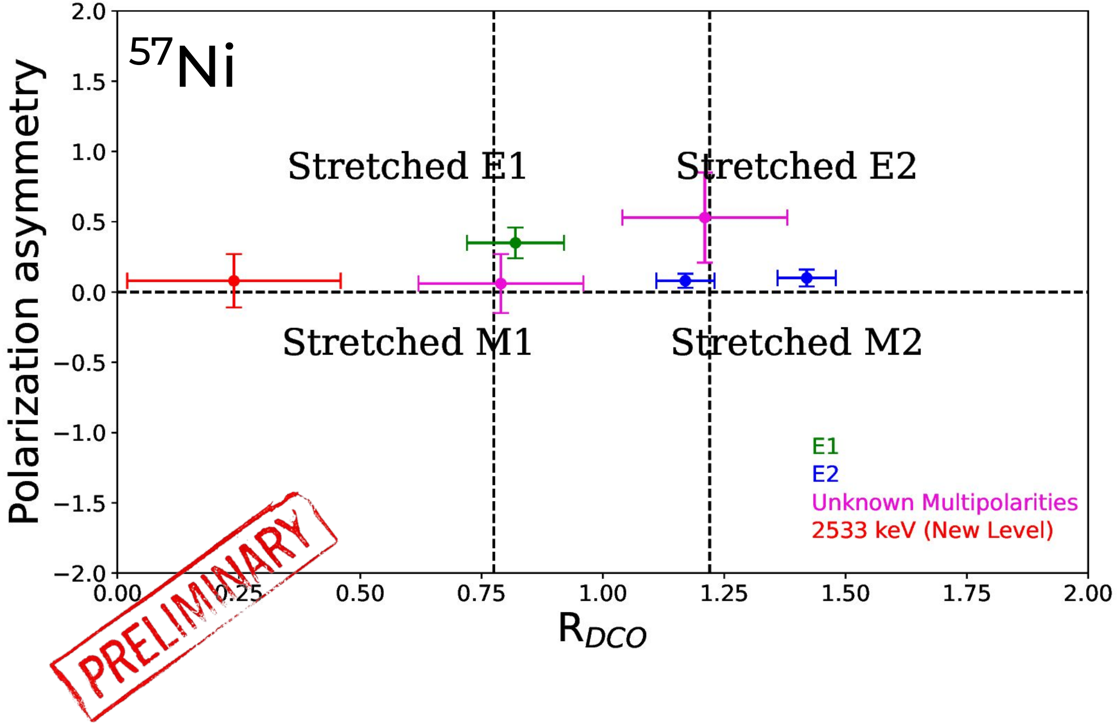
Nuclear alignment with fast neutrons



Alignment observed for the first time with fast neutron reaction.

Sensitive to assigning multipolarities to unknown and new transitions

Nuclear alignment with fast neutrons

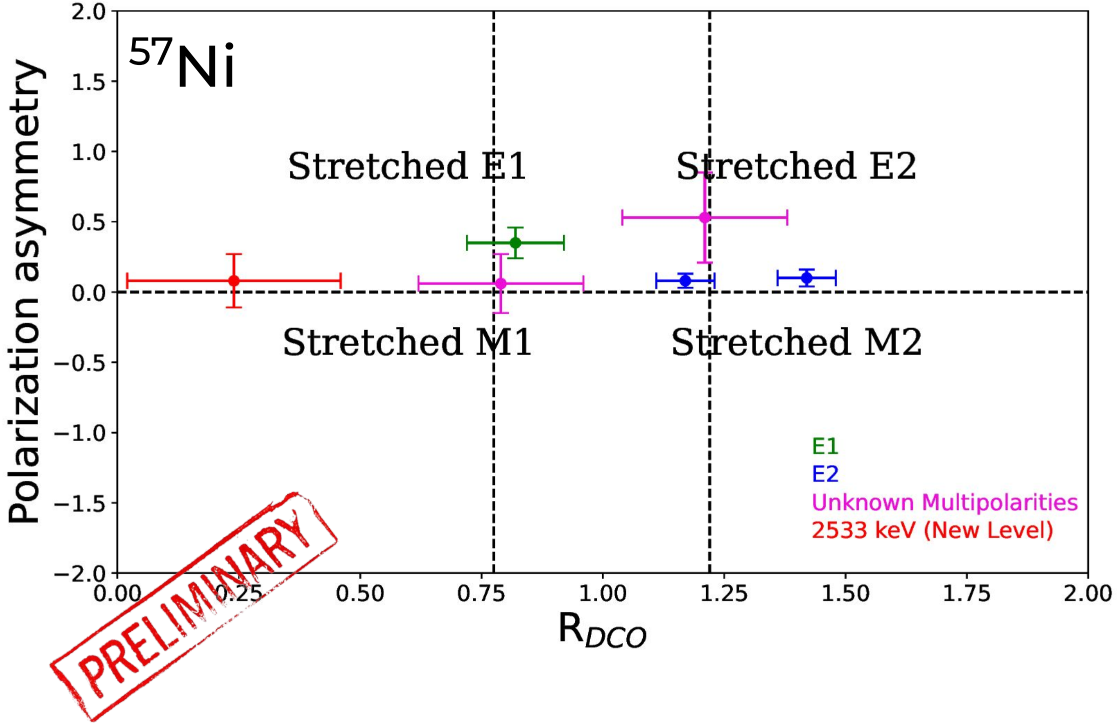


Alignment observed for the first time with fast neutron reaction.

Sensitive to assigning multipolarities to unknown and new transitions

⇒ can infer spin and parity of new levels.

Nuclear alignment with fast neutrons

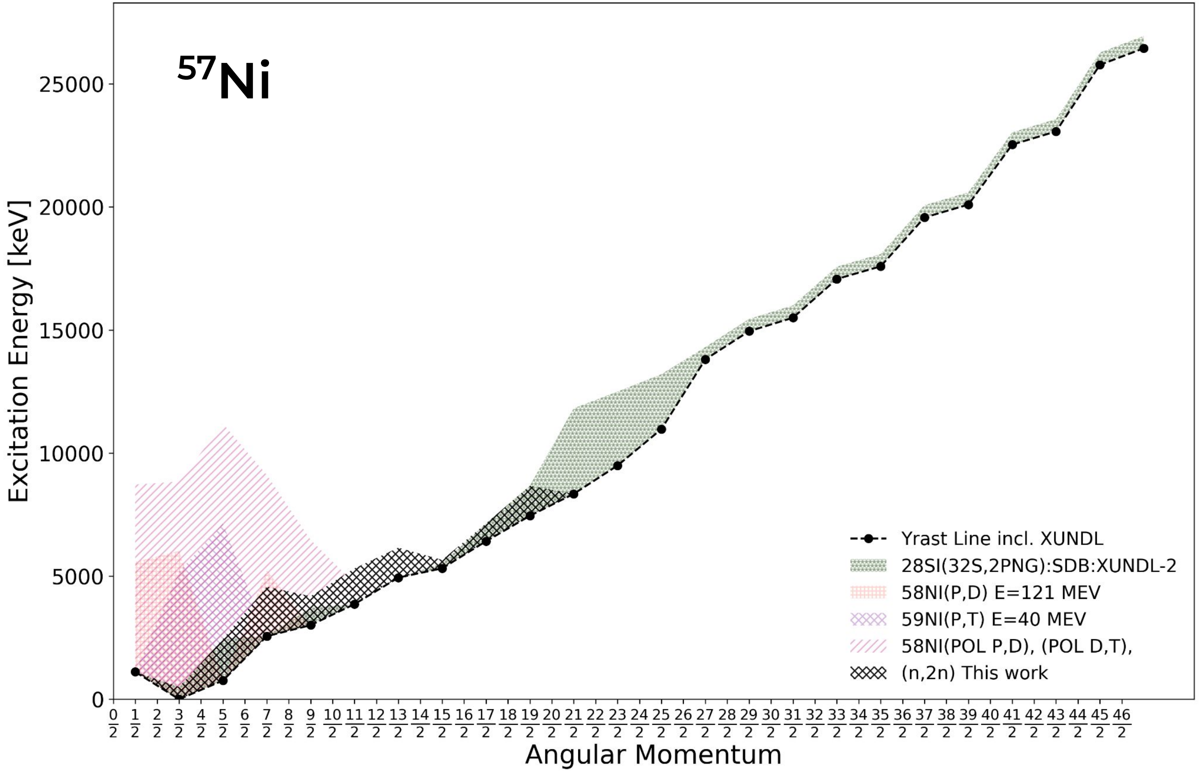


A 3701 keV state in ^{57}Ni was first identified as $(5/2)^-$ in pick-up reaction

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 $g_{9/2}$

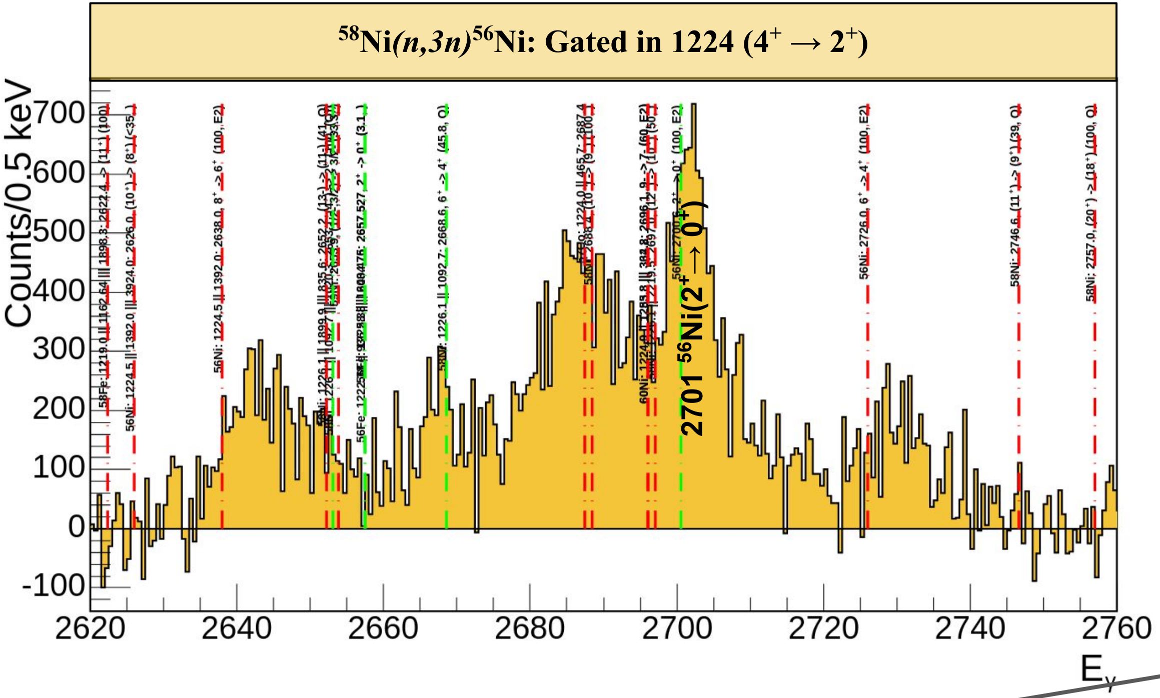
The E1 character of its decay validated using our independent (n,2n) data set!

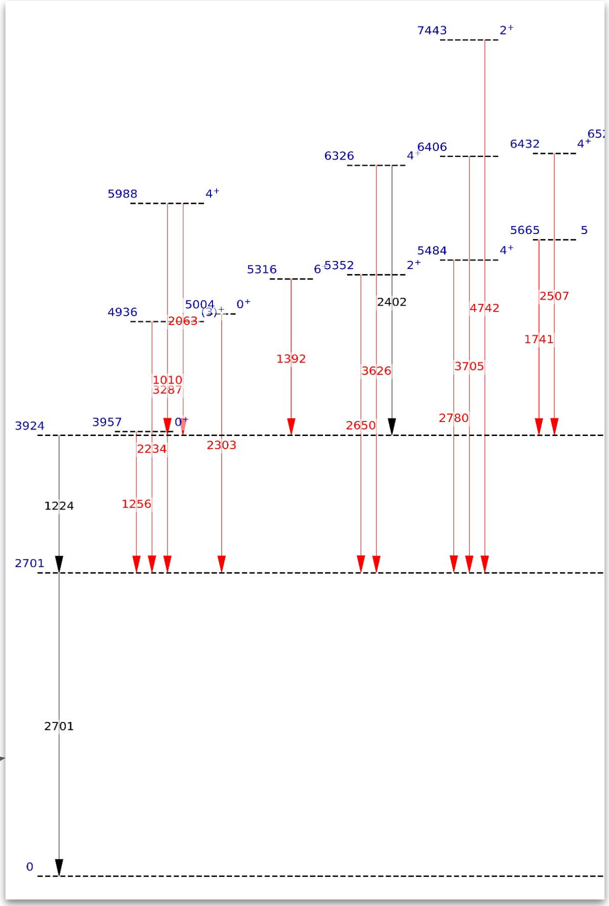
Where is (n, 2n) on the Yrast diagram?



- ➢ Overall (n,2n) behavior resembles heavy-ion fusion–evaporation
- ➢ No high-energy levels observed at low angular momentum (L)
- ➢ NFS limitation: beam energy ($E_n \approx 35$ MeV)
- ➢ Cannot probe whether higher angular momentum states can be excited

The (n, 3n) channel

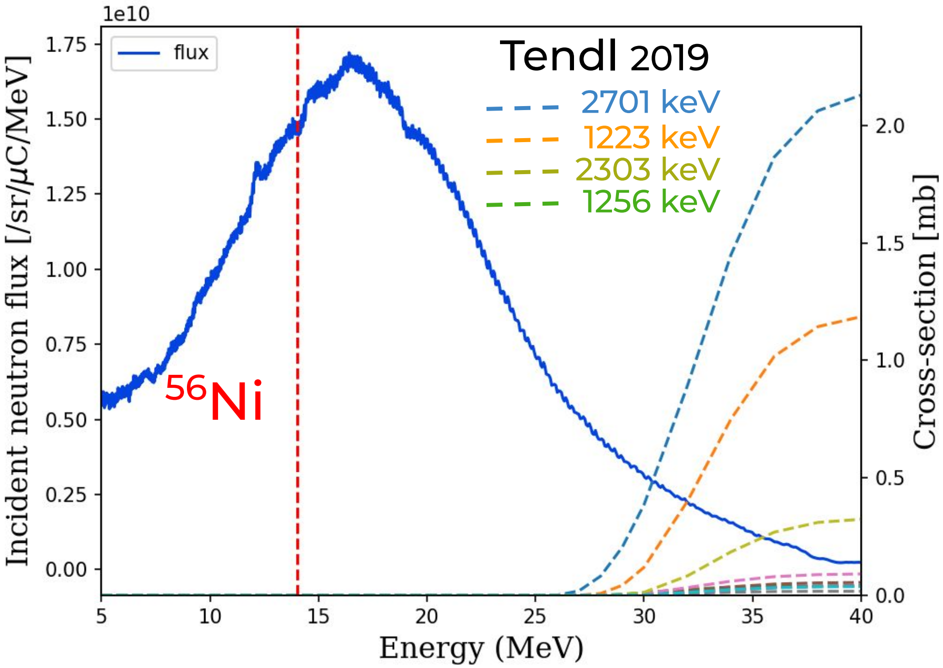




We are not populating ^{56}Ni extensively.

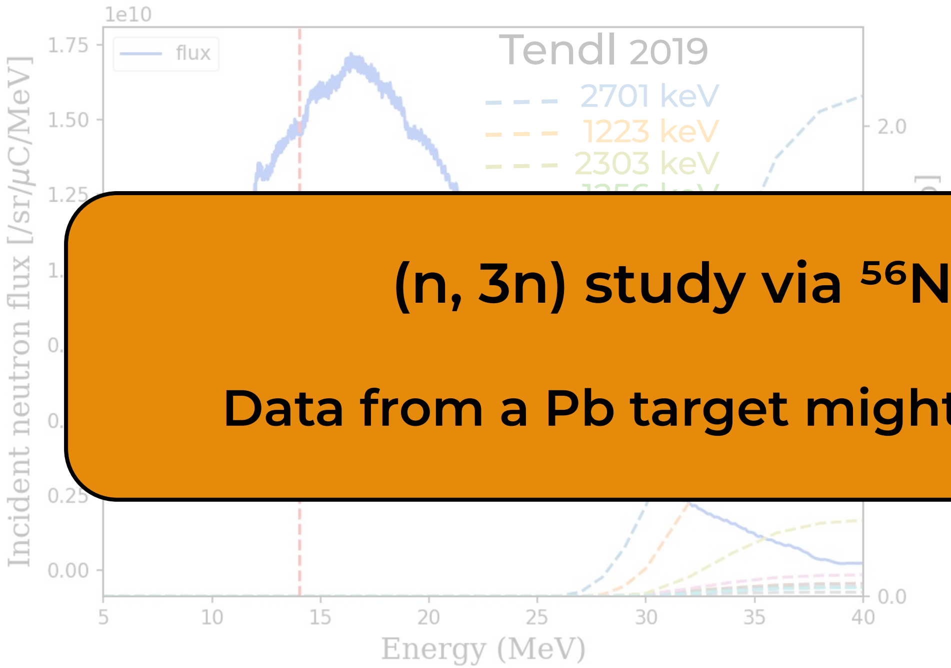
Threshold for this channel was experimentally verified at ~23 MeV.

The (n, 3n) channel



- ➢ 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

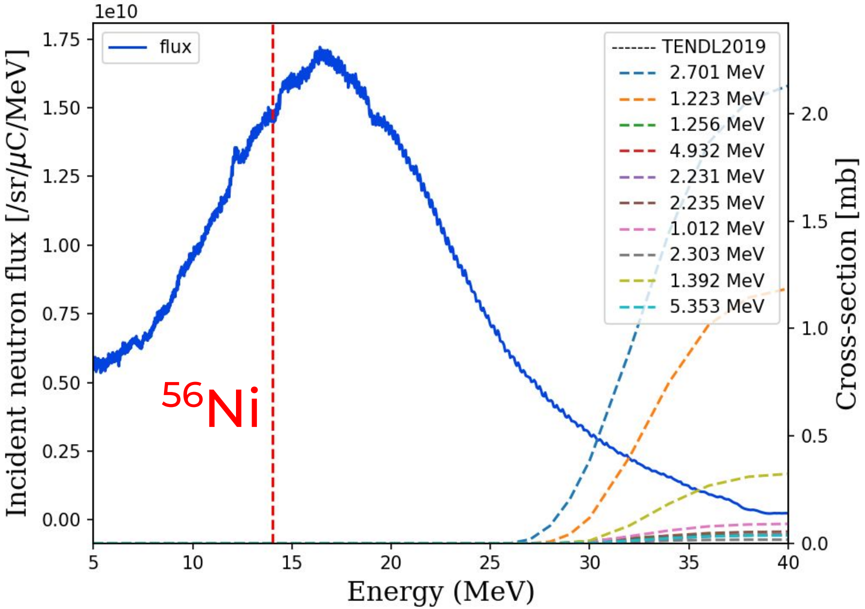
The (n, 3n) channel

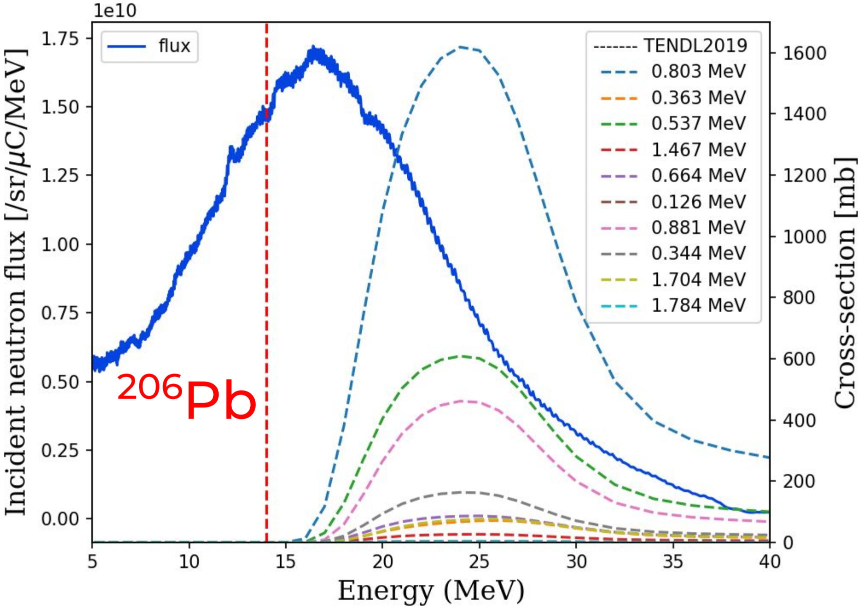


(n, 3n) study via ^{56}Ni is NOT feasible!

