Constraining the NiCu cycle in X-ray bursts: Spectroscopy of ^{60}Zn

UNIVERSITY OF SURREY

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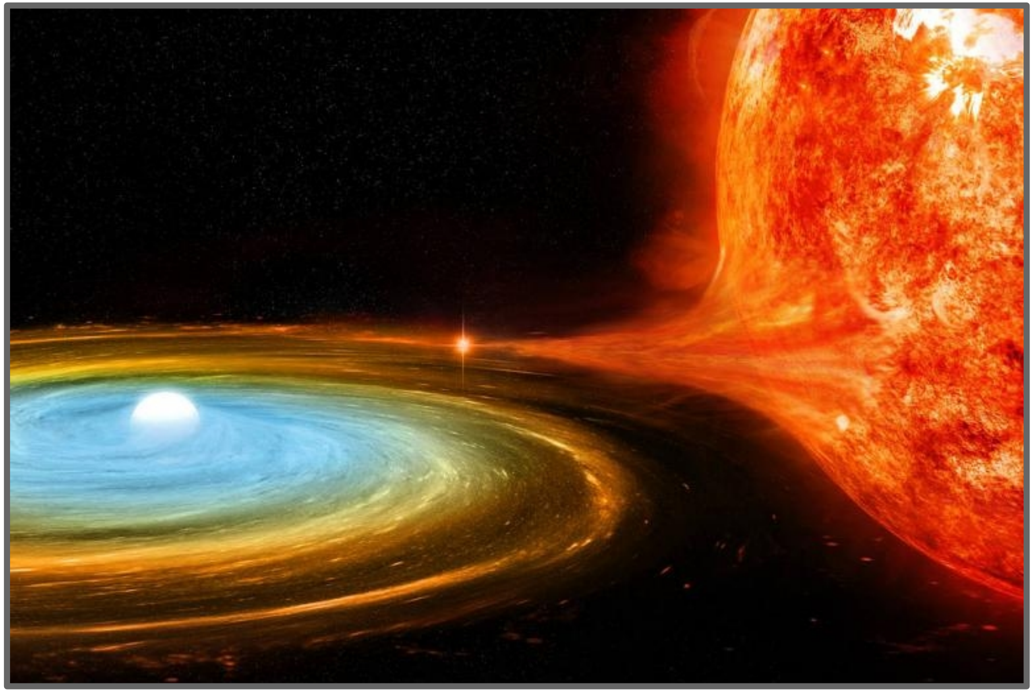
IOP Conference 2024

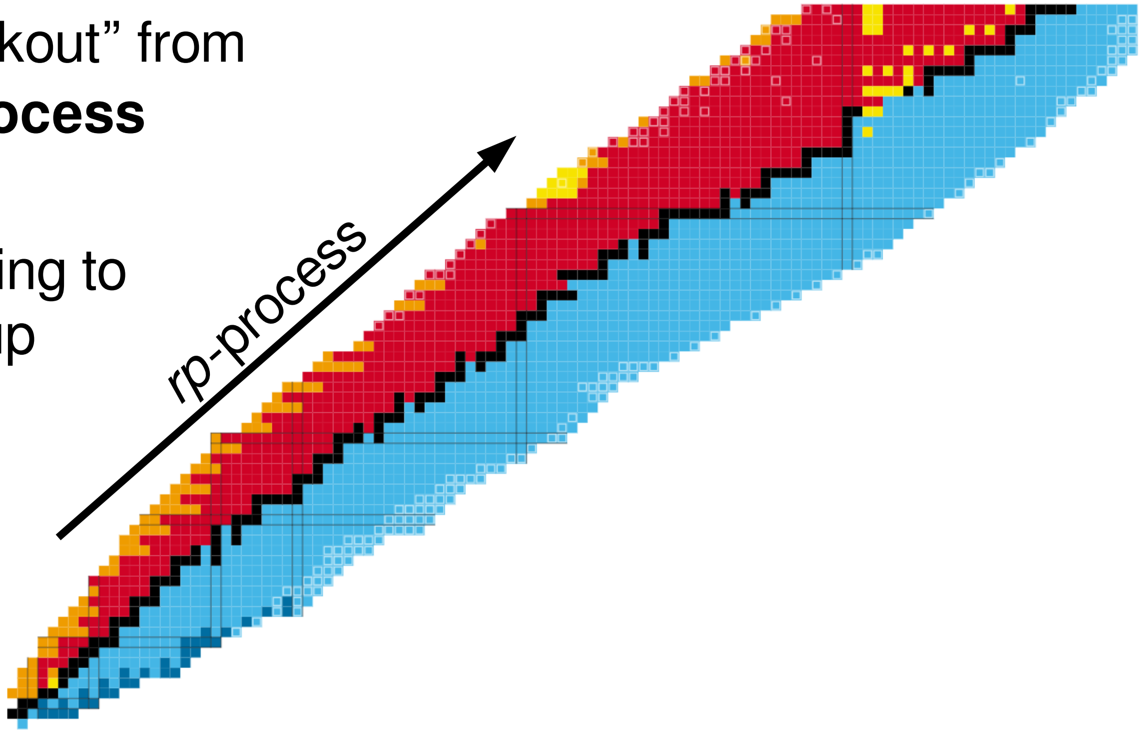
Astrophysical Motivation

- Type-I X-ray burst (XRB): **thermonuclear explosion** in the atmosphere of an **accreting neutron star**
- **Wealth of data** from space-borne satellites, e.g. RXTE, Chandra telescope
- **Questions remain** about shape of **light curves** and **nucleosynthesis products**



Astrophysical Motivation

- During burst:
  T_{peak} ~ 0.8 – 1.5 [GK] → "breakout" from hot CNO cycle into the ***rp*-process**
- *rp*-process:
  rapid proton captures leading to production of ***p*-rich nuclei** up to the Sn - Te region



