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Alpha transfer technique to constrain the $^{22}Ne(\alpha,n)^{25}Mg$ reaction rate

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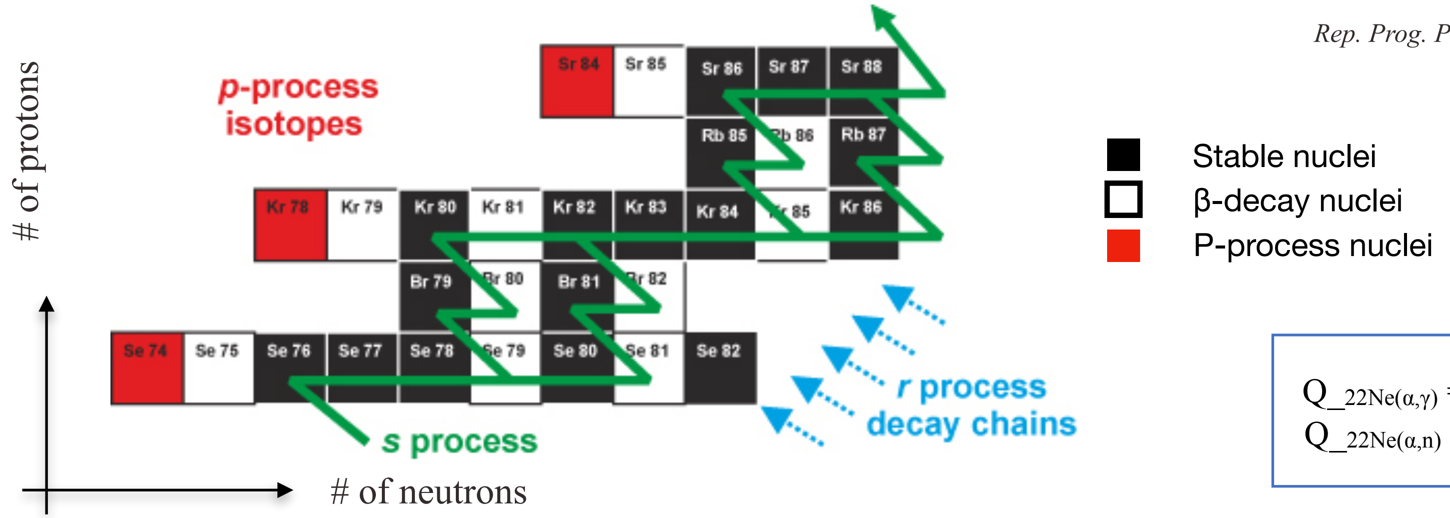
LA-UR-25-27007

$^{22}Ne(\alpha,n)^{25}Mg$ as a neutron source for the s-process

Rep. Prog. Phys. **76** *066201 (2013)*



$Q_{\_22Ne(\alpha,\gamma)}$ = 10.614 MeV
$Q_{\_22Ne(\alpha,n)}$ = -0.478 MeV

Competition between (α,n) & (α,γ) reactions!

Environment	Component	Mass range	T (GK)
AGB stars	Main s-process	$90 < A < 204$	~ 0.2 - 0.4
Massive stars	Weak s-process	$60 < A < 90$	~ 0.25 - 1

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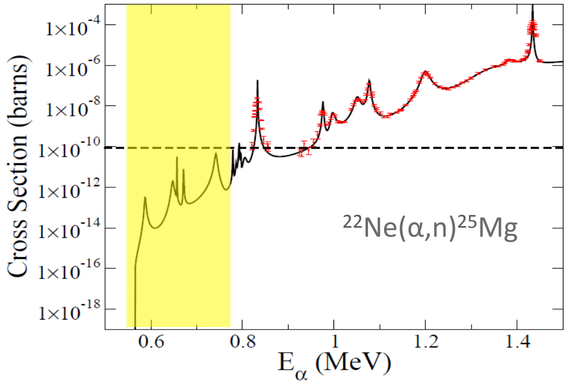
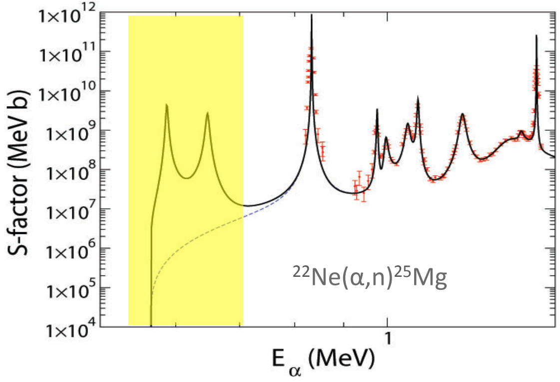
Difficulties with direct measurements if $^{22}Ne(\alpha,n)^{25}Mg$





- Low reaction cross sections in energies of interest.

T ~ 0.2-0.4 GK for AGB stars:

~ 450 keV < E_{cm} < 750 keV

- Neutron detection is hindered by high environmental backgrounds.
  → i.e cosmics

- Need to minimize detection background and high beam intensities.

  → Need underground laboratories.

