Measuring decays of excited states in ^{26}Si to improve reaction rate calculations of ^{22}Mg(α,p)^{25}Al relevant to type I X-ray bursts

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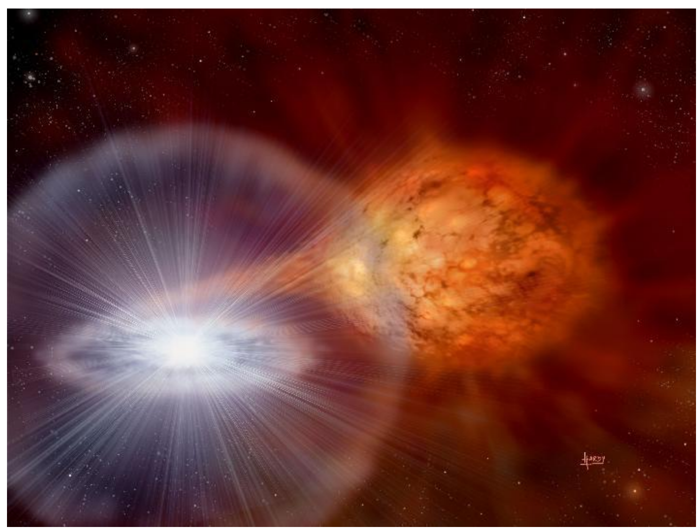
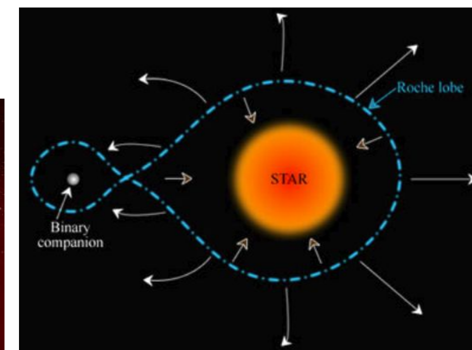
Outline

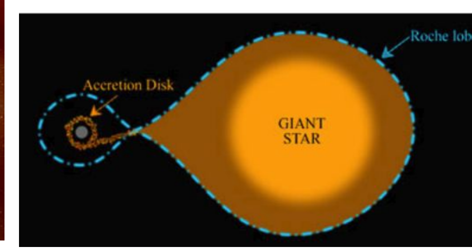
- Introduction
- Reactions of importance to XRBs
- Overview of the iThemba LABS facility, the K600 magnetic spectrometer and the CAKE silicon array
- Strategy of measuring various (α,p) reactions on unstable nuclei using stable beams
- Summary

What are XRBs and why do we study them?

- Large, sudden increase of x-ray luminosity for 10s-100s
- Binary system with neutron + donor star (red giant) that encroaches Roche lobe
- H/He rich material accretes onto neutron star surface, initiate thermonuclear runaway
- Importance and relevance to nuclear matter EOS, neutron star properties such as compactness (important sites for nucleosynthesis), composition, mass-radius ratio etc.
- One of the most abundant occurrences in the galaxy
- Uncertainties in (p,γ), (α,p), and (α,γ) reaction rates are important to constrain
- Need breakout from the HCNO: ^{18}Ne(α,p)^{21}Na, other α-induced reactions
- Measure indirectly with the K600 and the CAKE







Reactions of importance

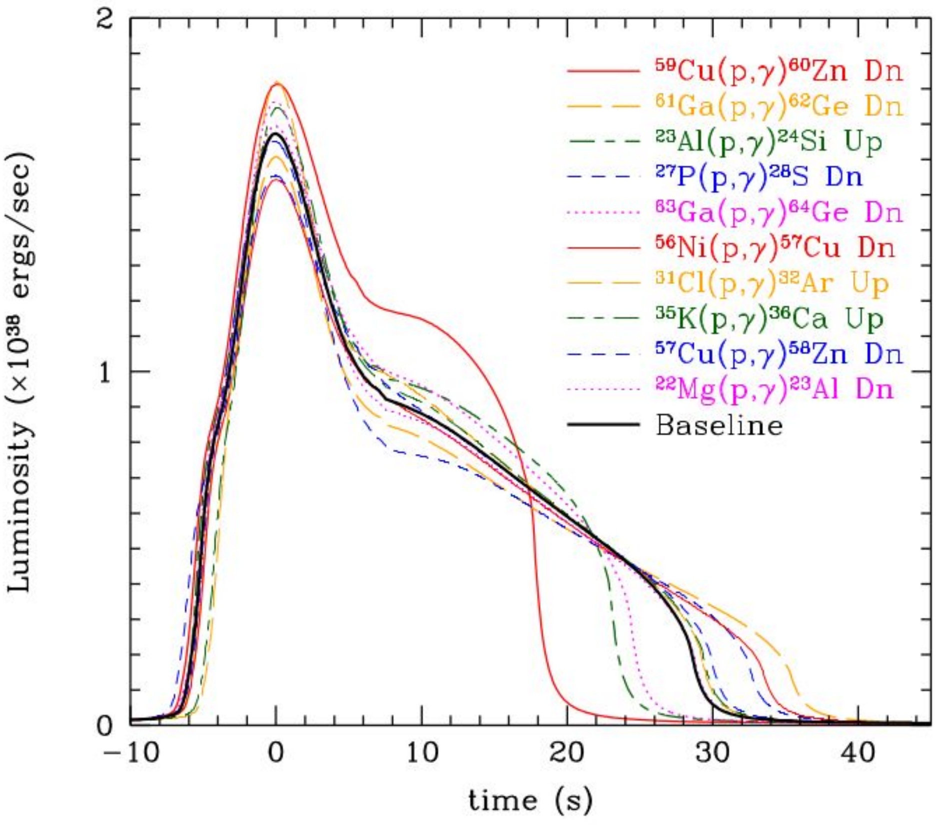
Reactions that Impact the Burst Light Curve in the Multi-zone X-ray Burst Model

