Decay properties of ^{22}Ne + α resonances and their impact on s-process nucleosynthesis

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Two experiments, Three papers from Texas A&M cyclotron

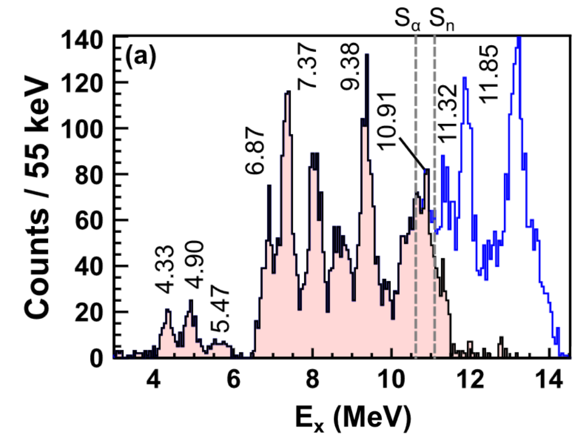
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Decay properties of ^{22}Ne + α resonances and their impact on *s*-process nucleosynthesis

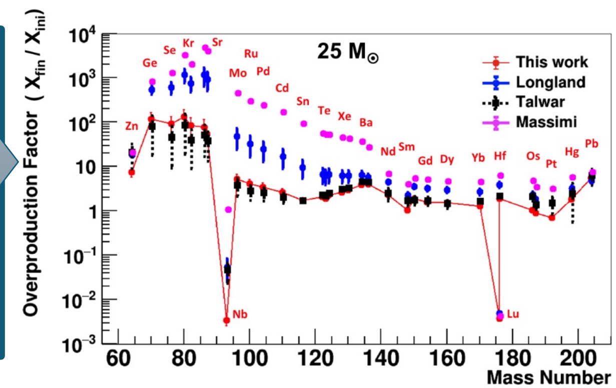
S. Ota[a,*], G. Christian[a,b,c,**,1], G. Lotay[d], W.N. Catford[d], E.A. Bennett[a,b], S. Dede[a,b], D.T. Doherty[d], S. Hallam[d], J. Hooker[a,b], C. Hunt[a,b], H. Jayatissa[a,b], A. Matta[d,2], M. Moukaddam[d,3], G.V. Rogachev[a,b,c], A. Saastamoinen[a], J.A. Tostevin[d], S. Upadhyayula[a,b], R. Wilkinson[d]



PHYSICAL REVIEW C **104**, 055806 (2021)

(^{6}Li, *d*) and (^{6}Li, *t*) reactions on ^{22}Ne and implications for *s*-process nucleosynthesis

S. Ota,[1,2,*] G. Christian,[1,3,4,5] W. N. Catford,[6] G. Lotay,[6] M. Pignatari,[7,8,9,2] U. Battino,[10,2] E. A. Bennett,[1,4] S. Dede,[1,4] D. T. Doherty,[6] S. Hallam,[6] F. Herwig,[11,7,2] J. Hooker,[1,4] C. Hunt,[1,4] H. Jayatissa,[1,4] A. Matta,[6] M. Moukaddam,[6] E. Rao,[1,12] G. V. Rogachev,[1,4,5] A. Saastamoinen,[1] D. Scriven,[1,4] J. A. Tostevin,[6] S. Upadhyayula,[1,4] and R. Wilkinson[6]



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Physics Letters B

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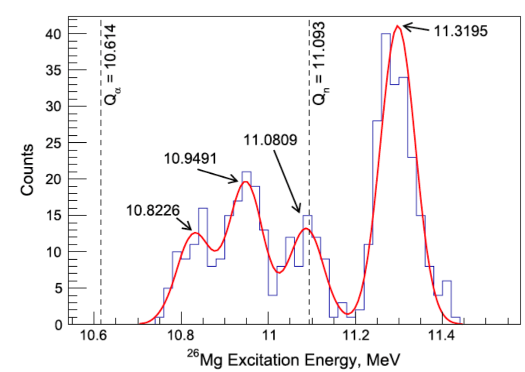
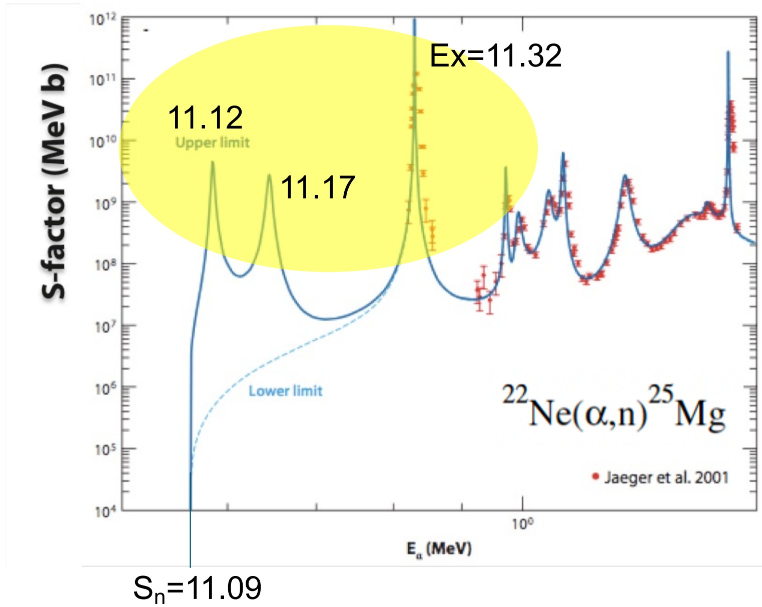
Constraining the ^{22}Ne(α,γ)^{26}Mg and ^{22}Ne(α,n)^{25}Mg reaction rates using sub-Coulomb α-transfer reactions

