X-ray bursts

Indirect measurement of the astrophysical $^{23}Al(p,\gamma)$ reaction

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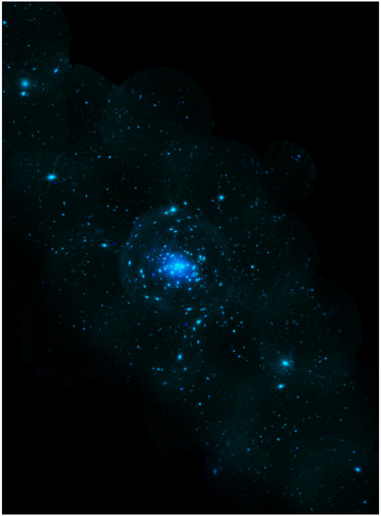
Plan

- Binary systems and X-Ray Bursts
- Experimental method
- Experimental setup
- Preliminary spectra

X-ray Bursts: Generalities

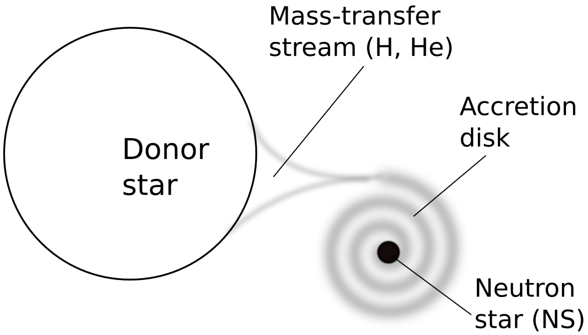
- Discovered in 1976 by Grindlay *et al.* and (ind.) Belian *et al.*
- Most frequently observed thermonuclear explosions in nature
- 3^{rd} in total energy output
- Nuclear process involving 100s of isotopes from valley of stability to proton-drip line (rp-process)
- Potential explanation of p-nuclei abundances



X-ray bursts: Anatomy

Neutron Star info

- Mass $\sim 1.4\ M_\odot$
- Radius $\sim$ 10-15 km
- Density $\sim 10^{14}\ g/cm^3$



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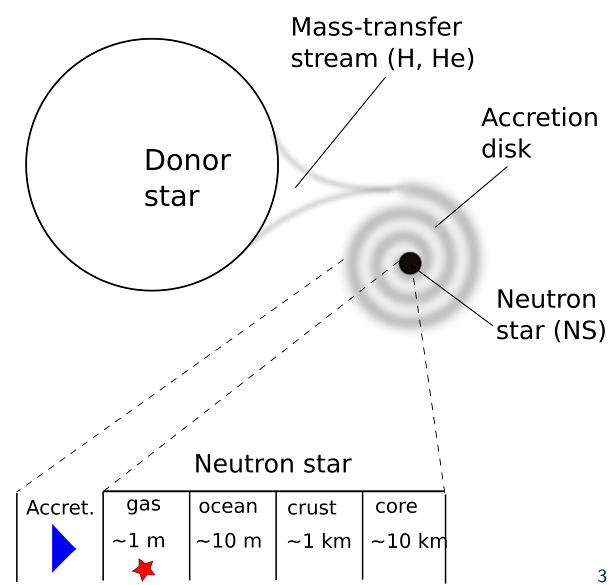

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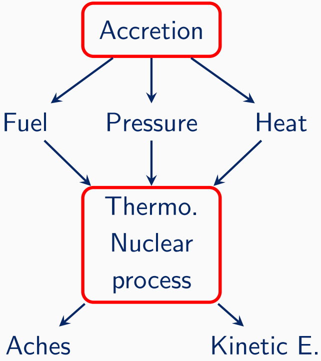