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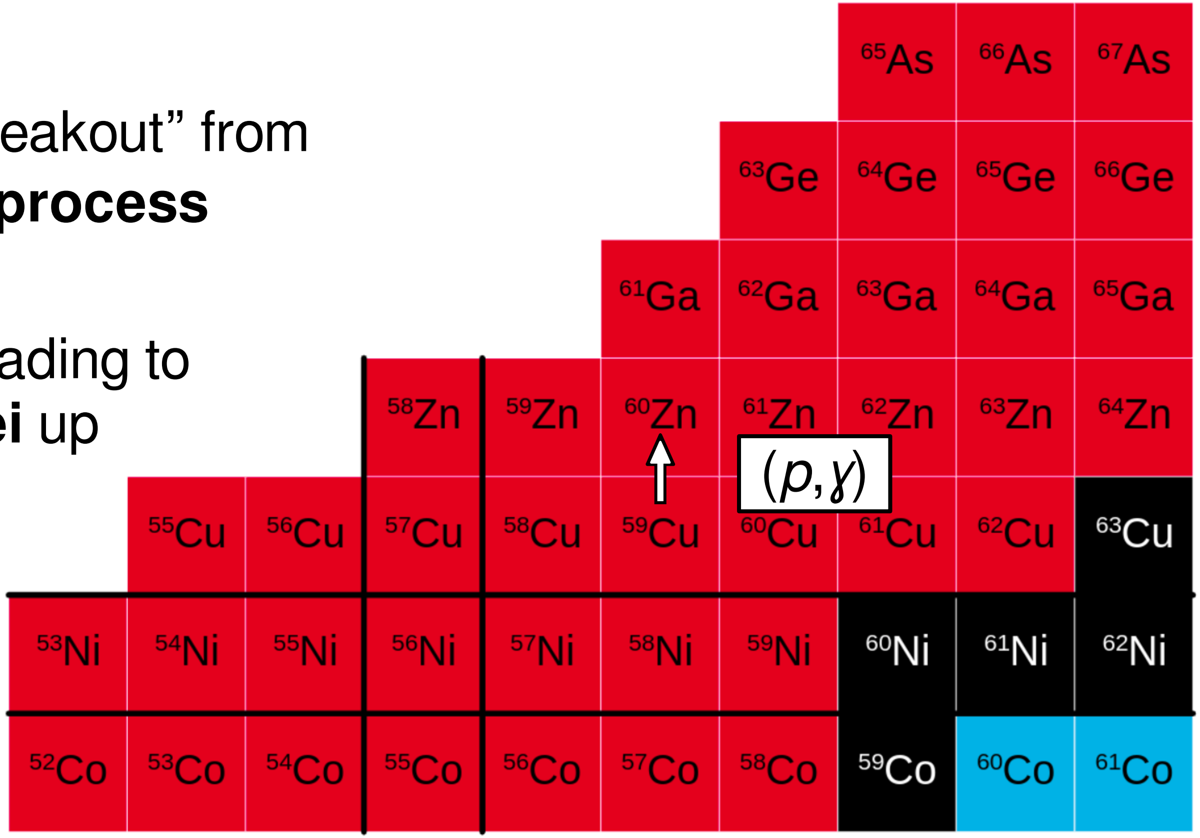
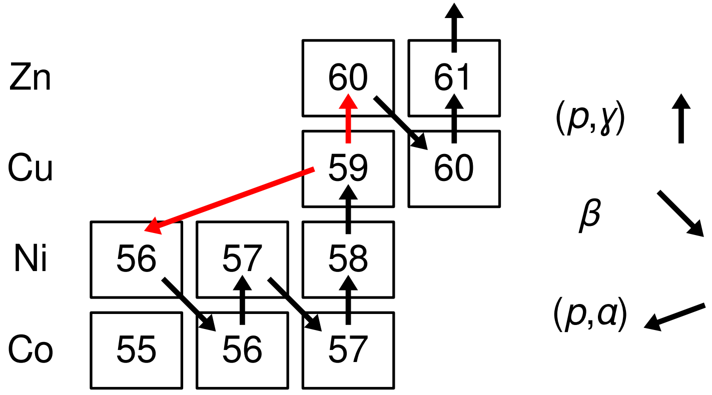
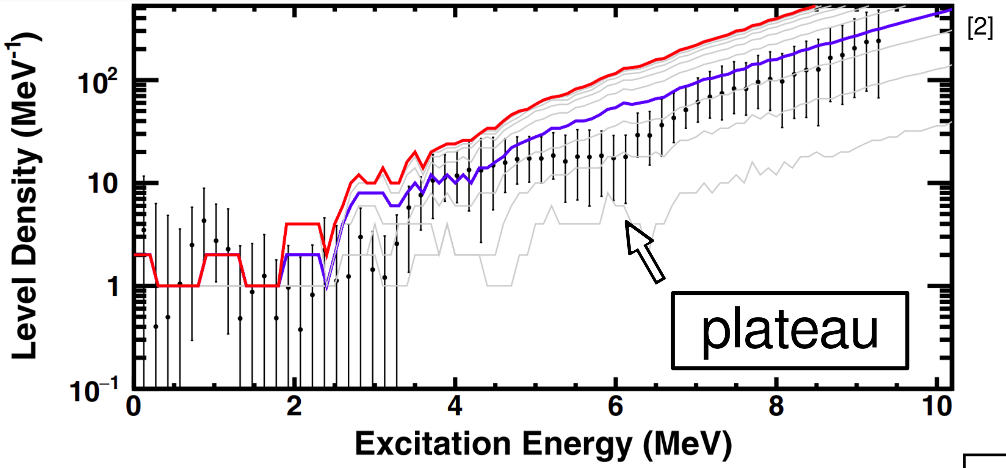
- Reaction of interest:
  $^{59}Cu(p,\gamma)$



Reaction of Interest - $^{59}Cu(p,\gamma)$

- **Competition in the NiCu cycle** between $^{59}Cu(p,\gamma)^{60}Zn$ - $^{59}Cu(p,\alpha)^{56}Ni$ determines nucleosynthesis towards higher masses
- Latter reaction previously studied [1]
- Present **reaction rate** based on **statistical-model** calculations
- Indirect study of ^{60}Zn [2] shows an abnormal **level-density plateau**





[1] J. S. Randhawa *et al.*, Phys. Rev. C **104**, L042801 (2021)
[2] D. Soltesz *et al.*, Phys. Rev. C **103**, 015802 (2021)

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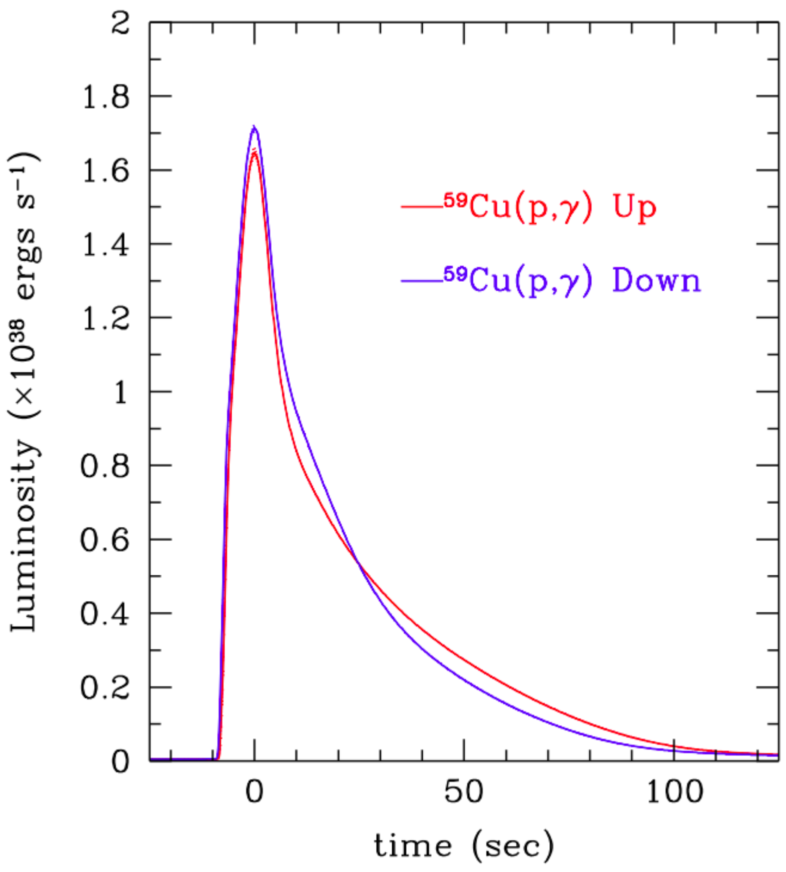