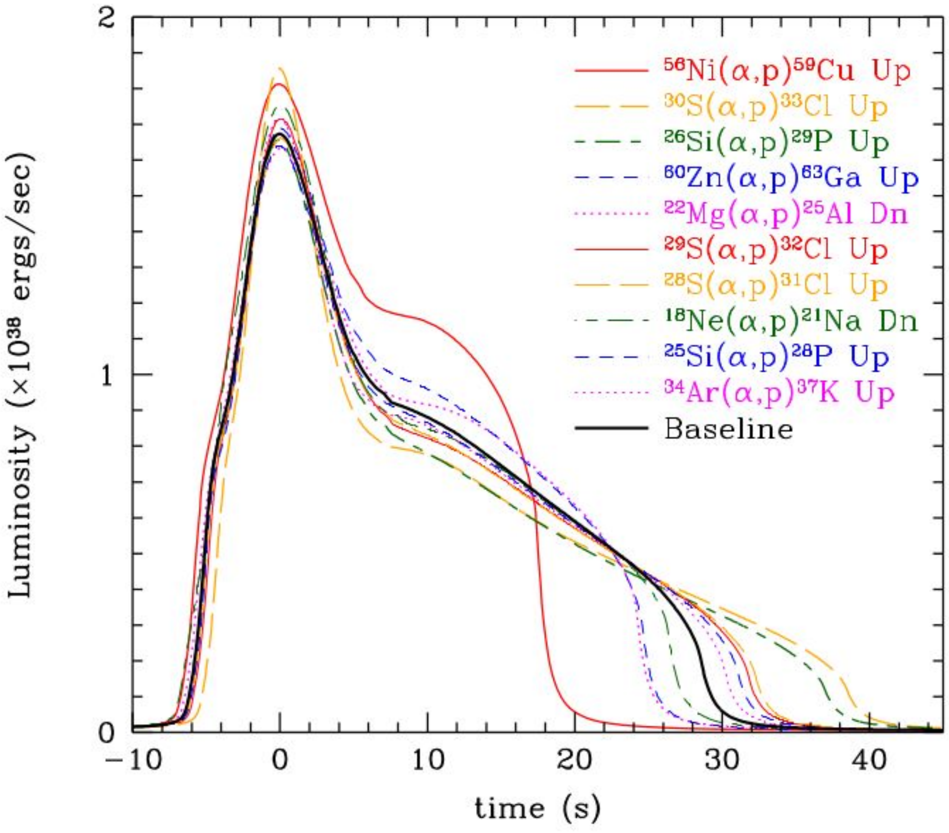
Rank	Reaction	Type[a]	Sensitivity[b]	Category
1	$^{15}O(\alpha, \gamma)^{19}Ne$	D	16	1
2	$^{56}Ni(\alpha, p)^{59}Cu$	U	6.4	1
3	$^{59}Cu(p, \gamma)^{60}Zn$	D	5.1	1
4	$^{61}Ga(p, \gamma)^{62}Ge$	D	3.7	1
5	$^{22}Mg(\alpha, p)^{25}Al$	D	2.3	1
6	$^{14}O(\alpha, p)^{17}F$	D	5.8	1
7	$^{23}Al(p, \gamma)^{24}Si$	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

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

R.H. Cyburt *et al., APJ* ***830*** *(2016)*

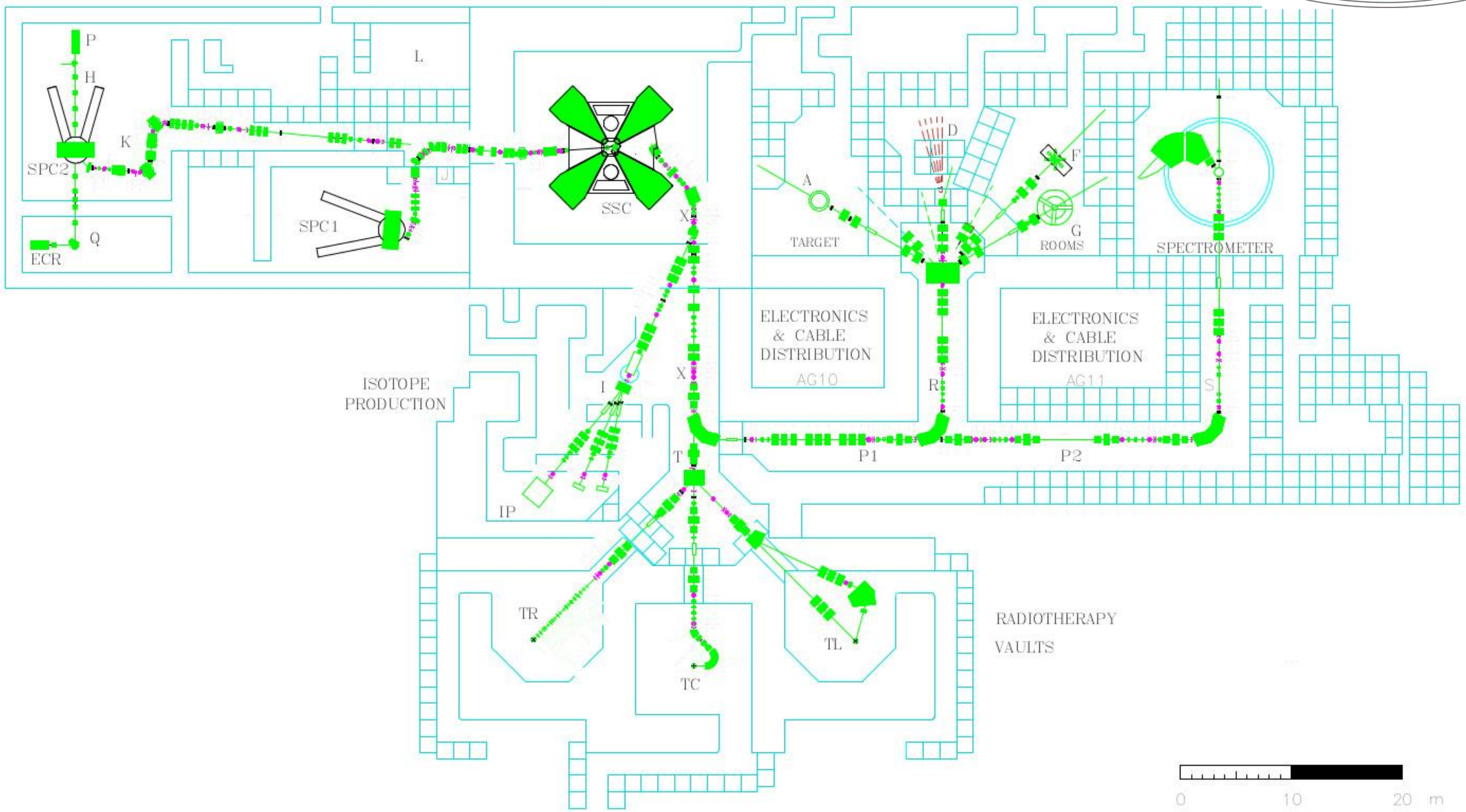
Variations in light curves: (p,γ) and (α,p) reactions