Data from a Pb target might yield valuable insights...

The (n, 3n) channel: Ni & Pb

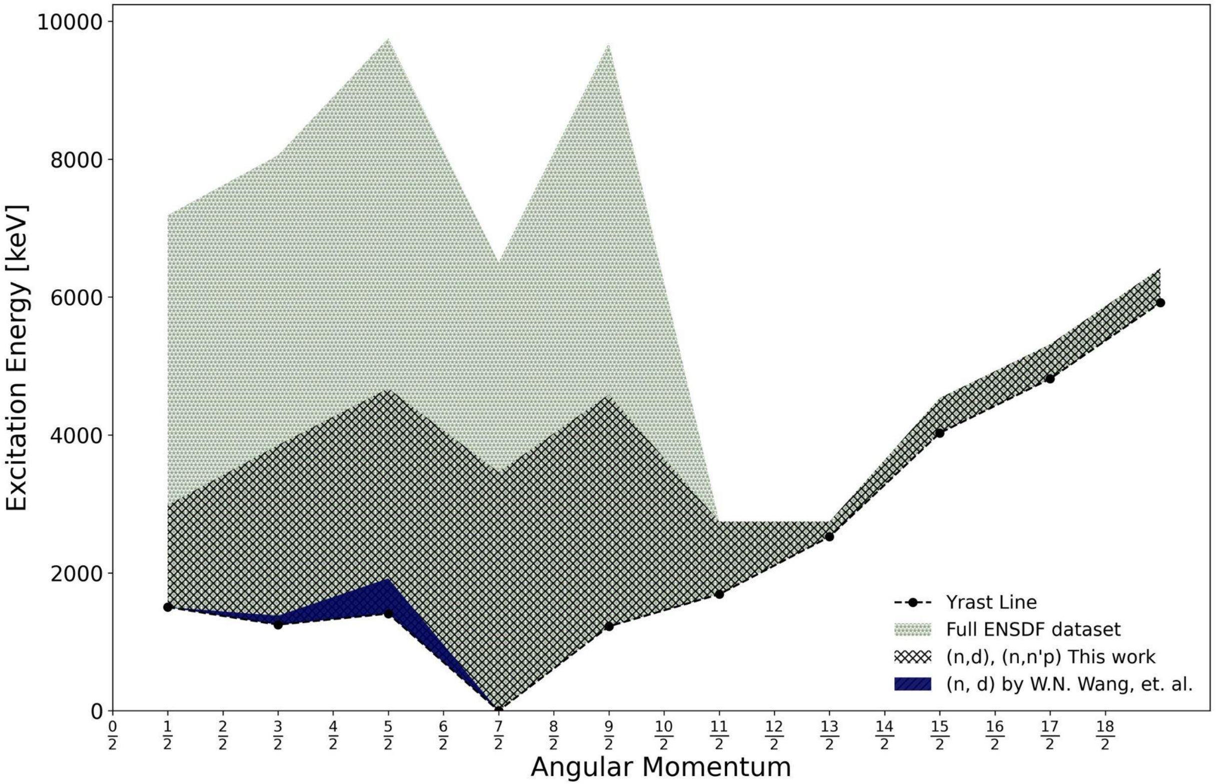




➢ Much lower thresholds and relatively higher c-s for ^{208}Pb(n,3n)^{206}Pb

Charged Particle Channels

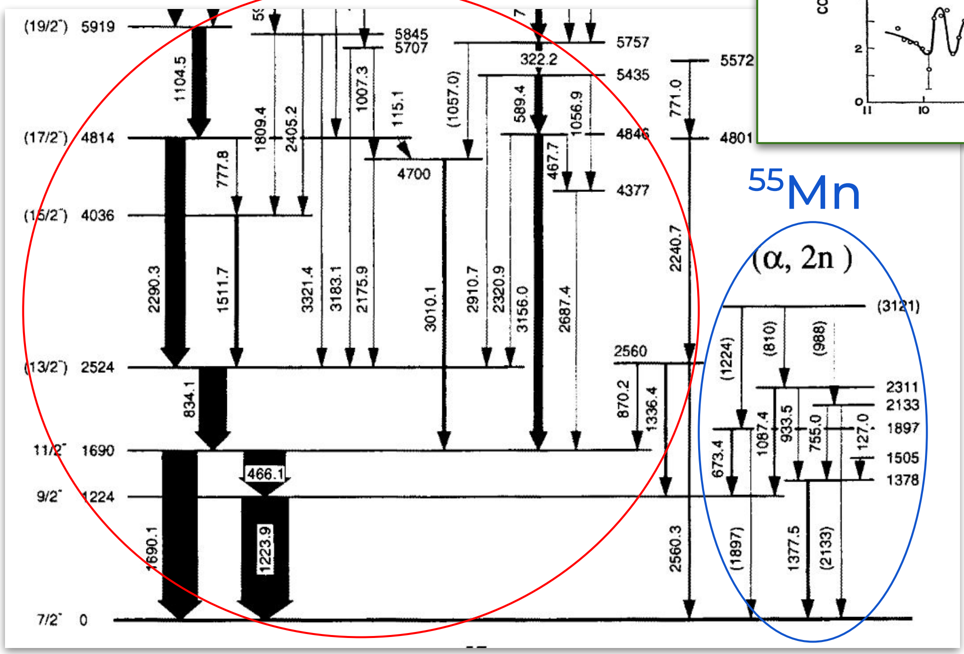
^{57}Co



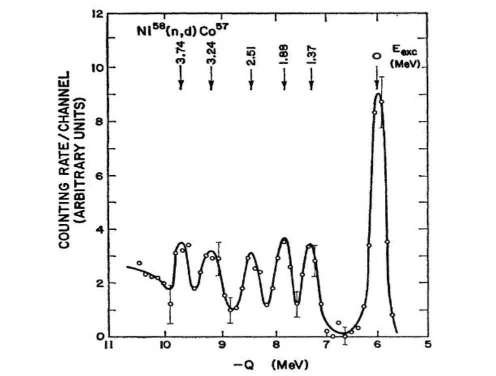
- ^{57}Co produced by (n, d) and (n, n'p) channels
- Extensively populating this isotope
- Very low selection rules

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

Heavy-ion: ^{40}Ca (^{20}Ne, 3pγ)



M. Rejmund et al.



^{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

DOI: https://doi.org/10.1103/PhysRev.140.B882

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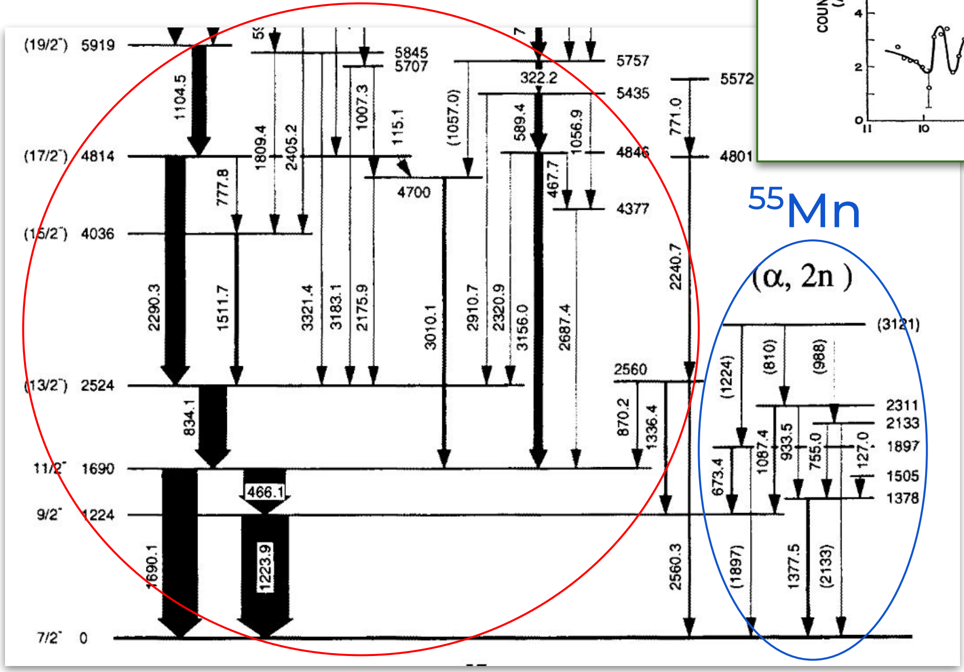
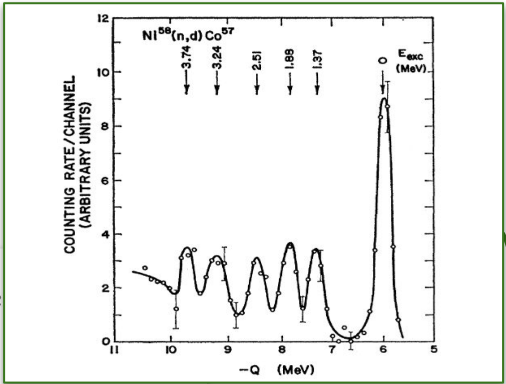


^{55}Mn

M. Rejmund et al.



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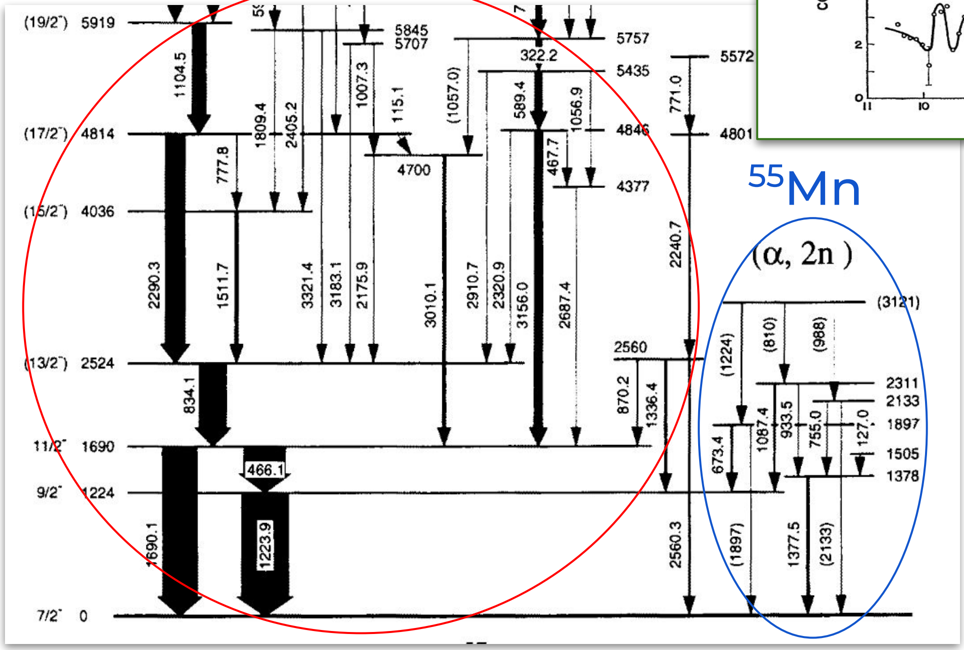

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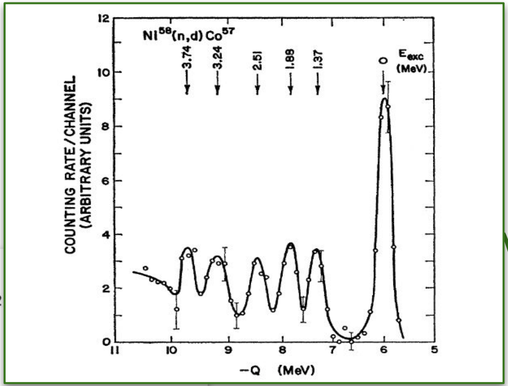

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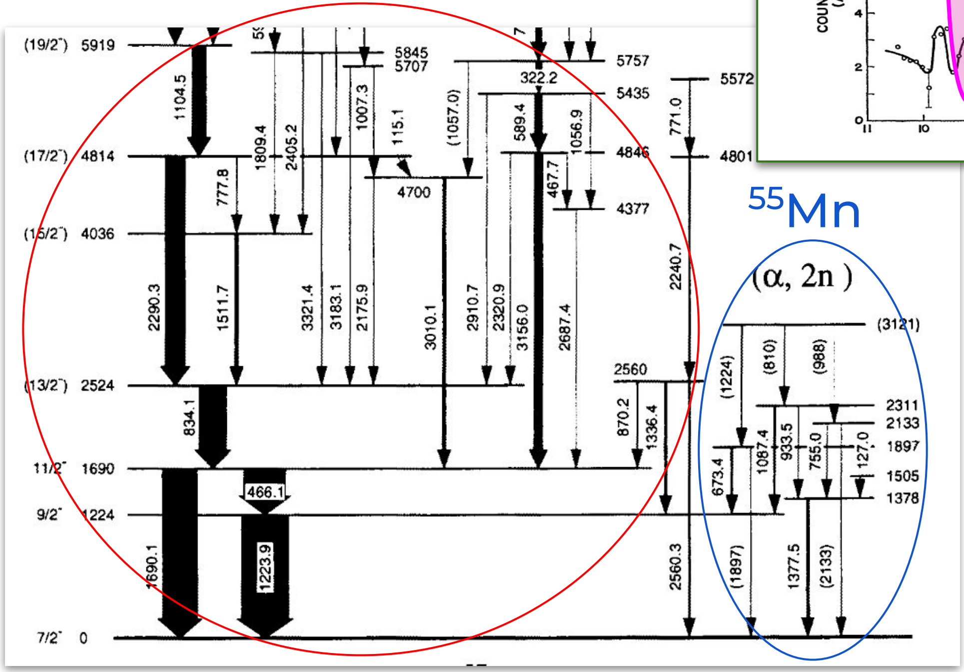

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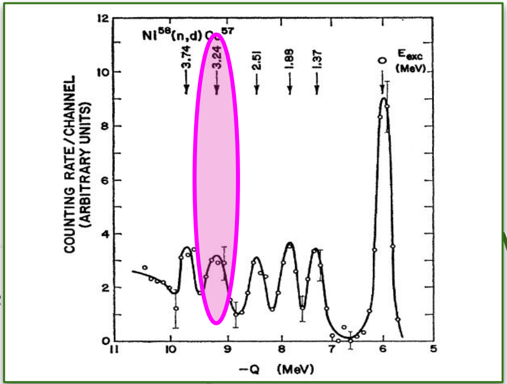

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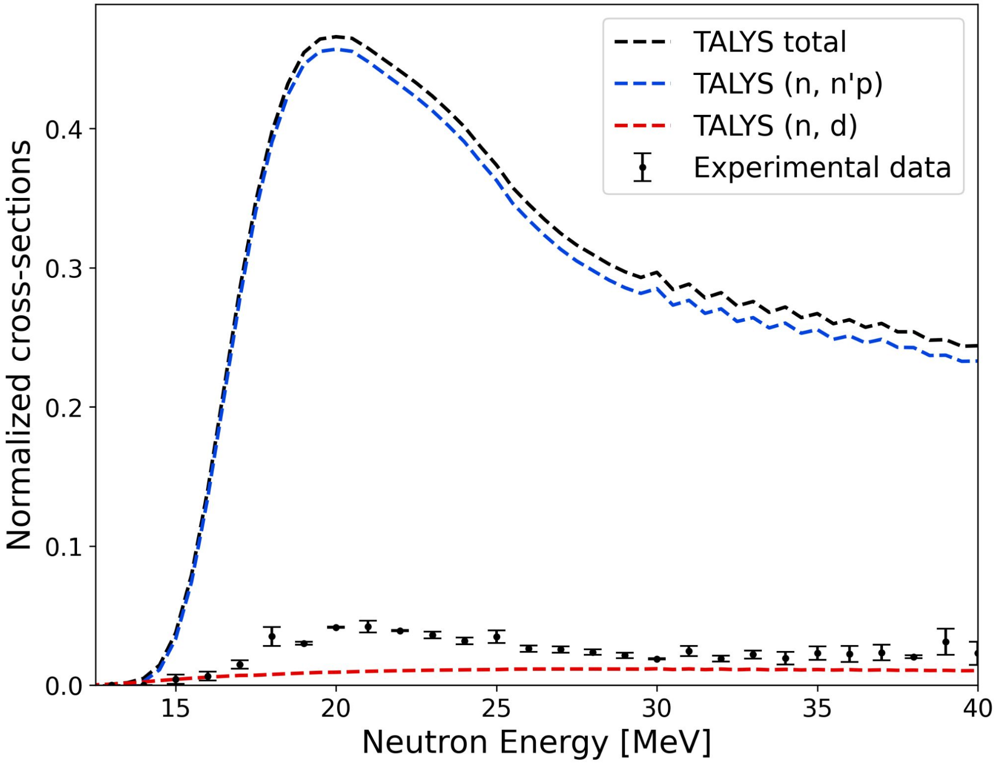
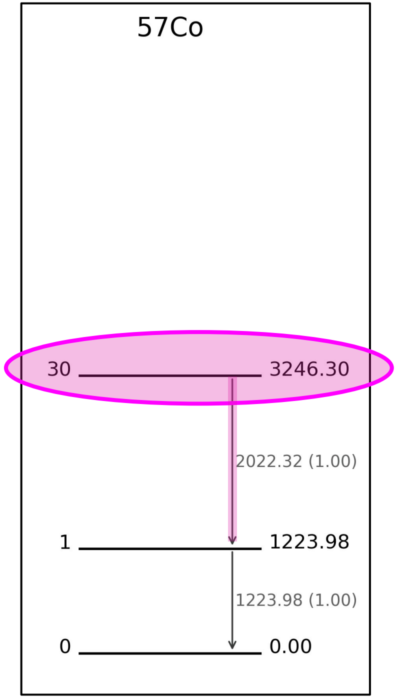
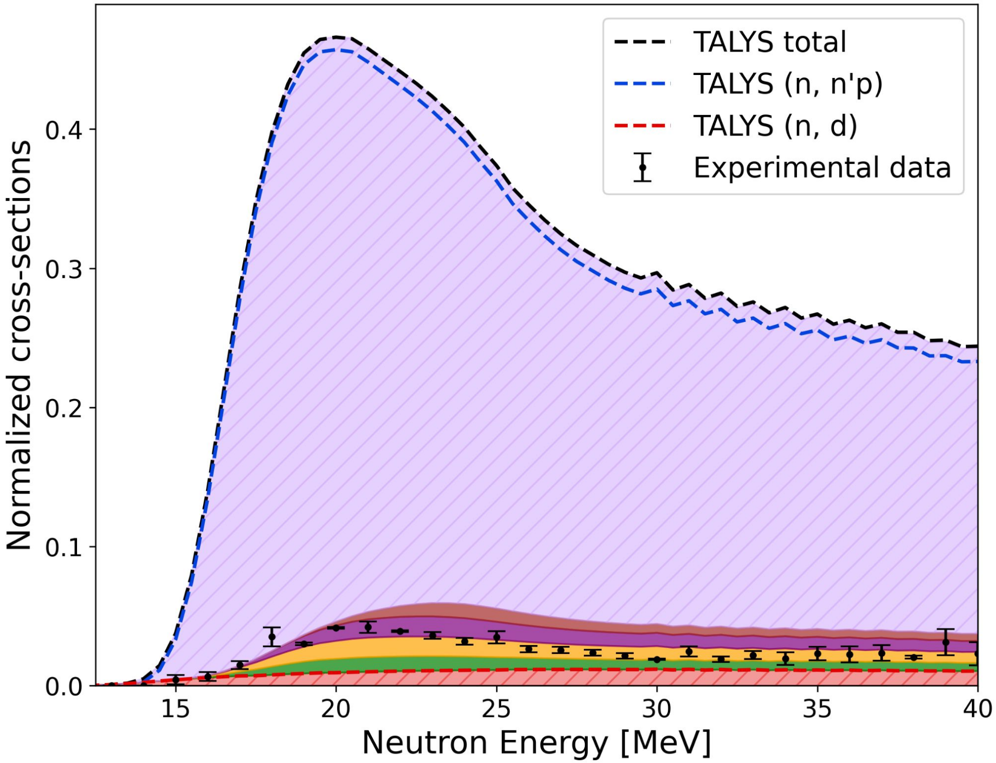
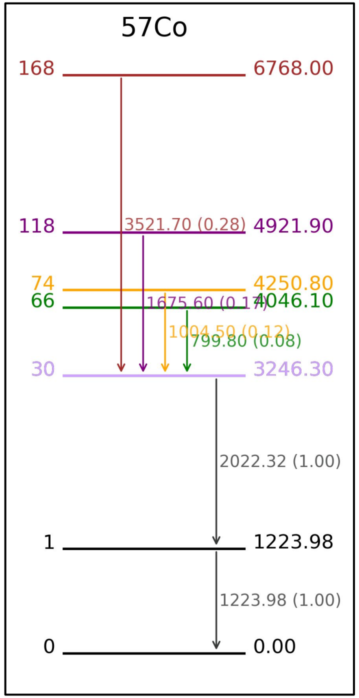


