Shedding new light on the structure of ^{57}Ni using *(n,2n)* reaction at GANIL-NFS

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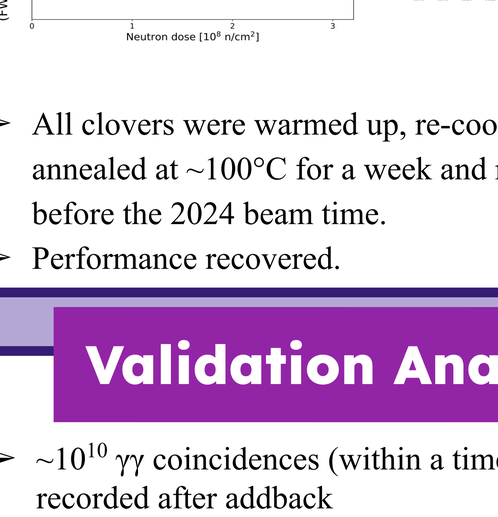
Motivation

- Re-investigating the ^{57}Ni structure via *(n, 2n)* reaction from ^{58}Ni provides a unique neutron probe, unveiling the interplay between single-particle and collective excitations.
- Using the unprecedented neutron flux at [20-40] MeV at GANIL-NFS, the project pioneers a pure neutron approach to study *(n, xn)*, while also allowing comparisons with Co isotopes produced via *(n, p/d/t)* channels.
- Such new spectroscopic information is also relevant for nuclear reaction mechanism formalism (like TALYS) and nuclear data evaluation.



We seek to know:

⟶ *Which area of the Yrast surface is being populated by (n,xn) reactions?*

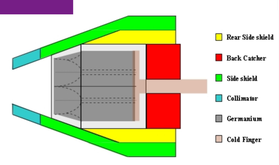
⟶ *How accurate are the predictions?*

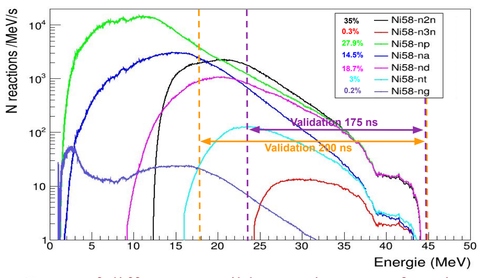
⟶ *What new do they bring?*

Experimental Set-up

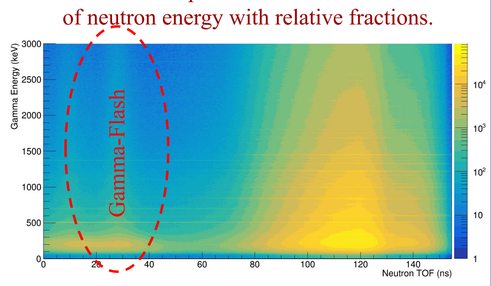
- 10 µA of 40 MeV deuteron beam on a thick Be converter
- ^{nat}Ni target (10cm x 10cm x 1mm) fixed in an Al holder at 8.6 m from the neutron converter
- 12 EXOGAM clovers (4 x 60 mm x 90 mm coaxial HPGe crystals) spherically arranged around it at a radius of ~14 cm covering ~31% of the solid angle
- Anti-compton shield (BGO) and back catcher (CsI) used as veto
- Fully digital electronics
- To enhance the composition of (n,3n) reactions, events with the fastest neutrons (> 18 MeV) are triggered
- TOF is obtained for each cristal from the time difference between constant fraction discrimination (CFD) of RF-Linac beam chopper and that of EXOGAM core
- TOF was calibrated using gamma-flash and the validation gates (175 ns and 200 ns)

TOF ↔ Neutron Energy Conversion



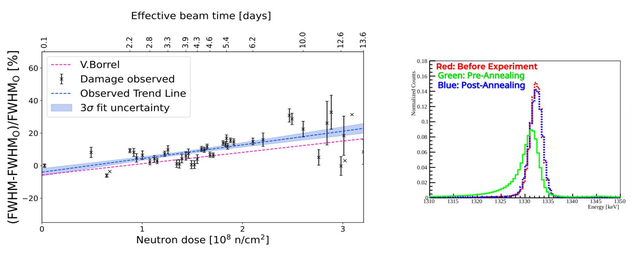


Rates of different possible reactions as a function of neutron energy with relative fractions.