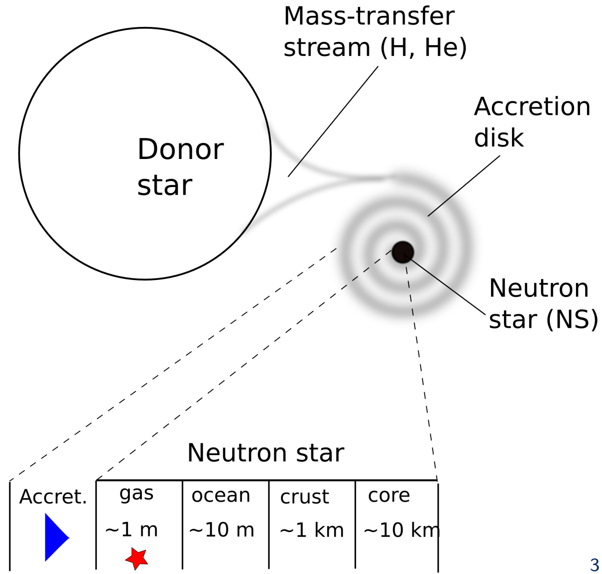

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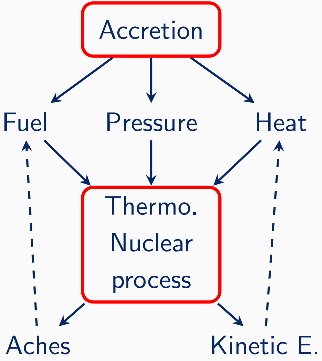
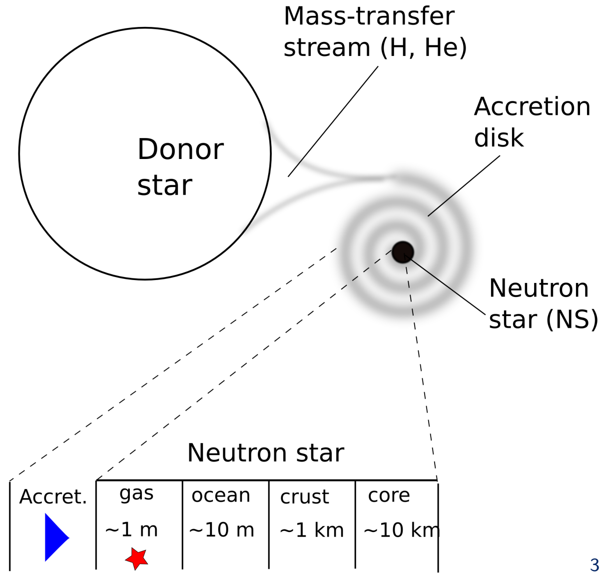
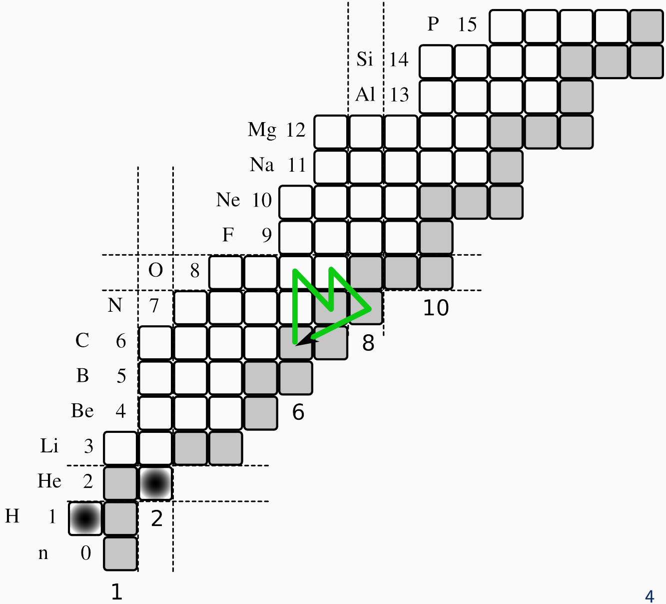




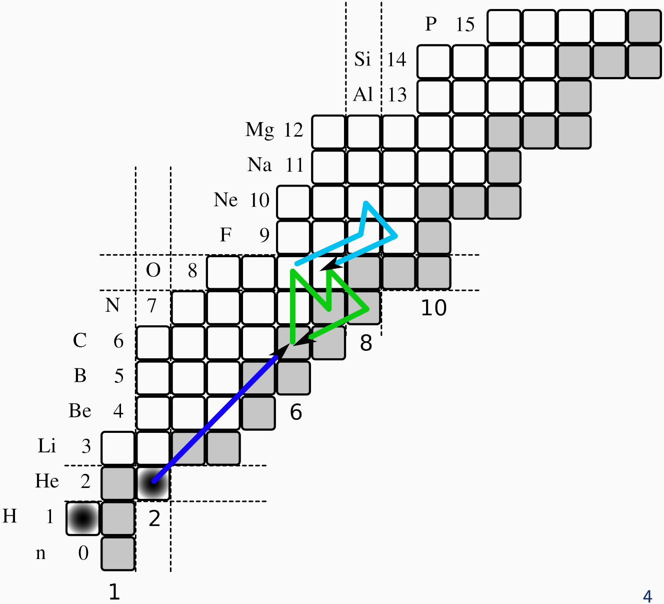
X-Ray Bursts: Ignition

- Hot CNO cycle
  (steady burning)