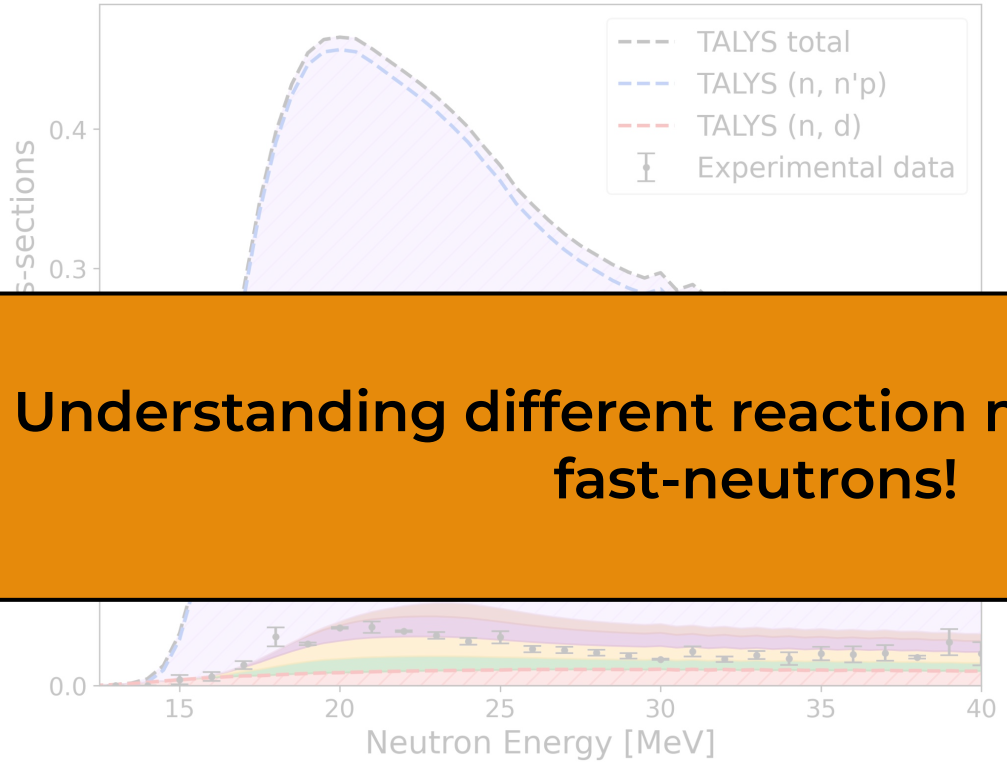


- ➢ TALYS overestimates the cs this transition, primarily from (n, n'p).
- ➢ Data suggests additional rxn mechanisms beyond pure (n, d)...





- ➢ TALYS says 3.2 MeV state is directly populated via (n, n’p) → likely incorrect.
- ➢ Seems (n, n’p) can excite higher states, which then decay to the 3.2 MeV state.



Understanding different reaction mechanisms with fast-neutrons!

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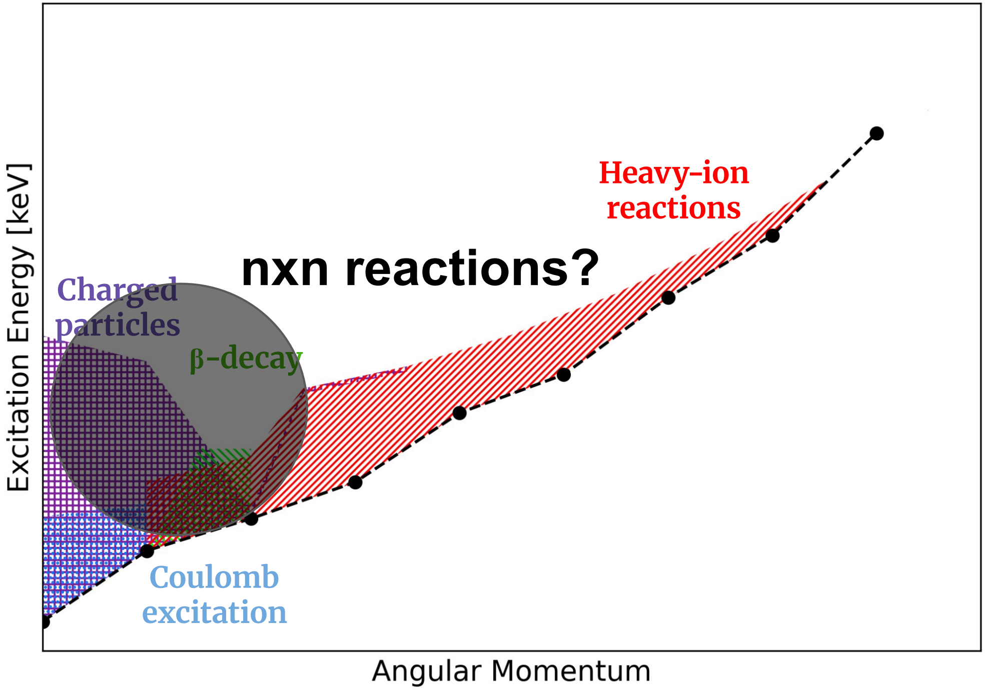
Summary and Future Plans



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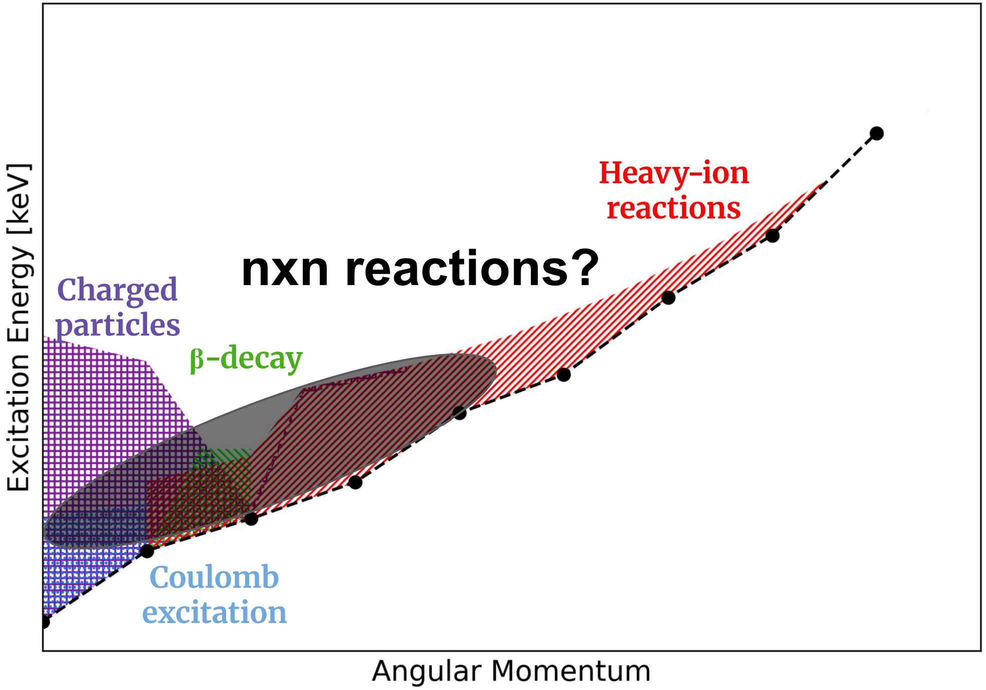

Summary and Future Plans

- Gained new insights into (n,xn) reactions from a nuclear structure perspective.

- ^{57}**Ni**: Discover new information with fast-neutron probes.

- Alignment observed for the first time with fast neutron reaction.

- Tools developed for complex γ-spectroscopy data analysis (briefly presented).

- **^{57}Co:**
  Extensively states populated → single-particle + collective excitations.
  Asymmetry & RDCO calculations applied to unknown/new transitions.
  Understanding (n,d) and (n,n'p) channels: ongoing...

- Ambitious final goal is to study the mechanism between direct and compound nuclear reactions.

THANK- YOU!

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Nuclear Physics A

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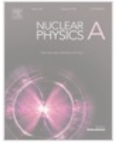


In-beam γ-ray spectroscopy with fast-neutron probes at NFS

H. Sengar [a], E. Clément [a], D. Ackermann [a], O. Aktas [a], L. de Arruda [a], G. de France [a], P. Dessagne [e], G. Henning [e], I. Jangid [a], D. Kalaydjieva [b], M. Kerveno [e], N. Kumar [e], X. Ledoux [a], A. Lemasson [a], I. Matea [d], P. Miriot-jaubert [c], A. Navin [a], J. Piot [a], D. Ramos [a], T. Roger [a], P. Sharma [a], T. Tanaka [a]

[a] Grand Accélérateur National d'Ions Lourds, CEA/DRF - CNRS/IN2P3, Caen, France

[b] University of Guelph, Canada

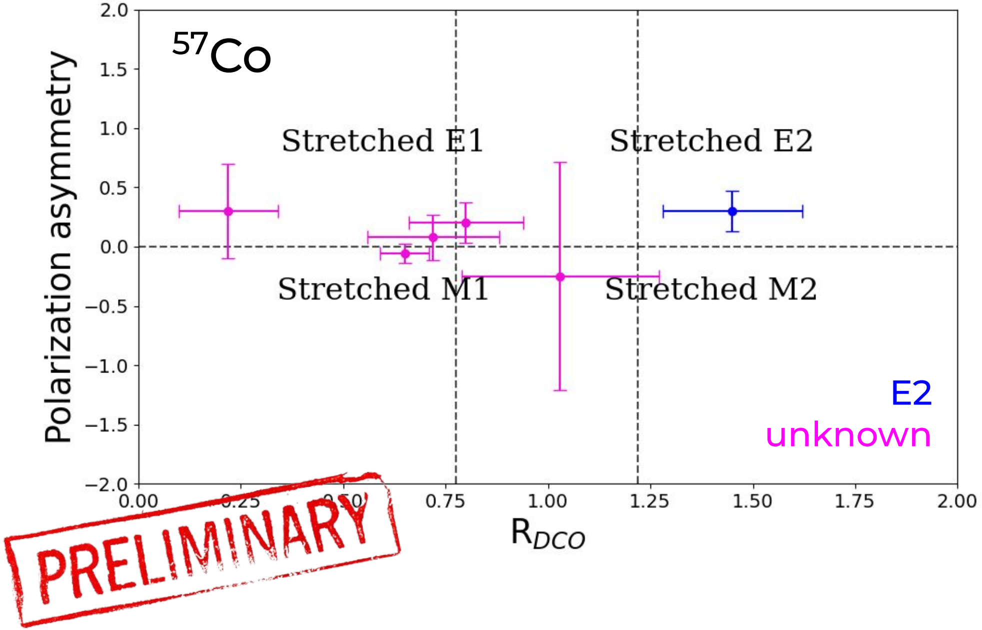
[c] IRFU, CEA Saclay, Université Paris-Saclay, France

[d] IJCLab, Université Paris-Saclay, France

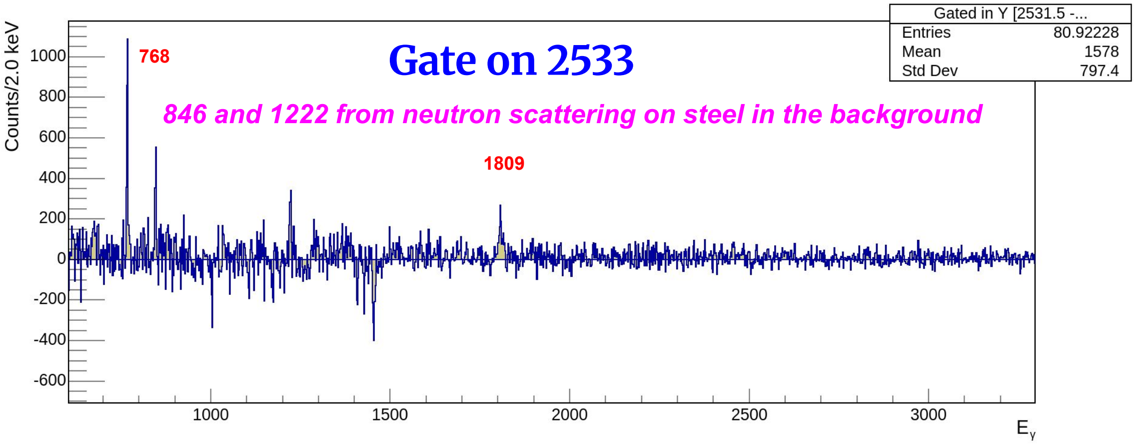
[e] Universite de Strasbourg, CNRS, IPHC/DRS UMR 7178, 23 Rue du Loess, F-67037 Strasbourg, France

Backup Slides

R_{DCO} vs Asymmetry

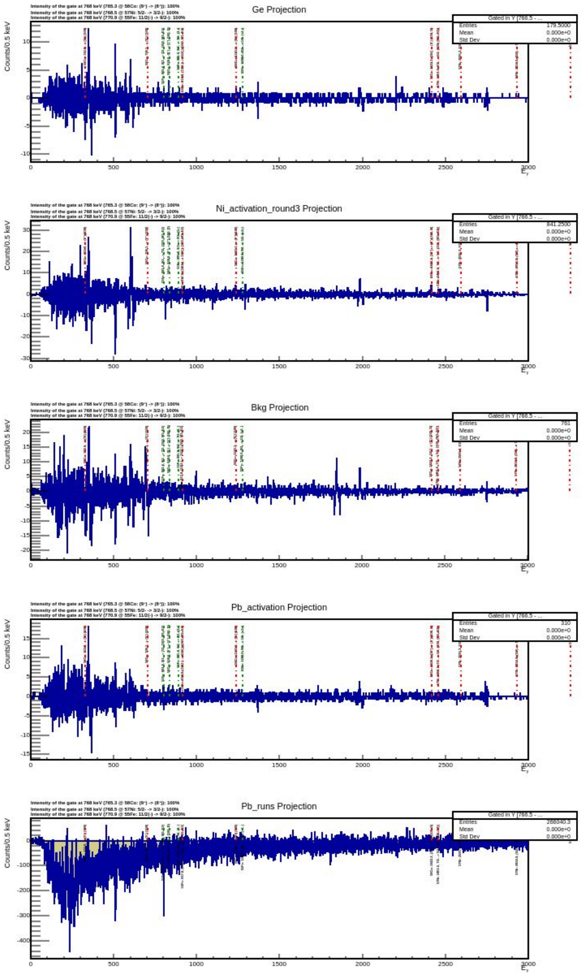


Validation of the new γ

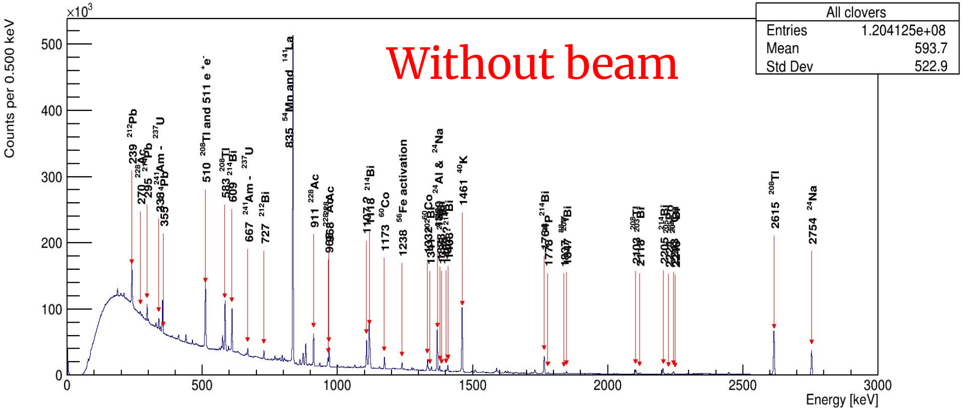


- ➢ Reverse gate on the new gammas to validate and study the full cascade
- ➢ Also, making sure this coincidence is not present in various other background, activation runs and beam runs with Pb target.
- ➢ Hence can be considered a true new coincidence from ^{57}Ni.

We validate the new gamma!



Background characterization



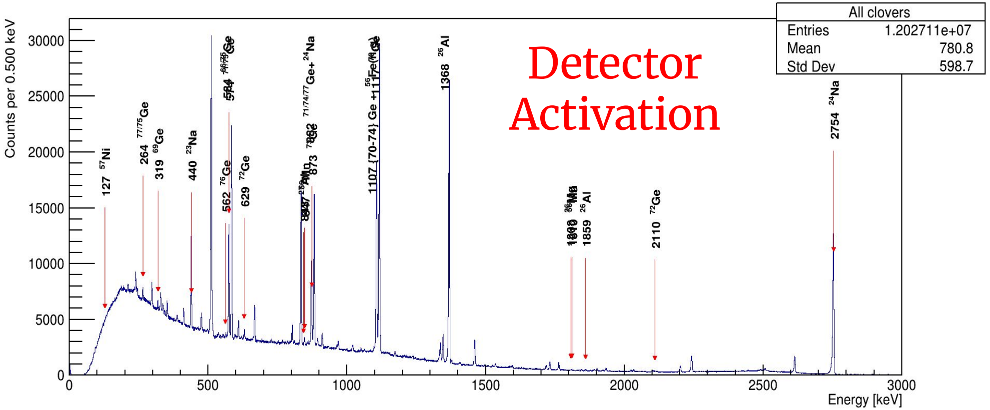
The natural background is first studied without the beam.

It consists of cosmic radiation and radionuclides formed due to it, as well as radiation from various sources in the experimental hall.
Majorly: ^{40}K, and decay chains of $^{238/235}$U and ^{232}Th.