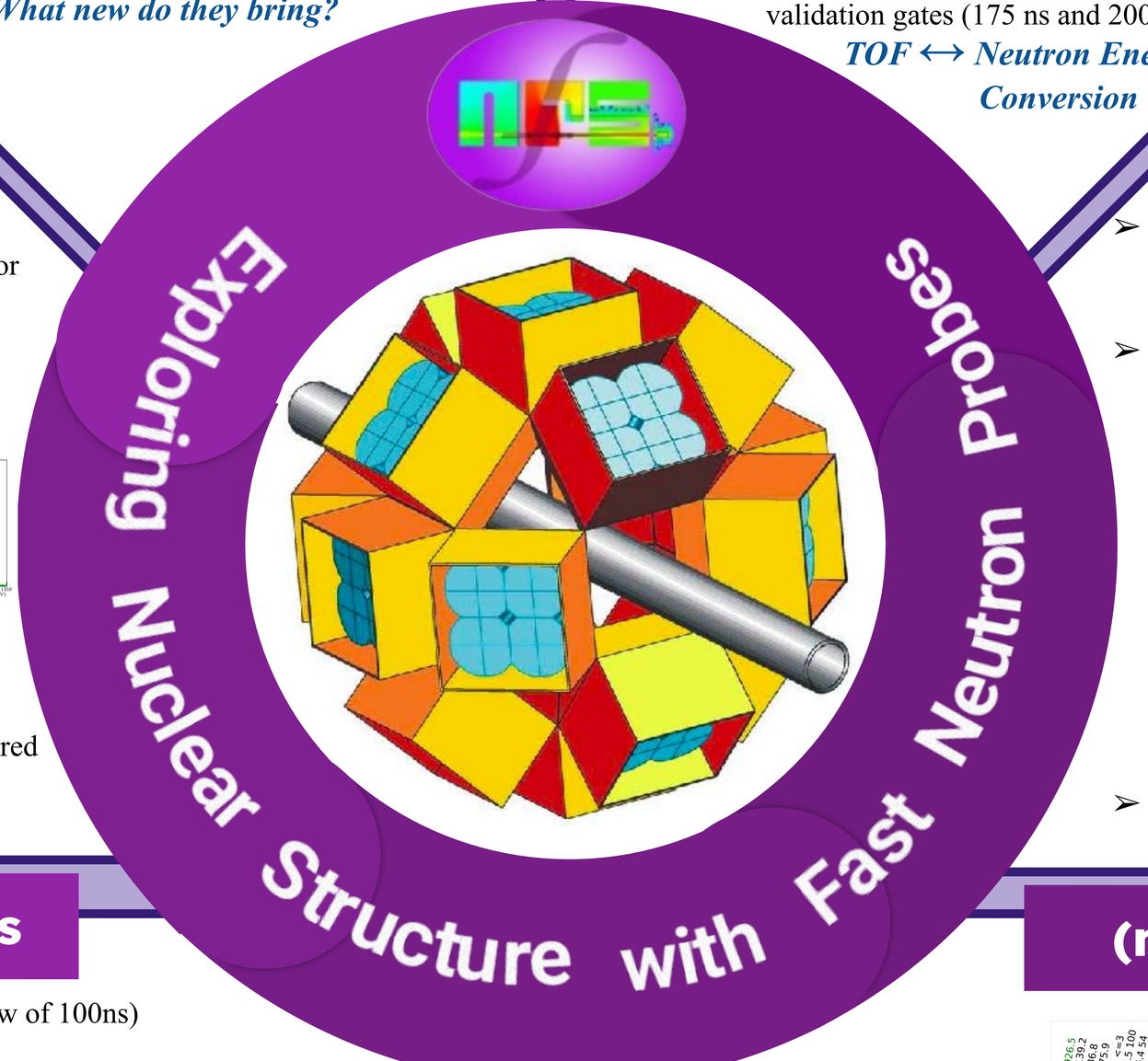


Fast neutrons and HPGe detectors?

- 4.5 x 10^6 neutron/cm^2/s beam reaching the target lead to ~50% worsening of the detector resolution at 1.32 MeV after ~11 days of effective beam run time.

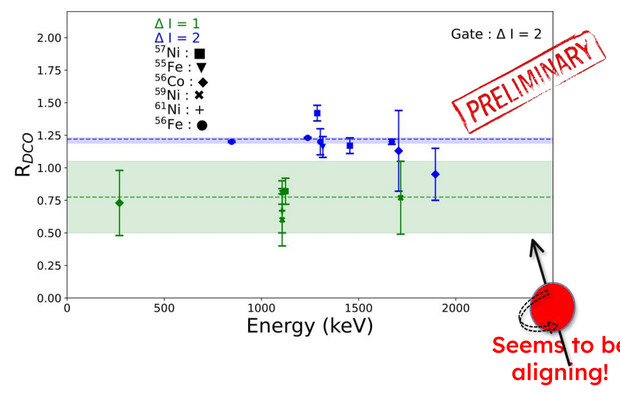


- All clovers were warmed up, re-cooldown, annealed at ~100°C for a week and remeasured before the 2024 beam time.
- Performance recovered.



Do fast neutrons align the nucleus?

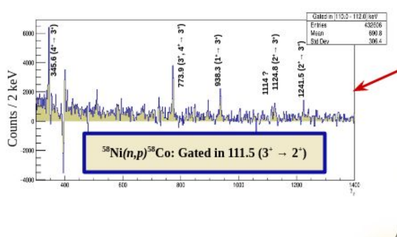
- In the present experiment, 4 (8) clover detectors are placed at ~135° (90°) with respect to the neutron beam axis.
- Validated that R_{DCO} = 1+- 0.02 always for unpolarized ^{60}Co and ^{152}Eu samples.