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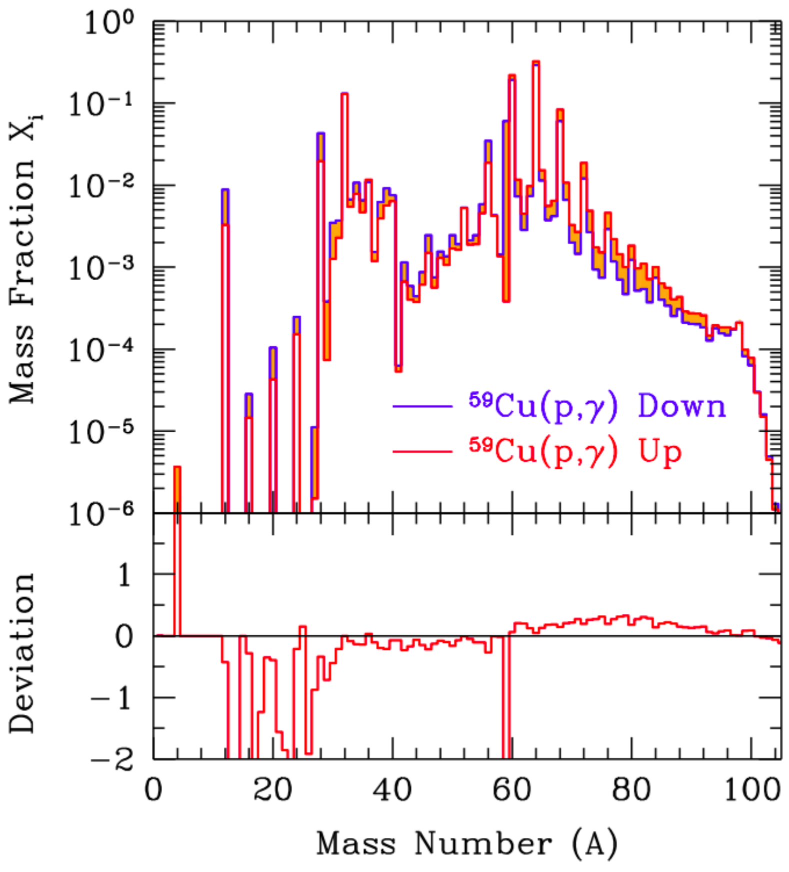
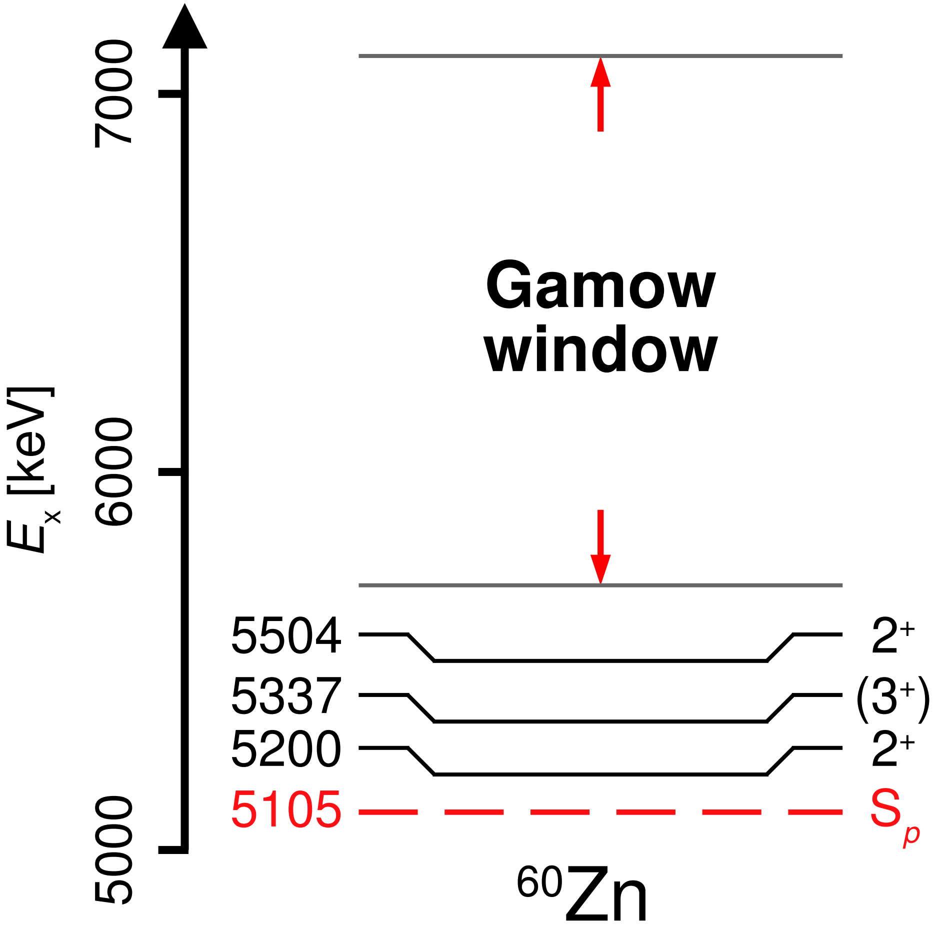


[3]

[3] R.H. Cyburt *et al.*, Astrophys. J. **830**, 55 (2016)

Reaction of Interest - ^{59}Cu(p,γ)

- ^{59}Cu(p,γ) rate expected to be dominated by **resonant capture** in ^{60}Zn above S_p to **low ℓ-transfer states** at E_x ~ 5.7 – 7.1 [MeV]
- Previous studies[4] of ^{60}Zn limited to high-spin states
- Almost **no experimental information** exists for p-unbound states in ^{60}Zn **within Gamow window**



[4] G. de Angelis *et al.*, Nuc. Phys. A **630**, 426433 (1998)

^{59}Cu(d,n) Transfer

- Study ^{60}Zn via ^{59}Cu(d,n) ***p*-adding transfer** in **inverse kinematics** at the Facility for Rare Isotope Beams (**FRIB**):
  1. **S800** for ^{60}Zn residue selection
  2. **GRETINA** for γ-ray energies → resonance **energies** E_{res}
  3. **LENDA** for (d,n) angular distributions → resonance **strengths** $\omega\gamma$

- Aim to place **constraints** on ^{59}Cu(p,γ) **reaction rate** in Type-I XRBs

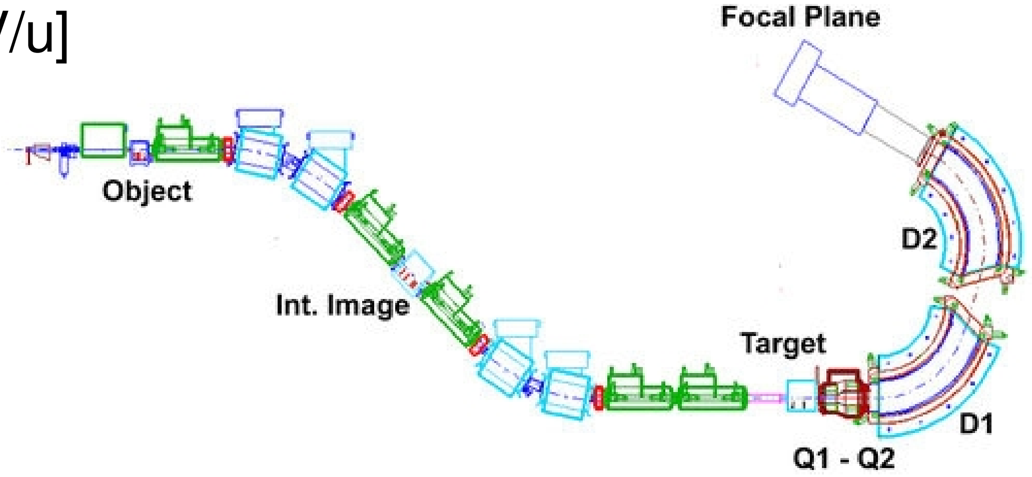
$$\langle \sigma \nu \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \sum_i \exp\left(- \frac{E_{\mathrm{res},i}}{kT} \right) (\omega\gamma)_i$$