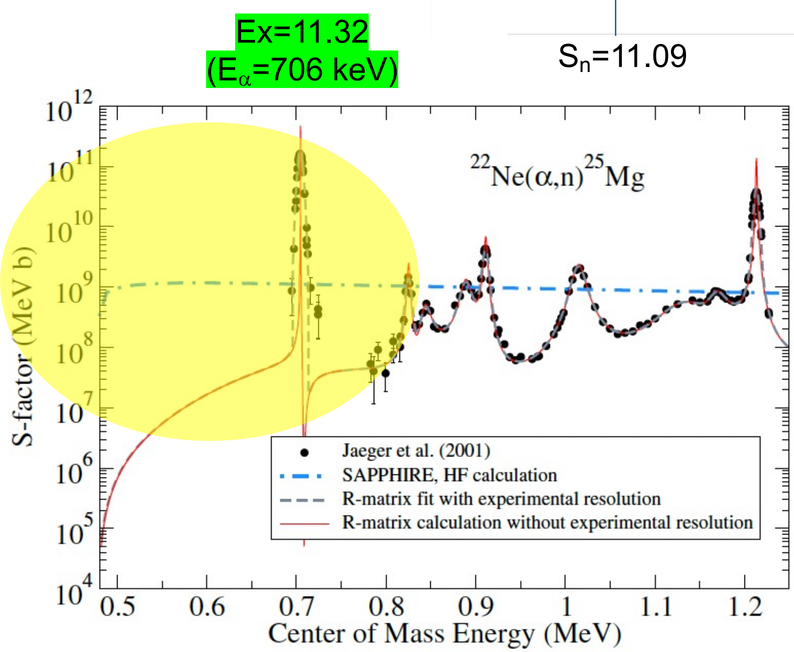
H. Jayatissa[a,b,*,1], G.V. Rogachev[a,b,c,*], V.Z. Goldberg[b], E. Koshchiy[b], G. Christian[a,b,c,2], J. Hooker[a,b,3], S. Ota[b], B.T. Roeder[b], A. Saastamoinen[b], O. Trippella[d], S. Upadhyayula[a,b], E. Uberseder[b]



