Experimental study of the ^{18}Ne(α,p)^{21}Na reaction via direct and indirect means

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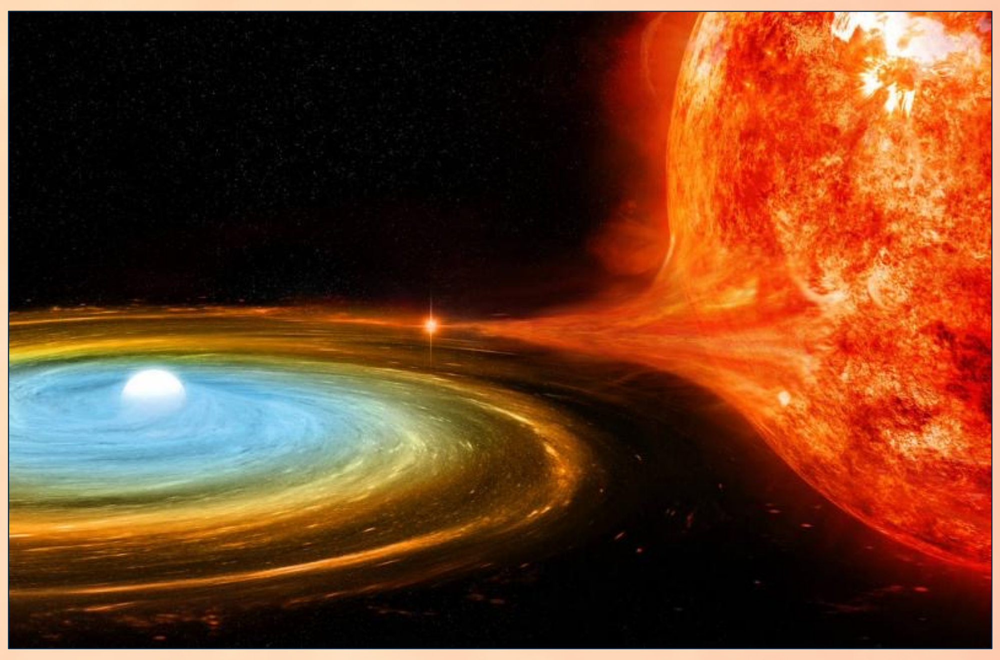
Abstract

Sensitivity studies indicate that the shape of the light curves of Type-I X-ray bursts—which is important for determining the mass-radius relationship and rotation frequency of neutron stars—is sensitive to the α-capture breakout rates of a few waiting point nuclei. One of these key Hot-CNO breakout reactions is ^{18}Ne(α,p)^{21}Na. Two complementary experiments are being planned to experimentally constrain the reaction rate: a direct measurement of the excitation function in inverse kinematics with the MUSIC detector and the ATLAS facility at Argonne National Laboratory, and a determination of the strengths of the key resonances in the compound nucleus ^{22}Mg from an indirect measurement via the ^{7}Li(^{18}Ne,t)^{22}Mg(p)^{21}Na reaction with MUGAST+EXOGAM+ZDD at LISE @ GANIL. The current plans for each experiment and the expected results will be discussed.

^{18}Ne(α,p)^{21}Na and X-ray bursts

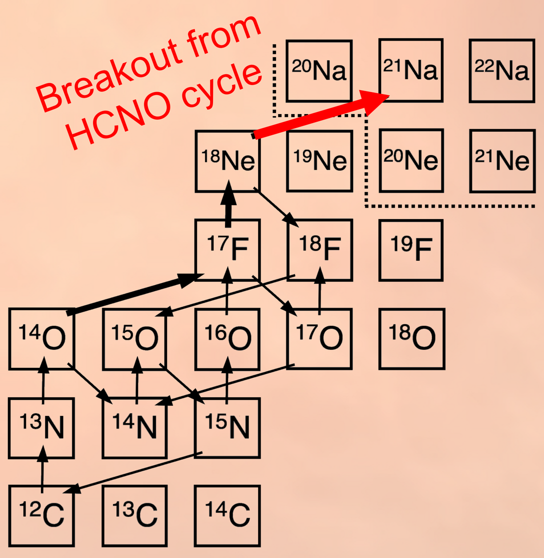
Type-I X-ray bursts arise from a thermonuclear runaway on the surface of a neutron star that is accreting H- and/or He-rich material from a companion star [1]