Facility for Rare Isotope Beams (FRIB)

- New $730M scientific user facility located on Michigan State University (MSU) campus, U.S.
- Utilises recently commissioned Advanced Rare Isotope Separator (**ARIS**) for delivery of high rate, high purity **rare isotope beams**
- Primary Beam:
  ^{78}Kr ions, ~ 10 [kW]
- Primary Target:
  Be, ~ 2 [g/cm^2]

S800

- **Spectrometer** used for **separation and selection** of ^{60}Zn residues by their **mass-to-charge** ratio, A/q
- Various detectors placed at stations for **time-of-flight** and **energy loss** measurements, **particle trajectory** tracking
- Secondary Beam:
  ^{59}Cu ions, ~ 10^7 [pps], 40 [MeV/u]
- Secondary Target:
  CD_2, ~ 10 [mg/cm^2]

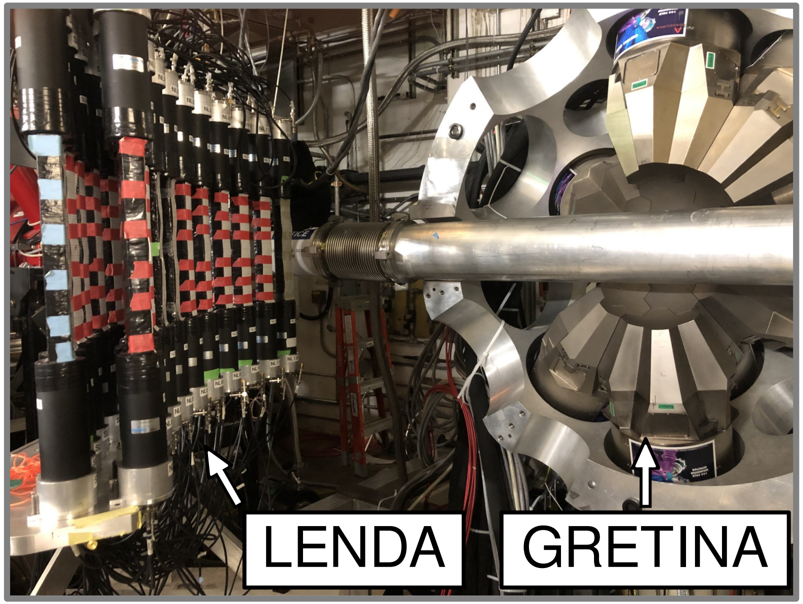


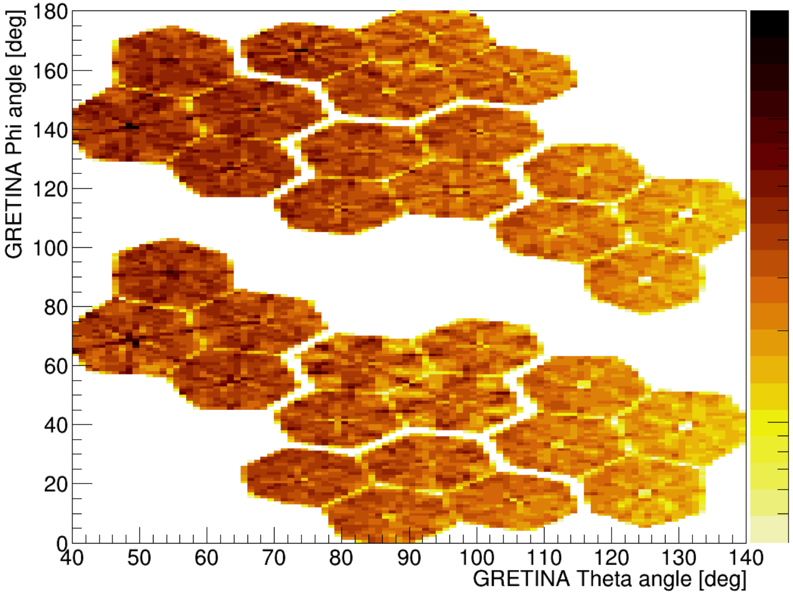
[5]