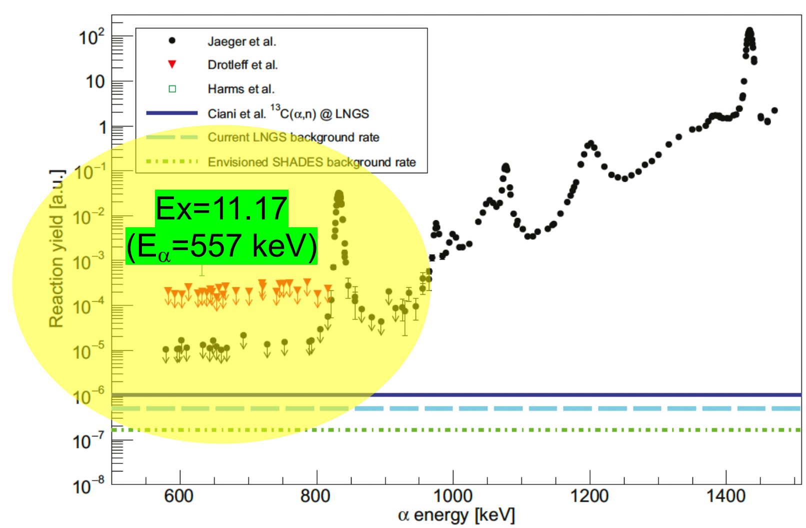
Resonance study related to this work



Wiescher et al., 2018

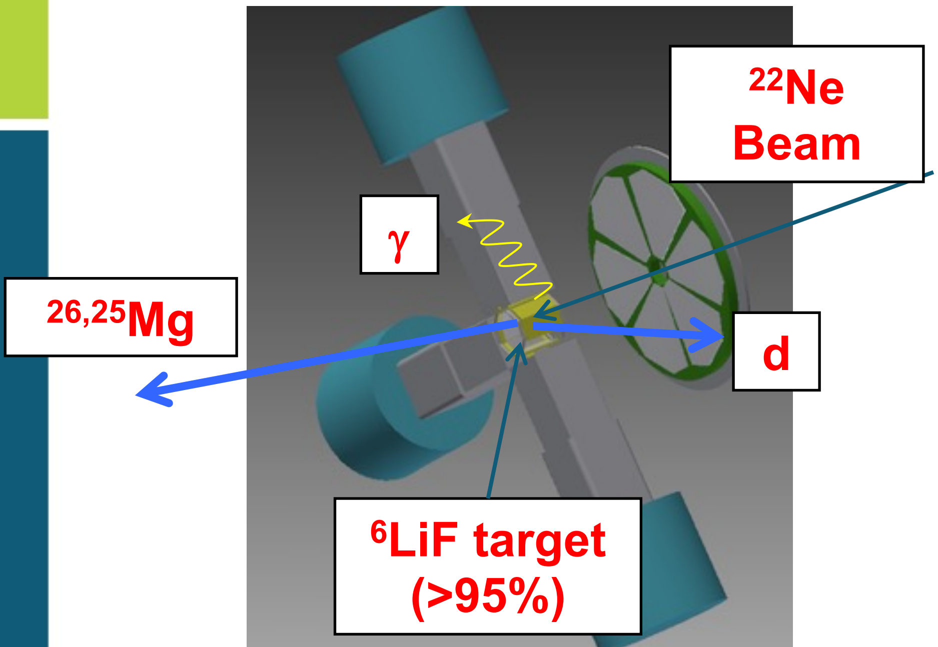


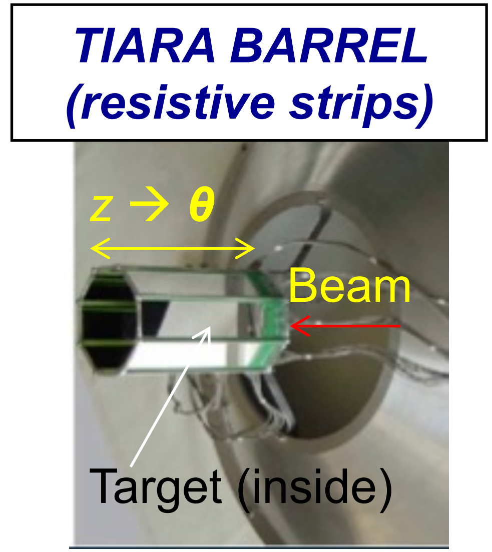
Wiescher et al., EPJA 2023

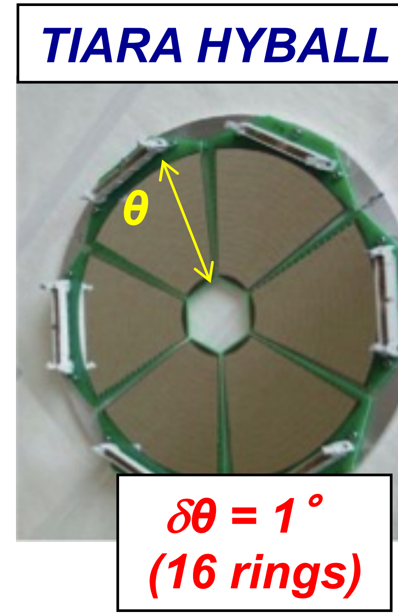


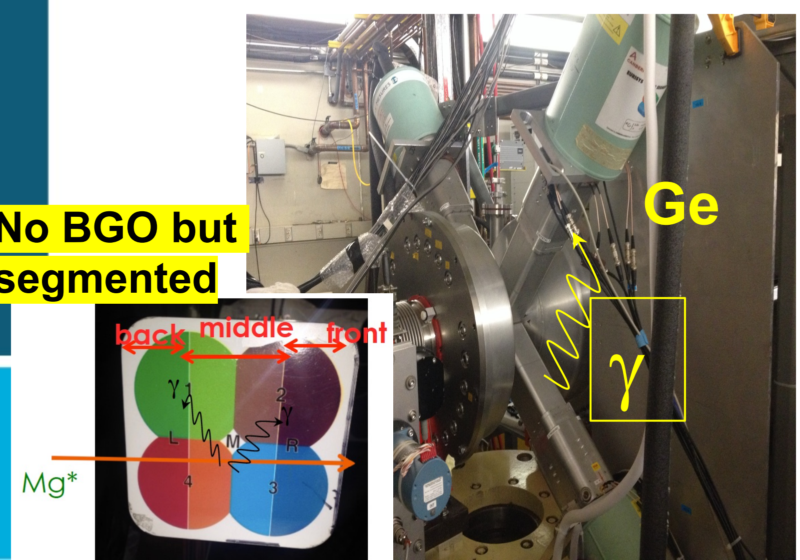
Rapagnani et al., NIC XVI, 2022