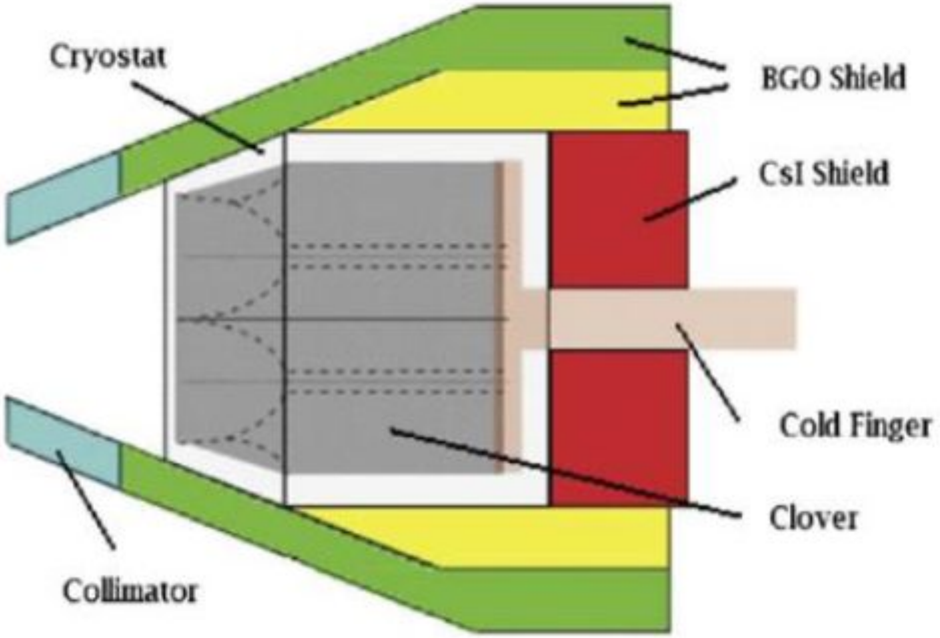
Along with activation of the Ni, we could also spot activation of Ge detector and collimator itself.

Steel/Iron activation ($^{54/56}$Mn/^{56}Fe) as well as ^{27}Al activation(843, 1808, 1368 keV) were observed.

Activation of ^{23}Na formed via ^{27}Al(n,nα)^{23}Na was also observed.



Counts at 10 uAmps ~ 20kHz per clover



How do we get high flux high energy neutrons?

The powerful LINAG [10 mAmps of deuteron at the beginning]:

In order to avoid the overlap of neutrons from successive bursts, the beam repetition rate is adapted to the flight path: 1 MHz and 250 kHz for 5 and 20 m respectively.

The maximum deuteron beam intensity is then 4 times lower at 20 m than at 5 m.

NFS is very competitive in terms of average flux in comparison with n_TOF, GELINA or WNR between 1 and 35 MeV.

This intense average flux is due to the high beam-repetition rate(~800 kHz), the instantaneous flux is lower than the other facilities.

The flux (Φ) of particles can be expressed by the following equation: $\Phi = I \times f$

Where: Φ is the particle flux, I is the beam current,f is the beam repetition rate.

However, it's important to note that increasing the repetition rate may have engineering and technical implications, such as increased power requirements, heat generation, and potential effects on beam stability. Additionally, the specific design and capabilities of the LINAC will influence how changes in repetition rate affect overall performance.

Moreover, NFS presents some advantages due to the neutron production mechanism itself: In spallation sources the high energy neutrons (up to hundreds MeV), may imply challenges for both collimation and background.

Secondly, the gamma-flash, which is known to be very penalizing, especially because it induces dead time, will probably be strongly reduced at NFS.

How do we calculate neutron flux?

Neutron detectors (liquid scintillators EJ309) at 607 cm

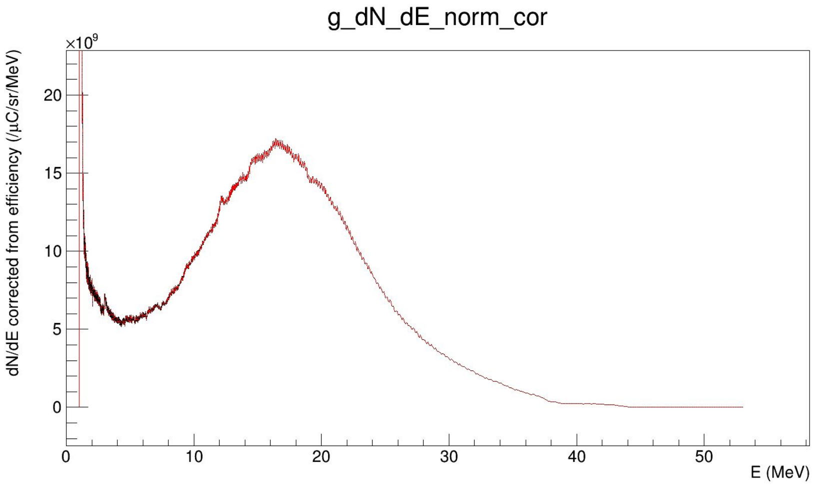
The time bw detection of an event and the RF signal is measured by TAC and we do neutron gamma discrimination using pulse shape analysis.

The neutron energy is measured by TOF technique

Neutron yield measurement:
Event by event we find energy of each neutron.

As shown before…

Flux reaching the target:



Integral of the spectrum = 3.159e+11 n/sr/µC
Distance to the target: d = 860 cm
Beam current: I ~ 10 micro Ampere

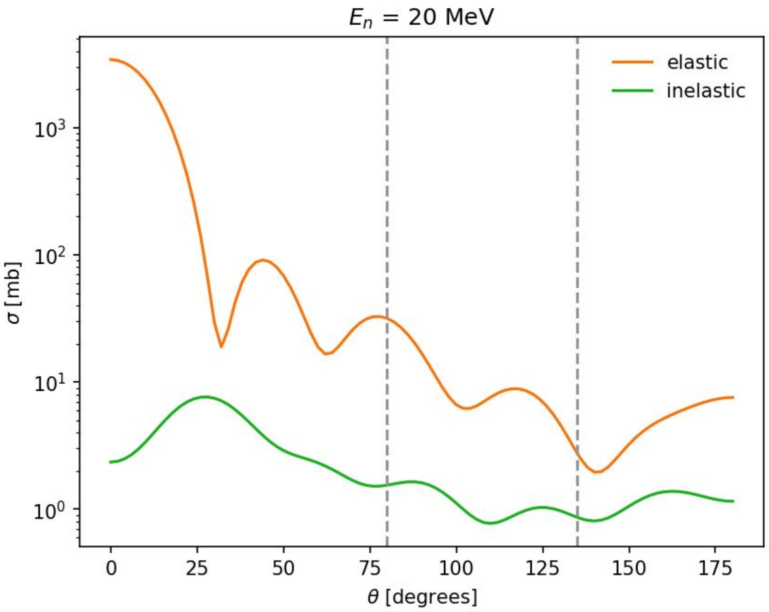
SO, flux = 4.27e+06 n/cm2/s

V_{target} = 0.1 cm * 10 cm * 10 cm
m_{Ni58} [g/target] = (0.1 cm * 10 cm * 10 cm) * (8.99 g/cm3) = ~90 g

N_{Ni58} . V = m_{Ni58} . N_A / M_{Ni58} = 90 g * 6.023e+23 / 58 = 9.3e+23 atoms/target

Reaction Rate = flux * nuclear_density * {c-s(n,n’) * 10^(-24) }

= 4.27e+06 n/cm2/s * 9.3e23 * {c-s(n,n’) * 10^(-24) }

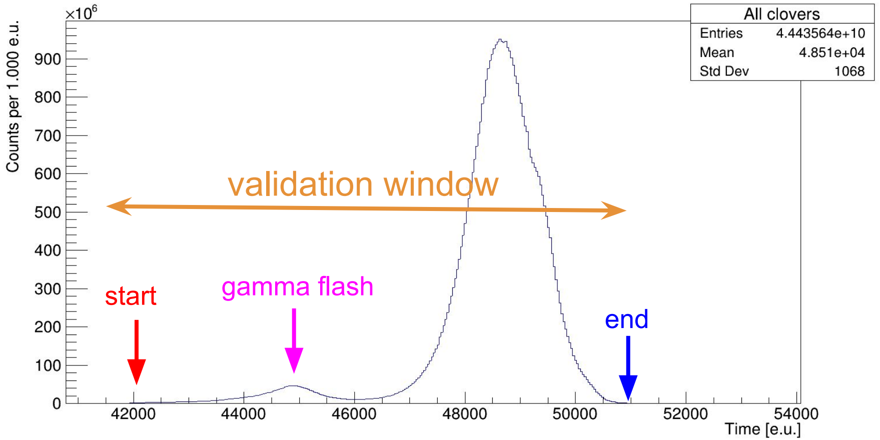


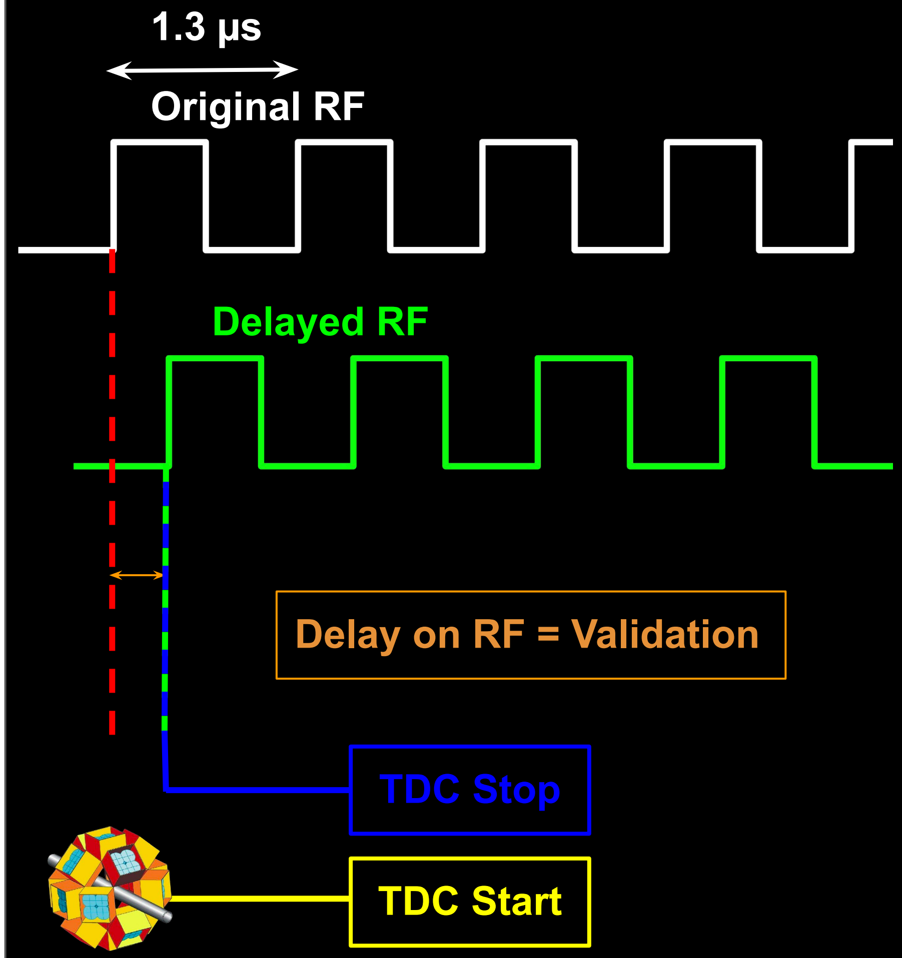
First we interpolate the c-s at neutron engines for at NFS
We multiply flux and c-s bin by bin
Now we can multiply with the runtime of all runs

Total neutrons so far.. / surface area of the ring(r=14 cm, 80° to 135°) = 2*math.pi*14*14*(0.17+0.7)
From here we get the neutron dose per unit area…

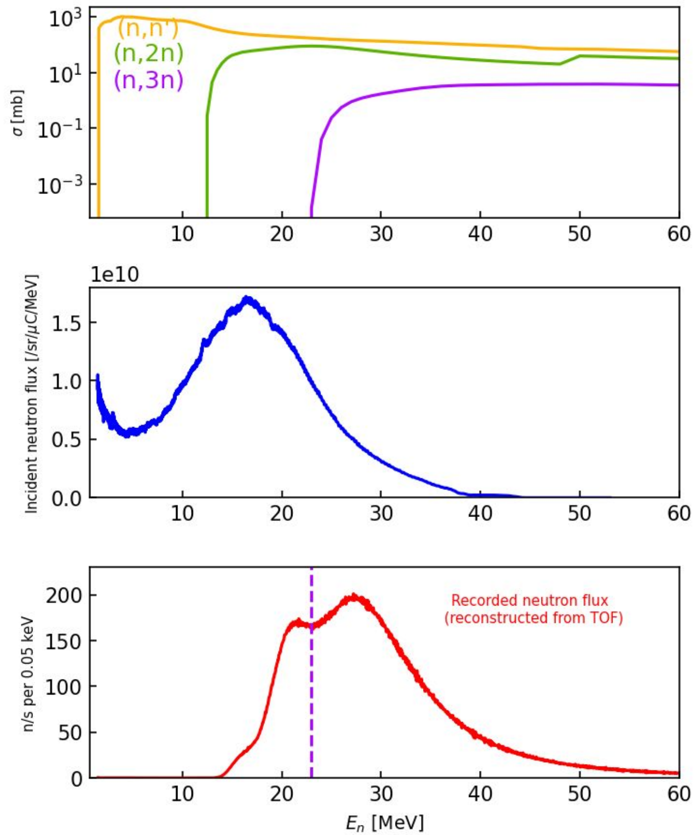
Estimating Neutron Energy

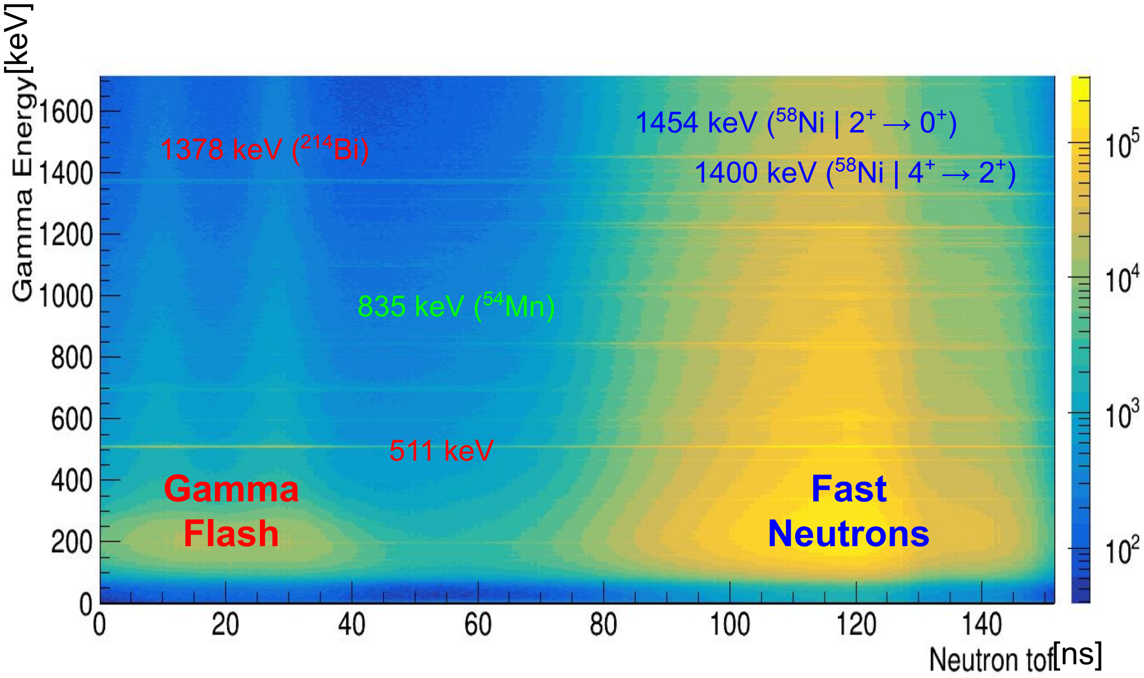
- Neutron TOF is started by the hit in EXOGAM and stopped by the delayed RF of the LINAC (duty cycle = 1.3 μs).
- TOF is calibrated using gamma flash (28.7 ns) from the neutron converter (8.6 m away) and the validation gate window (200 and 175 ns).





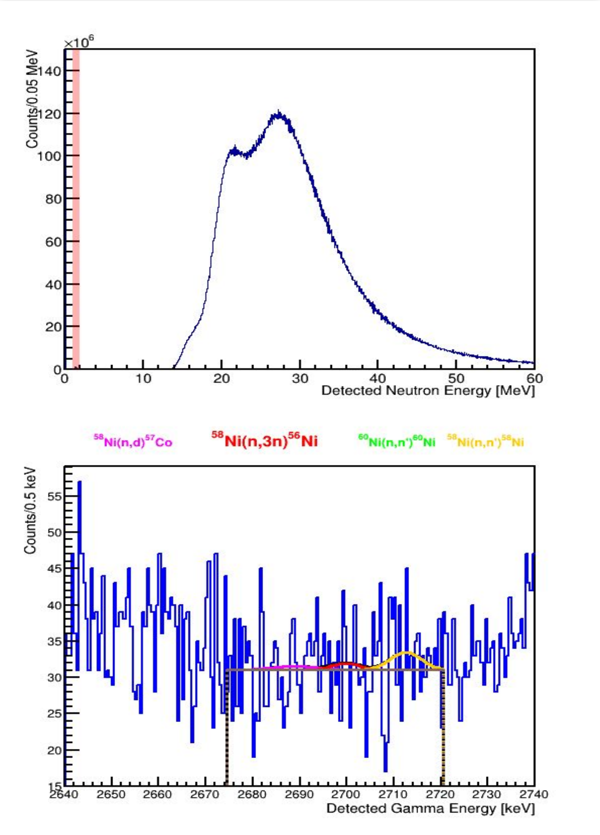
Estimating Neutron Energy

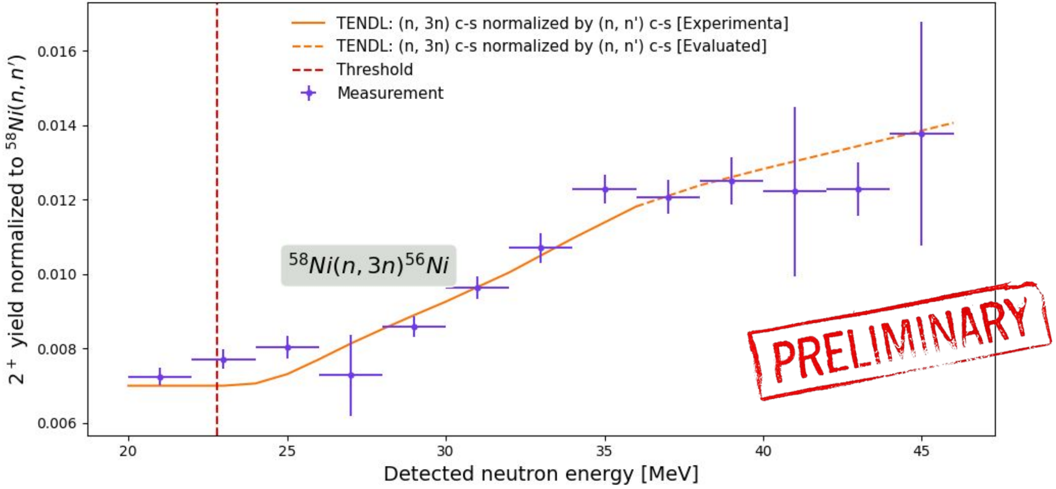




Despite the low resolution of tof with Ge detectors we can distinguish between gamma flash, activation gamma and prompt gamma from the fast neutrons