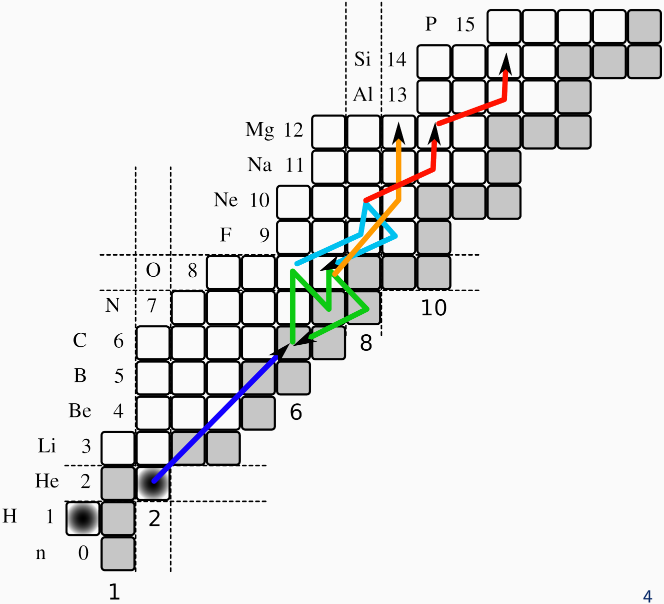
X-Ray Bursts: Ignition

- Hot CNO cycle (steady burning)
- ~0.2 GK: 3α (ignition), Hot CNO cycle II



X-Ray Bursts: Ignition

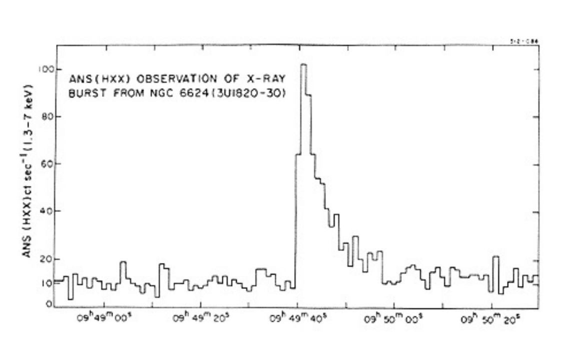
- Hot CNO cycle (steady burning)
- ~0.2 GK: 3α (ignition), Hot CNO cycle II
- ~0.7-0.8 GK: Breakout into rp-process ^{15}O(α,γ), ^{18}Ne(α,p) ~0.7-0.8 GK



X-Ray burst: Light curves

- Light-curves are the main direct observable from X-Ray Bursts
- Observation with space telescopes, XMM-NEWTON, SHANDRA, SWIFT etc..
- Single burst duration ∼10-100 sec.

XMM-Newton Space Telescope.



Single light curve from X-Ray Burst (XRB)

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- Typical frequency for a sequence of XRB ∼hours-days

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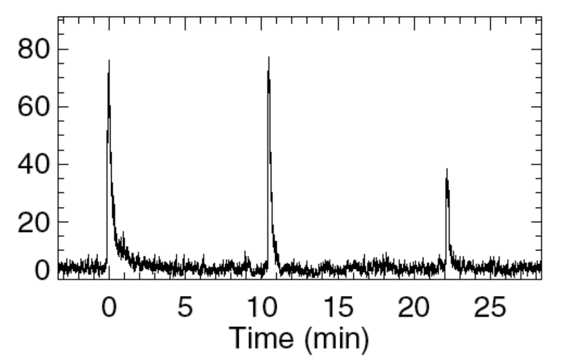
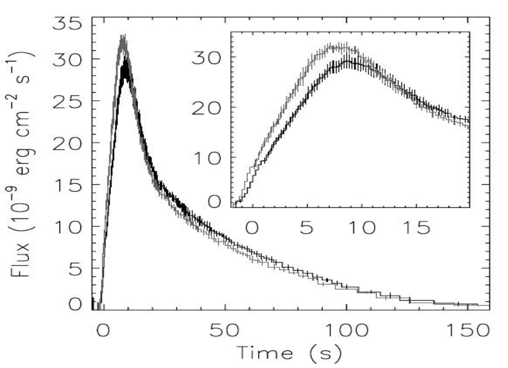


