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

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1. Motivation and Astrophysical Background

Type-I X-ray bursts describe huge spikes in X-ray emission that occur as a result of explosions on the surface of an **accreting neutron star**

The extreme temperatures and densities feed a set of reactions known as the ***rp* process**: a series of rapid proton-captures resulting in the **synthesis of proton-rich nuclei**

Present simulations of these stellar phenomena are ultimately **limited by uncertainties in reaction rates** of key *rp*-process reactions

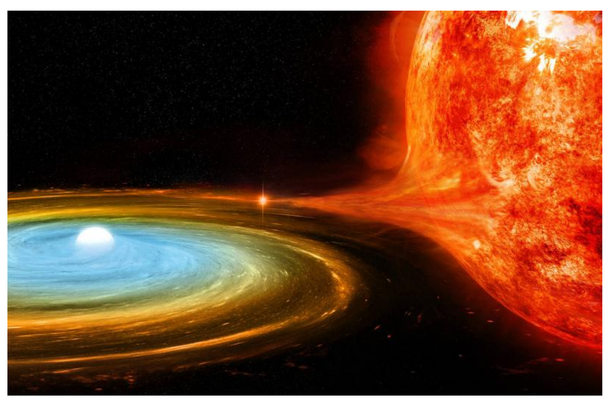

Fig 1. Artist Interpretation of an X-ray burst.

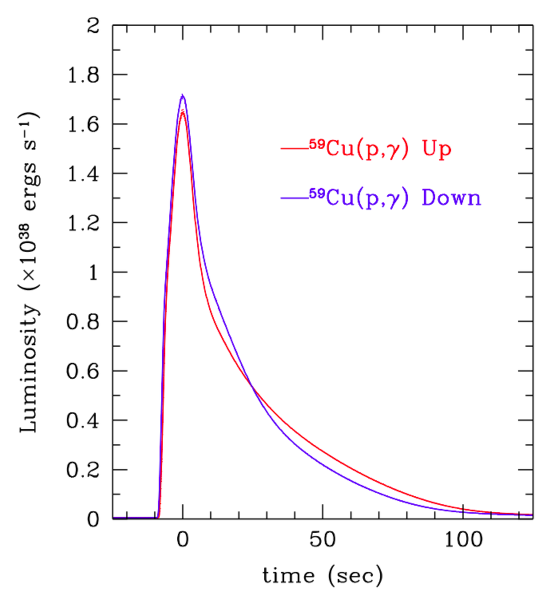

Fig 2. Influence on X-ray burst light curve from variation of the stellar reaction rate of ^{59}Cu(p,γ) [2].

Competition in the NiCu cycle between **^{59}Cu(p,γ)^{60}Zn – ^{59}Cu(p,α)^{56}Ni** determines higher-mass nucleosynthesis

Present ^{59}Cu(p,γ) rate based on **statistical-model calculations**, which may be insufficient [1]

Variation of present rate shown to have a **significant effect** on burster light curve [2], yet **no information** presently exists for **key states in ^{60}Zn** above threshold S_p = 5105.0(4) keV

Previous studies e.g. [3] limited to **high-spin states**, which have **no influence**

Aim: constrain the present ^{59}Cu(p,γ) reaction rate by measuring the relevant states in ^{60}Zn, which correspond to **low-ℓ transfer resonances** to the 3/2$^-$ ground state of ^{59}Cu

$$N_A\langle\sigma\nu\rangle = \frac{1.54\times10^{11}}{(\mu T_9)^{3/2}}\sum_i \exp\left[\frac{-11.605 E_{\mathrm{res},i}}{T_9}\right]\cdot(\omega\gamma)_i$$

2. Experimental Details

Populated states in ^{60}Zn via **^{59}Cu(d,n) transfer** conducted at the Facility for Rare Isotope Beams (FRIB), USA

Experimental setup previously shown as **effective** for studies relevant to **nuclear astrophysics** [4,5]

Gamma-rays from residues **detected by GRETINA** – a state-of-the-art tracking detector array consisting of 8 segmented HPGe modules

Neutrons from transfer **detected by LENDA** – a low-energy n-detector array consisting of 24 plastic scintillator modules (bars)

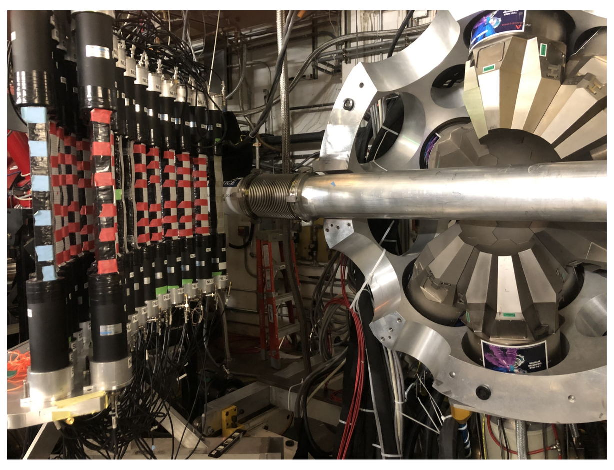

Fig 3. GRETINA (right), LENDA (left).