Alpha-transfer technique to probe $^{22}Ne(\alpha,n)^{25}Mg$

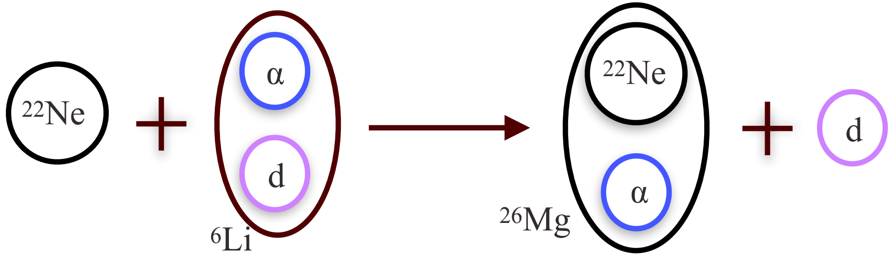
Advantages:

- Allows to probe lower energies compared to direct measurements.
- Selectively populated states in the compound ^{26}Mg that has high α spectroscopic factors, bypassing difficulties surrounding the high level density of ^{26}Mg in the excitation energies of interest.
- ^{6}Li and ^{7}Li have low Q values for alpha separation. → **(^{6}Li,d) & (^{7}Li,t)**

^{6}Li : Q_α = -1.473 MeV
^{7}Li : Q_α = -2.467 MeV

Disadvantages:

- Dependence on optical model potentials for Distorted-Wave Born Approximation (DWBA) calculations to model the interaction wavefunction.



Resonance strengths using partial widths

Resonance Strength:

$$\omega\gamma_{(\alpha,n)} = \frac{2J+1}{(2J_1+1)(2J_2+1)}\frac{\Gamma_\alpha\Gamma_n}{\Gamma}$$

$$\Gamma = \Gamma_\alpha + \Gamma_\gamma + \Gamma_n$$

$$J_1 = J_2 = 0$$

$$\boxed{\omega\gamma_{(\alpha,n)} = (2J+1)\frac{\Gamma_\alpha}{1+\Gamma_\gamma/\Gamma_n}} \qquad (\Gamma_\alpha \ll \Gamma_\gamma < \Gamma_n)$$

Reaction Rate:

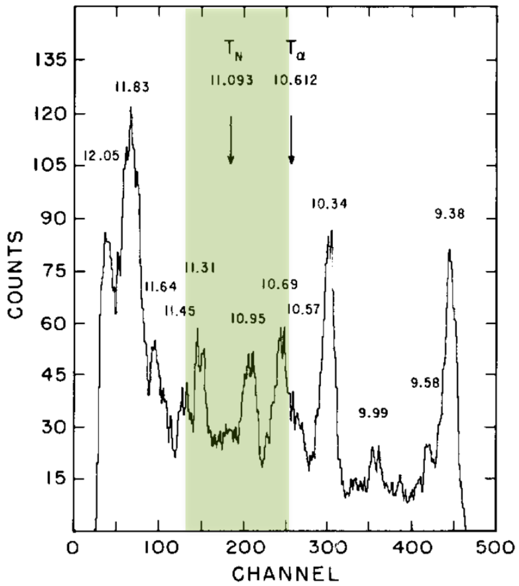
$$N_A\langle\sigma v\rangle = 1.54\times10^5(\mu T_9)^{-\frac{3}{2}}\sum_i(\omega\gamma)_i \exp\left[-\frac{11.605E_{R,i}}{T_9}\right] \quad \times(\ \mathrm{cm}^3\mathrm{s}^{-1}\mathrm{mol}^{-1})$$

Recent alpha-transfer measurements on ^{22}Ne

Last ~30 years

Reaction rate for $^{22}Ne(\alpha,n)^{25}Mg$ was provided by *Longland et al. (2012)* by compiling exiting experimental data and Monte Carlo sampling.

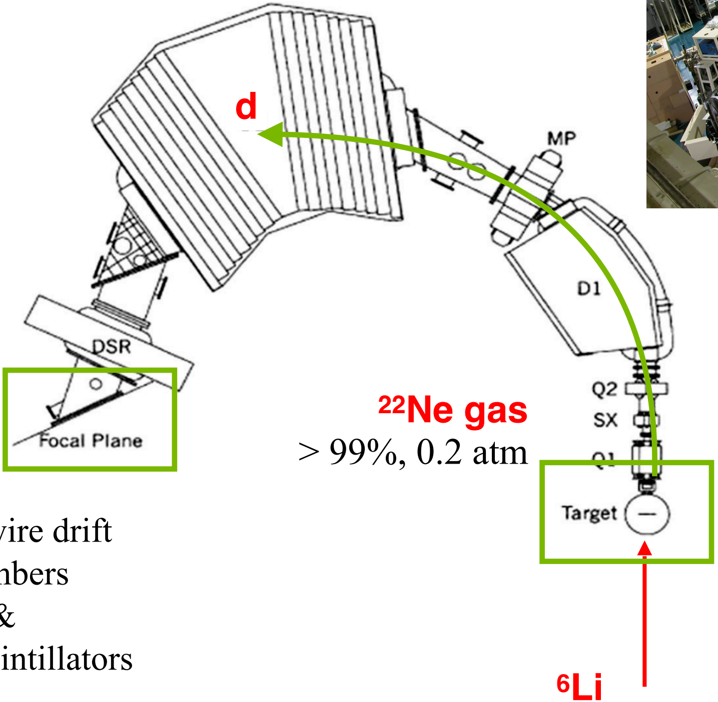
- $^{22}Ne(^{6}Li,d)^{26}Mg$ - *R. Talwar et al. (2016)*
- $^{22}Ne(^{6}Li,d)^{26}Mg$ - *S. Ota et al. (2020)*
- $^{22}Ne(^{6}Li,d)^{26}Mg$ & $^{22}Ne(^{7}Li,t)^{26}Mg$ - *H. Jayatissa et al. (2020)*
- $^{22}Ne(^{7}Li,t)^{26}Mg$ - *A. Best et al. (2024)*