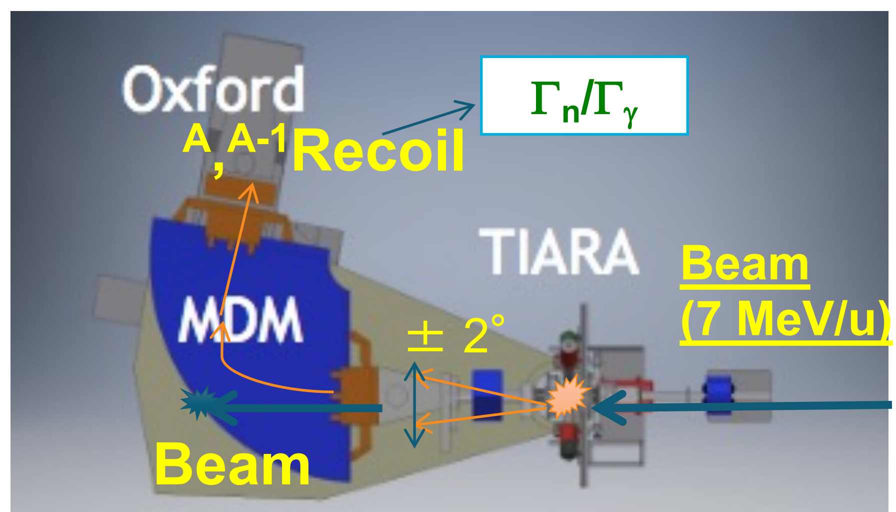
TIARA Si + HPGe + MDM at TAMU







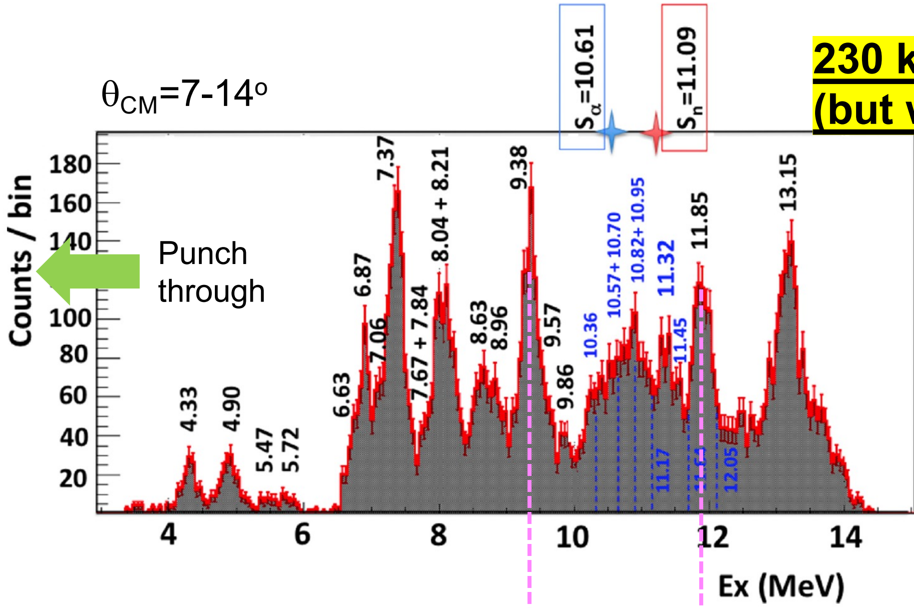


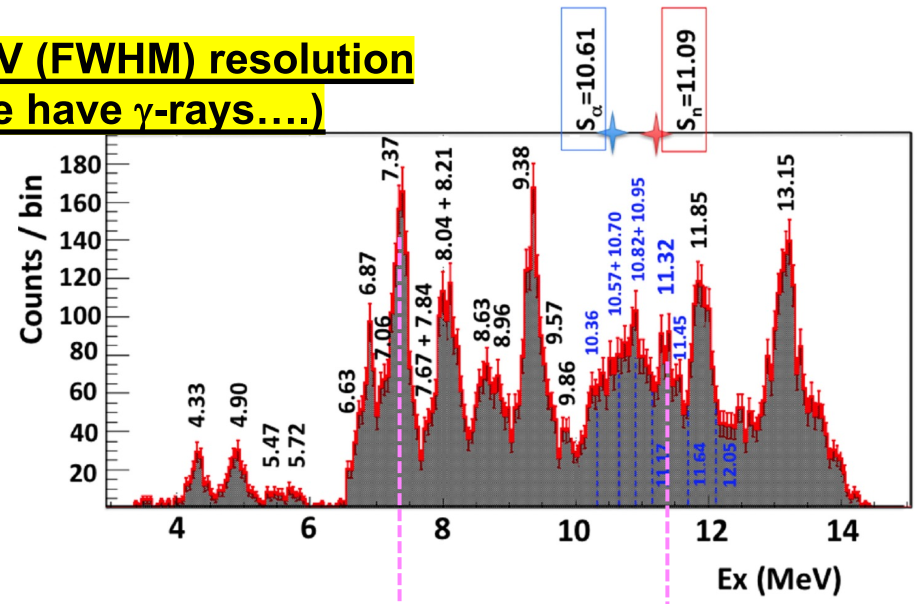


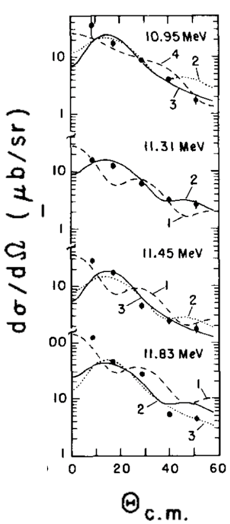
^{26}Mg Ex spectrum comparisons from other ^{22}Ne(^{6}Li,d) experiments

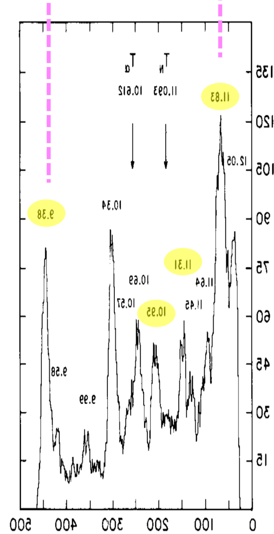
230 keV (FWHM) resolution
(but we have γ-rays….)