Residual particles then transmitted through the **S800**, where various detectors provide **time-of-flight** and **energy-loss** measurements

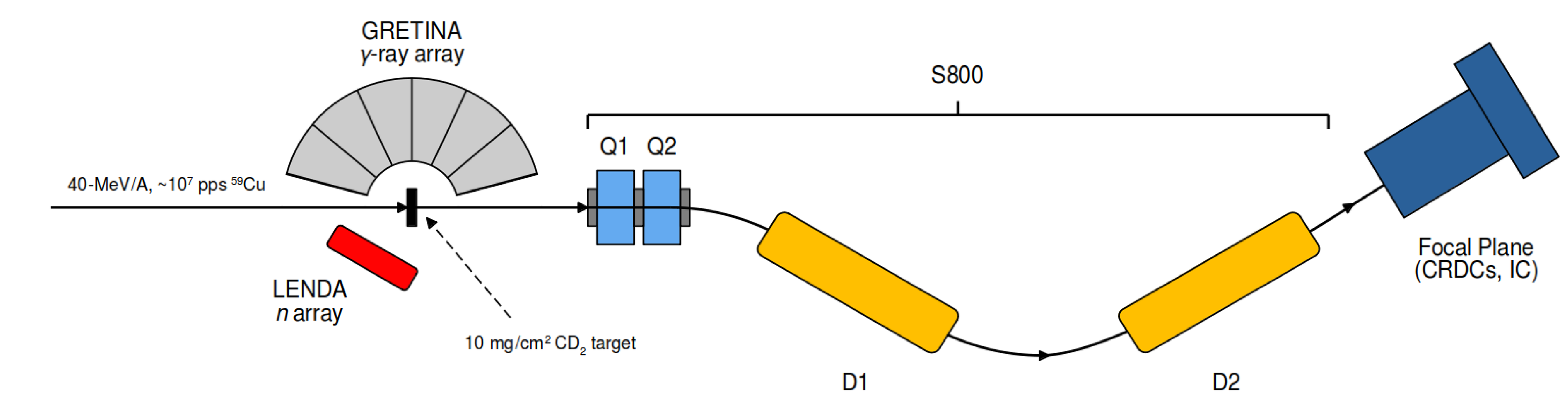

Fig 4. Illustration of the experimental setup, with GRETINA, LENDA, and the S800, at the Facility for Rare Isotope Beams (FRIB).

3. Focal Plane Analysis

Information on the residues produced by reactions at the target position used to **select** upon ^{60}Zn nuclei:

- Ionisation chamber – residues may be separated by **atomic number**, ***Z***, via a measurement of their **energy loss**, **d*E***
- Timing scintillators – residues may be separated by **mass-to-charge ratio**, ***A*/*q***, via a measurement of their **time-of-flight**, **TOF**

Plot of TOF versus dE achieves **seperation** on an **isotope-by-isotope basis** – may then look to the **γ rays detected coincident** with ^{60}Zn nuclei