[5] [online]: *https://wikihost.nscl.msu.edu/*

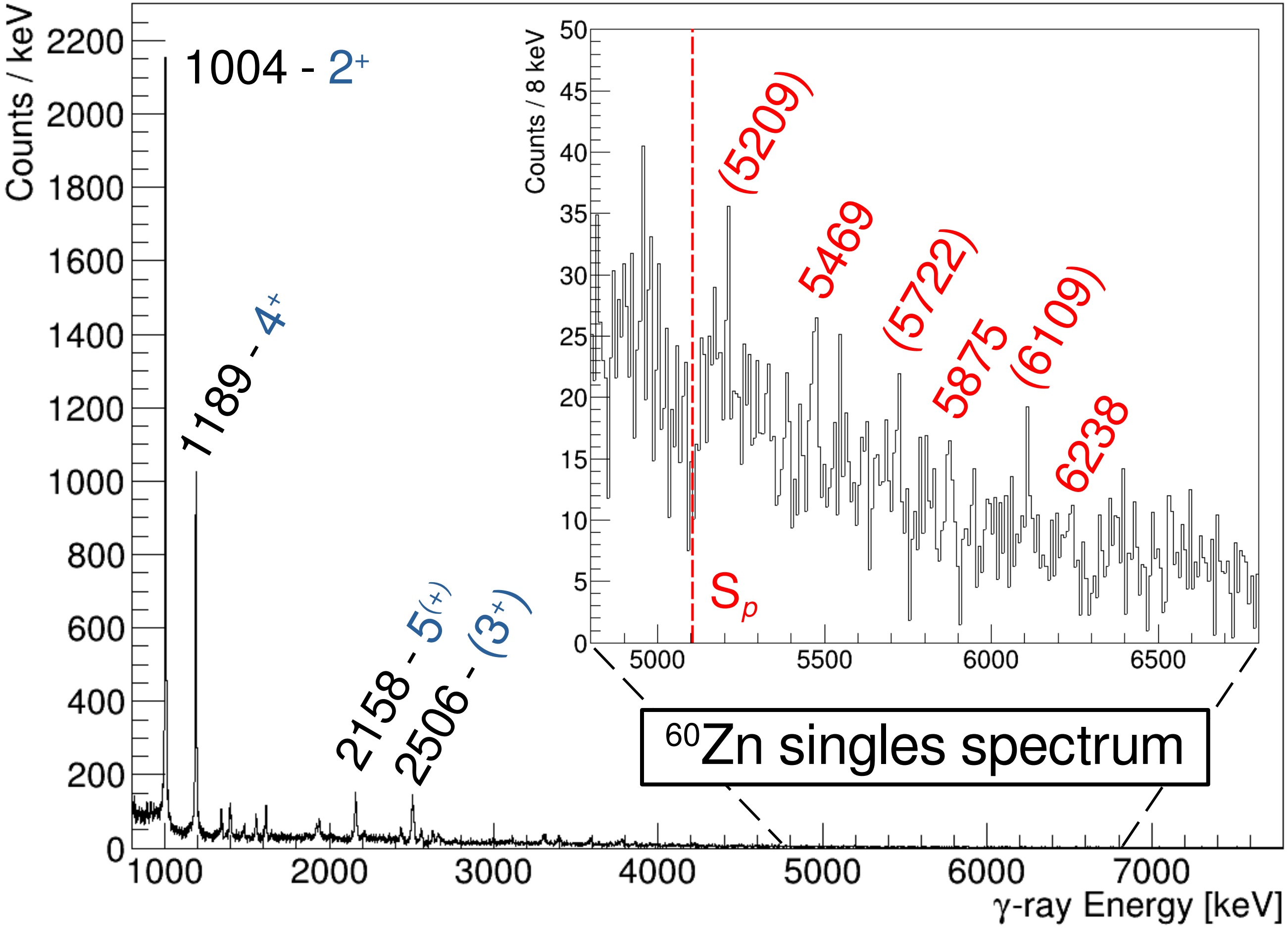
GRETINA & LENDA Detector Arrays

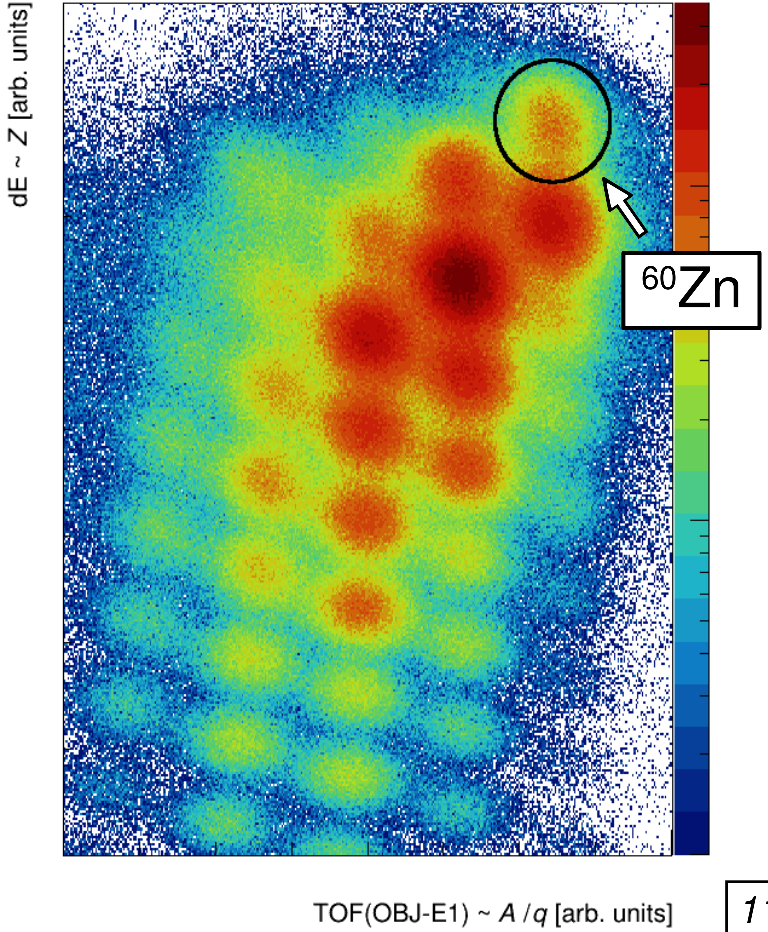
- GRETINA:
  8 HPGe modules used, each with 4 crystals, for ***γ*-ray detection**
- LENDA:
  24 plastic scintillation detector bars for **neutron detection**





^{59}Cu(d,n) Analysis – GRETINA + S800





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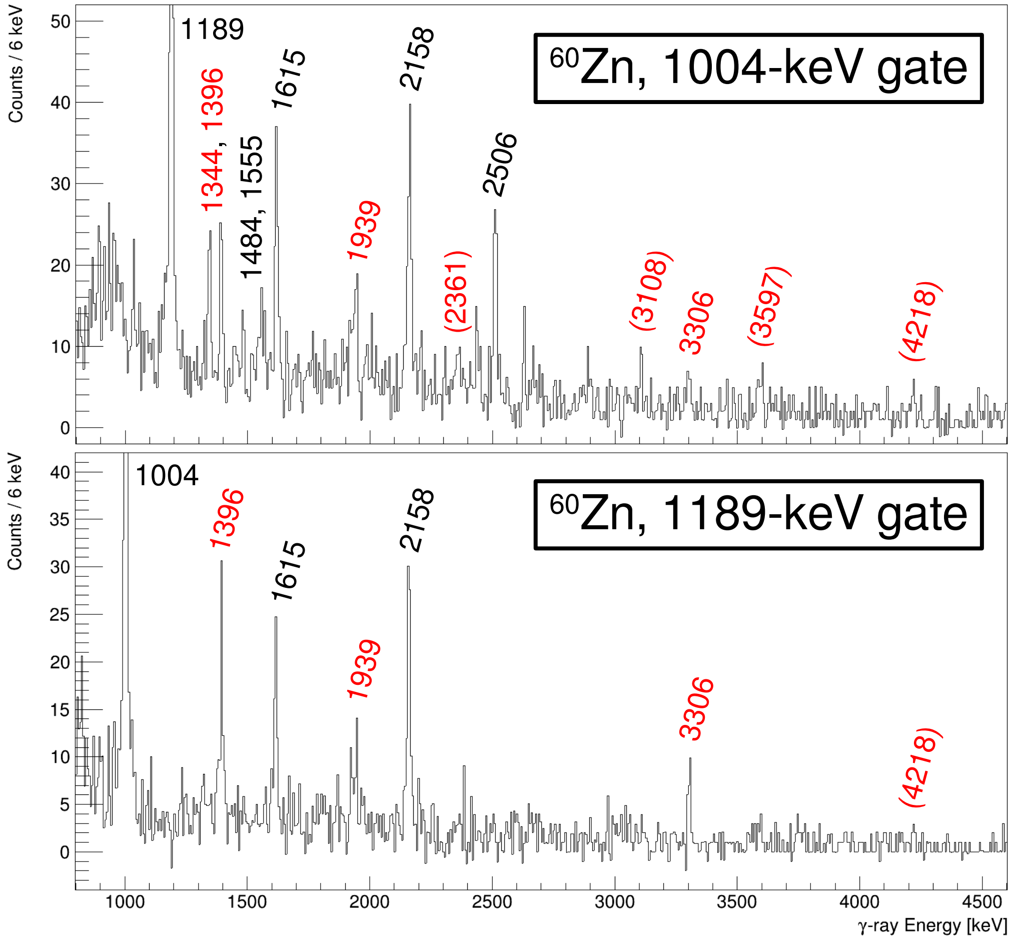