XRB light curves sequence

X-Ray burst: Light curves

- Light-curves are the main direct observable from X-Ray Bursts
- Observation with space telescopes, XMM-NEWTON, SHANDRA, SWIFT etc..
- Single burst duration $\sim$10-100 sec.
- Typical frequency for a sequence of XRB $\sim$hours-days
- Averaged light curve is the *final product* to be compared with theoretical model.

XMM-Newton Space Telescope.



Averaged light curve. Galloway *et al.*, APj, 2004

Nuclear reactions of high impact on the light curve

- Self-consistent model of X-ray burst Nucleosynthesis
- The rates of 1931 reactions involved in the *rp*-process
- Conclusion: **Only few have a high impact on the shape of the light curves**

Reactions that Impact the Burst Light Curve
in the Multi-zone X-ray Burst Model

Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	D	4.6	1
8	$^{18}Ne(\alpha, p)^{21}Na$	U	1.8	1
9	$^{63}Ga(p, \gamma)^{64}Ge$	D	1.4	2
10	$^{19}F(p, \alpha)^{16}O$	U	1.3	2
11	$^{12}C(\alpha, \gamma)^{16}O$	U	2.1	2
12	$^{26}Si(\alpha, p)^{29}P$	U	1.8	2
13	$^{17}F(\alpha, p)^{20}Ne$	U	3.5	2
14	$^{24}Mg(\alpha, \gamma)^{28}Si$	U	1.2	2
15	$^{57}Cu(p, \gamma)^{58}Zn$	D	1.3	2
16	$^{60}Zn(\alpha, p)^{63}Ga$	U	1.1	2
17	$^{17}F(p, \gamma)^{18}Ne$	U	1.7	2
18	$^{40}Sc(p, \gamma)^{41}Ti$	D	1.1	2
19	$^{48}Cr(p, \gamma)^{49}Mn$	D	1.2	2

Notes.
[a] Up (U) or down (D) variation that has the largest impact.
[b] $M_{LC}^{(i)}$ in units of 10^{38} erg s^{-1}.

Cybert *et al.* ApJ 830, 2016

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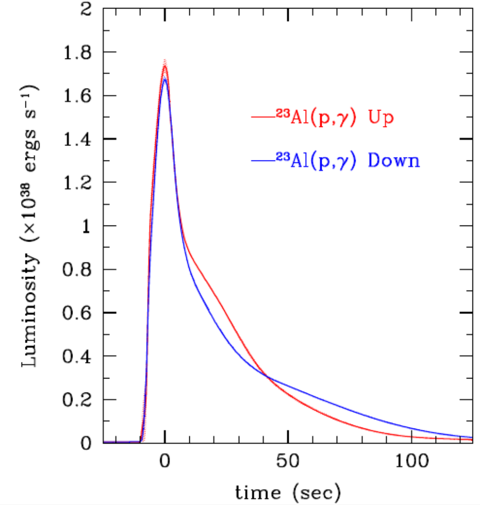
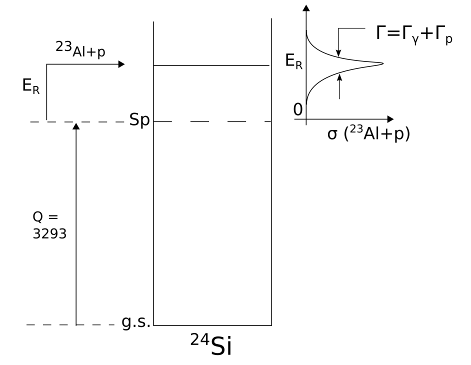


Cybert *et al.* ApJ 830, 2016

Astrophysical ^{23}Al(p,γ) reaction

^{23}Al(p,γ)^{24}Si reaction dominated by the resonances above ^{24}Si (S_p = 3293(20) keV).

$$\text{Reaction rate} = N_A < \sigma\nu >= N_A \left(\frac{2\pi}{m_{red.}kT}\right)^{3/2} \hbar^2 e^{(-E_r/kT)} \omega \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}$$