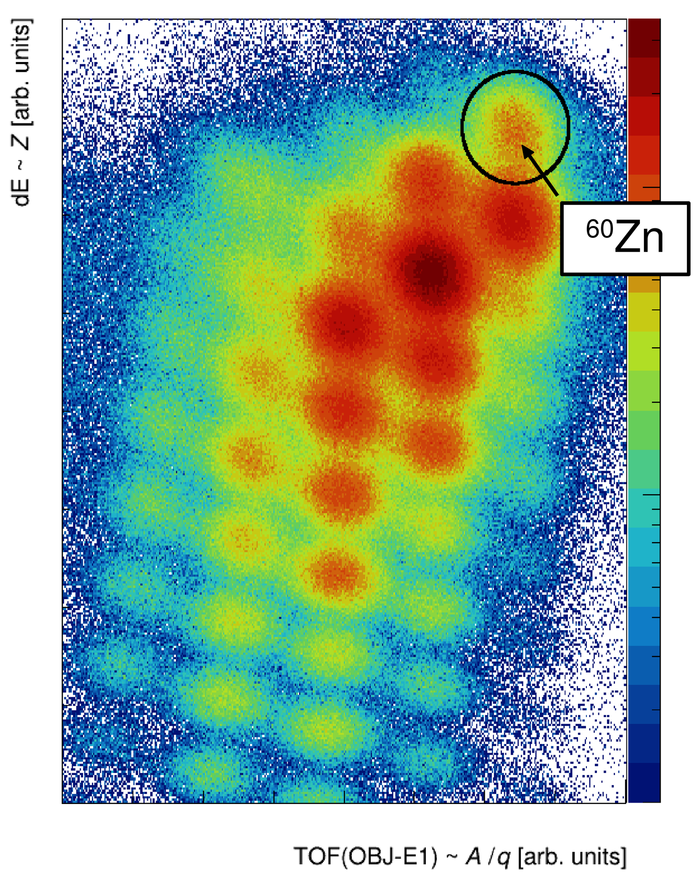

Fig 5. Separation of residues via A/q and Z.