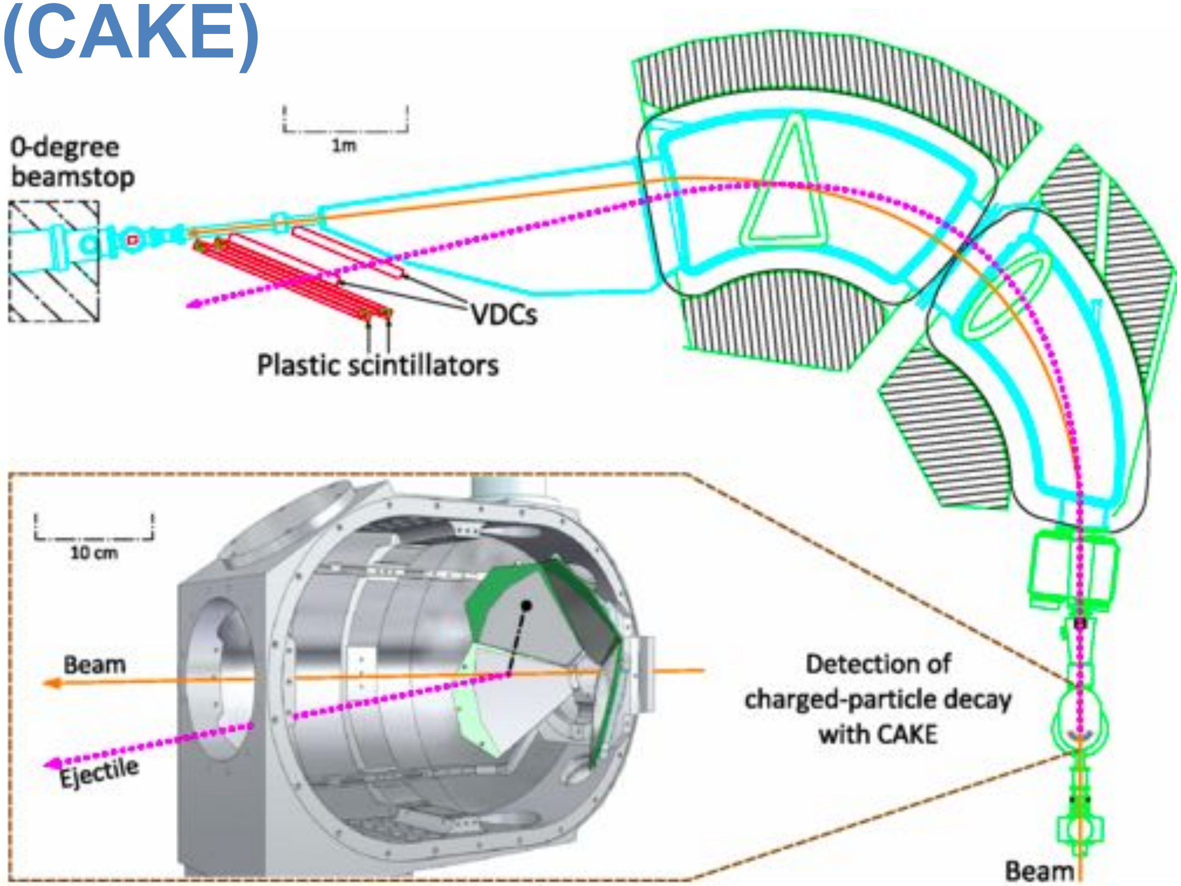


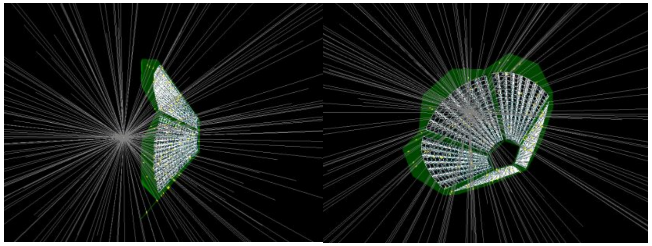
R.H. Cyburt *et al.*, *APJ* ***830*** *(2016)*

The iThemba LABS facility



The K600 and the Coincidence Array for K600 Experiments (CAKE)





The $^{28}Si(p,t)^{26}Si$ measurement

- Measure information regarding the decay of states from the recoil ^{26}Si nucleus to the ground state various excited states in ^{25}Al with the CAKE.

- Calculate proton branching ratios above S_α = 9.164 MeV to E_x = 13 MeV (Gamow window: 0.1-2 GK)

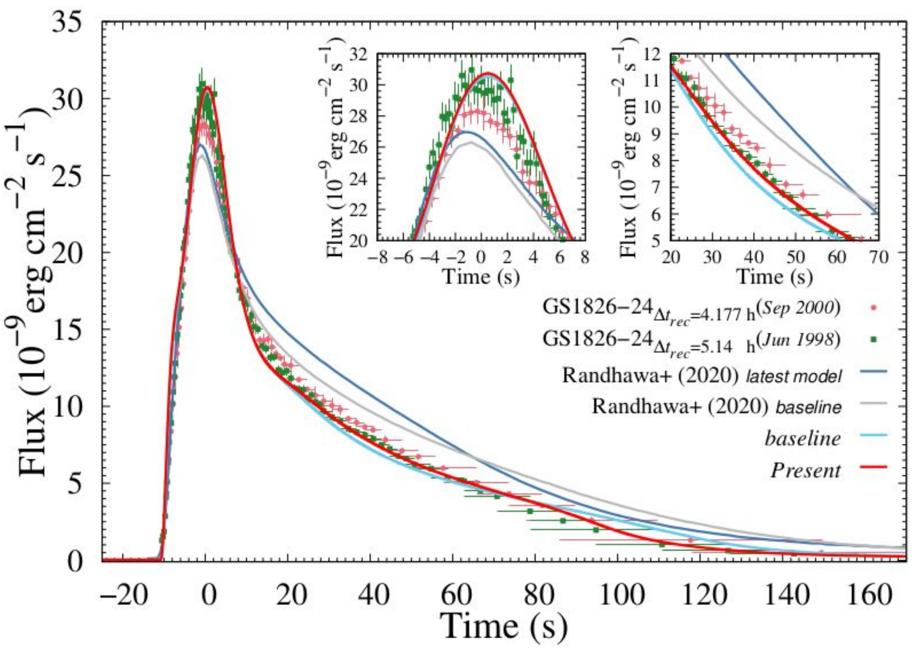
- Aim: observe resonances in ^{26}Si above alpha threshold. Address uncertainty in spin-parities of the measured states and the lack of resonance data above E_x = 10 MeV