Given $\Gamma_p << \Gamma_\gamma$

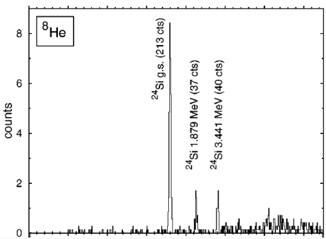
$$\frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma} \sim \frac{\Gamma_p \Gamma_\gamma}{\Gamma_\gamma} \sim \Gamma_p$$

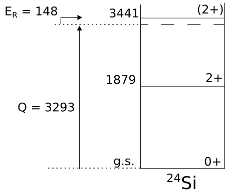
Which in turns, can be expressed as

$$\Gamma_p = \frac{\hbar}{2m} \times P_l \times C^2 S \times \theta^2$$

Previous studies of ^{23}Al(p,γ)^{24}Si Reaction

- First and only direct study of ^{24}Si using ^{28}Si(α,^{8}He) (Schatz *et al.*)
- **Resonance was identified at E_R=148 keV**





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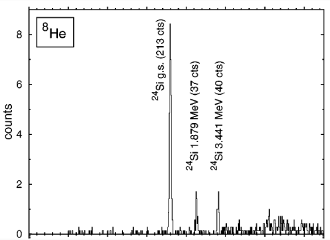

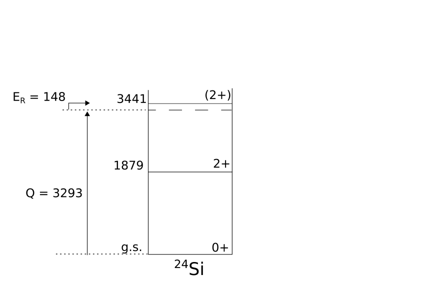

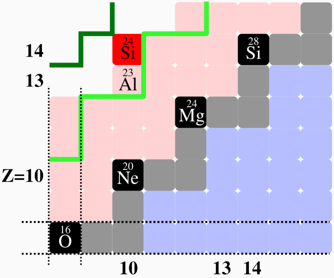

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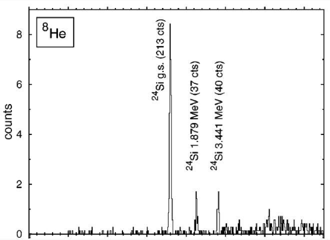
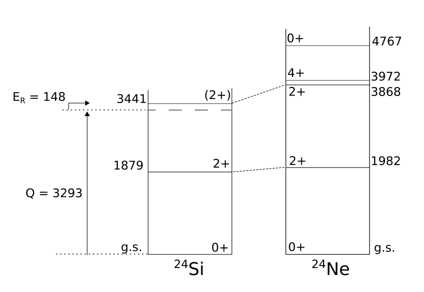
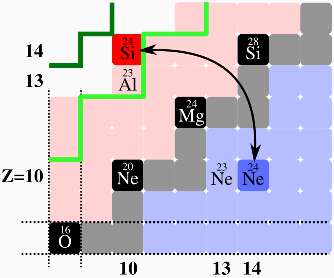
- Major difficulty: ^{24}Si right at the proton drip-line
- Solution: Indirect measurement using *mirror* symmetry.







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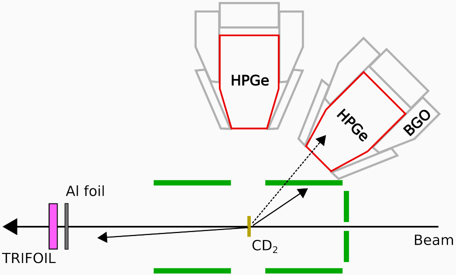
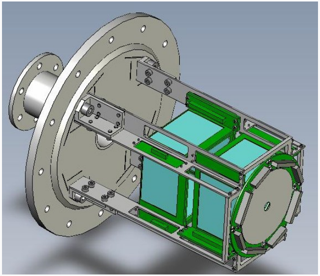
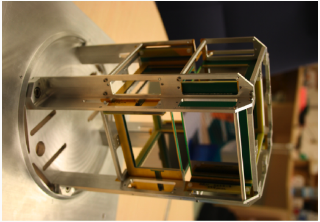
SHARC, measuring transfer and elastic channels