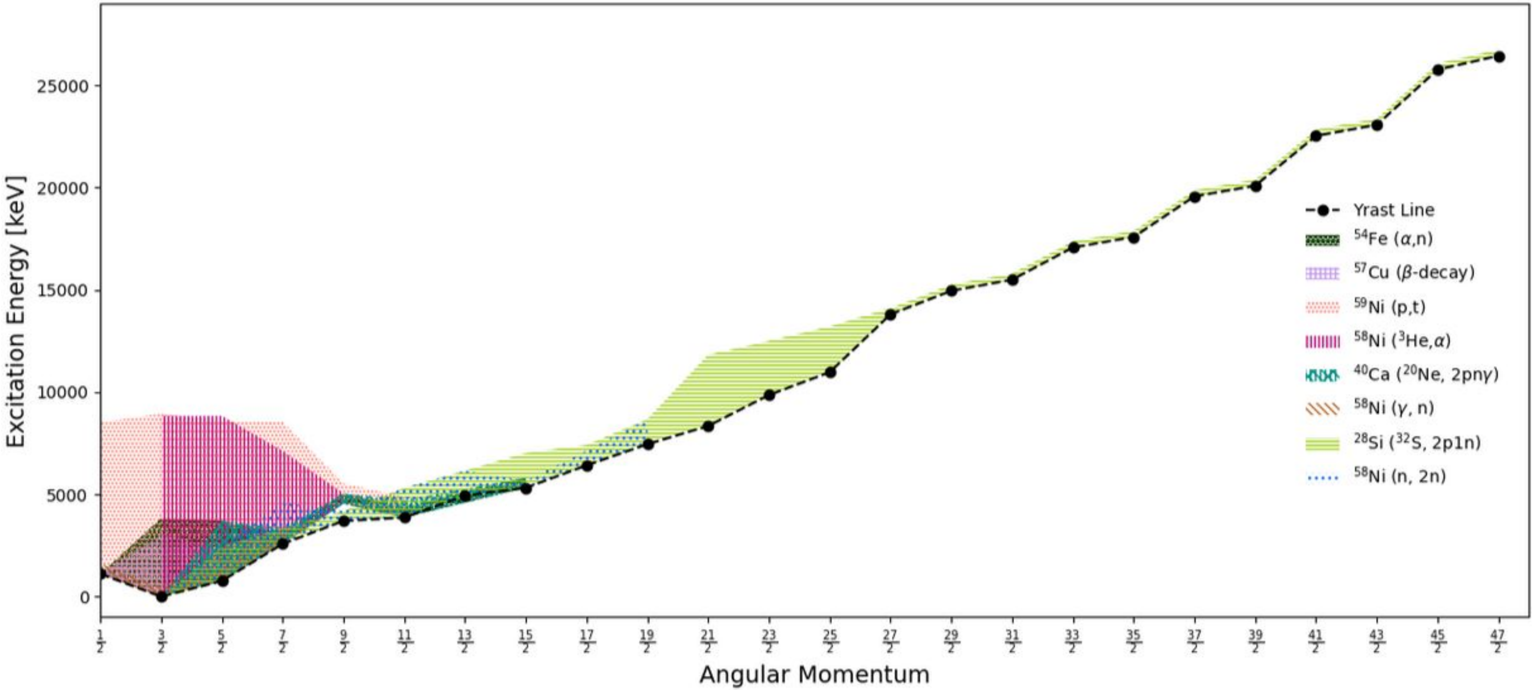
Production threshold of ^{56}Ni



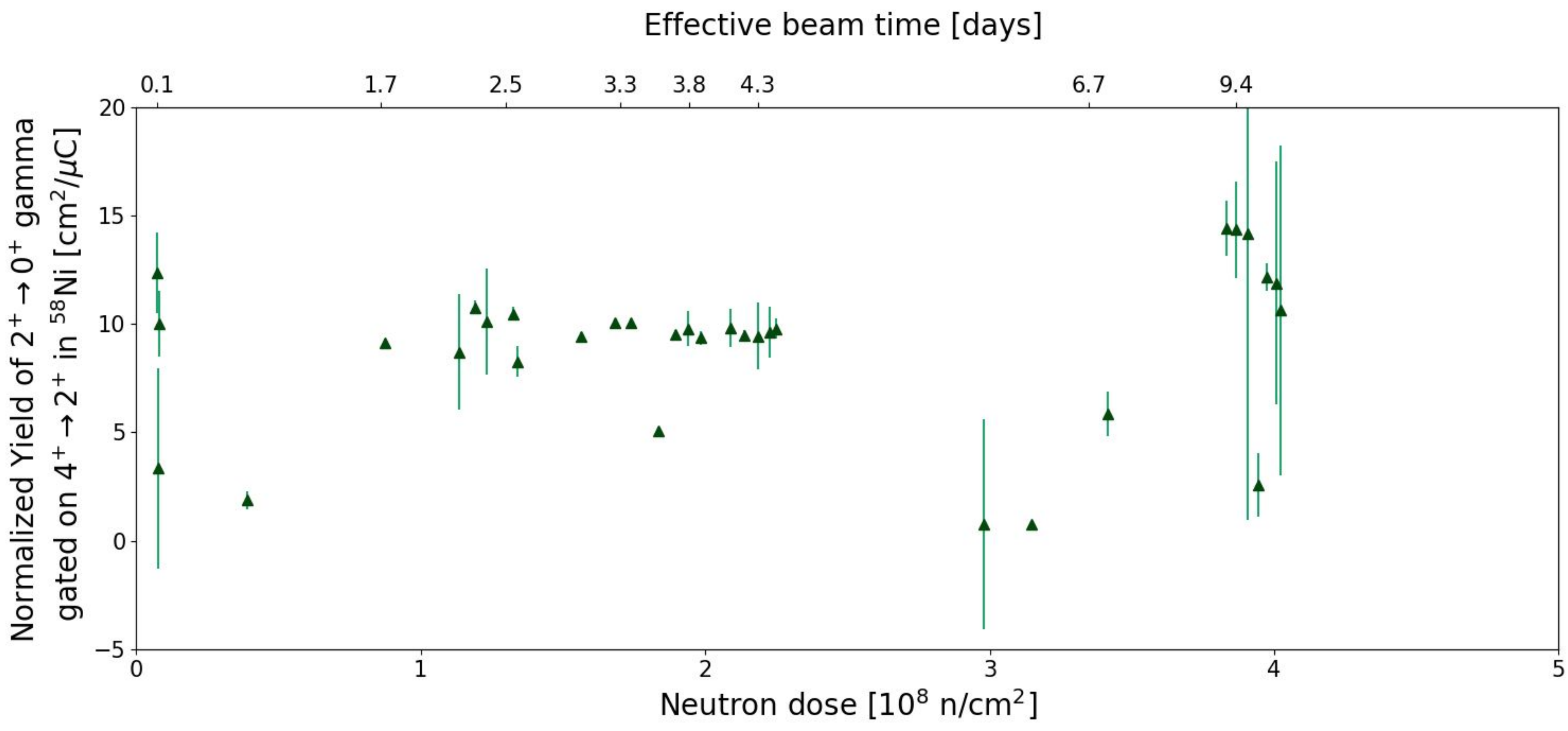


We can verify the neutron energy threshold (~23 MeV) for ^{58}Ni(n, 3n)^{56}Ni.

We also saw good agreement with the TENDL values, even though limited by statistics



Excitation Energy [keV]
25000
20000
15000
10000
5000
0
Yrast Line
^{54}Fe (α,n)
^{57}Cu (β-decay)
^{59}Ni (p,t)
^{58}Ni (^{3}He,α)
^{40}Ca (^{20}Ne, 2pnγ)
^{58}Ni (γ, n)
^{28}Si (^{32}S, 2p1n)
^{58}Ni (n, 2n)
1/2 3/2 5/2 7/2 9/2 11/2 13/2 15/2 17/2 19/2 21/2 23/2 25/2 27/2 29/2 31/2 33/2 35/2 37/2 39/2 41/2 43/2 45/2 47/2
Angular Momentum

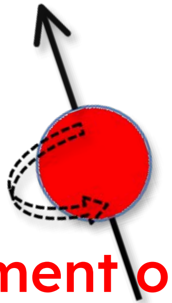


Effective beam time [days]
0.1
1.7
2.5
3.3
3.8
4.3
6.7
9.4
Normalized Yield of $2^+ \rightarrow 0^+$ gamma gated on $4^+ \rightarrow 2^+$ in ^{58}Ni [$cm^2/\mu C$]
20
15
10
5
0
−5
0
1
2
3
4
5
Neutron dose [10^8 n/cm^2]

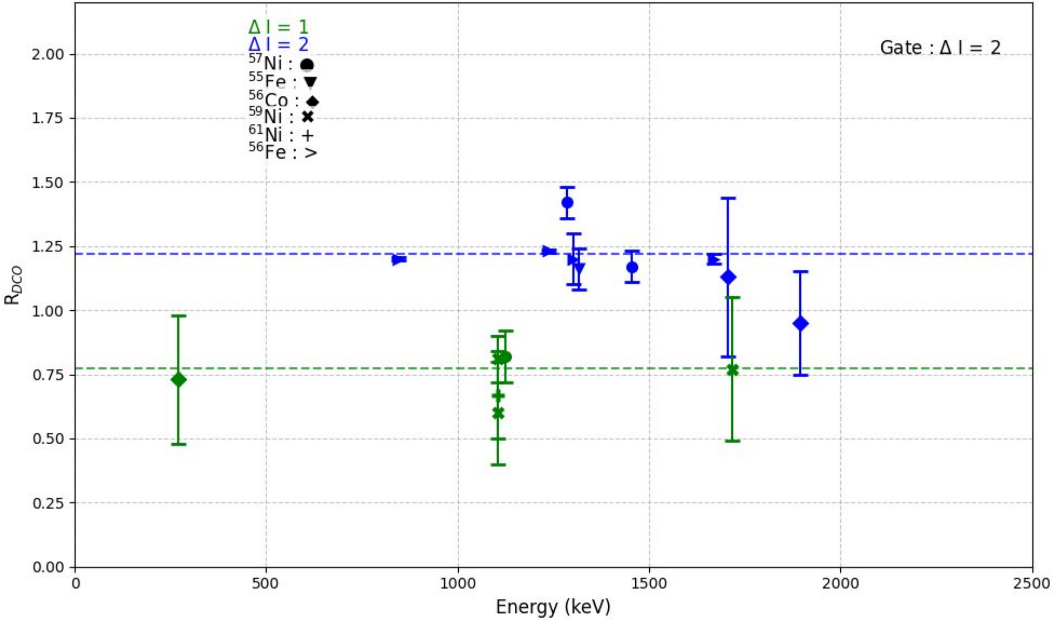
Do fast neutrons align the nucleus?

$$R_{\mathrm{DCO}} = \frac{I(\gamma_1 \text{ at } 135^\circ;\ \text{gated by } \gamma_2 \text{ at } 90^\circ)}{I(\gamma_1 \text{ at } 90^\circ;\ \text{gated by } \gamma_2 \text{ at } 135^\circ)}$$

Validated that R_{DCO} = 1+- 0.02 always for unpolarized ^{60}Co and ^{152}Eu samples



Alignment observed!



We seem to be sensitive to assigning spins.

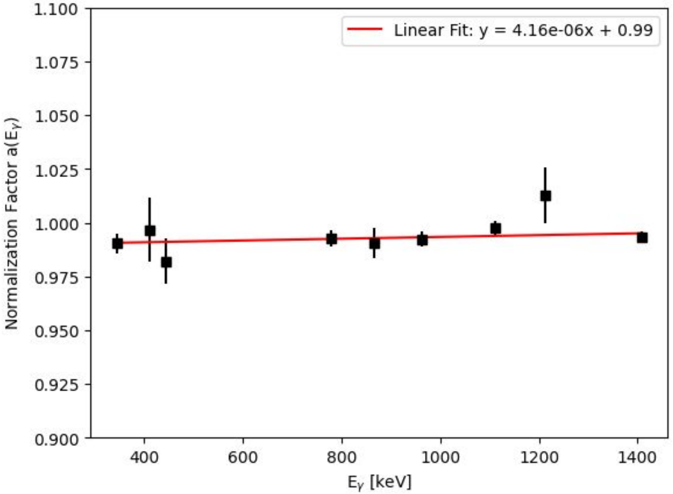
Asymmetry

- $a(E_\gamma)$ is the normalization factor corresponding to the asymmetry of the EXOGAM clover detectors and is defined as:

$$a(E_\gamma) = \frac{N_{\parallel}(\text{unpolarized})}{N_{\perp}(\text{unpolarized})}$$

- The experimental polarization asymmetry is defined by the ratio:

$$A = \frac{[a(E_\gamma)N_{\perp}] - N_{\parallel}}{[a(E_\gamma)N_{\perp}] + N_{\parallel}}$$



Gamma-Spectroscopy Analysis Tools

- ➢ Gate and identify which of the known* coincident γ are present in our data
- ➢ Compare measured yields to that of Talys simulations
- ➢ Identify new coincident γ and assign to corresponding isotope

*Present in ENSDF or XUNDL datasets

RadWare

- Histogram file format restricts number of bins
- Database file format outdated
- Does not draw identifiers for γ
- Calculates expected gamma spectrum but not using cs calculations

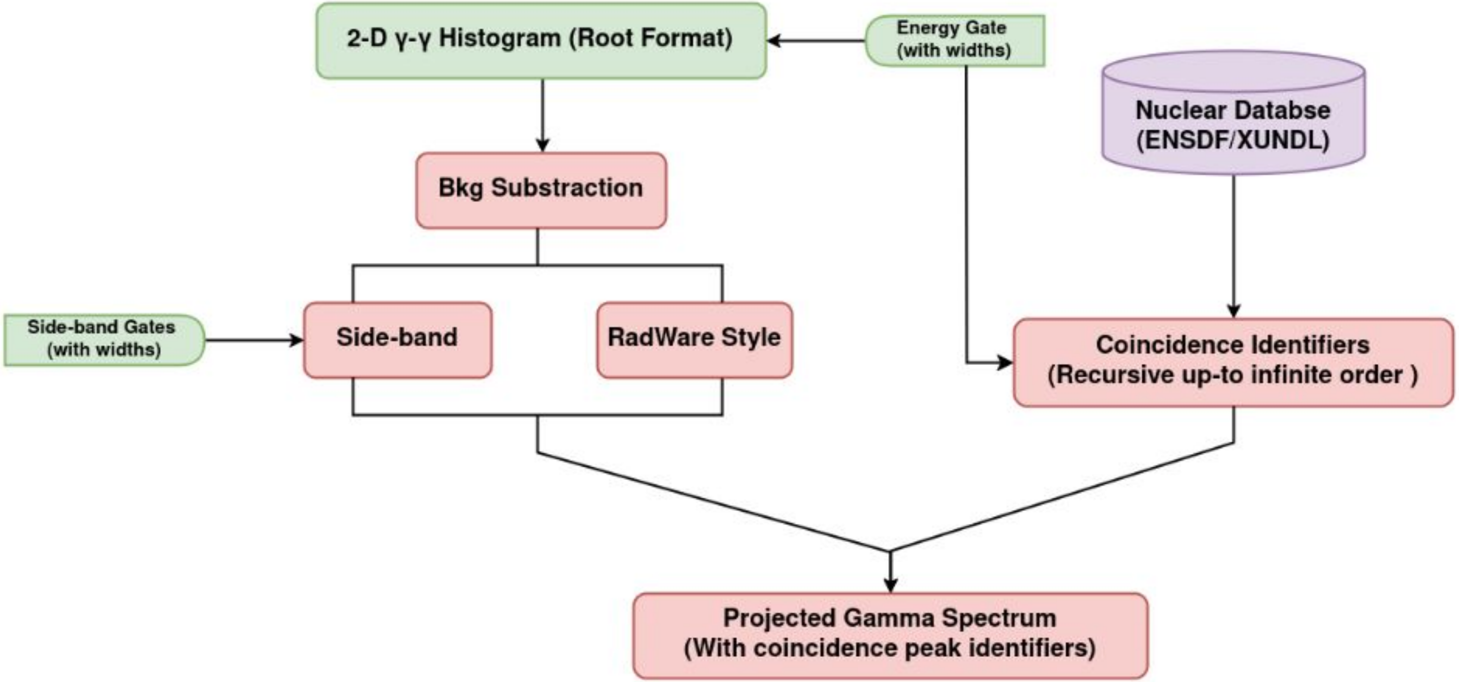
cubix

- Takes root histograms
- Background subtraction: side-band or RadWare style
- Database file non-editable
- Draws identifiers for γ in 1D
- Does not draw identifiers for coincident γ
- Does not calculate expected gamma spectrum

New Tool👉👈

- Takes root histograms
- Background subtraction: side-band or RadWare style
- Based on python notebooks, easy to debug and improve.
- Draws identifiers for both 1D spectrum and for coincident γ
- Calculates expected gamma spectrum using cs specific to the experiment (Talys...)
- Tracks history of gates (and params)
- Automate Level Schemes

The coincidence finder



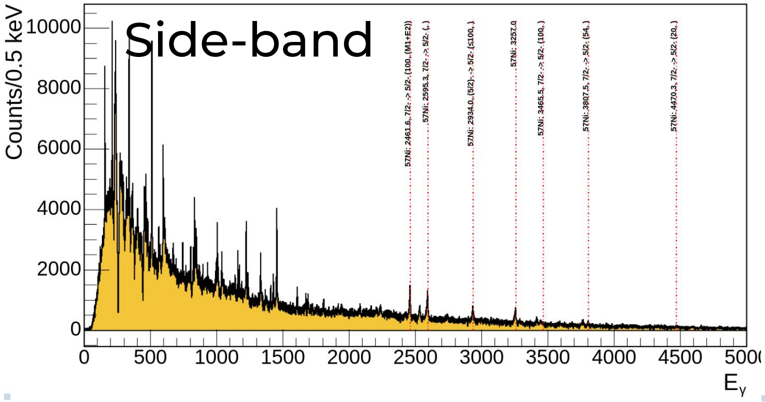
https://radware.phy.ornl.gov/bgsub/bgsub.html

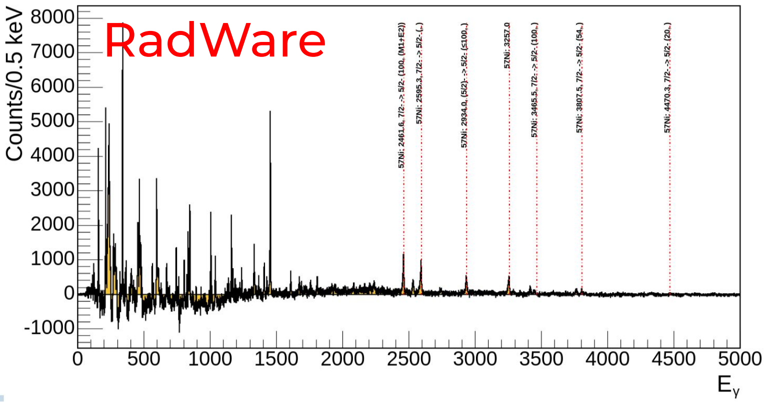
The coincidence finder

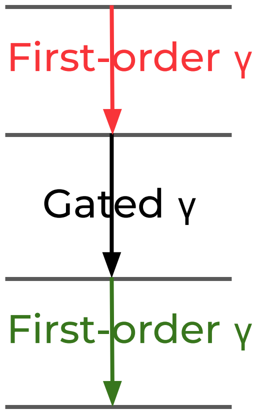
Start by choosing the gate (energy, width).