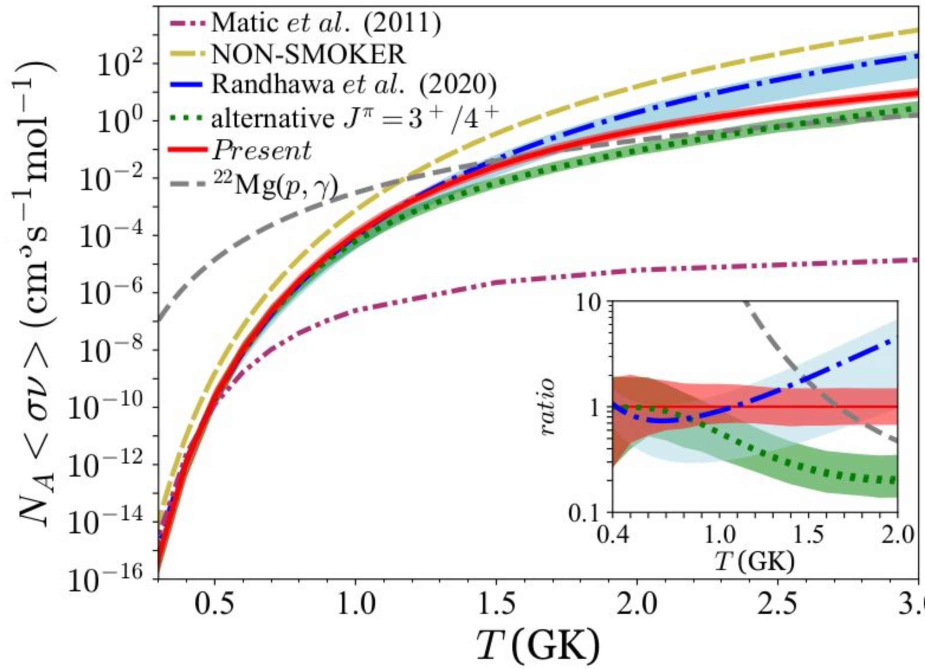
- Recent results* have added to the current dataset of rate estimations for this reaction by means of direct measurements

* J.S. Randhawa *et al.*, PRL 125 (2020), J. Hu *et al.*, PRL 127 (2021), H. Jayatissa *et al.*, PRL 131 (2023)

The $^{28}Si(p,t)^{26}Si$ measurement

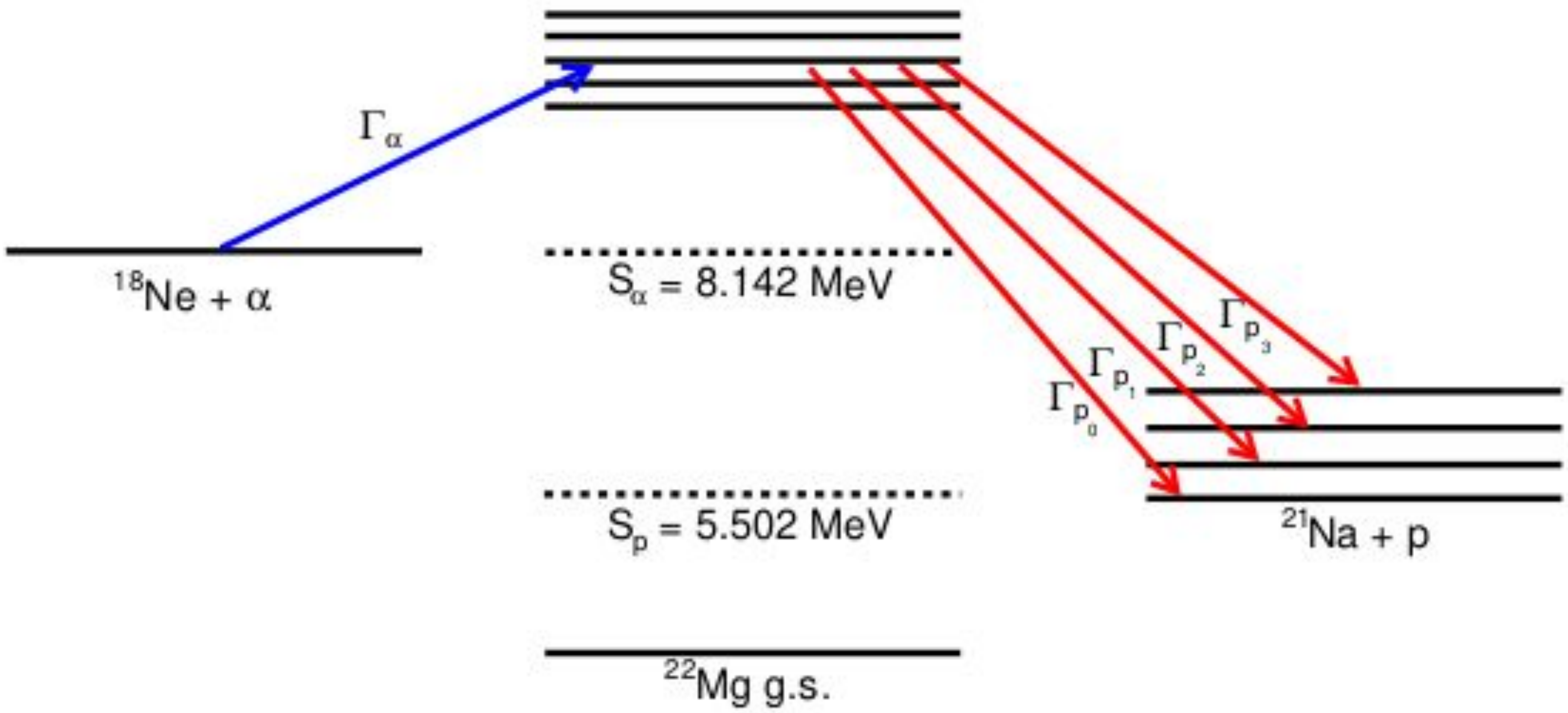
- First (in)elastic scattering measurement
- of $^{25}Al + p$ at RIKEN Nishina RIB facilty
- Spin-parities of 4 resonances above S_α