θ_{CM}=7-14°







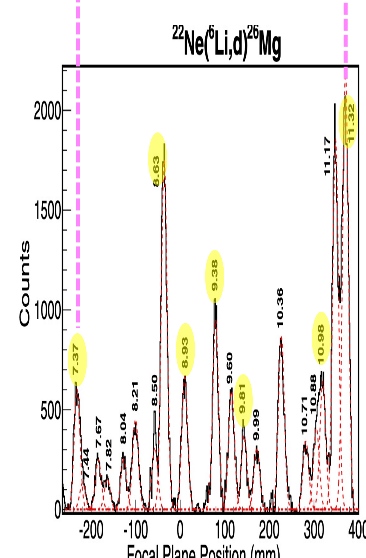


^{22}Ne(^{6}Li,d)^{26}Mg

120 keV resolution

θ_{CM}=25°

Giesen et al., NPA 1993

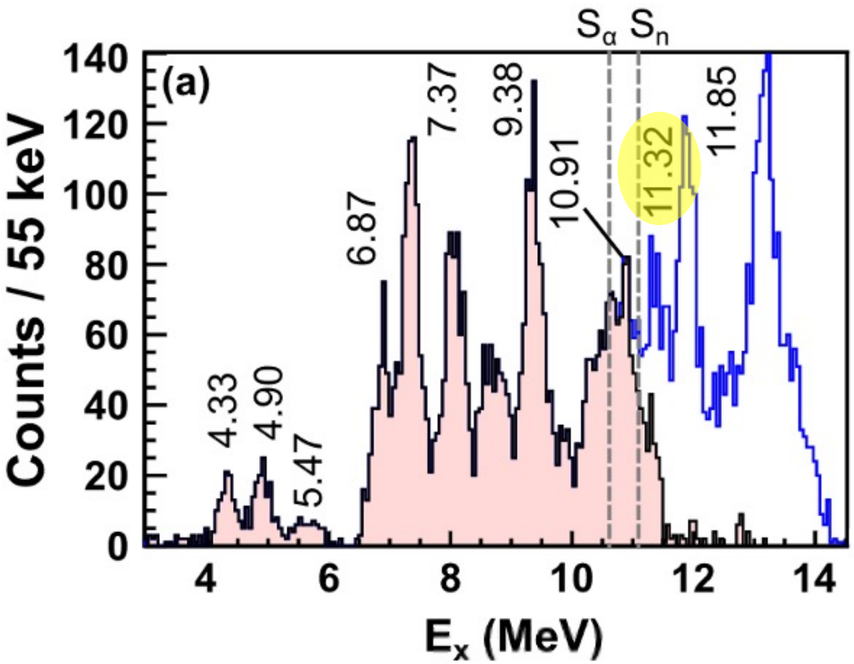


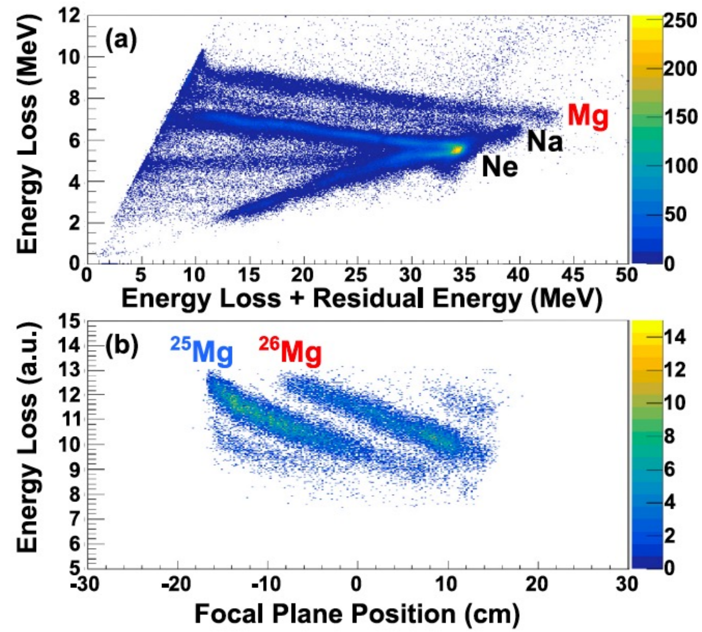
100 keV resolution

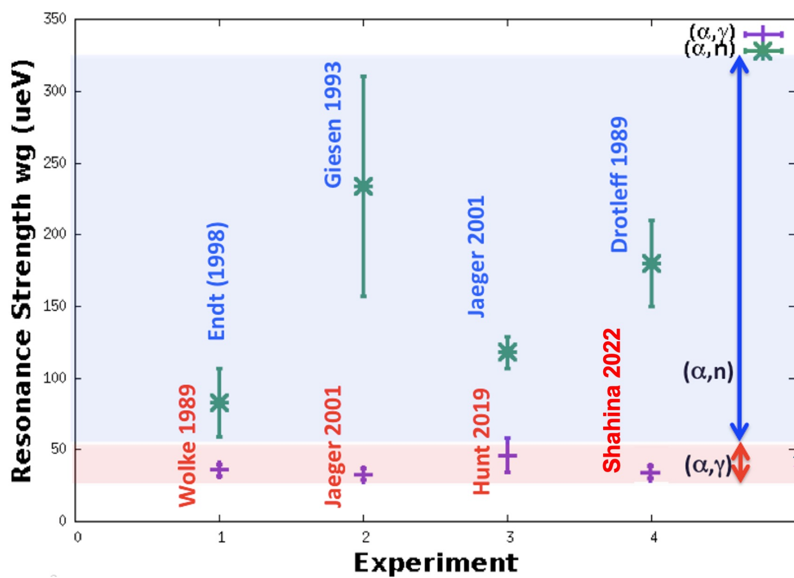
θ_{CM}=0°

Talwar et al., PRC 2017

$\Gamma_n/\Gamma_\gamma = 1.14\ (26)$ for Ex=11.32 MeV resonance



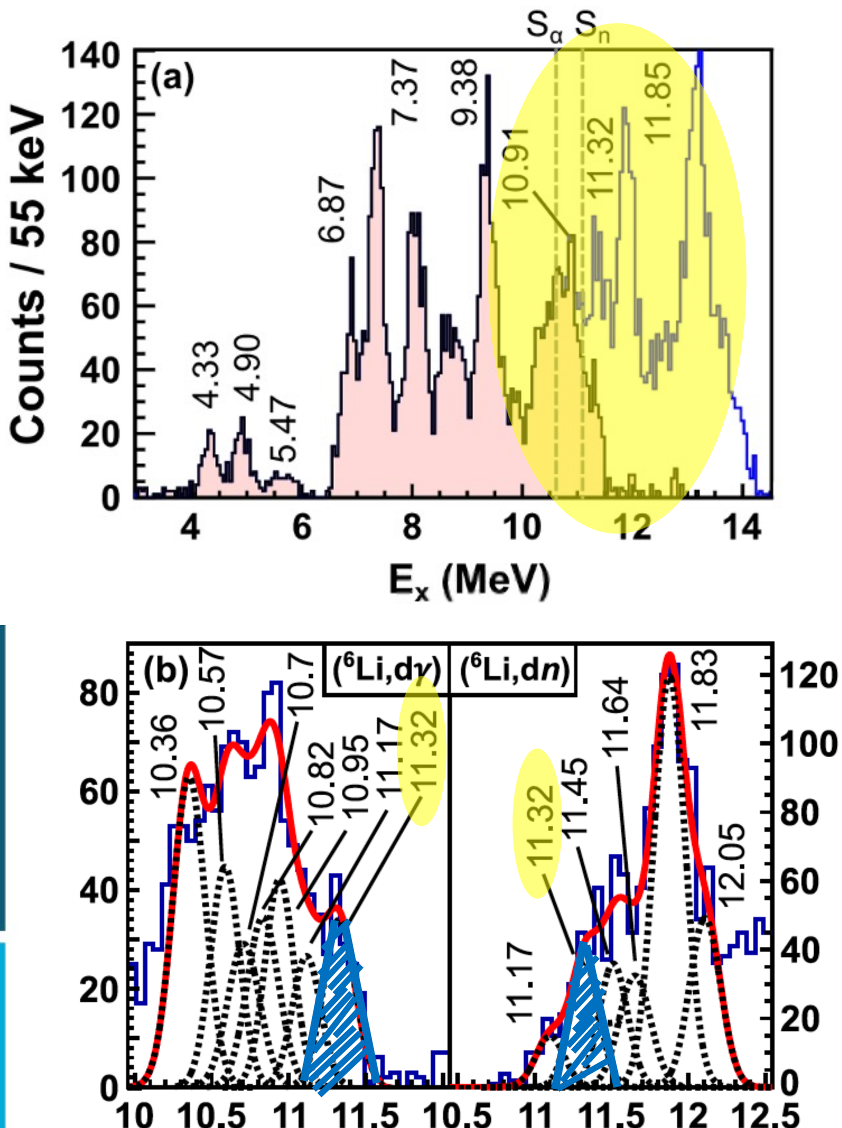




Ota 2020 (α,n); 42 (11) μeV

Ota 2020 (α,γ); 37 (4) μeV
(normalized to direct measurements)