Example: Here gating on $5/2^- \rightarrow 3/2^-$ of ^{57}Ni (768 keV, ±3 keV) :

Two options to do bkg sub: side-band or RadWare style



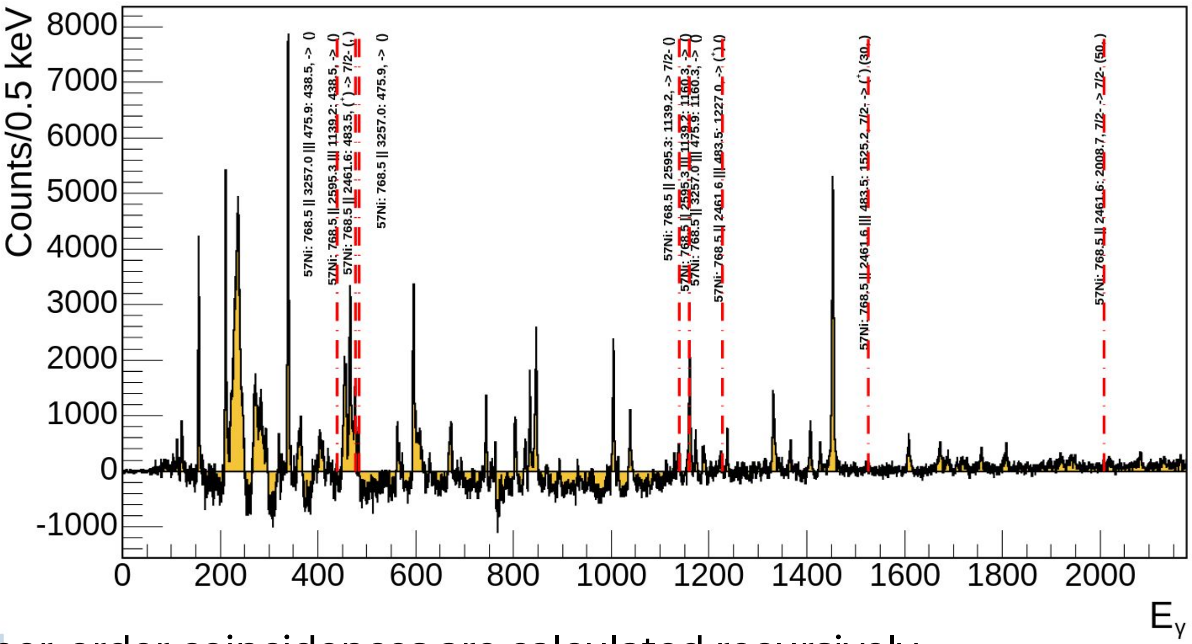


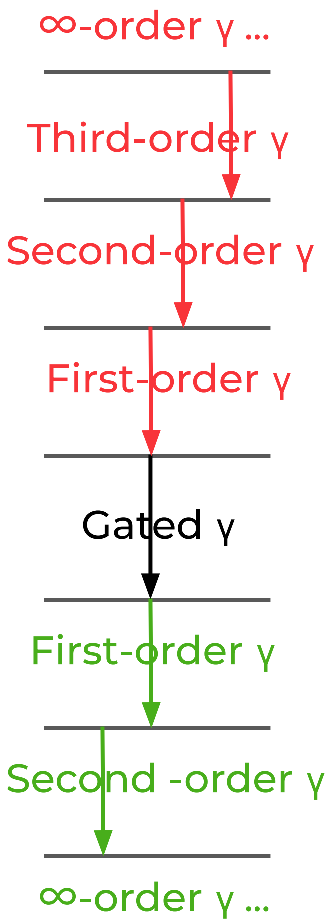


Draws identifiers for coincidence γs.

Can choose the isotopes and the maximum order of coincidences.
(only first order coincidences in ^{57}Ni shown here)

The coincidence finder





Higher-order coincidences are calculated recursively.

Can go up to infinite order...

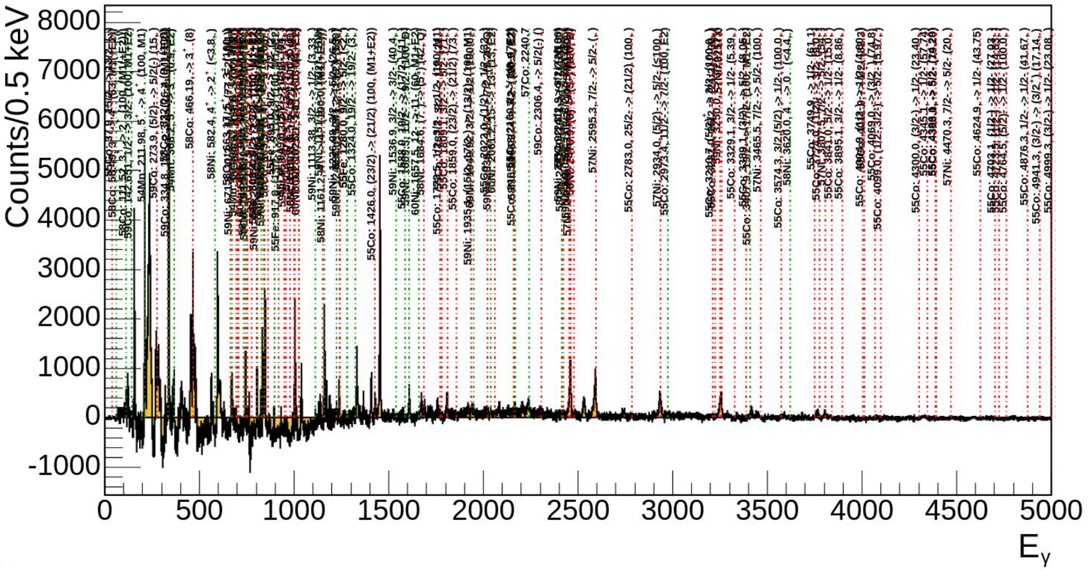
But 3 orders seem to sufficiently describe most peaks from ^{57}Ni

The coincidence finder

Looking at all isotopes in database is necessary before identifying new gammas.

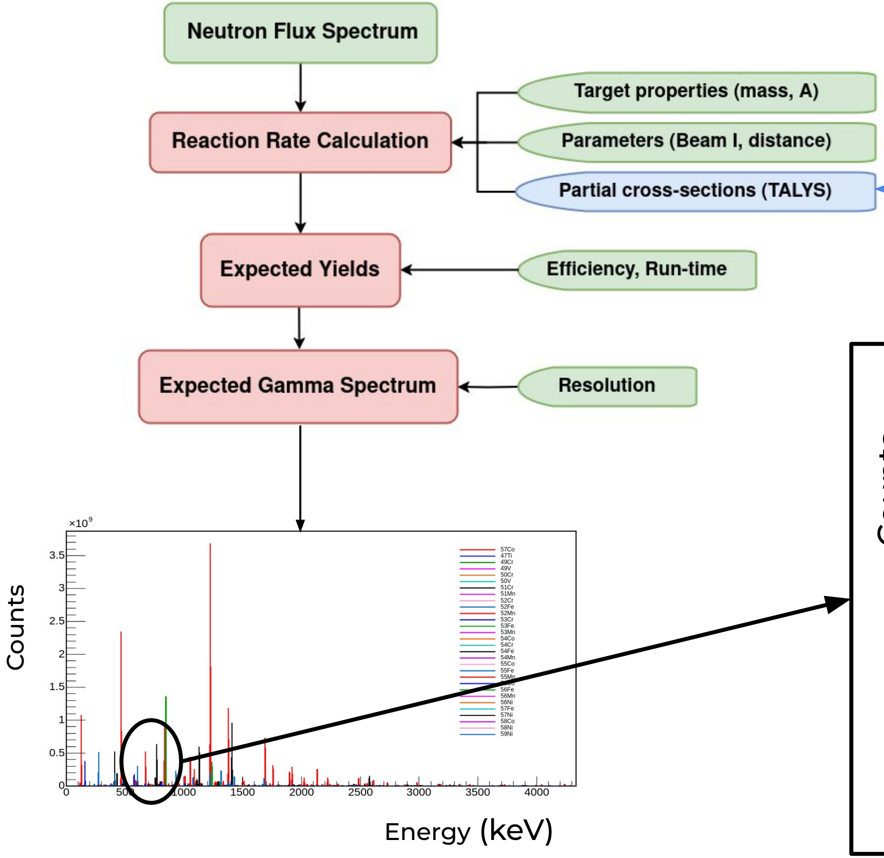
Intensity of the gate at 768 keV (768.87 @ 54Mn: 6^+ -> 5^+): 100%
Intensity of the gate at 768 keV (770.9 @ 55Fe: 11/2(-) -> 9/2-): 100%
Intensity of the gate at 768 keV (772.2 @ 55Fe: 9/2- -> 9/2-): %
Intensity of the gate at 768 keV (773.14 @ 55Co: 1/2- -> 3/2-): 100%
Intensity of the gate at 768 keV (763.2 @ 55Co: 13/2- -> 11/2-): 100%
Intensity of the gate at 768 keV (766.4 @ 55Co: (21/2) -> 19/2-): 100%
Intensity of the gate at 768 keV (771.0 @ 57Co): ???%
Intensity of the gate at 768 keV (773.93 @ 58Co: 3^+,4^+ -> 3^+): 100%
Intensity of the gate at 768 keV (765.3 @ 58Co: (9^+) -> (8^+)): 100%
Intensity of the gate at 768 keV (770.5 @ 59Co: 5/2(-) -> 1/2-): 26%
Intensity of the gate at 768 keV (768.5 @ 57Ni: 5/2- -> 3/2-): 100%
Intensity of the gate at 768 keV (763.0 @ 58Ni: (5^+) -> 4^+): 100.0%
Intensity of the gate at 768 keV (766.65 @ 59Ni: 3/2(-) -> 3/2-): 5.32%
Intensity of the gate at 768 keV (764.17 @ 59Ni: (13/2)- -> 11/2-): 92%
Intensity of the gate at 768 keV (764.2 @ 60Ni: 13- -> 12-): 100%

Only first order coincidences shown here



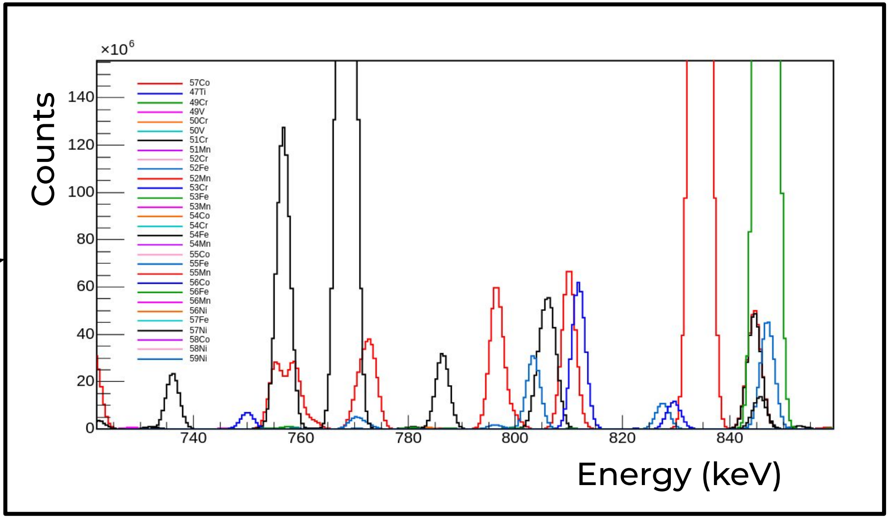
The overwhelming number of contributions in a single gate shows the complexity of the task.

Expected Spectrum

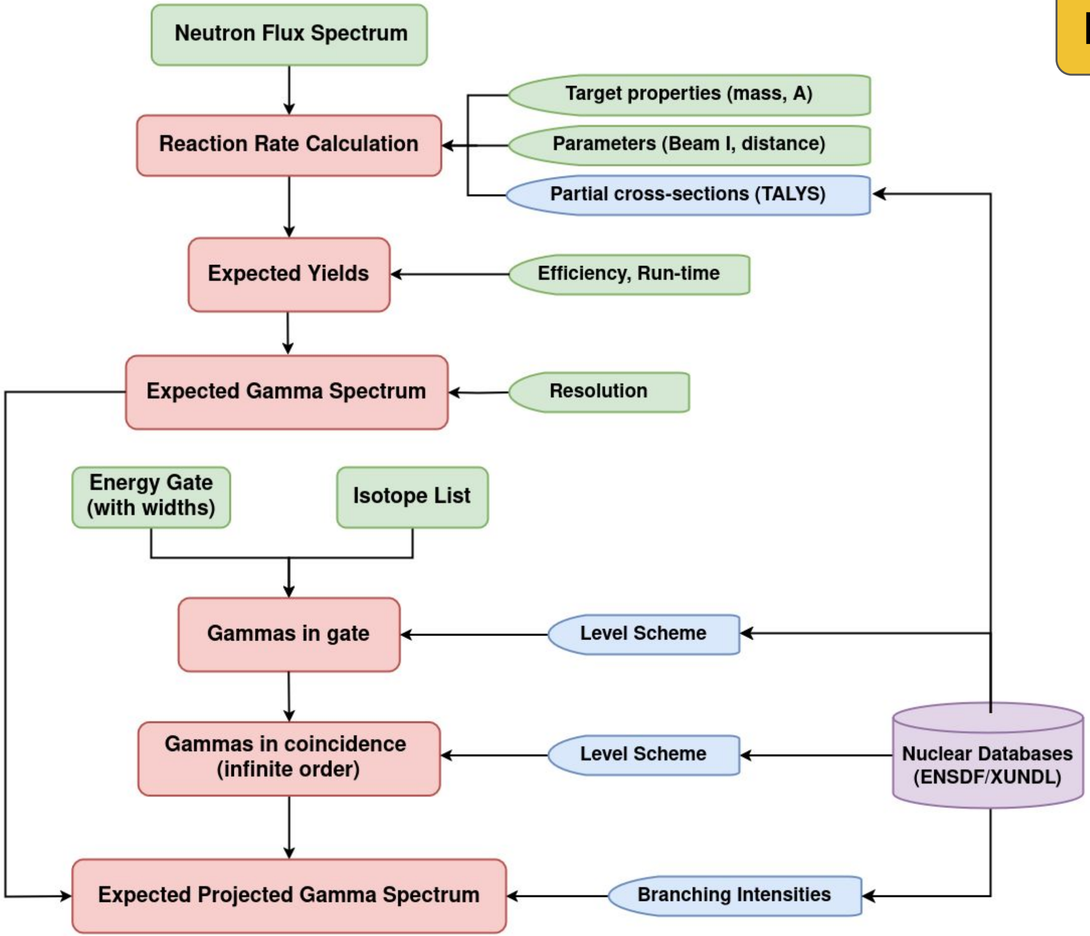


Gamma transition cross-sections for all isotopes locally simulated with TALYS

tps://nds.iaea.org/talys/ht



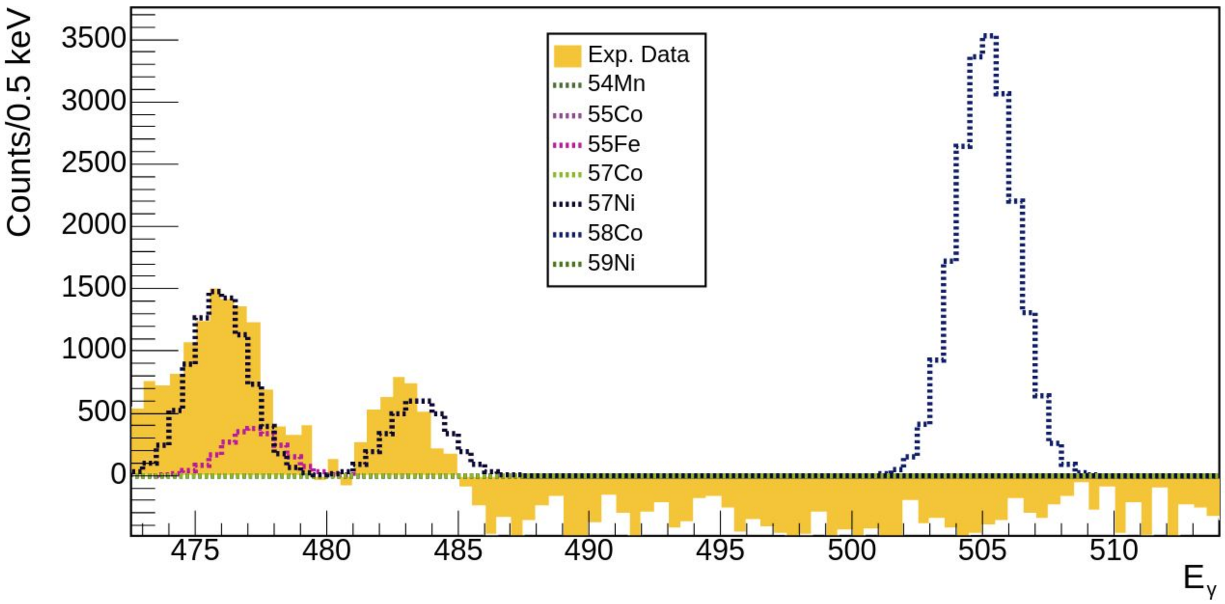
Expected Projected Spectrum



- ➢ User can input parameters specific to experiment.
- ➢ TALYS can be replaced by any c-s generator relevant for experiment.
- ➢ Relevant information taken from the nuclear databases (ENSDF/XUNDL).
- ➢ Projected expected spectrum for each energy gate.

Expected Spectrum

Can overlay the simulated spectrum on the experimental spectrum, one example shown here:



Since the plot is more readable, we go upto infinite order here.

Current limitations of the code:

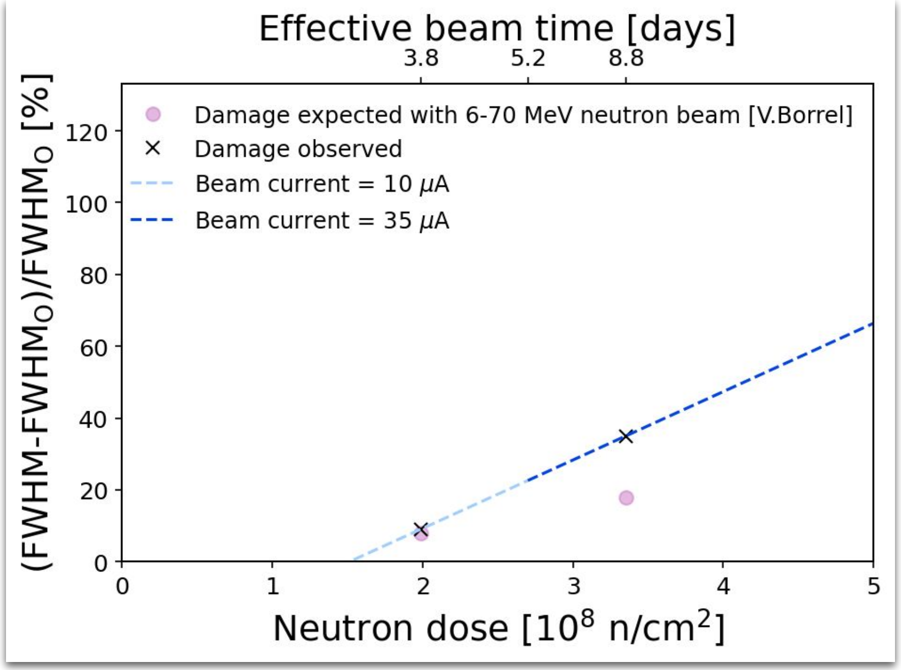
- Normalization is needed
- Fraction of peak in gate window not considered
- More realistic FWHM

Did such high flux of fast neutrons damage EXOGAM?

The beam flux on the Ni target is **~4.5 x 10^6 neutron/cm^2/s.**

Upto 50% degradation in FWHM after 12 days of effective beam time.