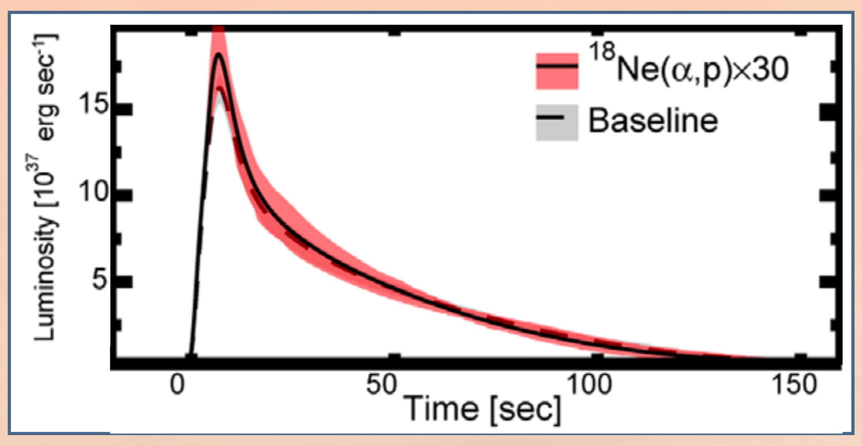
Artist's rendition of a neutron star accreting H- and He-rich matter from a companion star

Waiting-point nuclei in the Hot-CNO cycles (e.g. ^{18}Ne, $T_{1/2} = 1.67$ s) restrict energy generation to be independent of temperature, and material to $A < 20$

The ^{18}Ne(α,p)^{21}Na reaction becomes relevant around $T \geq 0.8$ GK and is one of two paths to breakout of the Hot-CNO cycles, initiating explosive energy generation and creating the $A \geq 20$ seed nuclei for the rp-process path



Breakout from the $A < 20$ mass region via the ^{18}Ne(α,p)^{21}Na reaction [2]



Effect of varying the ^{18}Ne(α,p)^{21}Na reaction rate on the light curve [4]

The shape of the light curve of the X-ray burst is sensitive to the ^{18}Ne(α,p)^{21}Na reaction rate [3, 4]

The light curve shape is **critical for understanding neutron stars**—they are used to study the neutron star mass-radius relationship and rotational frequency [5,6]