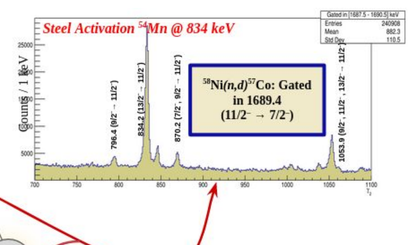


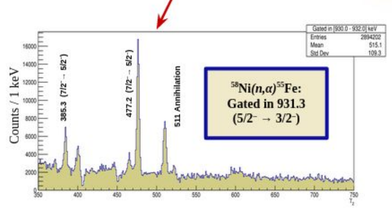
- We seem to be sensitive to assigning spins and parities.

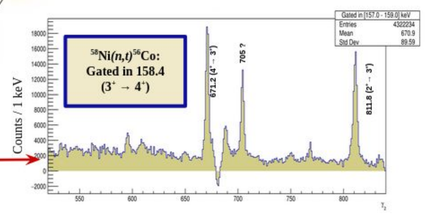
Validation Analysis

- ~10^{10} γγ coincidences (within a time window of 100ns) recorded after addback
- Background studies were done in two parts:
  {i} natural background of NFS hall
  {ii} γ that occur from activated isotopes like *Fe*, *Al* and steel around the experimental setup and also *Ge(n,n'γ)*
- We observe much more states than the previous study focusing purely on (n,d) channel by *W. N. Wang and E. J. Winhold, Phys. Rev. 140, 4B (1965)*. Potential to understand the interplay between (n,d) and (n,n'p) channels.
- Validation with standard charge particle reaction channels:

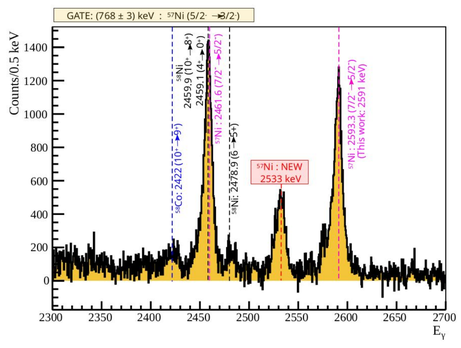


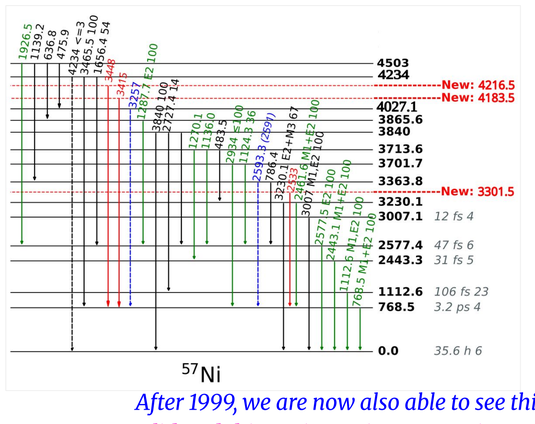






(n, 2n) Channel





After 1999, we are now also able to see this 3701 keV level.
We validated this parity assignment using our independent data!

- Overall (n,2n) seems to be quite like the heavy ion fusion evaporation but limited to low angular momentum. But not just a subset…

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

The intruder multiplet and the N = 28 shell gap

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

Conclusion: 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 $\nu(\mathrm{pf})^{-1}g_{9/2}$ 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 $\nu(\mathrm{pf})^{-1}g_{9/2}$ intruder multiplet in ^{57}Ni

Summary and plans

- With EXOGAM @ NFS, we showed that fast neutron reactions can
  - Identify new transitions even in well-studied isotopes
  - Assign multipolarities to new and uncharacterized transitions
  - Measure gamma cross sections to improve nuclear codes & libraries
  - Disentangle different reactions producing same isotope.
- Demonstrated that nuclear reactions mechanism, structures and cross-section measurements are build on each other.
- Overall, a wealth of information with Ni and Pb targets, and many more possibilities.
- Acts as a reference for future experiments running Ge detectors in intense fast neutron environments.

References

1. H. Nann and W. Beneson Phys. Rev C 10, 1880 (1974)
2. W. Bohne, H. FUCHS, K. GRABISCH, D. HILSCHER, et al. Nucl. Phys. A 285, 107(1974)
3. Nuclear Data Sheets 155, 1 (2019).
4. D. Rudolph, C. Baktash, M. J. Brinkman, et al. Phys. Rev. Lett. 82, 3763 (1999)
5. D. Rudolph et al, EPJ A 4, 115 (1999)
6. M. Horoi, B. A. Brown, T. Otsuka, M. Honma, et al. Phys. Rev. C 73, 061305(R) (2006)
7. X. Ledoux et al, AIP Conf. Proc. 1412 , 1 (2011)
8. V. Borrel, B. Kandel, F. Albernhe, P. Frabel, et al. Nucl. Phys. A 430, 348(1999)

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