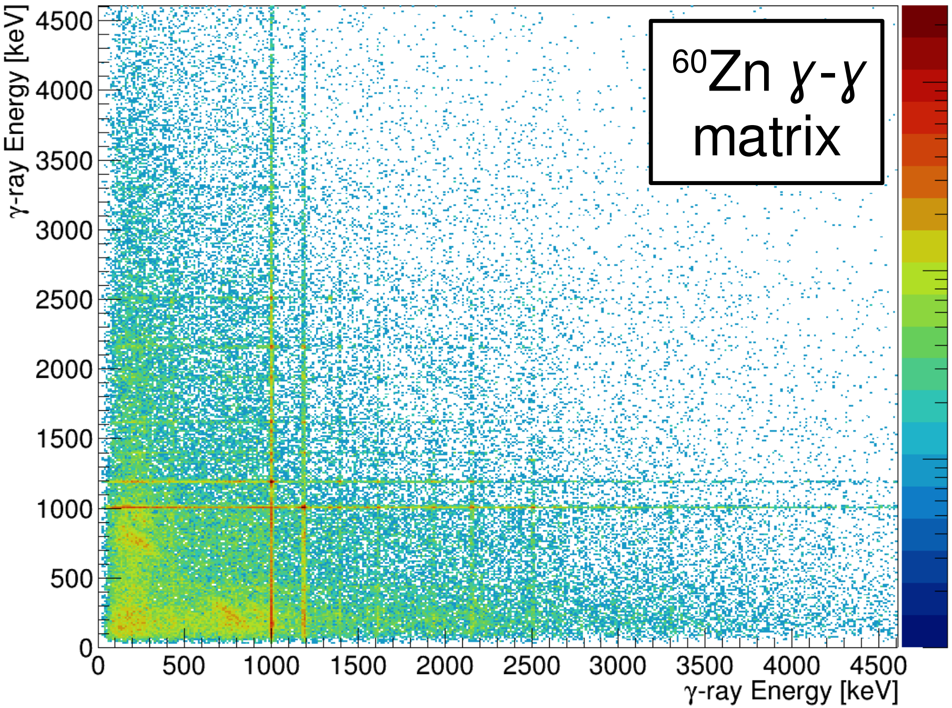

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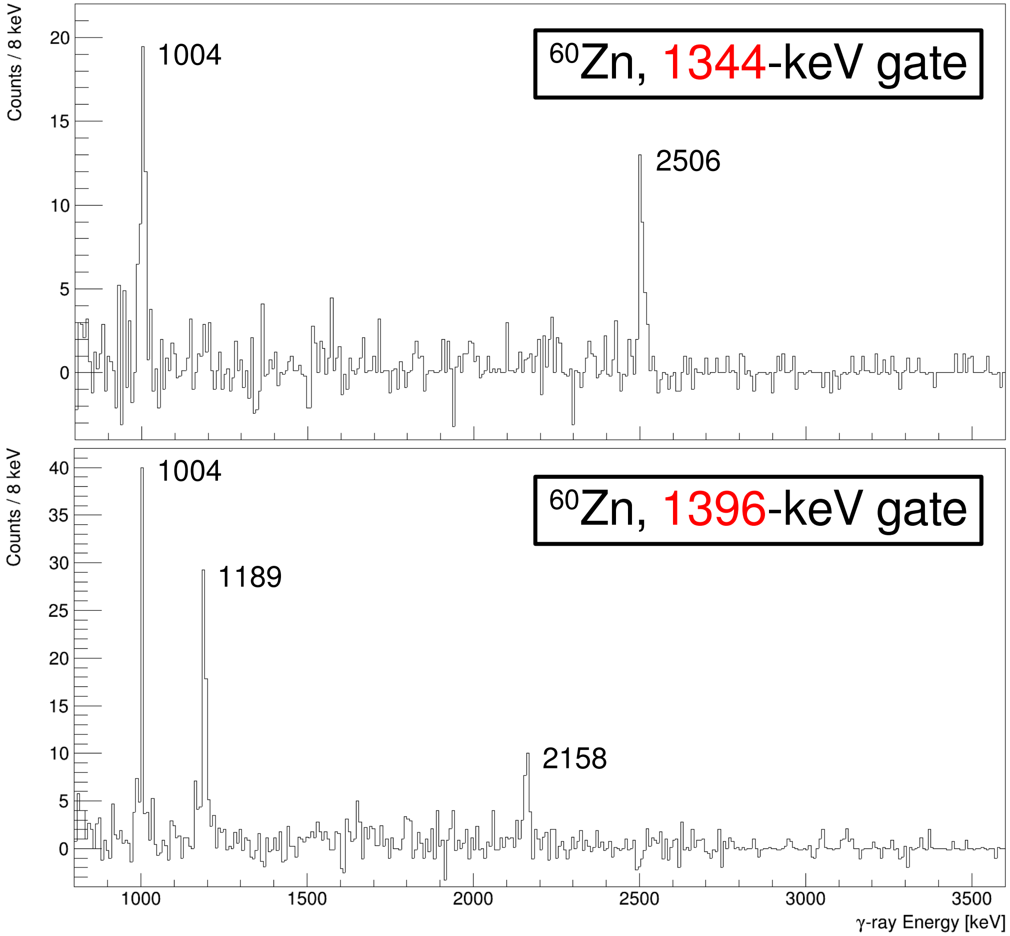
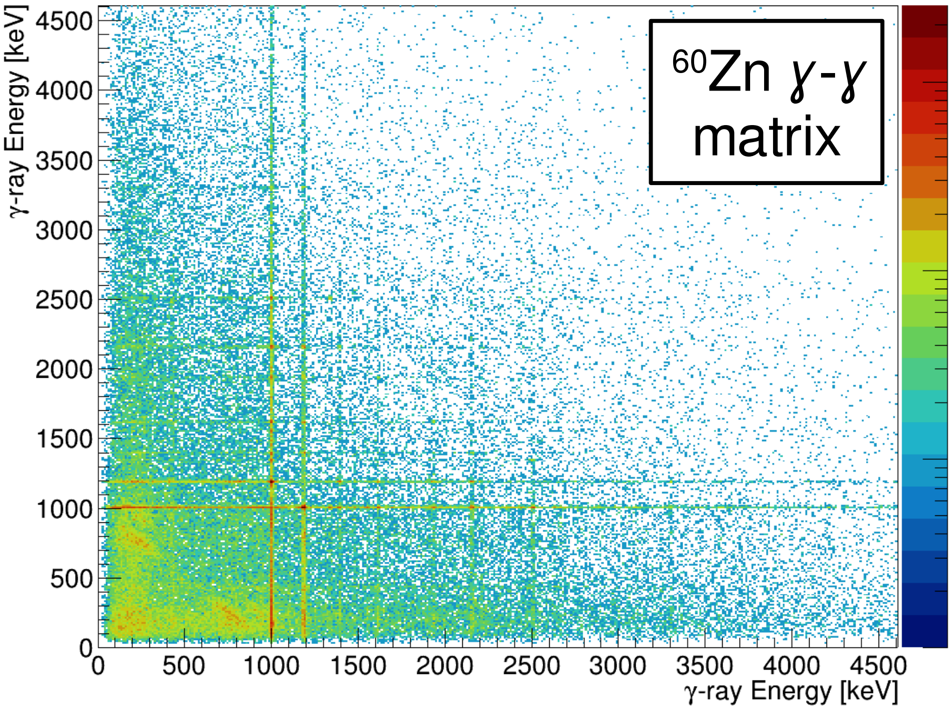
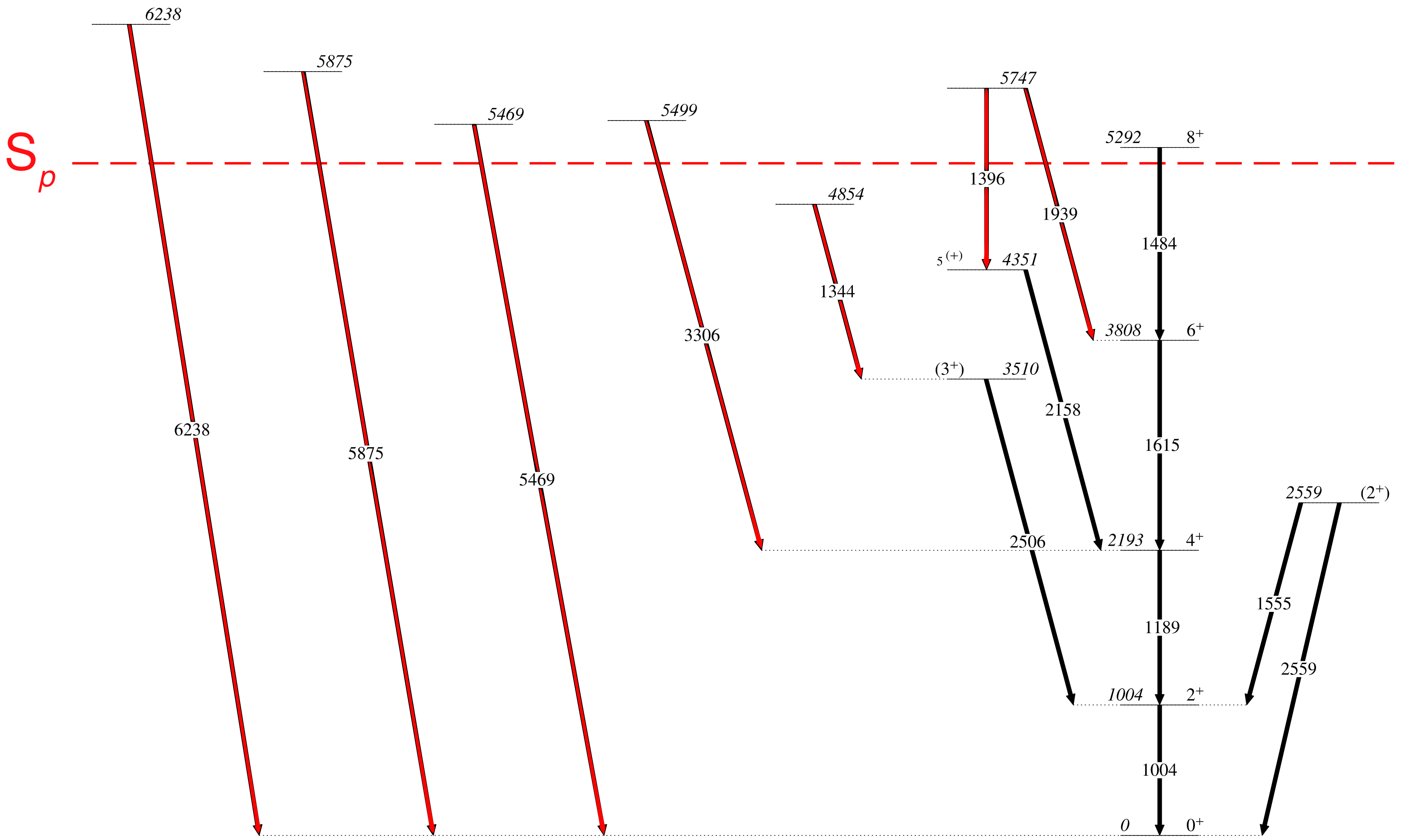