[U. Giesen et al., Nuclear Physics ***A561*** *(1993) 95-111]*

1) $^{22}Ne(^{6}Li,d)^{26}Mg$ @ RCNP

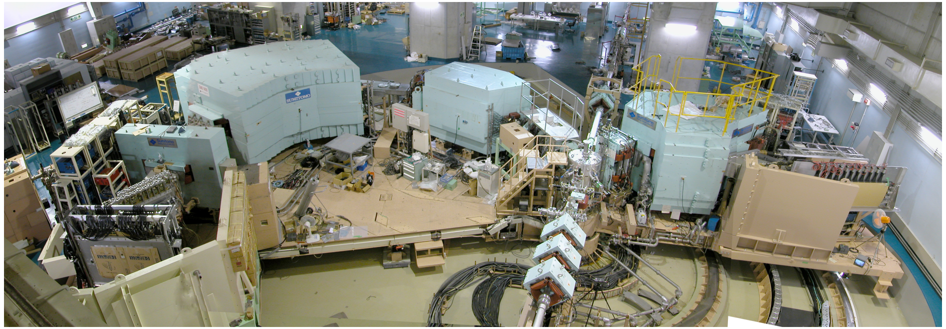
R. Talwar et al. (2016)



^{22}Ne gas
> 99%, 0.2 atm

^{6}Li
E = 82.3 MeV

Multi-wire drift chambers
&
plastic scintillators



Grand Raiden Spectrometer

Measured two reactions:

- $^{26}Mg(\alpha,\alpha')$ @ 0.45^0, 4.1^0, 8.6^0, and 11.1^0
- $^{22}Ne(^{6}Li,d)^{26}Mg$ @ 0^0 & 10^0

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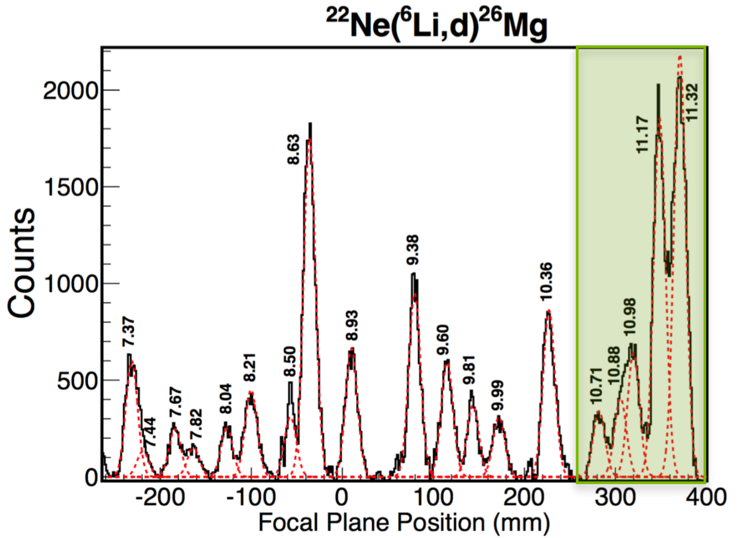
Results

Observed 6 resonances above the α-decay threshold of ^{26}Mg.

E_x (keV)	E_R (keV)	Present work ^{26}Mg(α,α')^{26}Mg	Present work ^{22}Ne(^{6}Li,d)^{26}Mg	Adopted value(s)
10717(9)	102	$1^-, 2^+$	$1^-, 2^+, 4^+$	$1^-, 2^+$
10822(10)	207	$0^+, 1^-$		1^-
10951(21)	336	$1^-, 2^+$	$1^-, 2^+, 4^+$	1^-
11085(8)	471	$2^+, 3^-$		$2^+, 3^-$
11167(8)	553	$1^-, 2^+$	1^{-} [a]	1^- (2^+)
11317(18)	702		1^{-} [a]	1^- (2^+)

S_n



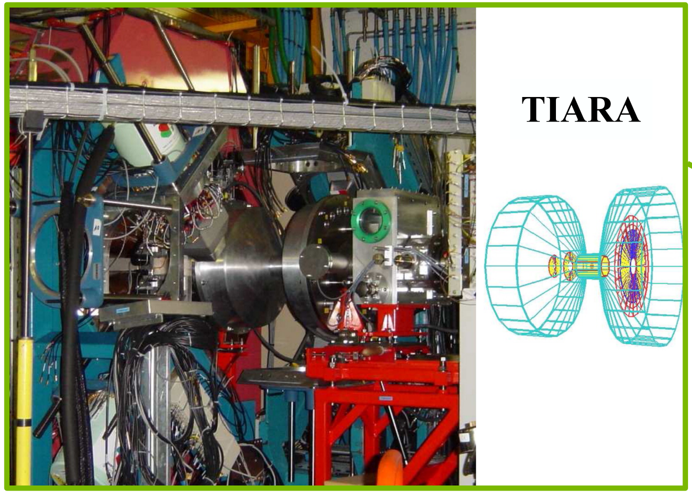
(E_x = 10.61–11.32 MeV)