SHARC characteristics

- Angular coverage: $\approx 2\pi$ sr
- Angular resol.: $\delta\theta = 1.6^\circ$, $\delta\phi = 3.5^\circ$
- Energy resolution: ≈ 25 keV
- Particle identification: ΔE-E ($> 90^\circ$)



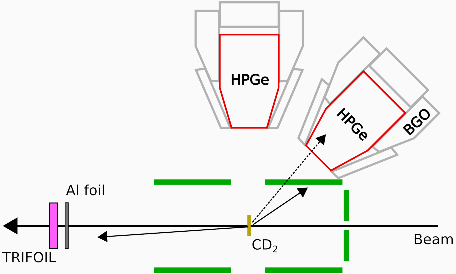


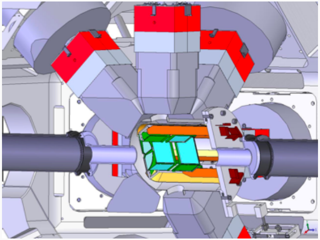


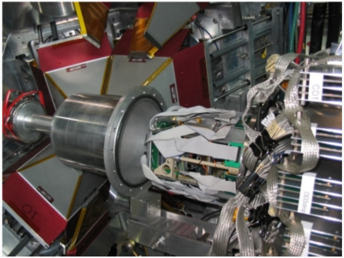
TIGRESS, resolving close energy states

TIGRESS characteristics

- HPGe, 9cm deep, 8 fold segmentation
- Efficiency ∼12% at 1 MeV
- BGO suppression shields (Compton catcher)
- Fully digital electronics



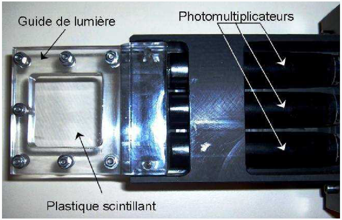




TRIFOIL, dealing with beam contamination

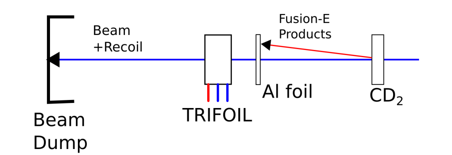
TRIFOIL characteristics

- Designed in LPC Caen
- Scintillator Material: BC400, Pilot-B
- 3 independent photomultiplier tubes
- Variable thickness (material, rotation)
- logic signal yes/no (veto)

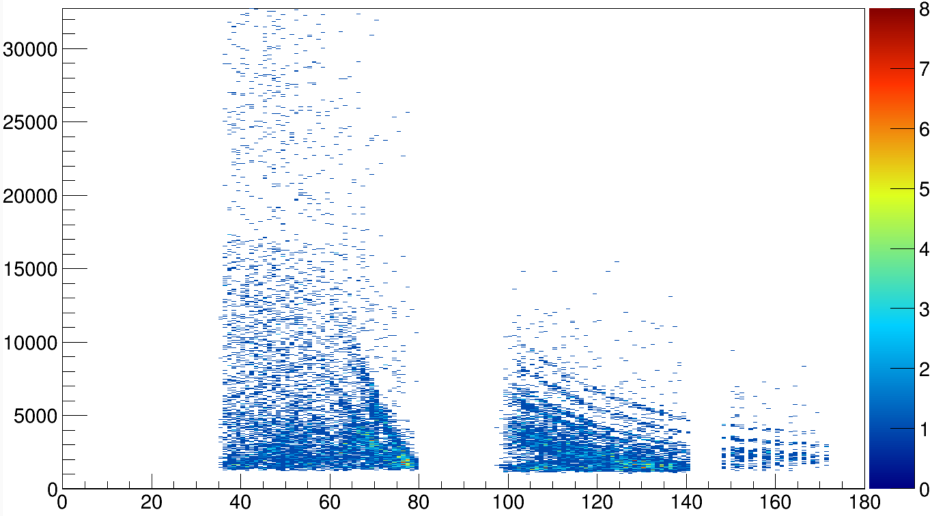


Principle of operation

- Zero-degree beam/recoil detector
- Coupled with a passive foil Catcher (e.g. Al $\approx$10-100μm)
- Fusion-Evap. products stopped in the catcher
- Beam + Recoil of interest leave a TRIFOIL signature