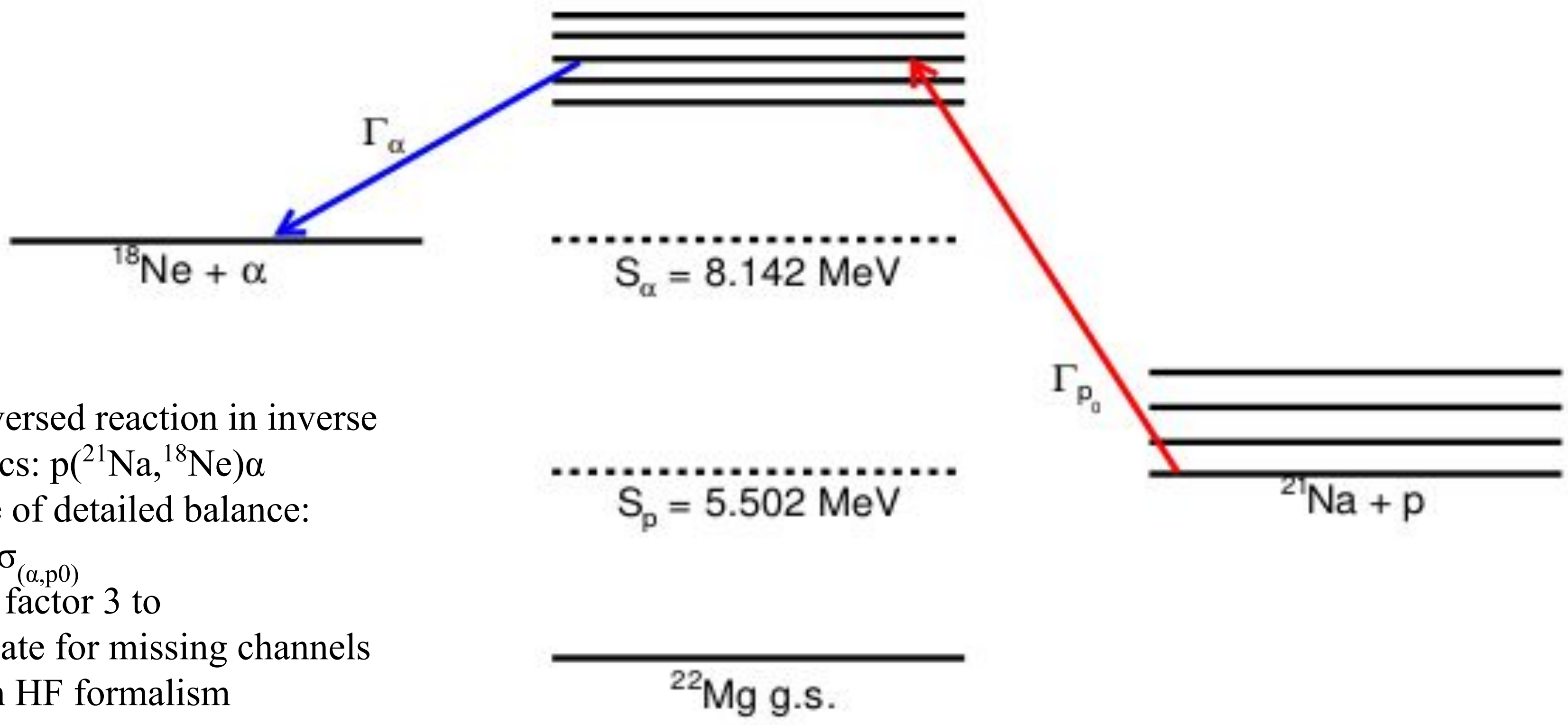


J. Hu et al., PRL 127 (2021)

Reactions induced by α-particle capture in XRBs



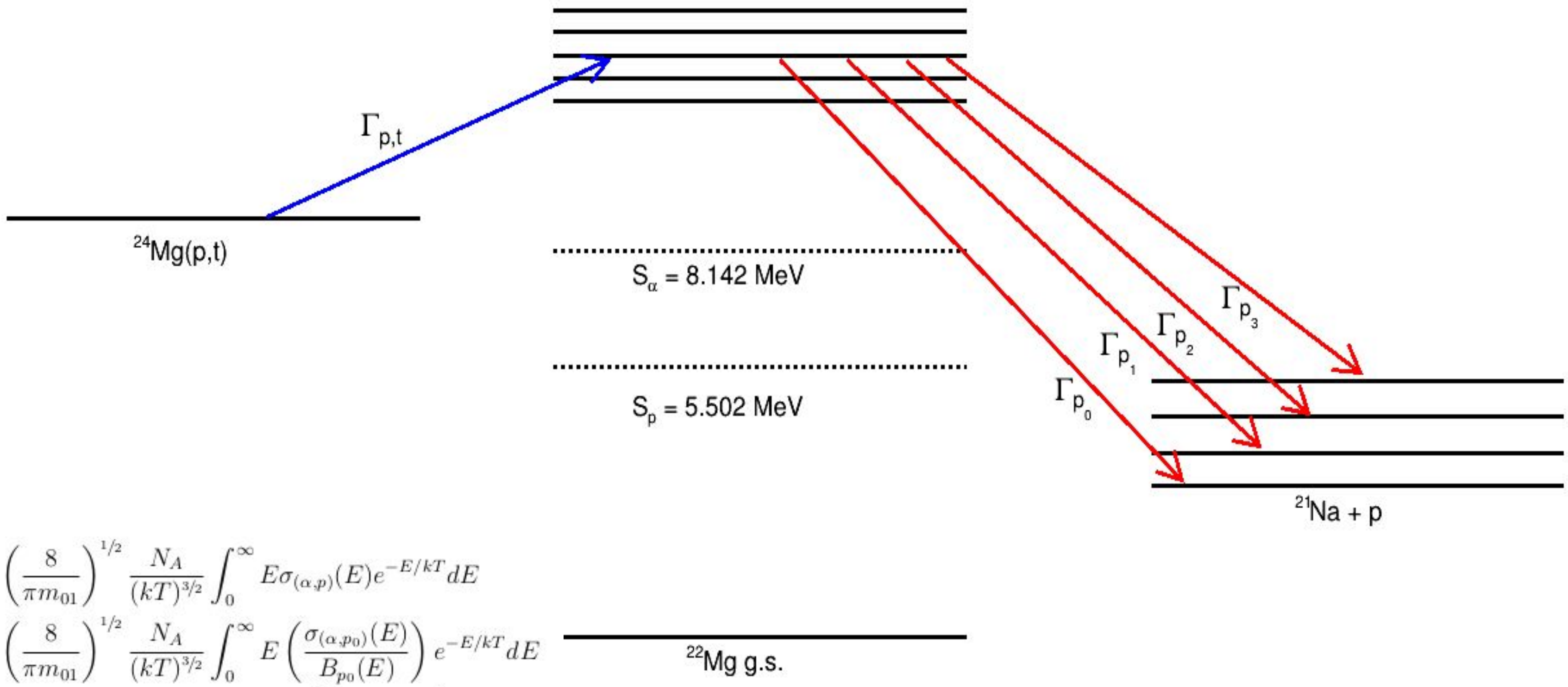
Measurements at RIB facilities



- Time-reversed reaction in inverse kinematics: $p(^{21}Na,^{18}Ne)\alpha$
- Principle of detailed balance: $\sigma_{(p0,\alpha)}$ to $\sigma_{(\alpha,p0)}$
- Scale by factor 3 to compensate for missing channels
- Based on HF formalism

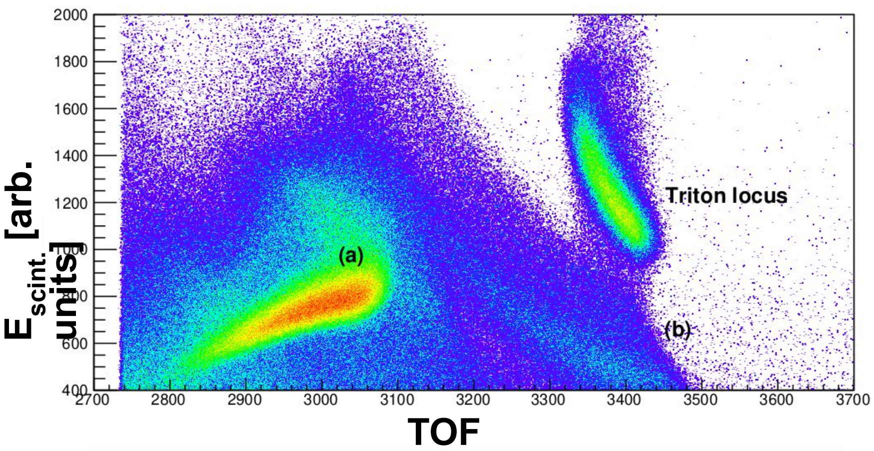
P. Salter *et al.*, PRL 108 (2012)

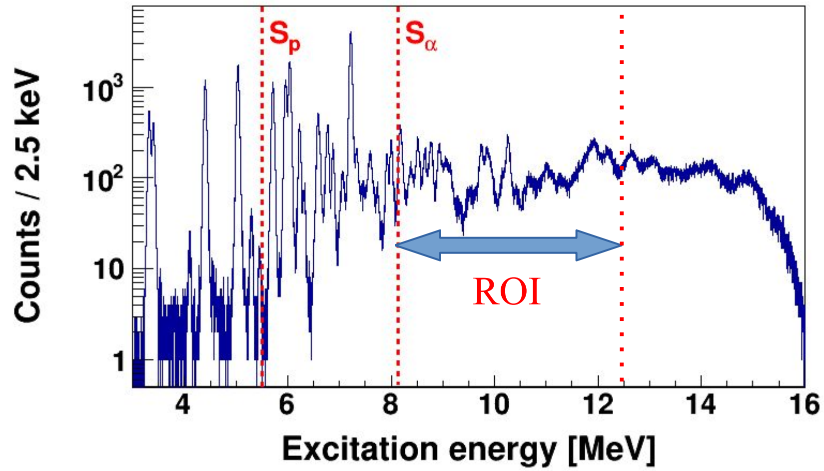
Methods using indirect measurements with stable beams