$d\sigma/d\Omega$ for (^{6}Li,dγ) and (^{6}Li,dn) → S_α, Γ_n/Γ_γ, and J^π



- Peaks observed in our experiments were commonly observed by other (^{6}Li,d) at similar intensities.

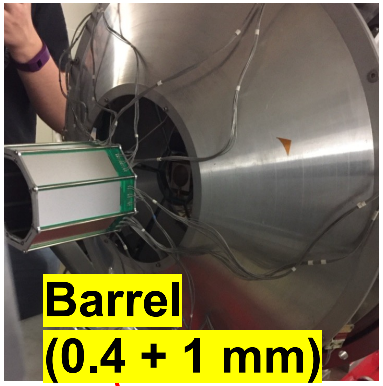
- Multi-Gaussian fitting was tested, assuming various situations (e.g., no Ex=11.17 MeV). But the Γ_n/Γ_γ converges within 1.14 (26).

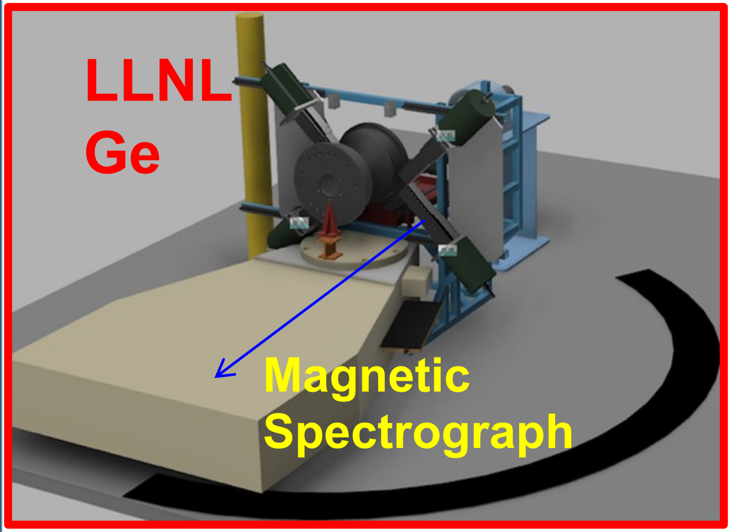
- If Γ_n/Γ_γ = 140/35 = 4.0, $N_{11.32}$ for (^{6}Li,dγ) must be ¼ smaller or $N_{11.32}$ for (^{6}Li,dn) must be x4 larger → Unrealistic.