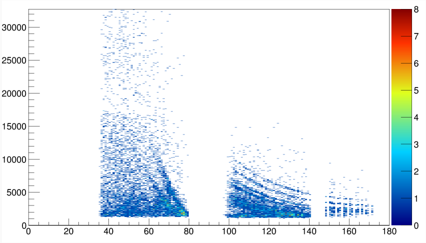


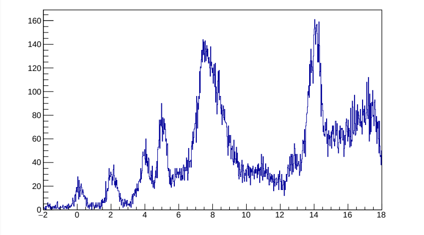
Preliminary spectra

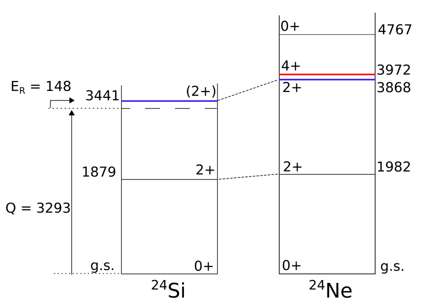


Energy (keV) vs angle (deg.) for light charged particles in SHARC

Preliminary spectra







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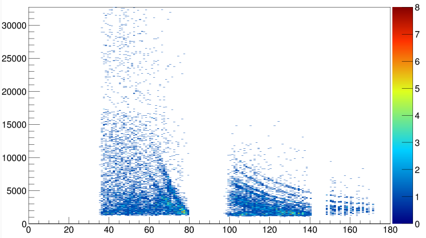

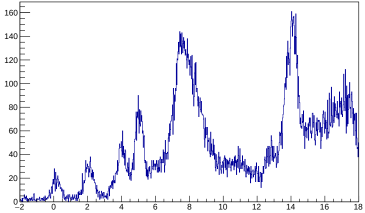

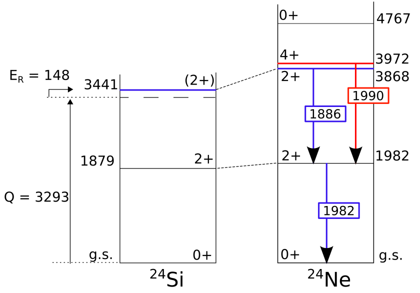

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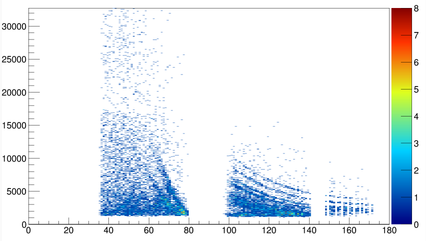

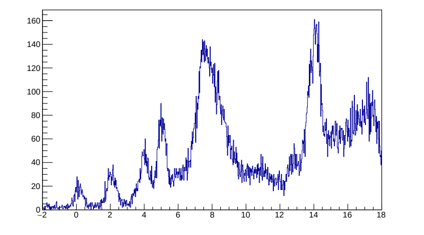

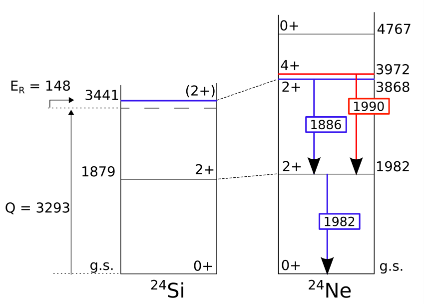

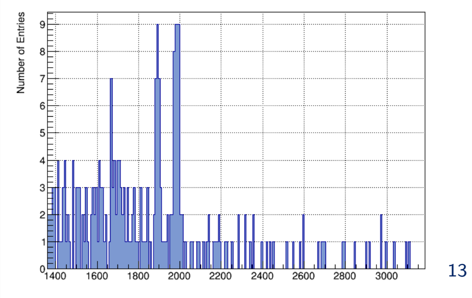

Conclusion

- **X-Ray Bursts** are the most frequent type of thermonuclear stellar explosion in the Galaxy,
- Studying their light curves provides **key aspects of Neutron Stars, processes, composition**,
- **Transfer reaction on the mirror nuclei is an alternative method** to constrain the rate of the reaction of interest,
- Combining **efficient charged-particle and gamma arrays** with a passive zero-degree detector is a simple but powerful setup for d, p reaction

Collaborators

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Thank you for your attention