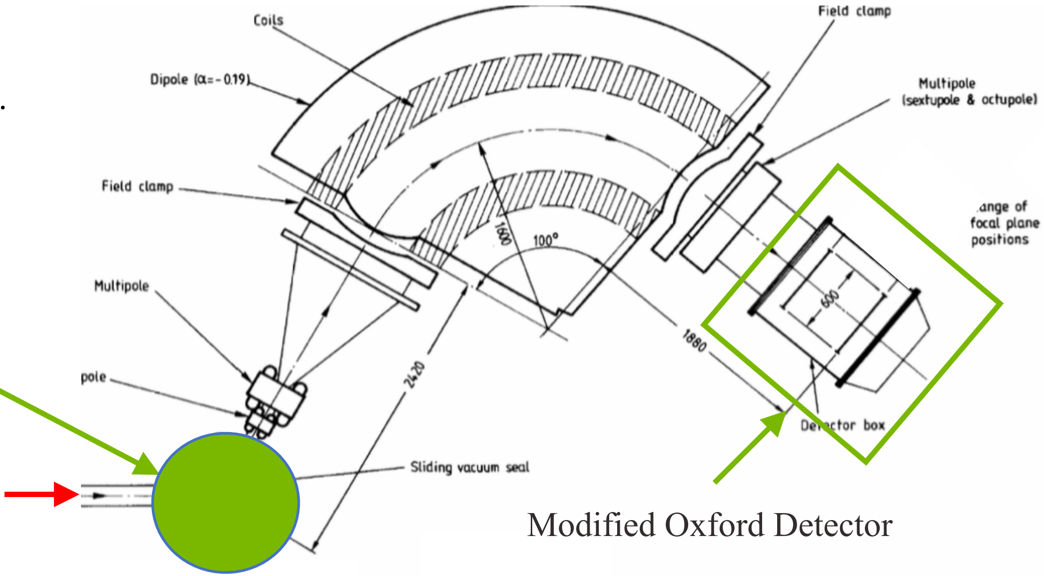
- *Two resonances above the neutron threshold have large α-SFs.*
- *11.167 MeV resonance strength increases the (α,γ) rate by ~2 orders of magnitude from Longland et al. (2012).*
- *Reduction in s-process overabundances in massive stars and intermediate-mass AGB stars*

2) ^{22}Ne(^{6}Li,d)^{26}Mg @ TAMU Cyclotron Institute

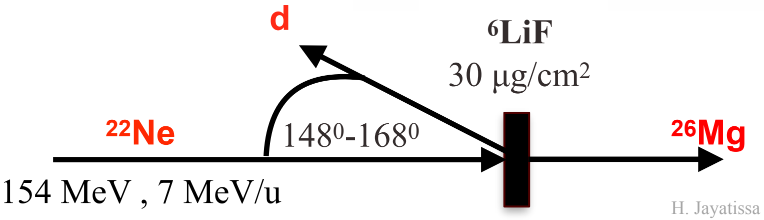
S. Ota, et al. (2020)

Measured deuterons in coincidence with ^{25}Mg and ^{26}Mg.

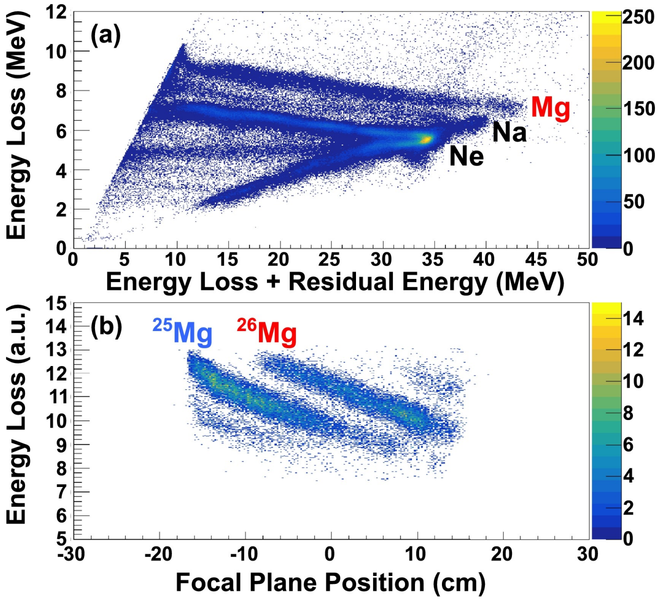


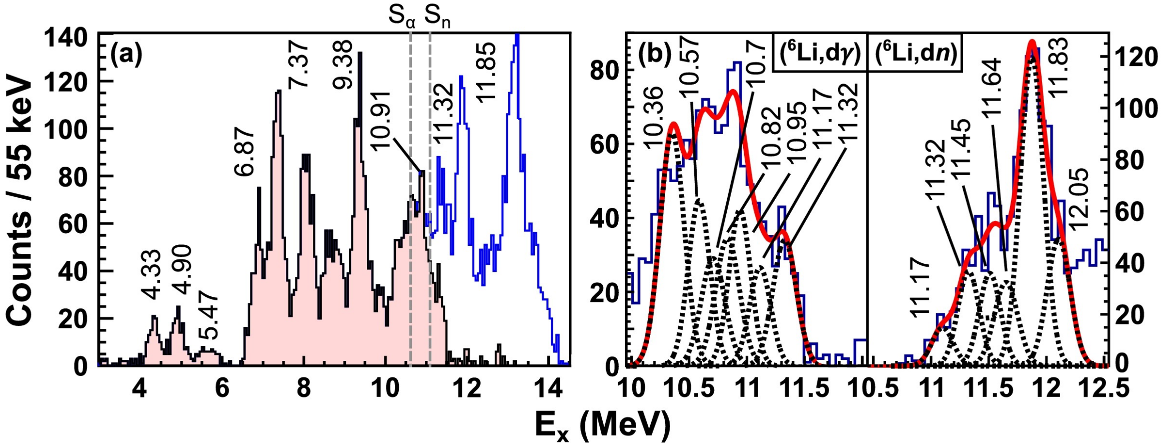


- Silicon detector barrel around target
- Annular Silicon detectors at endcaps
- 4 Ge detectors



Results





- Measured the neutron-gamma branching ratio of the 11.32 MeV resonance.