4. Key Results

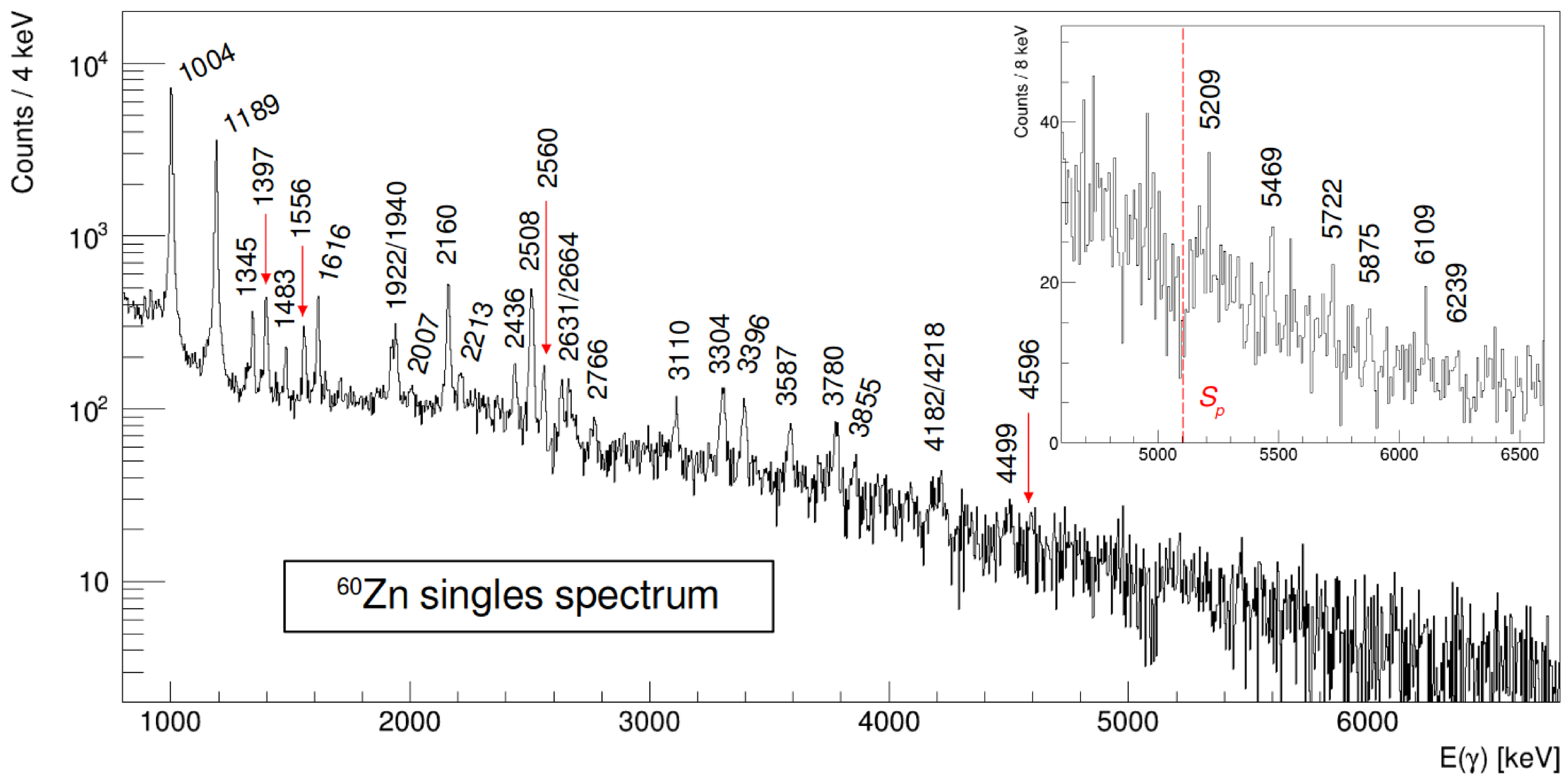

Fig 6. Singles spectrum coincident with ^{60}Zn recoils. Gamma-ray transitions, both known and new, resulting from de-excitation of ^{60}Zn labelled. Inset: first identification of multiple ground-state transitions, indicating the existence of excited states above S_p = 5105.0(4) keV.

Observation of **new ground-state transitions in ^{60}Zn**, providing energies for **six proton-unbound excited states** at E_{ex} = 5208.9(74), 5469.6(34), 5722.3(35), 5875.4(35), 6109.7(25), and 6239.4(67) keV

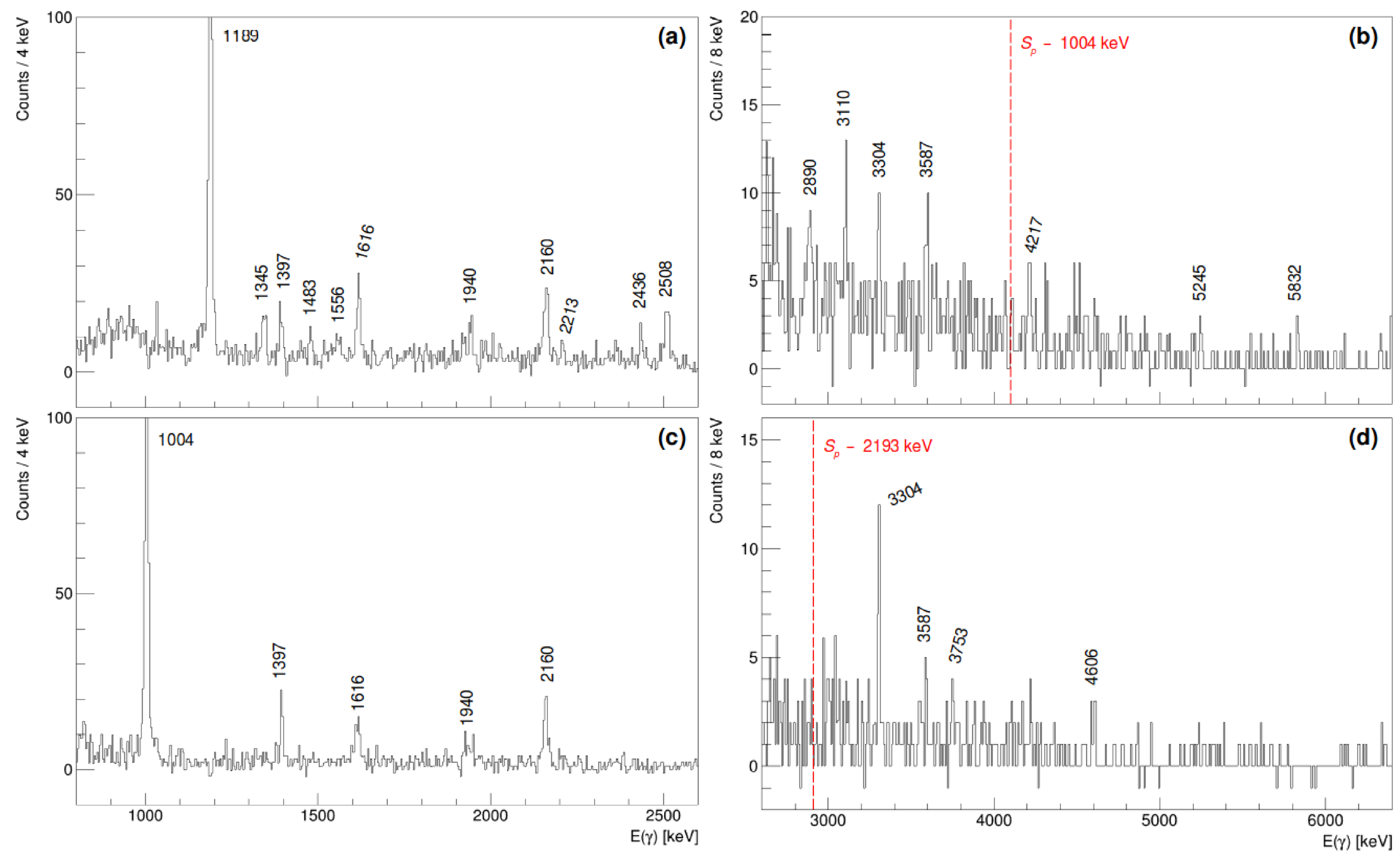

Fig 7. (a) γ-γ coincidence projection of the 1004-keV transition at low energies. (b) γ-γ coincidence projection of the 1004-keV transition at high energies. (c) γ-γ coincidence projection of the 1189-keV transition at low energies. (d) γ-γ coincidence projection of the 1189-keV transition at high energies.