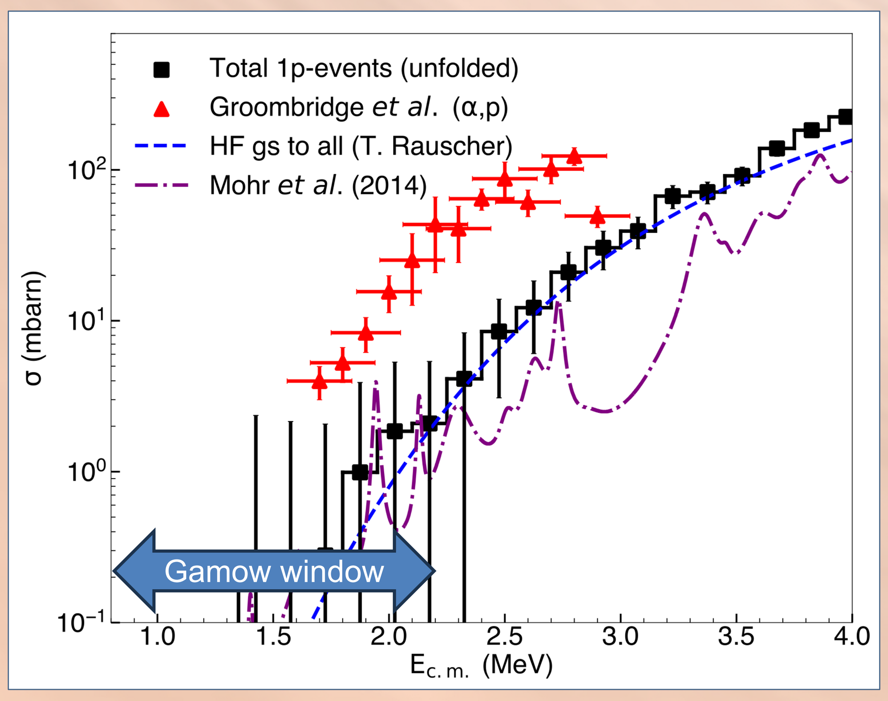
Previous investigations

The ^{18}Ne(α,p)^{21}Na breakout reaction becomes significant once the temperature reaches $T \geq 0.8$ GK, with peak temperatures $T \sim 1.4$ GK [7]. The Gamow windows for this temperature range cover center-of-mass energies $\boldsymbol{E_{\text{c.m.}} = 0.8 - 2.2}$ **MeV**.

The current leading experimental constraint from Anastasiou et al. [8] reached down to $\boldsymbol{E_{\text{c.m.}} = 2.5}$ **MeV** (sensitivity limit) with 56% statistical uncertainty

TALYS calculations suggest cross sections of ~ 1 mbarn at $E_{\text{c.m.}} \sim 2$ MeV

- **Direct** reaction measurements can reach the upper edge of the Gamow window
- **Indirect** measurements must be used to explore lower $E_{\text{c.m.}}$ in the Gamow window



Total ^{18}Ne(α,p)^{21}Na cross section measurement (black points) by Anastasiou *et al.* [8], compared to Groombridge *et al.* [9] and calculations from resonance strengths of the mirror nucleus by Mohr *et al.* [10] and Hauser-Feshbach caltulations with SMARAGD [11]

Direct reaction at Argonne

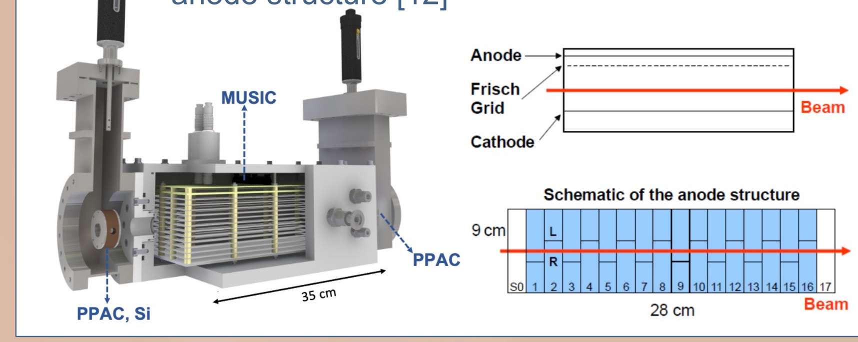
The Multi-Sampling Ionization Chamber (MUSIC) at Argonne can be used to directly measure the excitation function in inverse kinematics across a large center-of-mass energy range with a single beam energy

Parameters

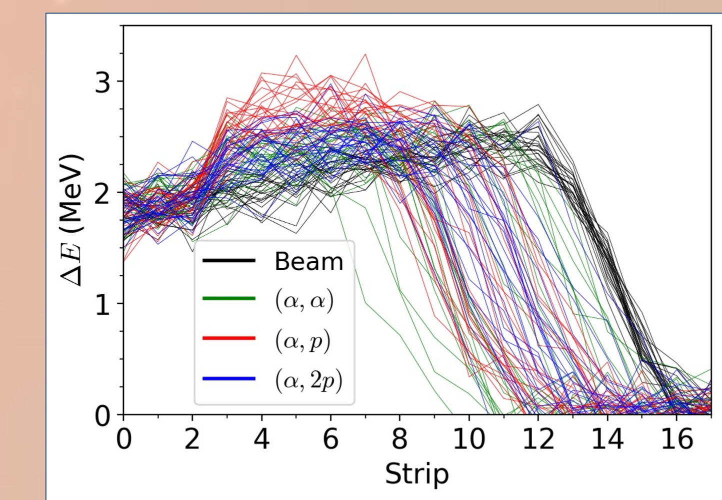
Experiment to be proposed:

- ^{18}Ne beam @ 2.5 MeV/u, $\sim 2 \cdot 10^3$ pps
- MUSIC detector: active ^{4}He target at ~560 mbar
- $E_{\text{c.m.}} = 1.9 - 5.9$ MeV

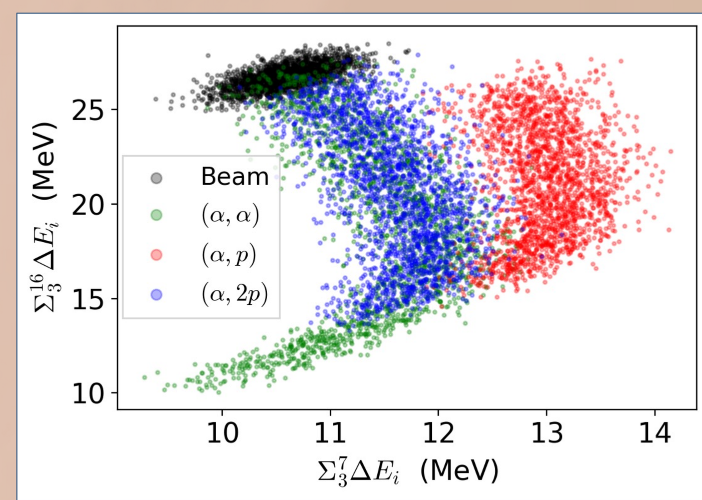
3D render of the MUSIC chamber and MUSIC anode structure [12]



Simulations

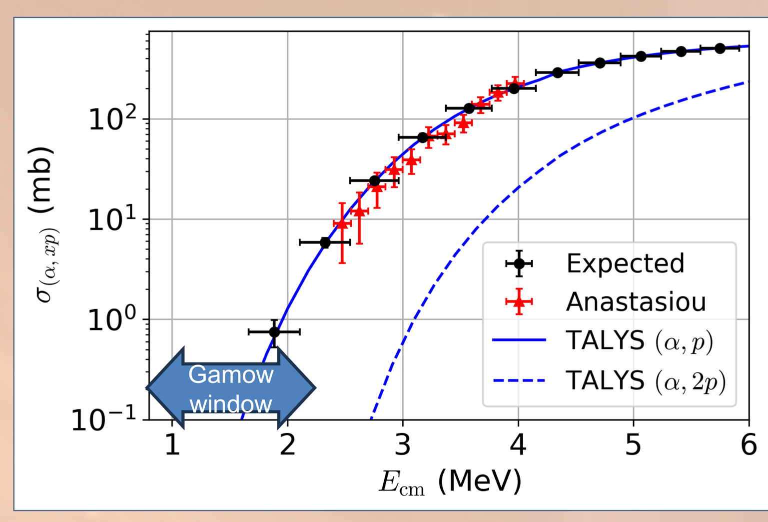


Simulated MUSIC traces for the possible reactions



(α,p) events can be separated based on different stopping power of the ^{21}Na recoil

Expected results



Expected results for 5 days of beam time: place leading constraints on reaction rate in the upper Gamow window

- 10% statistical uncertainty at $E_{\text{c.m.}} = 2.33$ MeV
- 28% statistical uncertainty at $E_{\text{c.m.}} = 1.89$ MeV
- Proposal in progress

Expected measurement based on TALYS calculations, compared to the measurement of Anastasiou et al. [8]