$$\boxed{\frac{\Gamma_n}{\Gamma_\gamma} = 1.14(26)}$$

~ 3x lower than the ratio established from direct measurements

- By combining with the (α,γ) resonance strength by S. Hunt et al. (2019):
$\omega\gamma_{(\alpha,\gamma),11.3} = 37 \pm 4 \quad \mu eV$

$$\boxed{\omega\gamma_{(\alpha,n),11.32} = 42 \pm 11 \ \mu eV}$$

~ 2-3x lower than the lowest measured strength from direct measurements

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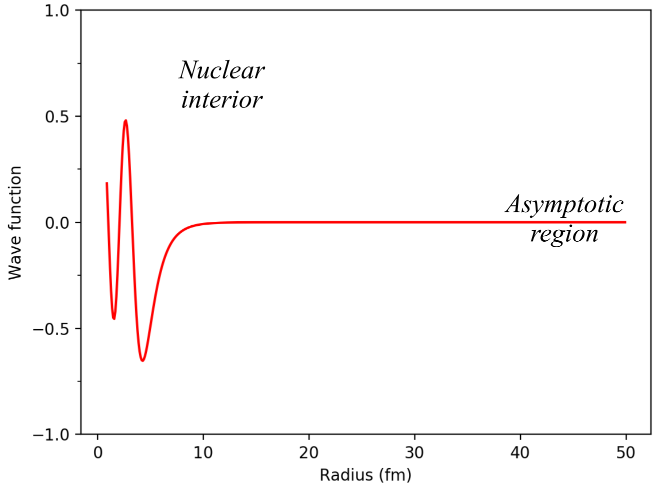
3) ^{22}Ne(^{6}Li,d)^{26}Mg & ^{22}Ne(^{7}Li,t)^{26}Mg @ TAMU Cyclotron Institute

H. Jayatissa, et al. (2020)

Sub-Coulomb α-transfer technique:

- Use sub-Coulomb energies to facilitate independence from optical model potentials required to model the interior of a nucleus.
- Extract Asymptotic Normalization Coefficients (ANCs) instead of Spectroscopic factors (SFs).



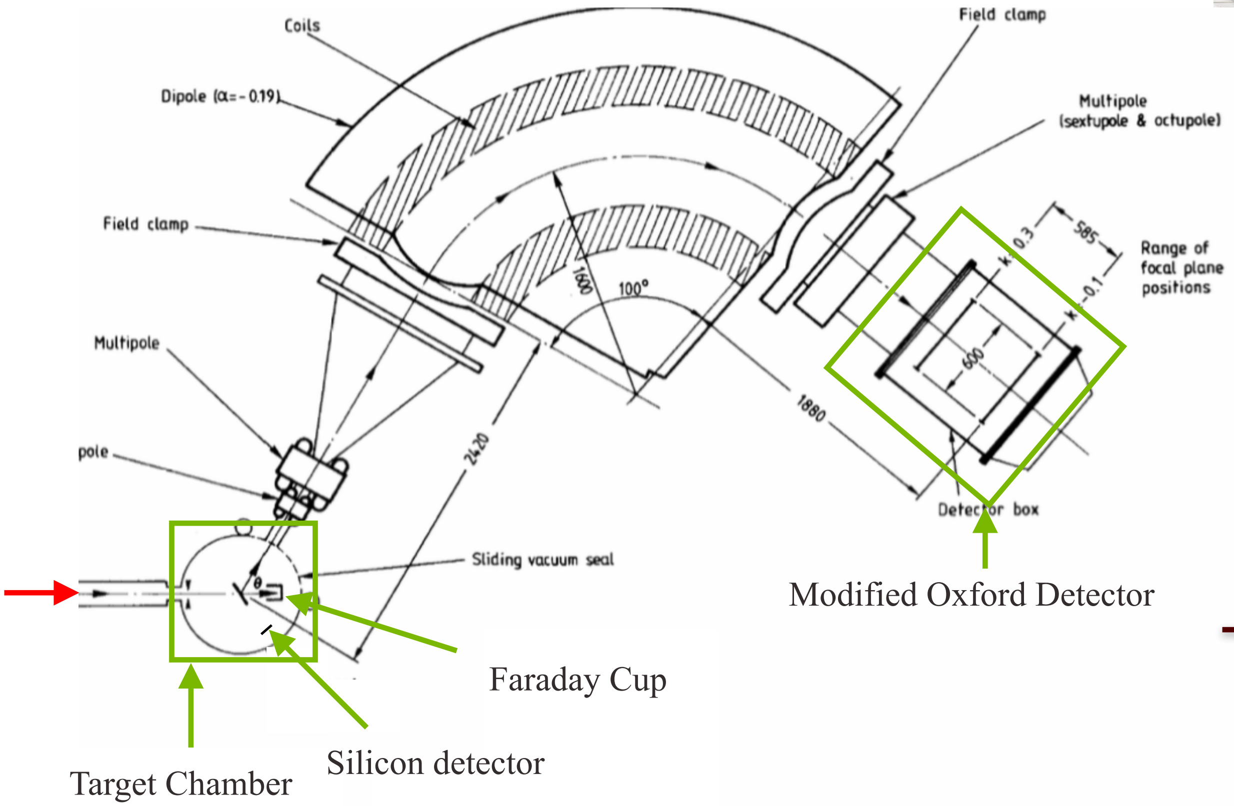
Advantages:

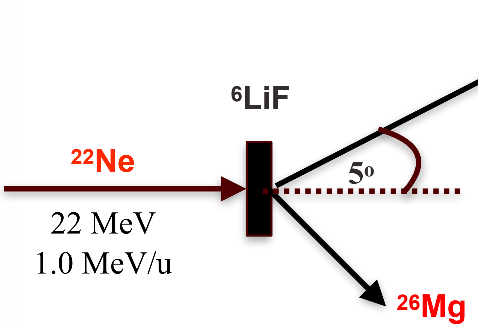
- ANC represents the ^{22}Ne+α wavefunction far from the nuclear center, more representative of interactions at stellar energies.
- ANCs and corresponding resonance strengths are less dependent on OMPs.
- Energies only allow to populate low-spin states.
- α-ANC of ^{6}Li is relatively well known.