$^{59}Cu(d,n)$ Analysis – ^{60}Zn Level Scheme



Summary and Future Work

In summary:

1. Aim to place **constraints** on the **reaction rate** of ^{59}Cu(p,γ) in Type-I XRBs
2. Require **energies** E_{res} and **strengths** $\omega\gamma$ of resonances in ^{60}Zn
3. Ongoing analysis of ^{59}Cu(d,n) transfer has led to **first identification** of relevant **resonant states** in ^{59}Cu(p,γ)

Next steps:

1. Finalise ^{60}Zn-gated γ-ray spectroscopy; revisit corrections (S800 particle track, Doppler shift)
2. Begin LENDA data analysis

Acknowledgements

C. O'Shea[1], G. Lotay[1], D. T. Doherty[1], A. Gade[2], T. Ahn[3], D. Bardayan[3], P. C. Bender[4], B. A. Brown[2], S. Byrne[4], L. Canete[1], W. N. Catford[1], C. Cousins[1], A. Estrade[5], P. Gastis[6], S. A. Gillespie[2], J. Henderson[1], R. Kanungo[7], B. Longfellow[8], Z. Meisel[9], F. Montes[10], M. Moukaddam[11], S. Noji[2], P. O'Malley[3], C. Paxman[1], J. Pereira[10], J. S. Randhawa[2], B. J. Reed[1], A. M. Rogers[4], H. Schatz[10], D. Seweryniak[12], A. Spyrou[10], N. K. Timofeyuk[1], D. Weisshaar[10], M. Wiescher[3], R. G. T. Zegers[10]

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Acknowledgements

Thank you for your attention

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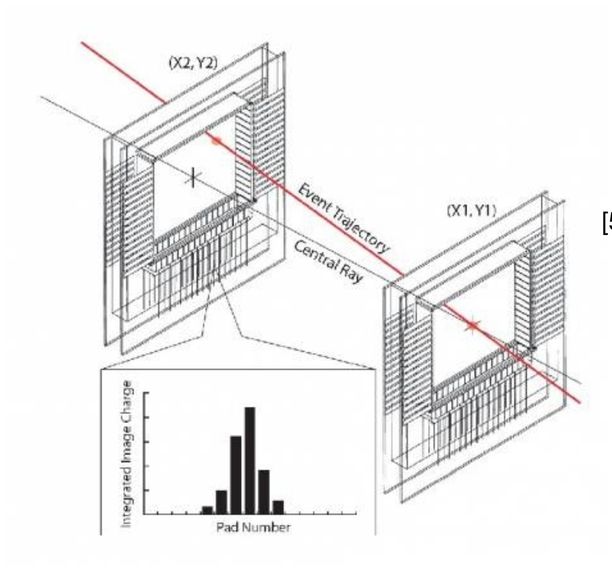
Backup slides

Dispersive Parameter Gate

- Additional gate on particles' **dispersive parameters** (a_{fp}, x_{fp}) ~ (0,0) to remove random scatter, ^{59}Cu bleed-in events