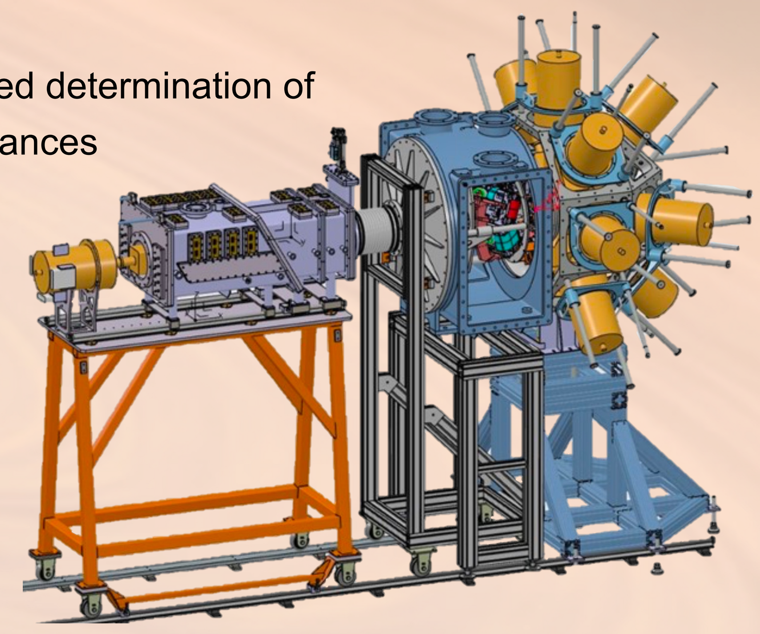
Indirect reaction at GANIL

Coincident measurement of ^{22}Mg* population via α-transfer reaction and proton decay to ^{21}Na via MUGAST+EXOGAM+ZDD at LISE, scheduled for march 2026

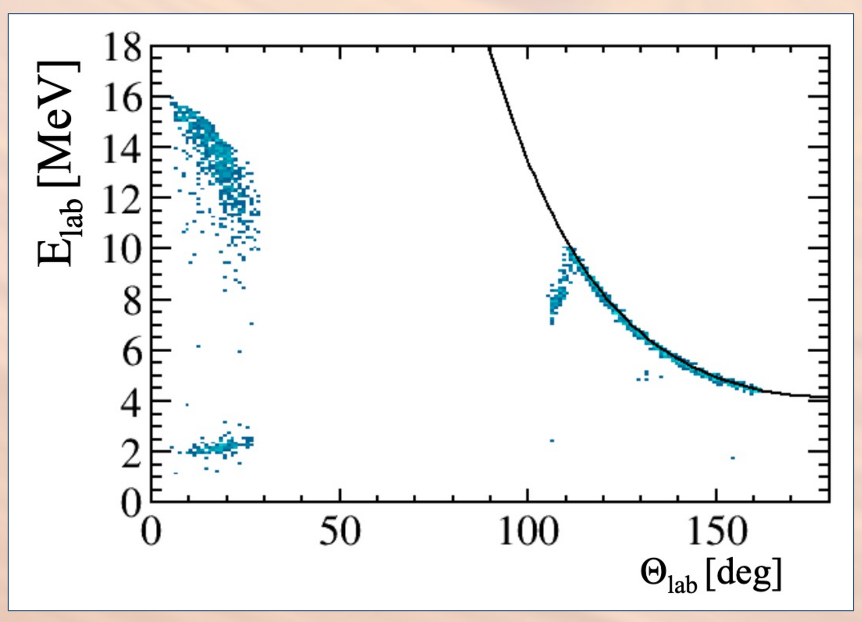
Use α-transfer reaction to search for strong α states in ^{22}Mg near the alpha threshold ($S(\alpha) = 8143$ keV), via the ^{7}Li(^{18}Ne,t)^{22}Mg*(p)^{21}Na reaction

Constrain ^{18}Ne(α,p)^{21}Na reaction rate through combined determination of

- Alpha partial width ($\Gamma_\alpha = C^2 S_\alpha \times \Gamma_\alpha^{s.p.}$) of ^{22}Mg resonances
- Branching ratio of proton in the final state (B_p)
- Resonance strength: $\omega\gamma = \omega \Gamma_\alpha \times \text{B}_p$



3D render of the MUGAST + EXOGAM + ZDD setup @ LISE



Kinematic lines of the ^{7}Li(^{18}Ne,t)^{22}Mg*(p)^{21}Na reaction. Protons (tritons) are emitted at forward (backward) angles.

Experiment parameters:

- ^{18}Ne beam @ 6 MeV/u from LISE, $\sim 10^6$ pps
- t-p-^{21}Na triple coincidence in MUGAST + ZDD
  - 332-keV γ-ray from ^{21}Na in EXOGAM

References

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