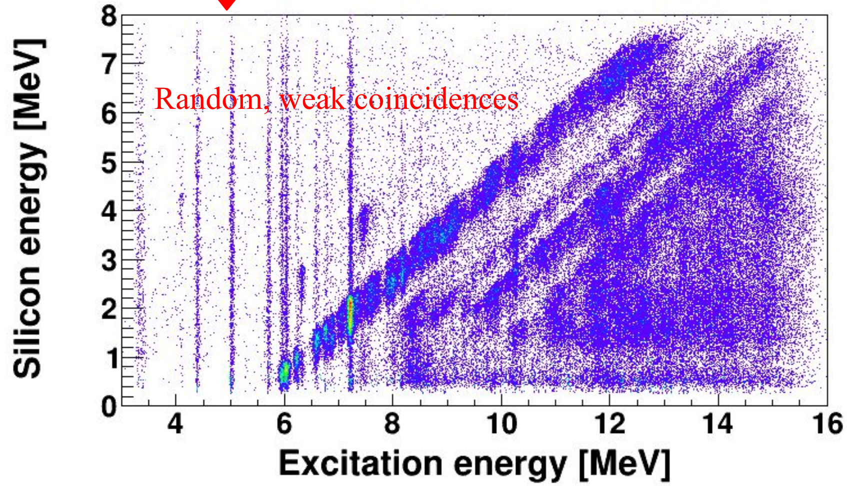


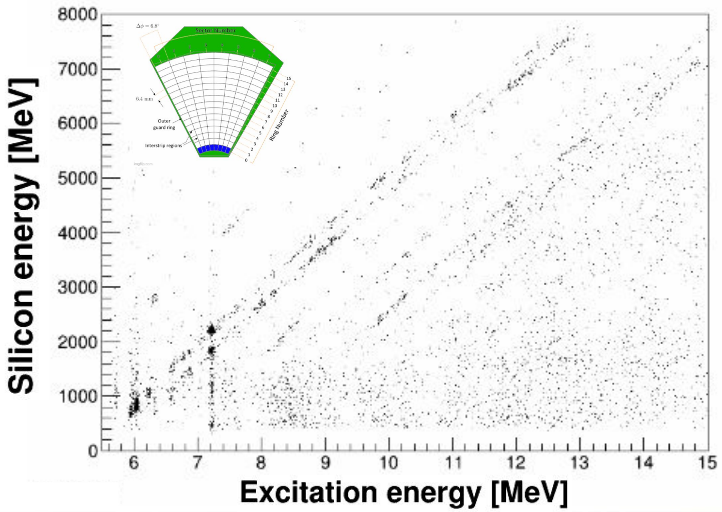
$$
\begin{aligned}
N_A < \sigma\nu > &= \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\sigma_{(\alpha,p)}(E) e^{-E/kT} dE \\
&= \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E \left(\frac{\sigma_{(\alpha,p_0)}(E)}{B_{p0}(E)}\right) e^{-E/kT} dE \\
&= \left(\frac{8}{\pi m_{01}}\right)^{1/2} \frac{a_1 c_1 N_A}{(kT)^{3/2}} \int_0^\infty \frac{\exp\left(\frac{-2\pi c_2}{\sqrt{E}} - \frac{E}{kT}\right)}{b_0 + b_1 E + b_2 E^2} dE,
\end{aligned}
$$