Disadvantage:

Γ_α are calculated using a bound-state approximation, and *linearly* extrapolated to unbound energies.

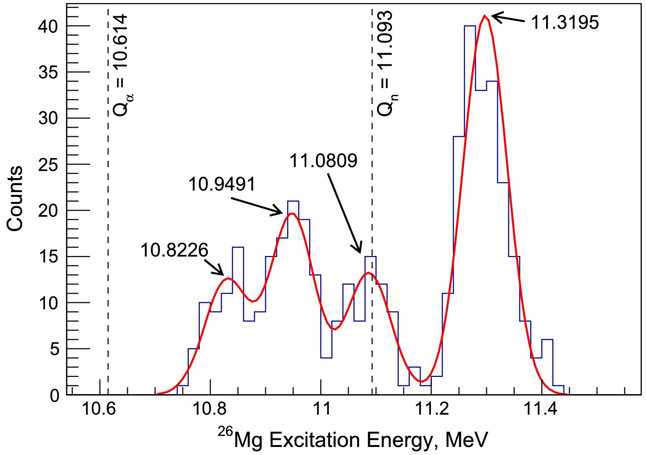
Experimental setup





Results

Measured 4 resonances above α-decay threshold to obtain Γ_α for $J^\pi = 0^+$, 1^- and 2^+.



E_{ex} (MeV)	Adopted E_{ex} (MeV)	E_r (keV)	Exp. CS[d] (μb/sr)	J^π	Γ_α (eV)	Expt.
11.30(2)	11.3195(25)[a]	706.6(25)[a]	$82 \pm 6^{+13}_{-8}$	0^+	$6.1 \pm 0.4 \pm 1.0$ [b]	−5
				1^-	$1.3 \pm 0.1 \pm 0.2$ [b]	−5
				2^+	$3.0 \pm 0.2 \pm 0.5$ [b]	−6
11.17	11.1717(30)[c]	557.0(30)[c]	<0.8	0^+	<3	−9
				1^-	<6	−10
				2^+	<1.3	−11
11.08(2)	11.0809(40)[c]	466.2(40)[c]	$26 \pm 3^{+4}_{-3}$	0^+	$1.3 \pm 0.1 \pm 0.3$	−9
				1^-	$2.5 \pm 0.3^{+0.7}_{-0.5}$	−10
				2^+	$5.7 \pm 0.7^{+1.4}_{-1.2}$	−11
10.95(2)	10.9491(8)[c]	334.4(8)[c]	$39 \pm 4^{+6}_{-4}$	0^+	$1.5 \pm 0.2^{+0.4}_{-0.3}$	−13
				1^-	$3.0 \pm 0.3^{+0.75}_{-0.6}$	−14
				2^+	$6.4 \pm 0.6^{+1.0}_{-0.6}$	−15
10.83(2)	10.8226(30)[c]	207.9(30)[c]	$24 \pm 3^{+4}_{-3}$	0^+	$5.3 \pm 0.7^{+1.1}_{-1.0}$	−21
				1^-	$1.0 \pm 0.1^{+0.3}_{-0.2}$	−21
				2^+	$2.1 \pm 0.3 \pm 0.4$	−22

- *No evidence of a resonance near 11.17 MeV.*
- *J^π of the 11.3 MeV resonance is favored to be 0^+ (1^- cannot be fully excluded).*
- *Strength of the 11.3 MeV resonance is smaller than previous direct measurements, significantly reducing the ^{22}Ne(α,n)^{25}Mg reaction rate.*

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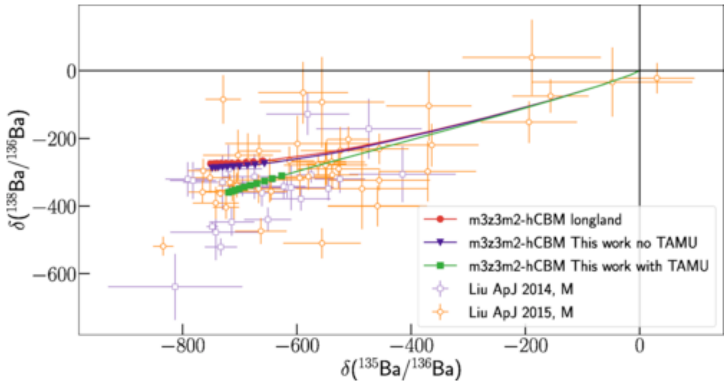
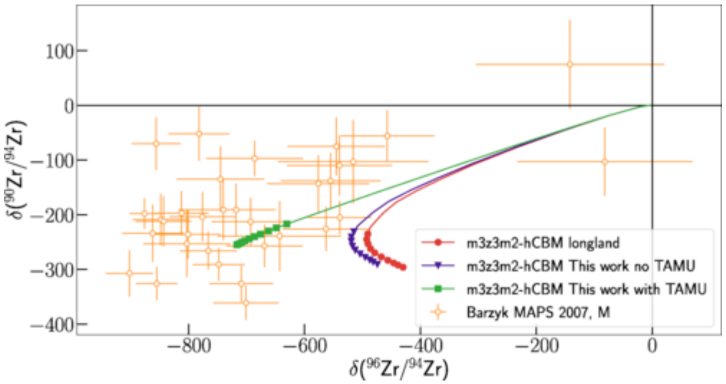
Astrophysical Implications

P. Adsley et al. (2021)

Re-evaluated the ^{22}Ne(α,n)^{25}Mg rate using new experimental data:
E_x, J^{π}, Γ_α, $\omega\gamma$, etc.