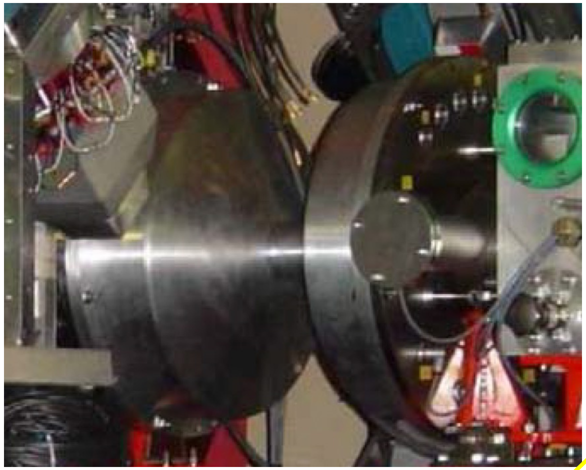
- $N_{11.32}$ for (^{6}Li,dγ) can only increase (not decrease!) by excluding Ex=11.17

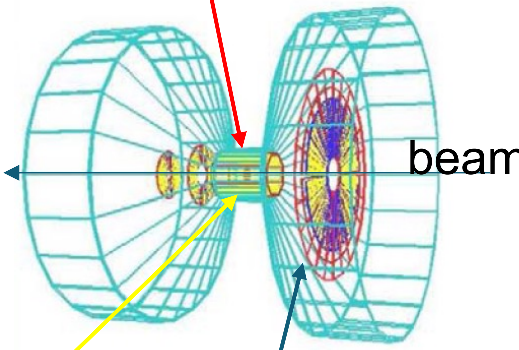
- $N_{11.32}$ for (^{6}Li,dn) could increase, but not like x3-4!.

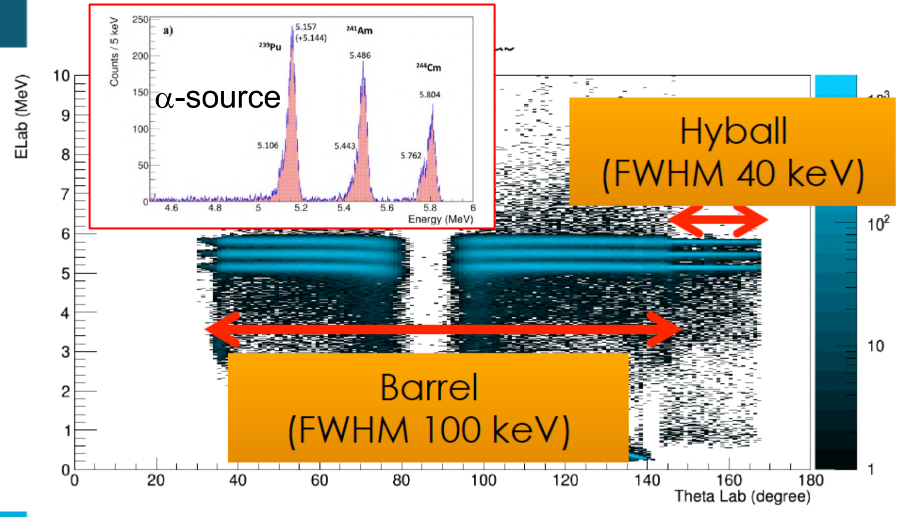
TIARA experiment at TAMU (2016 Dec for two weeks)