Previously: we only had two points from source calib runs



Fast neutron-induced damage in INTEGRAL n-type HPGe detectors, V. Borrel et al. Nucl. Phys. A 430, 348(1999)

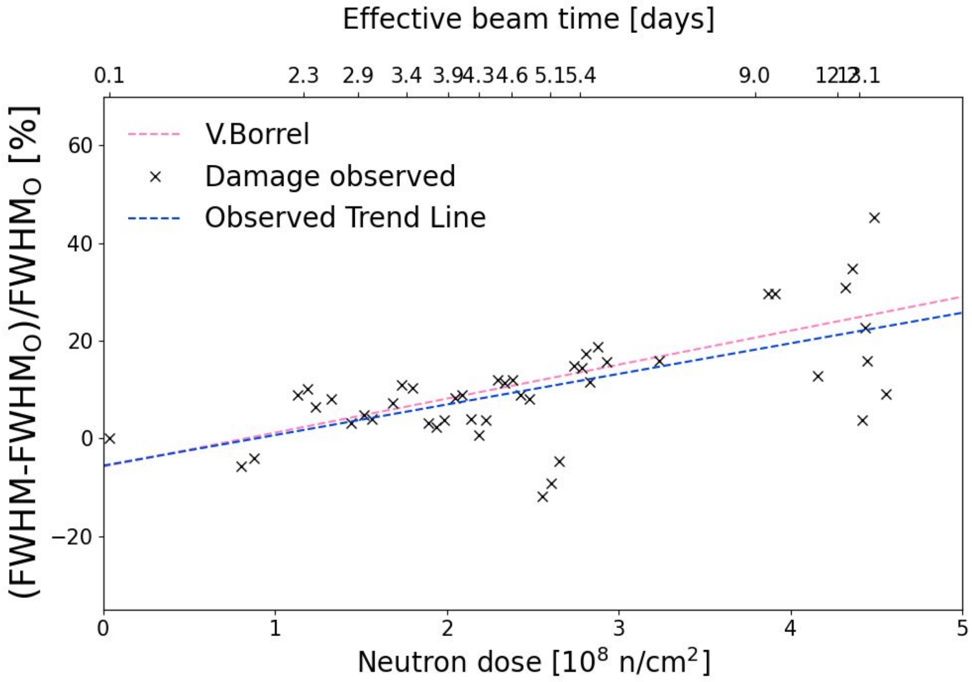
Did such high flux of fast neutrons damage EXOGAM?

The beam flux on the Ni target is **~4.5 x 10^6 neutron/cm^2/s.**

Upto 50% degradation in FWHM after 12 days of effective beam time .

Consistent with V.Borrel[1999]

Now: Taking all target runs



Fast neutron-induced damage in INTEGRAL n-type HPGe detectors, V. Borrel et al. Nucl. Phys. A 430, 348(1999)

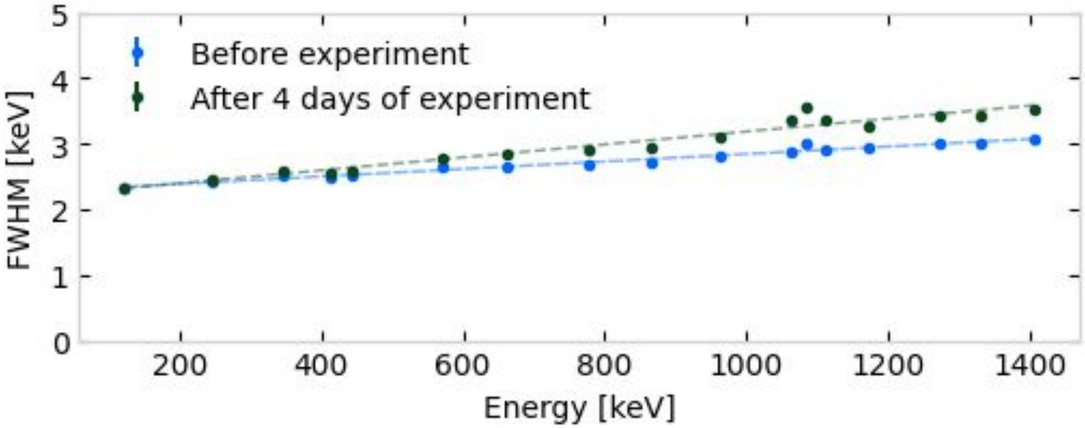
Did such high flux of fast neutrons damage EXOGAM?

The beam flux on the Ni target is ~4.5 x 10^6 neutron/cm^2/s.

Upto 50% degradation in FWHM after 12 days of effective beam time .

Consistent with V.Borrel[1999]

Higher degradation at higher energies

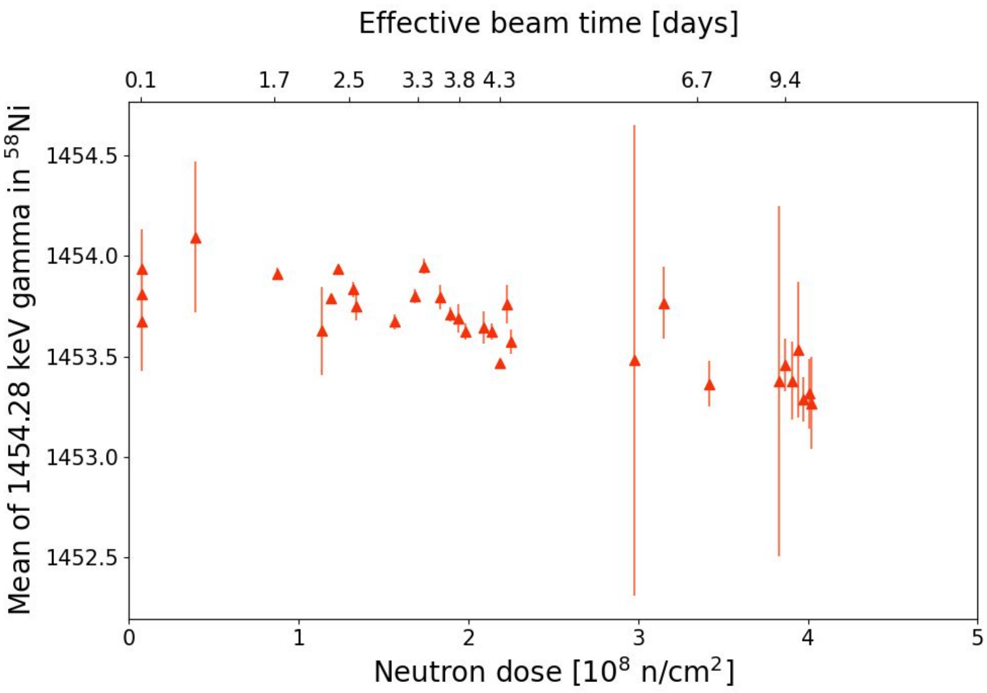


Fast neutron-induced damage in INTEGRAL n-type HPGe detectors, V. Borrel et al. Nucl. Phys. A 430, 348(1999)

Did such high flux of fast neutrons damage EXOGAM?

Max 1 keV shift of the peak mean position is observed

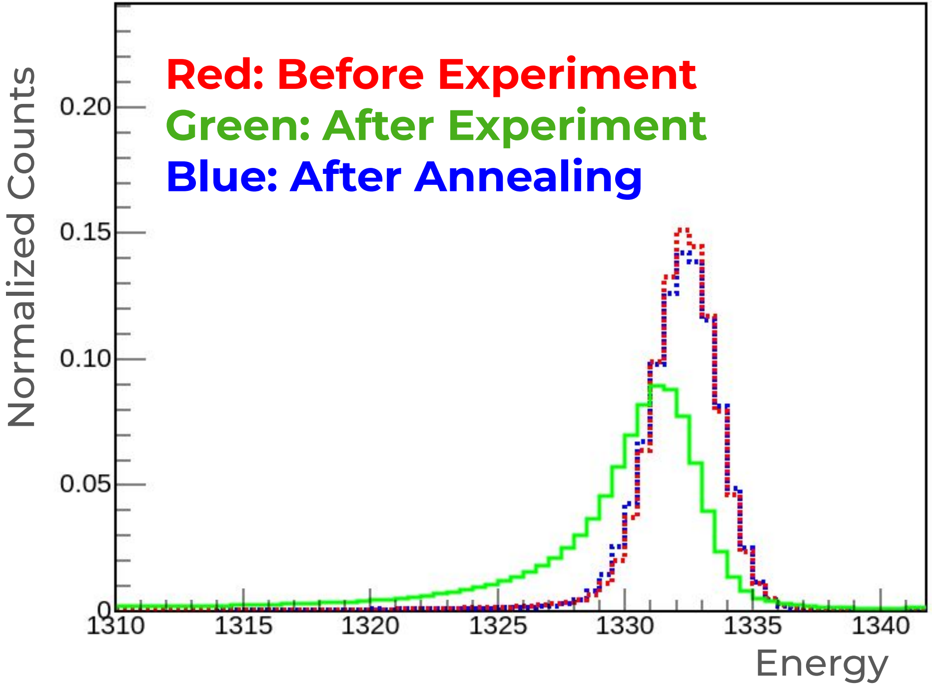
No observable effect on efficiency

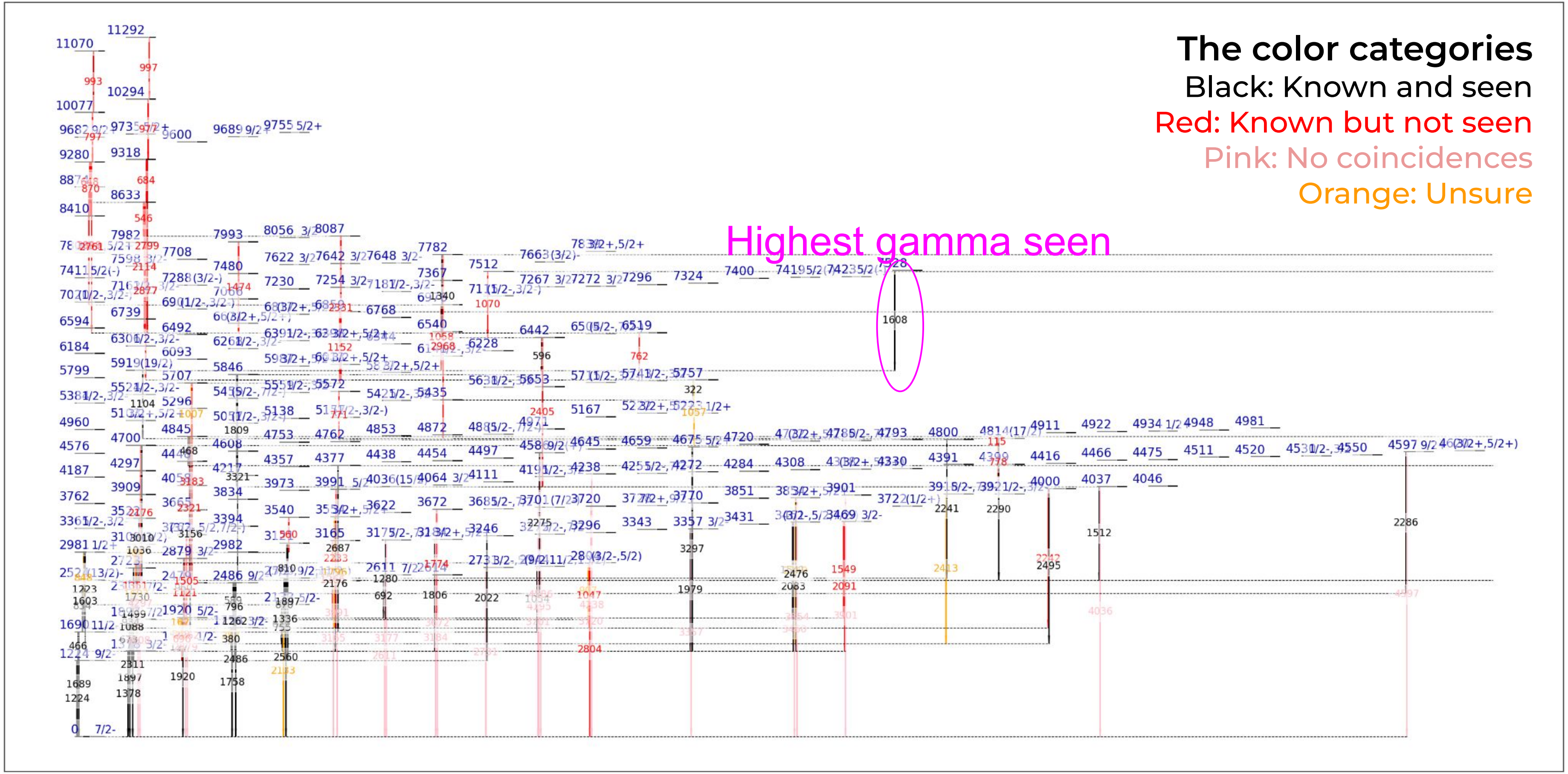


Recovered damage from neutrons

The resolution and central mean were successfully recovered after annealing.

Possible to use thick Ge detectors for high-resolution γ-spectroscopy at high neutron flux of fast neutrons.





The color categories

Black: Known and seen

Red: Known but not seen

Pink: No coincidences

Orange: Unsure

^{57}Co

Built on ENSDF/NuDAT database

(~150 gamma transitions)

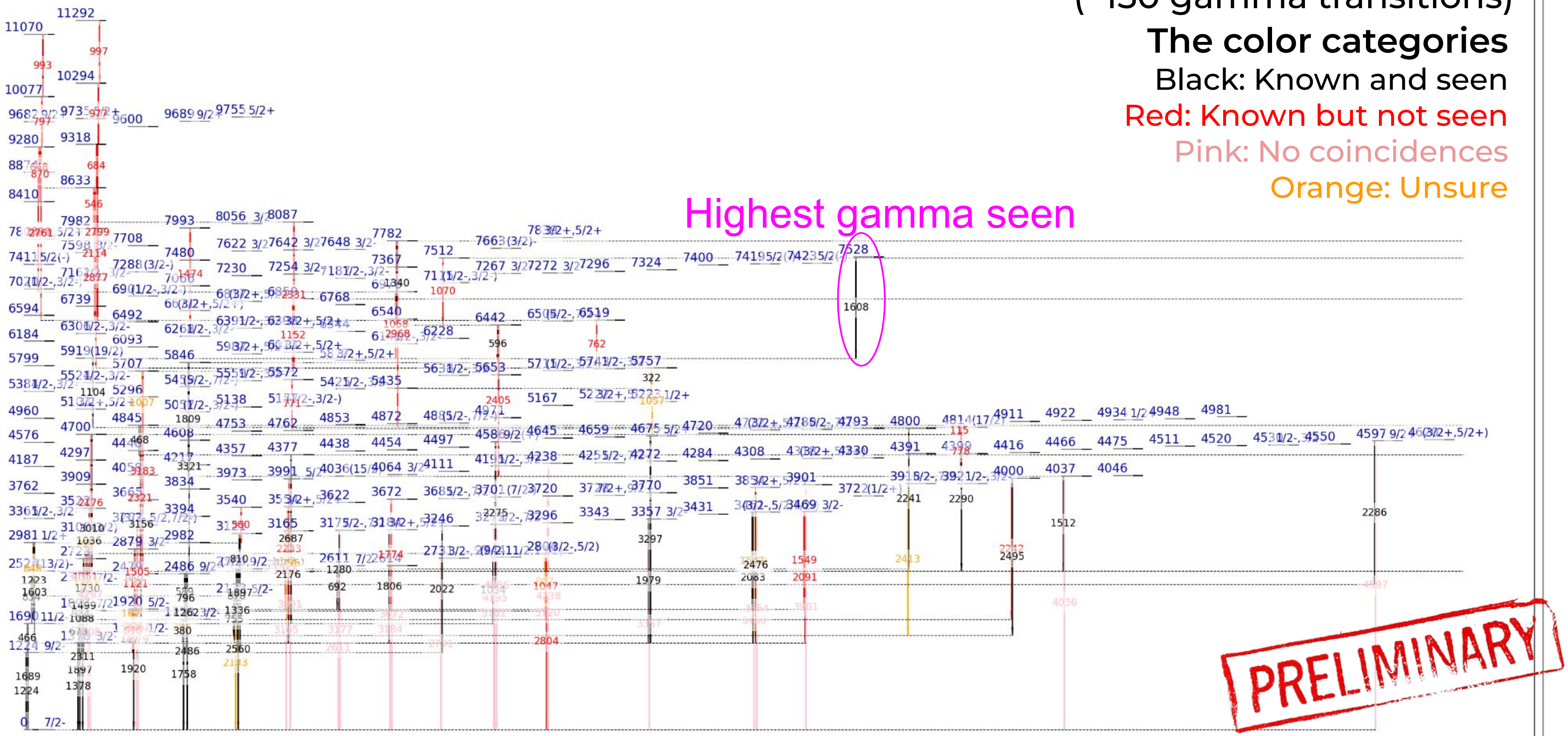
The color categories

Black: Known and seen

Red: Known but not seen

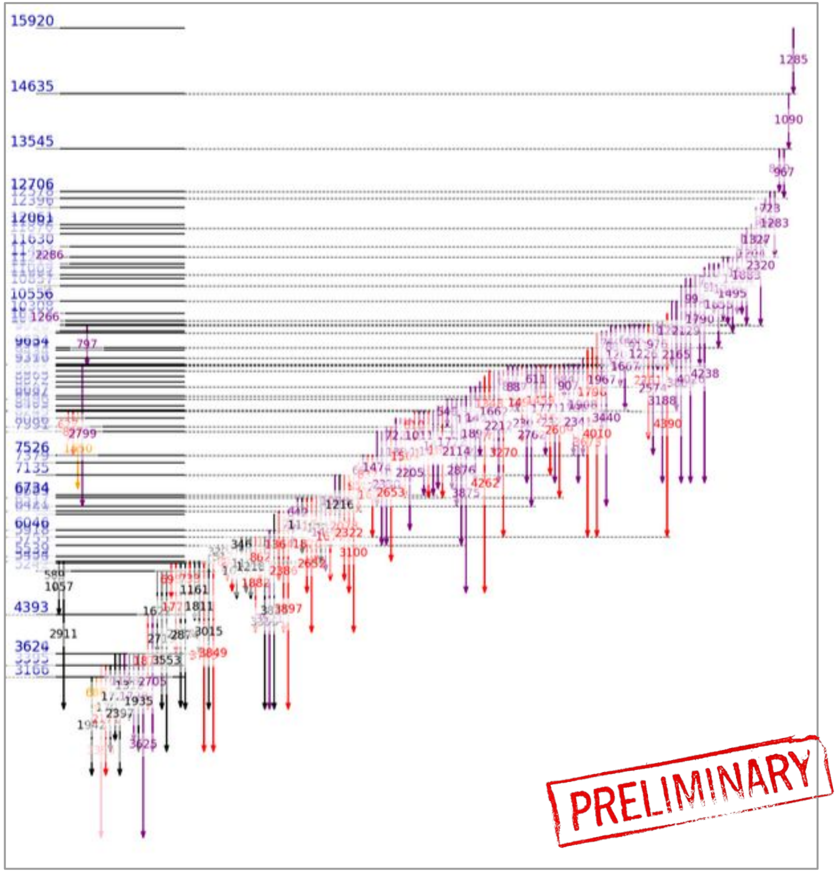
Pink: No coincidences

Orange: Unsure



^{57}Co

Built on XUNDL database

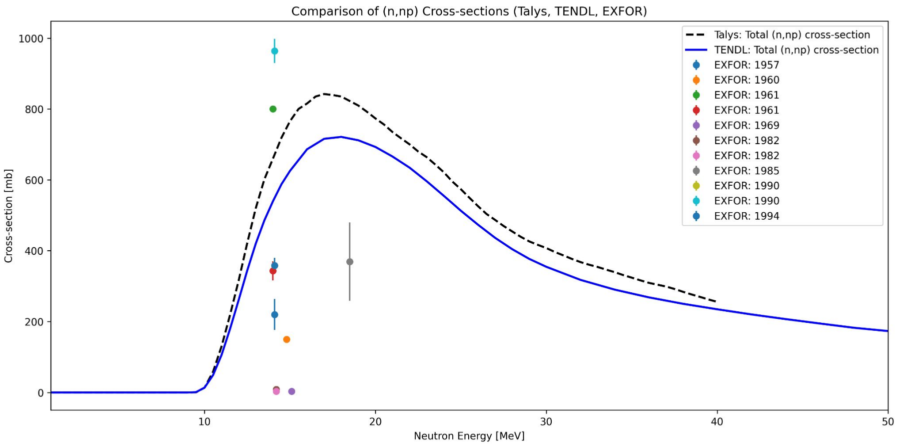


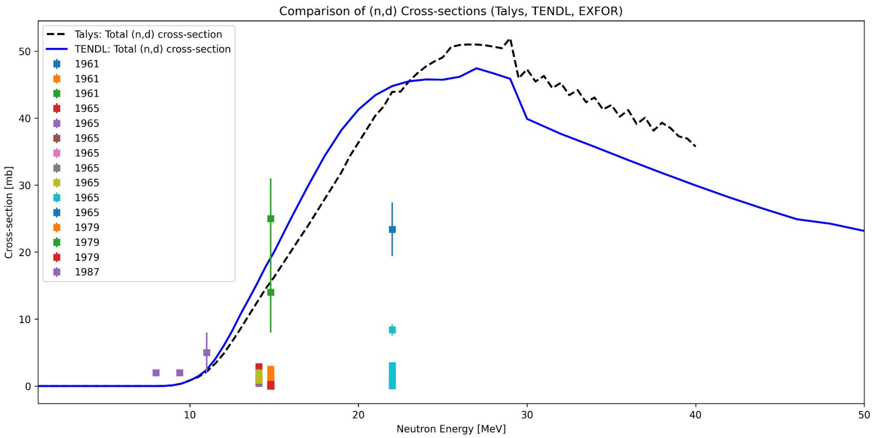
There are additional ~190 gamma transitions which have been observed but not critically evaluated (Not included in ENSDF)