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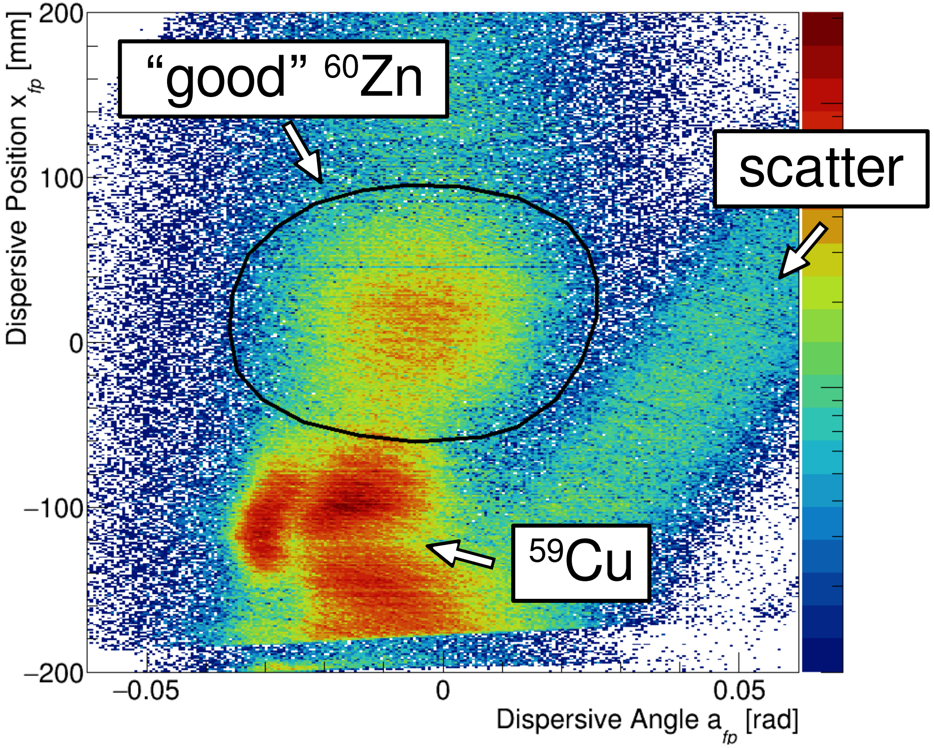
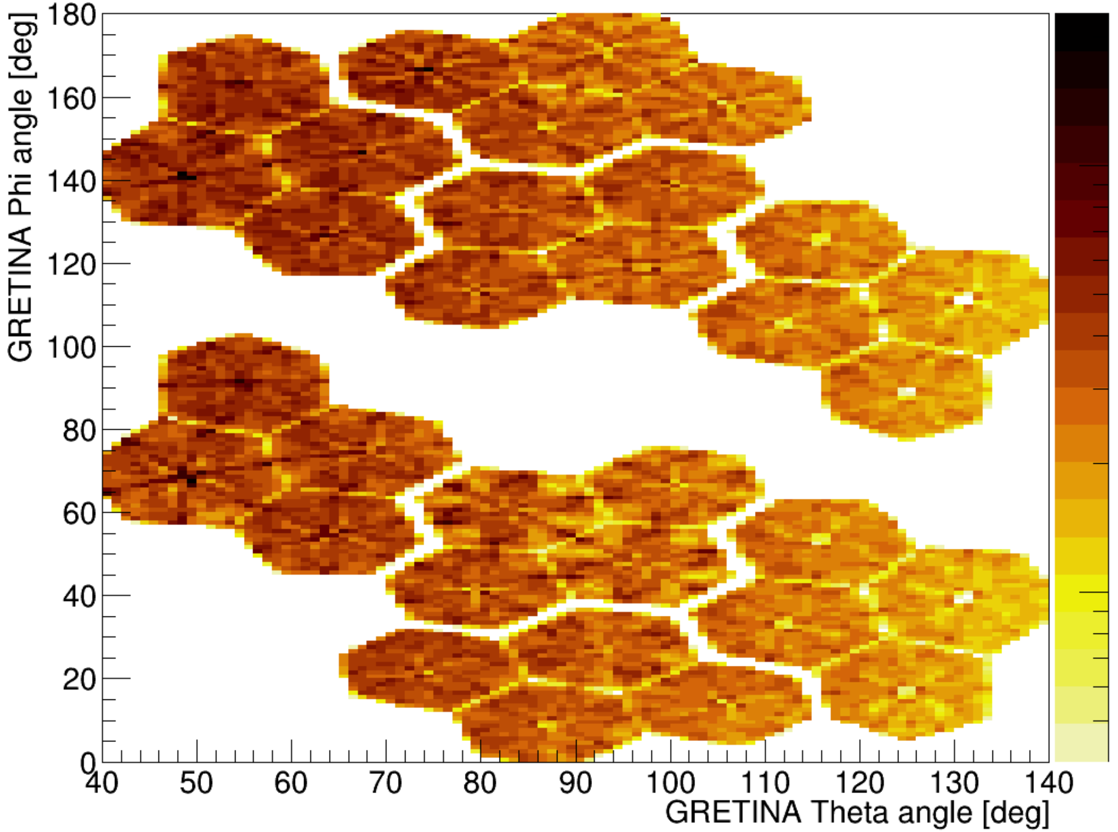


[5] [online]: *https://wikihost.nscl.msu.edu/*

Add-back Algorithm

- Add-back algorithm implemented as seen in D. Weisshaar *et al.* [6]
- Looks to nearest-neighbour crystal events, and increments spectrum for *n0n1* events
- *n2ng* events are discarded



[6] D. Weisshaar *et al.*, Nuc. Inst. and Meth. In Phys. Res. A **847**, 187198 (2017)

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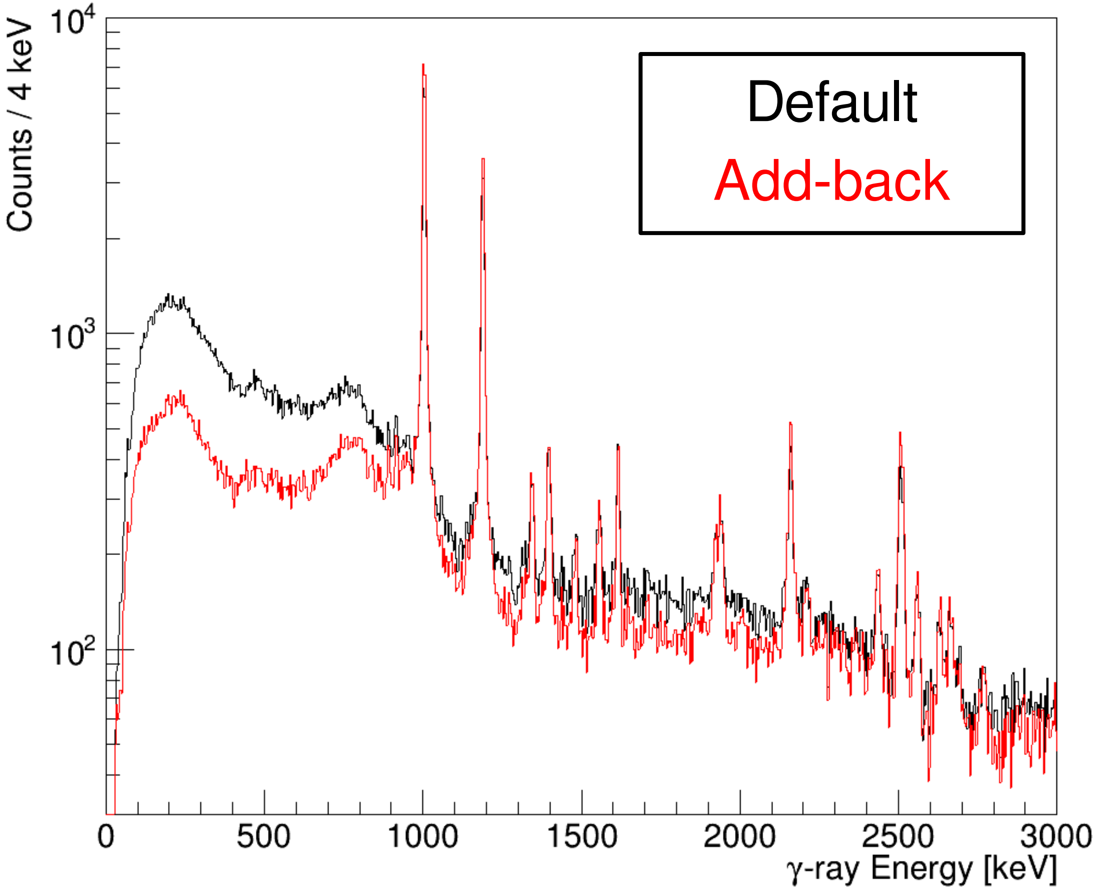
- ABF(1004 keV) = 1.15



[6] D. Weisshaar *et al*., Nuc. Inst. and Meth. In Phys. Res. A **847**, 187198 (2017)

Present Status of LENDA Analysis

- LENDA data still requires some work - γ flash currently too wide for reliable n/γ discrimination
- Need to **calibrate light outputs**, and **correct time-of-flights** for accurate neutron selection