Previous measurements

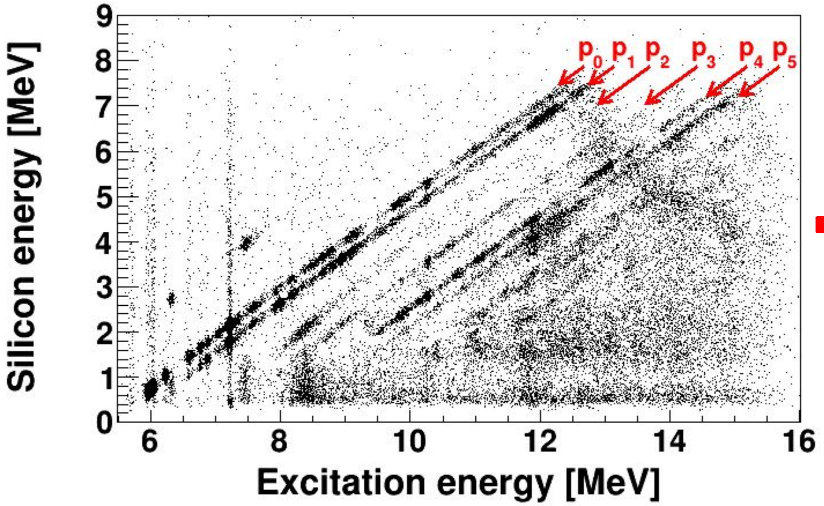


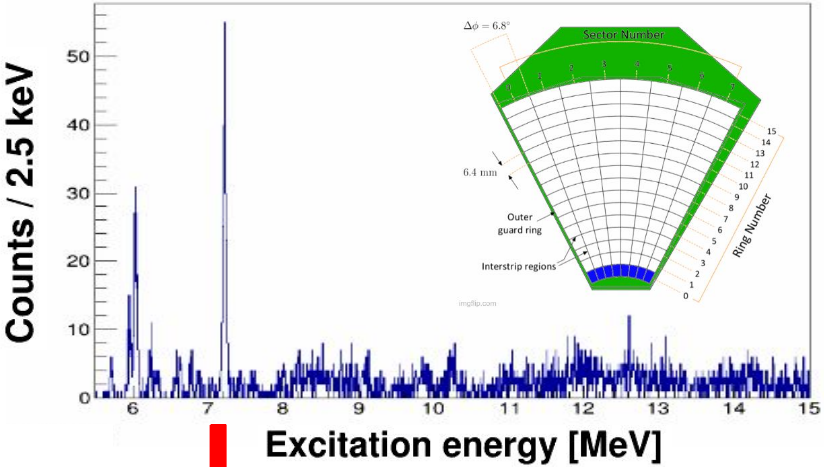


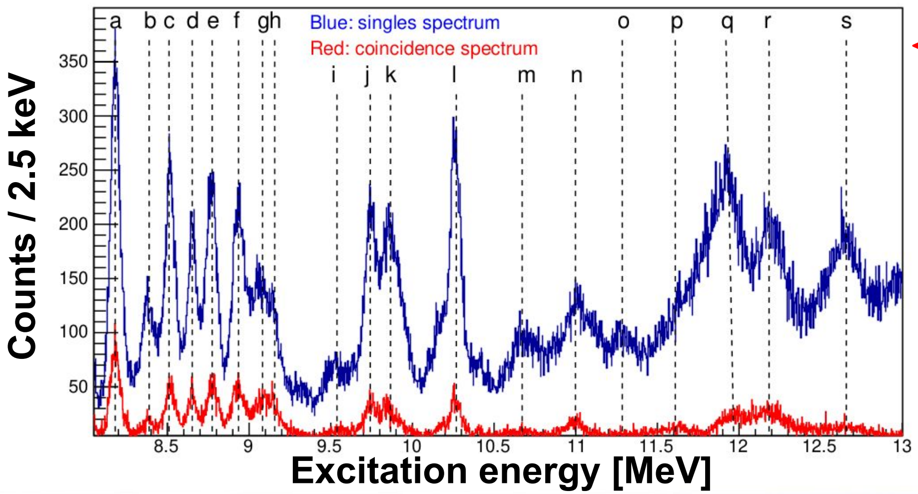


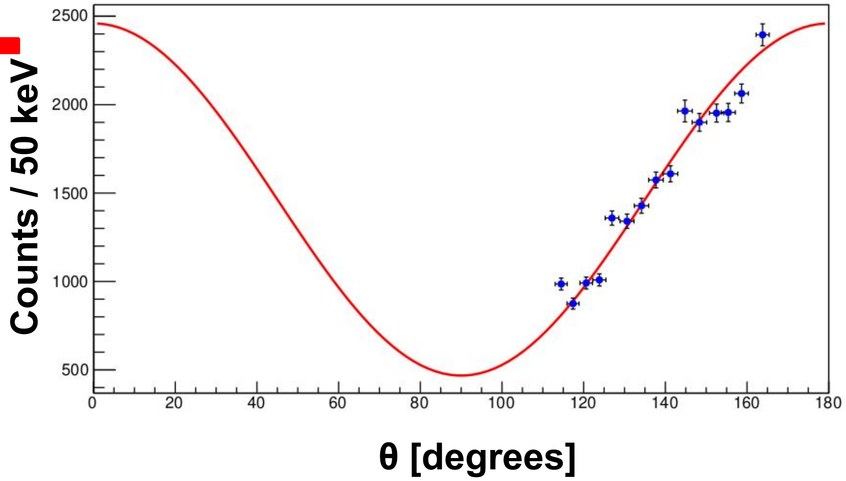


Previous measurements







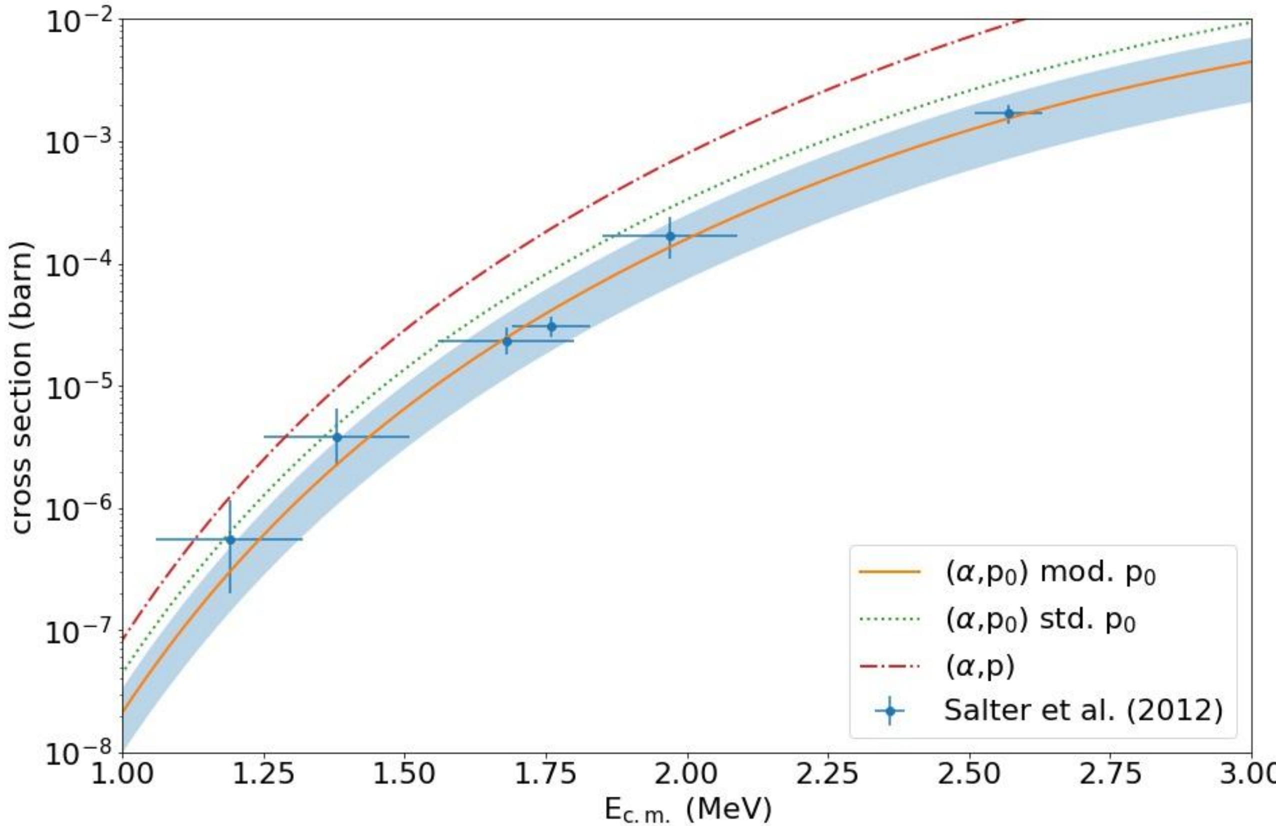


Results from the $^{24}Mg(p,t)^{22}Mg$ measurement

Cross section for $^{18}Ne(\alpha,p)^{21}Na$ and cross section for $^{18}Ne(\alpha,p_0)^{21}Na$ calculated with SMARAGD with and without modified p_0 width.

Breakout reaction from HCNO cycles. Needed for increase in energy generation that leads to XRBs

Shaded band shows experimental uncertainty on average p_0 branching



T. Rauscher, SMARAGD code, v0.10.2

Summary and outlook

- The K600 magnetic spectrometer and the CAKE is a powerful coincidence combination to perform interesting measurements relevant to the field of nuclear astrophysics
- Experiments, performed in the past, have demonstrated strong potential to generate high-quality datasets and yield interesting results and conclusions
- We aim to measure further possible reactions with the K600 and the CAKE to which XRBs are sensitive
- Concentrate on reactions whose uncertainties greatly influence model predictions
- Similar measurements will be proposed for upcoming beamtime

Thank you for your attention

- A special thank you to all collaborators:

- P. Adsley[1], T. Rauscher[2], R. Neveling[3], A. Bahini[3,4], J.A.C. Bekker[3,4], S.D. Binda[3,4], L.M. Donaldson[3], S. Jongile[3], T. Khumalo[3], R.E. Molaeng[3,4], L. Pellegri[3,4]

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