- *^{22}Ne(α,γ)^{26}Mg reaction remained similar to that of Longland et al. (2012).*
- *^{22}Ne(α,n)^{26}Mg reaction rate was lower than Longland et al. (2012); lower production of the weak s-process.*
- *Better agreement between the measured ^{96}Zr/^{94}Zr and ^{135}Ba/^{136}Ba ratios from presolar SiC grains and theoretical models.*

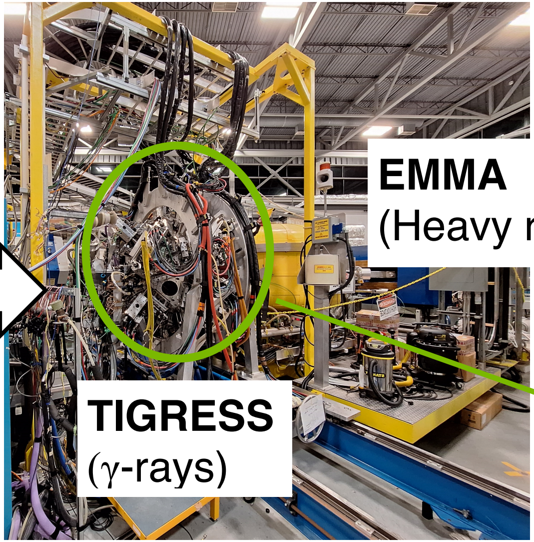
4) ^{22}Ne(^{7}Li,t)^{26}Mg @ TRIUMF

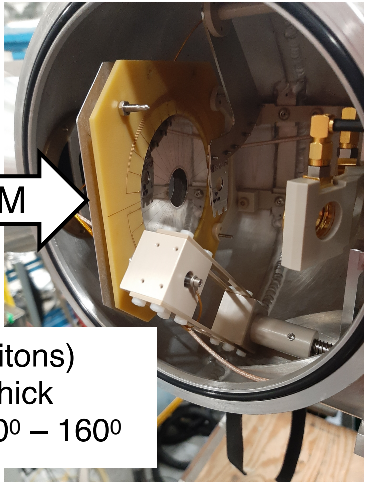
A. Best, et al. (2024), T. Chillery

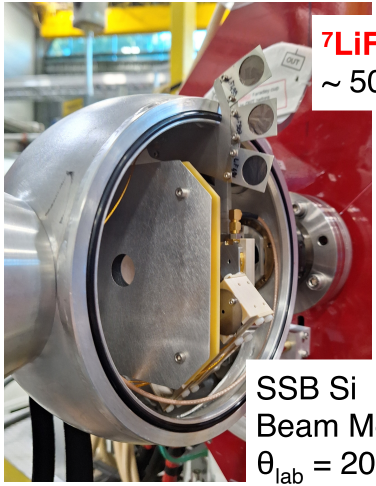
TRIUMF Experiment: **S2223**
Spokespersons: Andreas Best, Philip Adsley, Christian Diget, Alison Laird

Beam time completed: 5th – 13th December 2024

Main Goals:
1. dσ/dΩ of **^{22}Ne(^{7}Li,t)^{26}Mg** from tritons (Γ_α + spectroscopic factors)
2. γ-ray branching ratios and J^π







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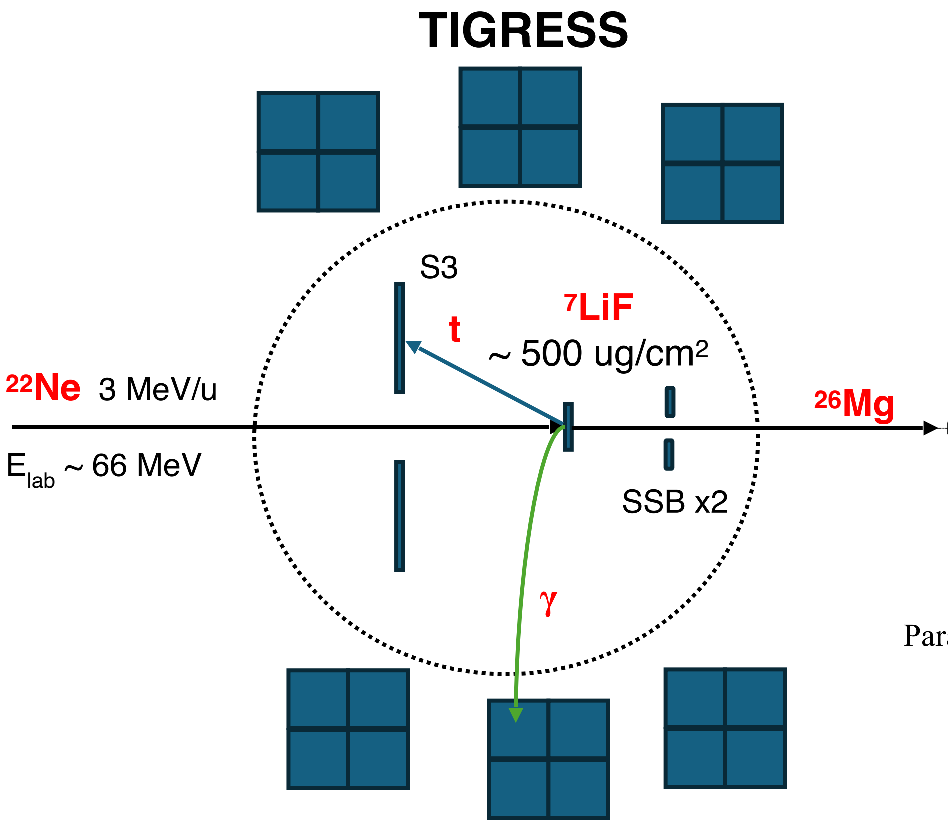
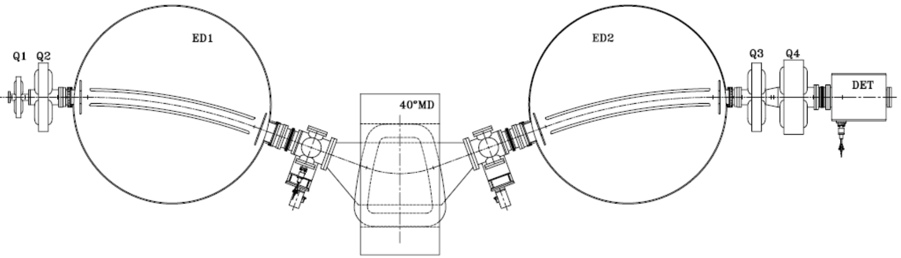
Schematic of the experimental setup