Our data can provide the first cross-validation of these transitions

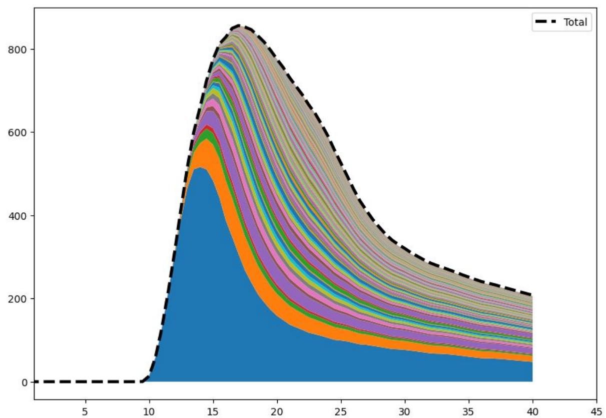
After verifying everything we can start looking for new transitions

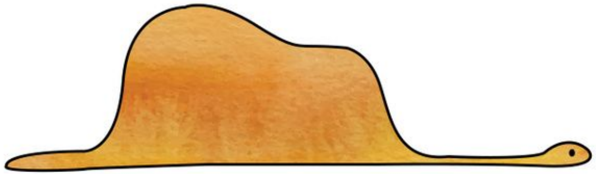
^{57}Co is interesting because it can be produced by (n,d) AND (n,n'p) channels



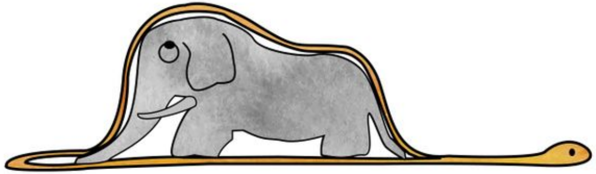


- ➢ Discrepancy between simulation and data
- ➢ Disagreement between datasets
- ➢ Better measurements needed





"My drawing was not a picture of a hat.
It was a picture of a boa constrictor digesting an elephant."



CUSTOM TOOLS

Built custom tools inspired by:

cubix RadWare

With additional features including:

- ➢ User-friendly
- ➢ Draws identifiers for coincident γ for all orders
- ➢ Calculates simulated coincident gamma spectrum using experiment-specific cross sections and parameters (e.g., Talys).

The coincidence finder

Gating on $5/2^- \rightarrow 3/2^-$ of ^{57}Ni : 768 keV, ±3 keV

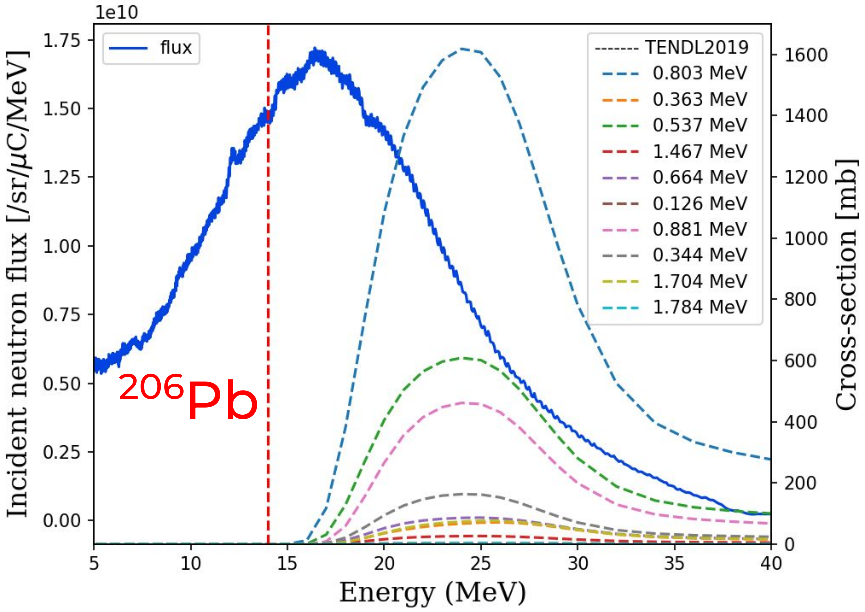
Intensity of the gate at 768 keV (768.87 @ 54Mn: 6^+ -> 5^+): 100%
Intensity of the gate at 768 keV (770.9 @ 55Fe: 11/2(-) -> 9/2-): 100%
Intensity of the gate at 768 keV (772.2 @ 55Fe: 9/2- -> 9/2-): %
Intensity of the gate at 768 keV (773.14 @ 55Co: 1/2- -> 3/2-): 100%
Intensity of the gate at 768 keV (763.2 @ 55Co: 13/2- -> 11/2-): 100%
Intensity of the gate at 768 keV (766.4 @ 55Co: (21/2) -> 19/2-): 100%
Intensity of the gate at 768 keV (771.0 @ 57Co): ???%
Intensity of the gate at 768 keV (773.93 @ 58Co: 3^+,4^+ -> 3^+): 100%
Intensity of the gate at 768 keV (765.3 @ 58Co: (9^+) -> (8^+)): 100%
Intensity of the gate at 768 keV (770.5 @ 59Co: 5/2(-) -> 1/2-): 26%
Intensity of the gate at 768 keV (768.5 @ 57Ni: 5/2- -> 3/2-): 100%
Intensity of the gate at 768 keV (763.0 @ 58Ni: (5^+) -> 4^+): 100.0%
Intensity of the gate at 768 keV (766.65 @ 59Ni: 3/2(-) -> 3/2-): 5.32%
Intensity of the gate at 768 keV (764.17 @ 59Ni: (13/2)- -> 11/2-): 92%
Intensity of the gate at 768 keV (764.2 @ 60Ni: 13- -> 12-): 100%

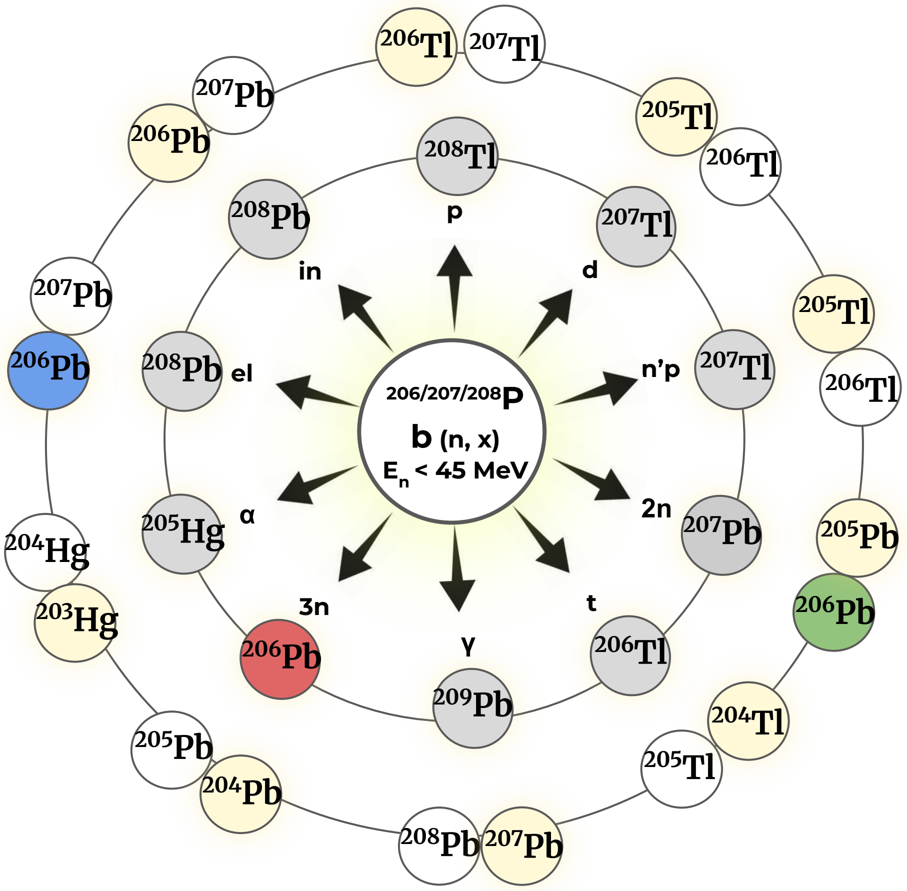
- ➢ The overwhelming number of contributions in a single gate shows the complexity of the task.
- ➢ Looking at all isotopes in database is necessary before identifying new gammas.

The (n, 3n) channel

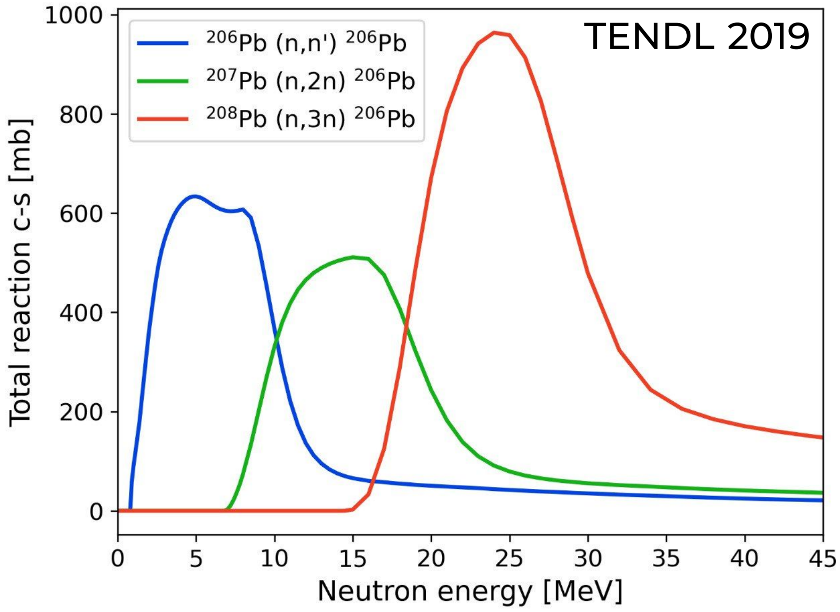
- Much lower thresholds and relatively higher c-s for ^{208}Pb(n,3n)^{206}Pb

- ^{nat}Pb target ⇒
  - ^{208}Pb(~52%)
  - ^{206}Pb(~24%) ✗
  - ^{207}Pb(~22%)



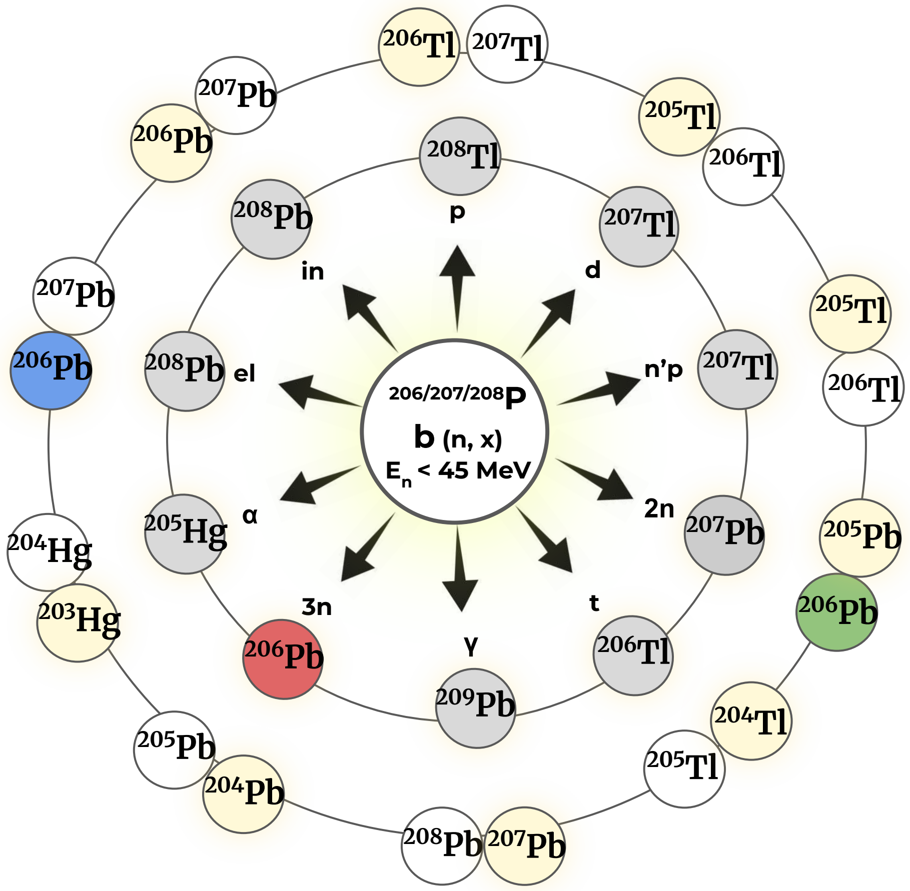


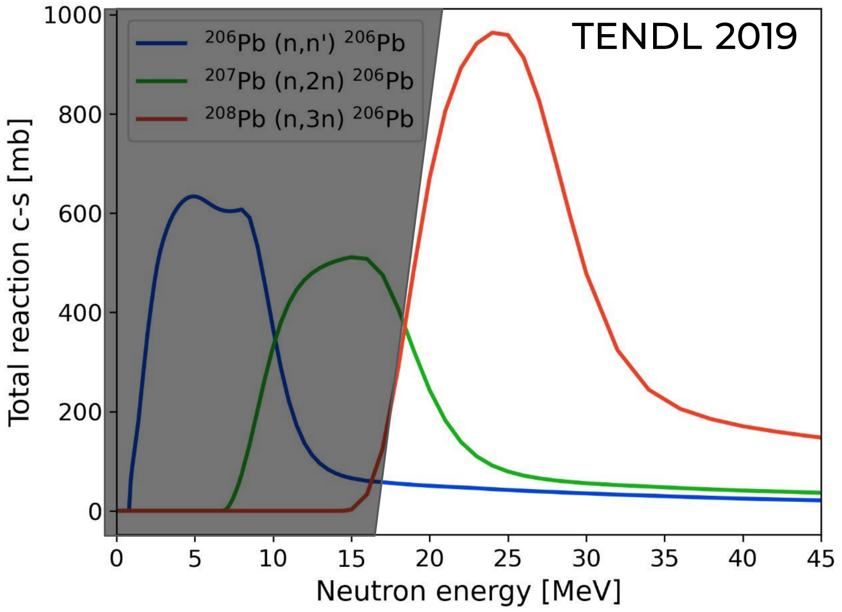
206/207/208Pb (n, x)
E_n < 45 MeV
p
d
n'p
2n
t
γ
3n
α
el
in
208Tl
207Tl
207Tl
207Pb
206Tl
209Pb
206Pb
205Hg
208Pb
208Pb
206Tl
207Tl
205Tl
206Tl
205Tl
206Tl
205Pb
206Pb
204Tl
205Tl
207Pb
208Pb
204Pb
205Pb
203Hg
204Hg
206Pb
207Pb
206Pb
207Pb



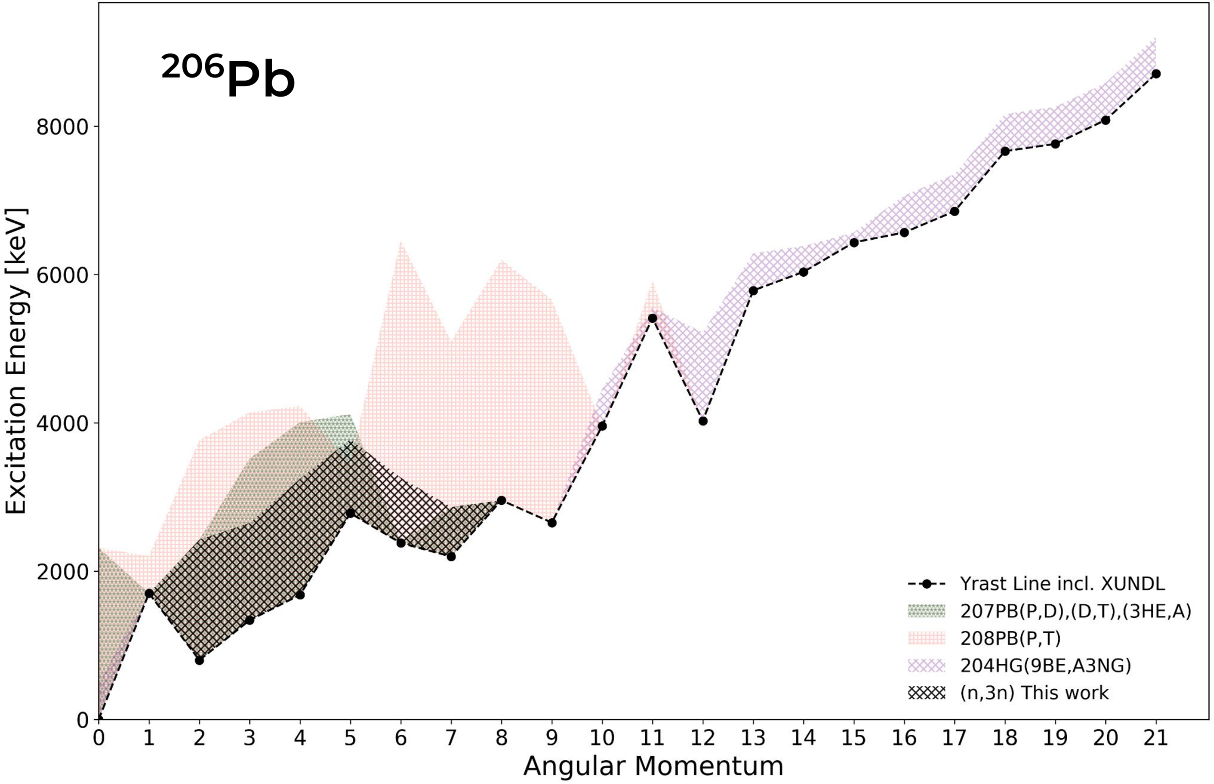
TENDL 2019
206Pb (n,n') 206Pb
207Pb (n,2n) 206Pb
208Pb (n,3n) 206Pb
Total reaction c-s [mb]
Neutron energy [MeV]
0
200
400
600
800
1000
0
5
10
15
20
25
30
35
40
45

Data stored for ~15 < E_n





Where is (n, 3n) on the Yrast diagram?



- More statistics is needed.
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