Observation of **new coincident transitions in ^{60}Zn**, providing energies for an additional **seven proton-unbound excited states** at E_{ex} = 5222.4(38), 5497.2(32), 5780.4(36), 5948.0(29), 6249.1(52), 6799.1(46), and 6836.1(58) keV

5. ^{60}Zn Level Scheme

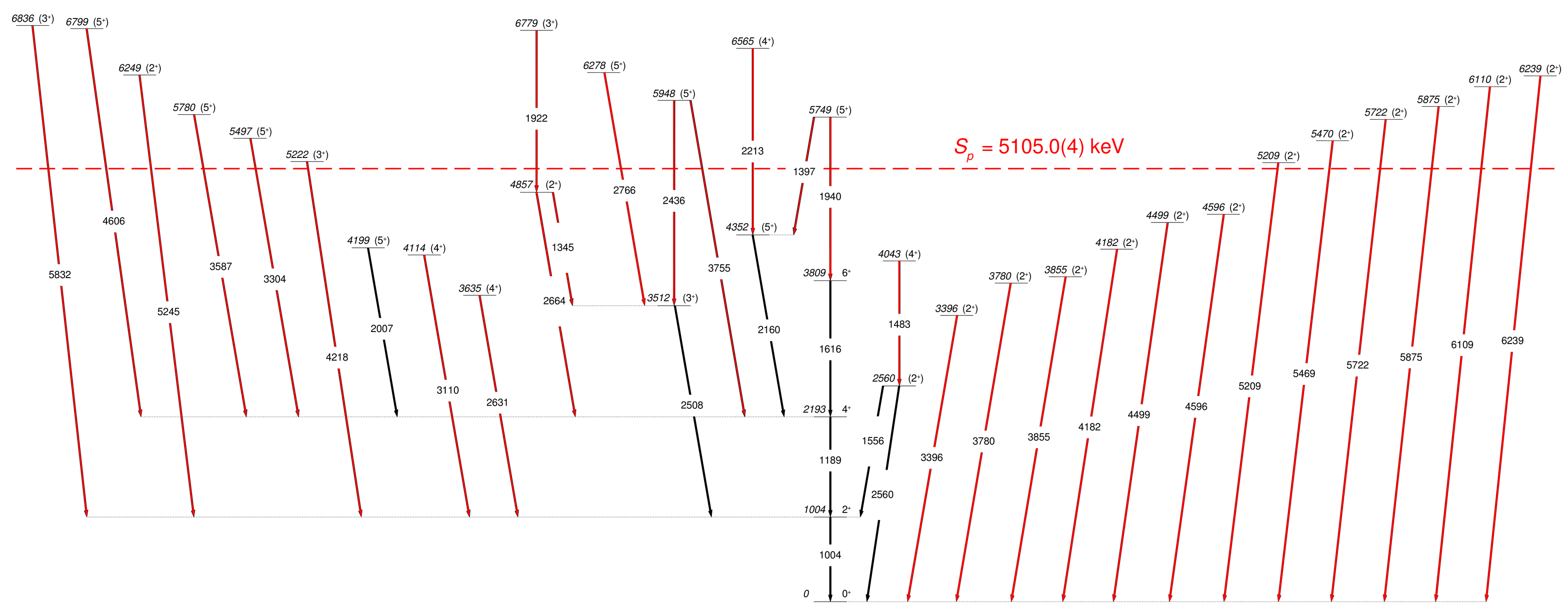

Fig 8. Level scheme of ^{60}Zn from the present work. New transitions highlighted in red. Gamma-ray energies in units of keV.

6. Conclusions and Future Work

First observation of 30 γ rays in ^{60}Zn, leading to the measurement of 27 new states, 17 of which are above threshold, 6 of which are presumed low-ℓ transfers

Next steps include **completing calculations** for resonances' **proton partial widths** (finalise integrated cross sections, spin-parity assignments) as to determine the new constraints for the **^{59}Cu(p,γ) reaction rate**

References

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