EMMA

B. Davids & C.N. Davids NIMA 544 (2005) 565 – 576



Parallel-grid avalanche counter (Multi-wire proportional counter)

↓

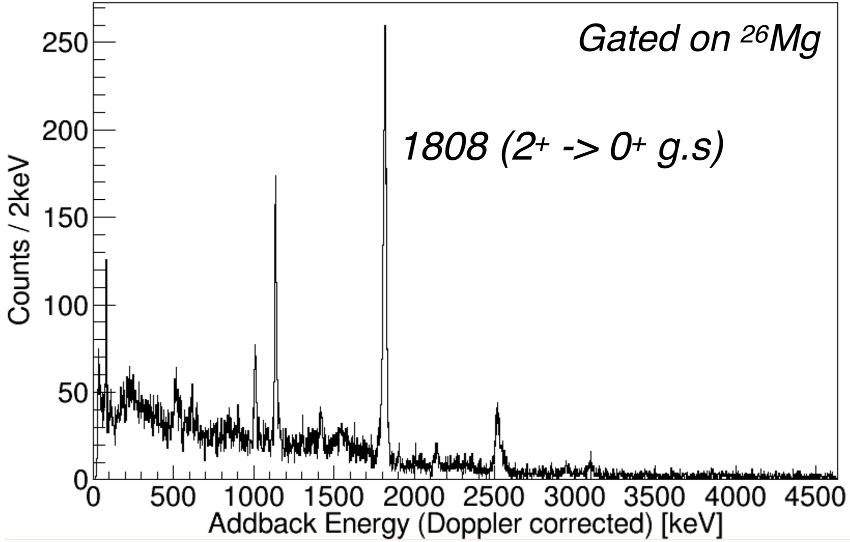
Ionization chamber (4 segments)

↓

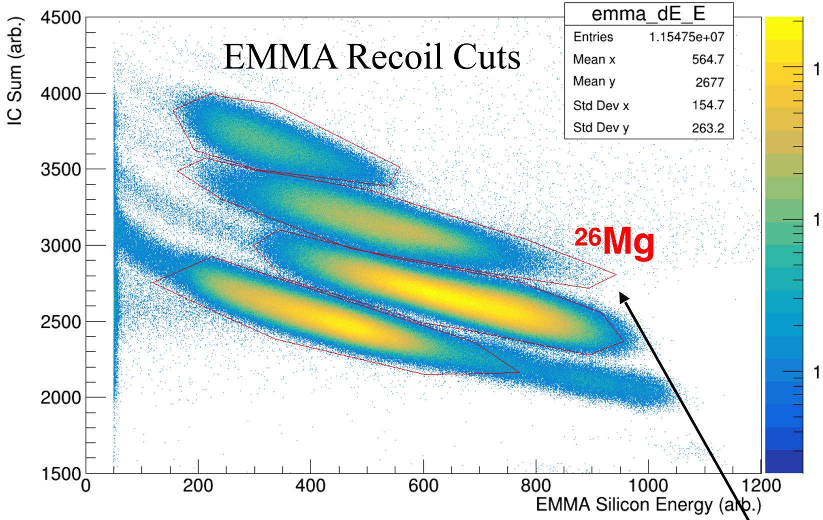
Focal plane Si detector

Preliminary results

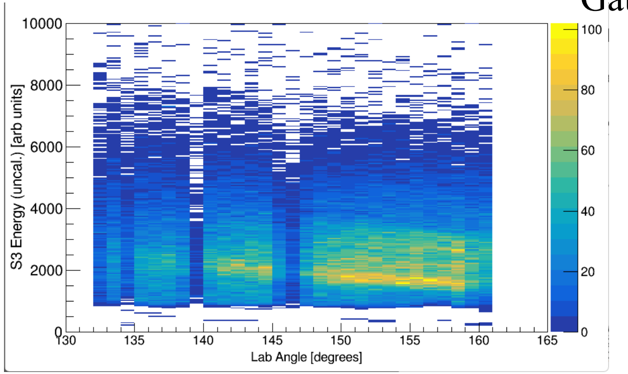
<u>TIGRESS Gamma-ray Energy Spectrum</u>



$$E_{dopp} = E_{addback} * \gamma * \left[1 - \beta_{vel} * \cos(\theta)\right] \qquad \gamma = 1/\sqrt{1-\beta_{vel}^2}$$



Gated on ²⁶Mg



Summary

- Alpha-transfer technique is very useful probe study low-energy resonances currently challenging for direct measurements.

- This technique selectively populated levels with high alpha-spectroscopic factors.

- Many of the recent alpha-transfer measurements suggest a lower ^{22}Ne(α,n)^{25}Mg reaction rate than previously established, affecting the s-process abundances.

- Future measurements at energies of interest are highly encouraged to address the differences between the various alpha-transfer measurements.

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TRIUMF

Thank you to all the contributors of the work presented here!