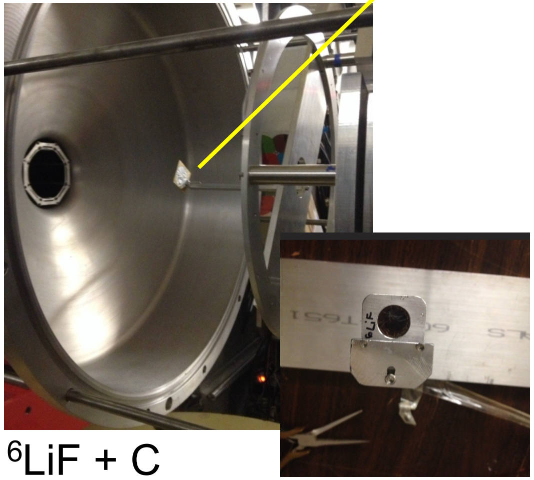




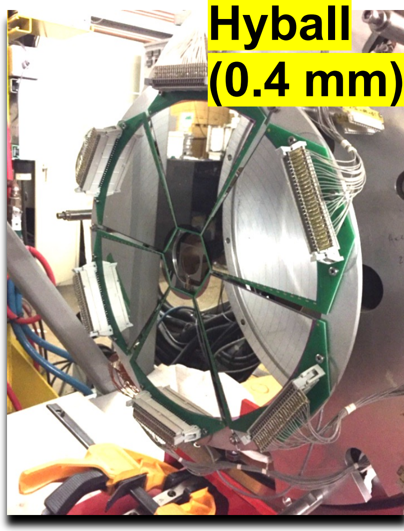






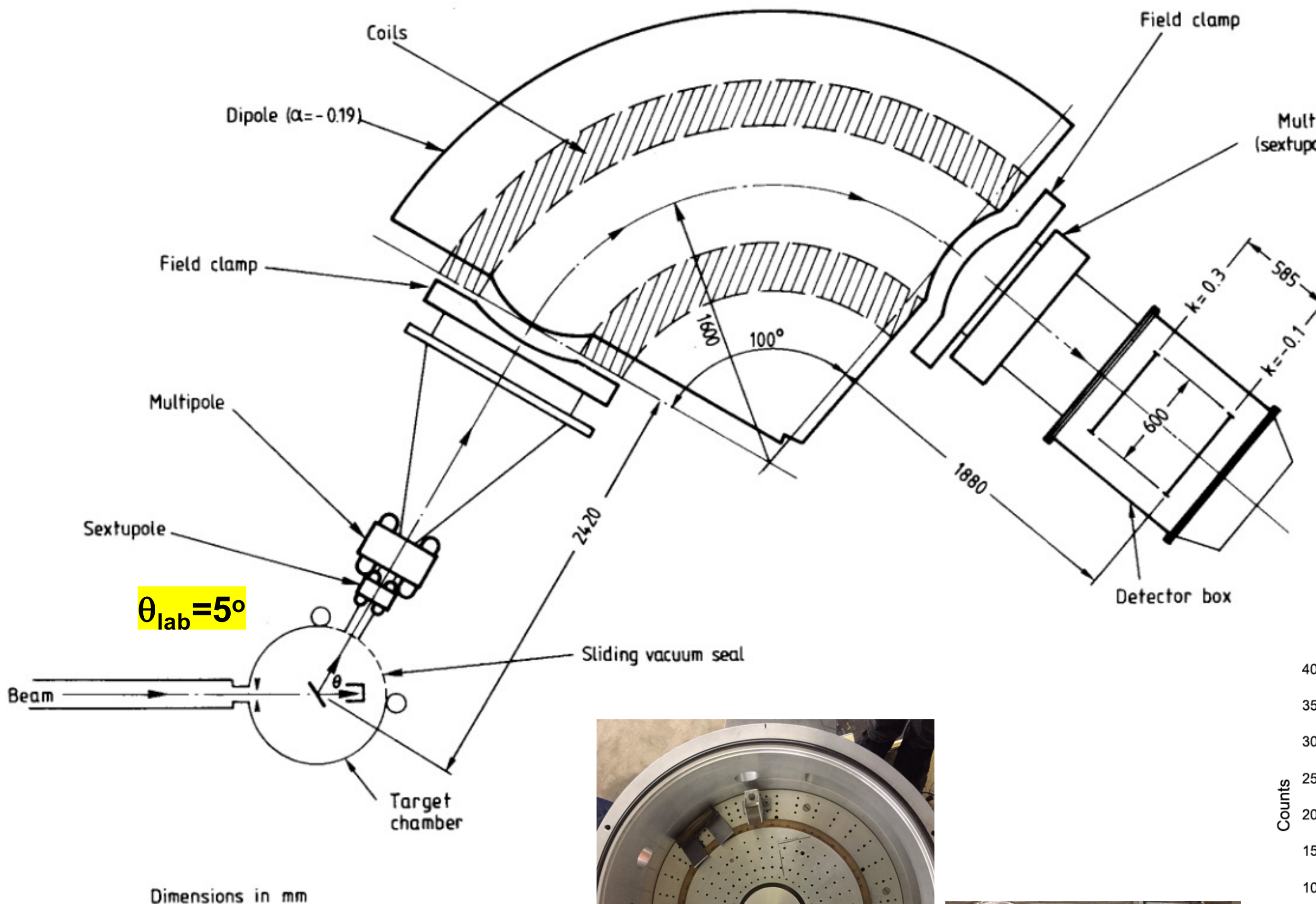


^{6}LiF + C
(30 + 10 ug/cm^{2})



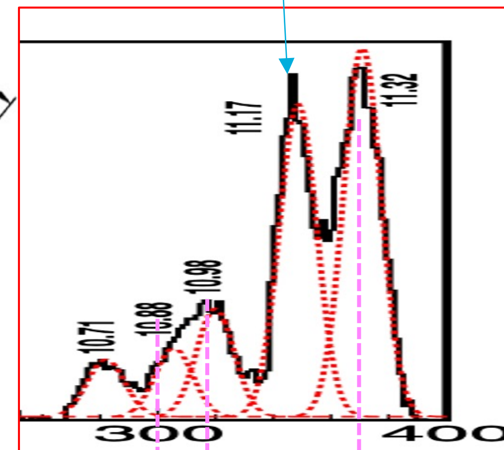
MDM spectrometer [Multipole-Dipole-Multipole]

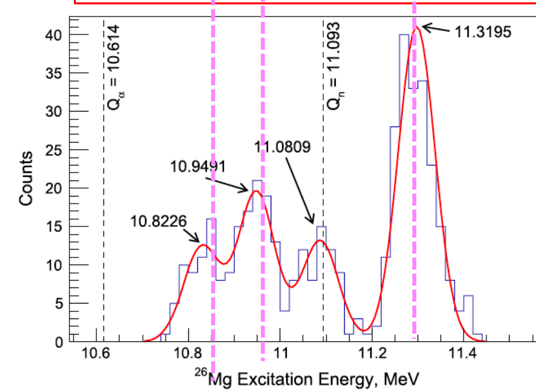
Ex=11.17 MeV resonance can be high *L* that does not contribute (α,n)



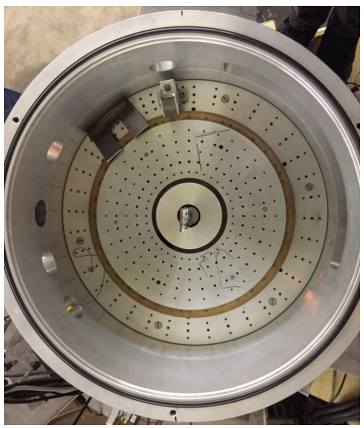
θ_{lab}=5°

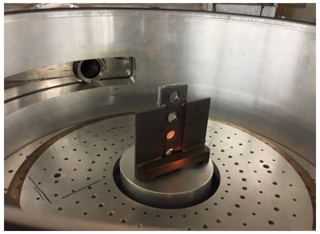
Talwar et al., PRC 2017





^{22}Ne beam 1 MeV/u + ^{6}LiF → d (Jayatissa et al.)

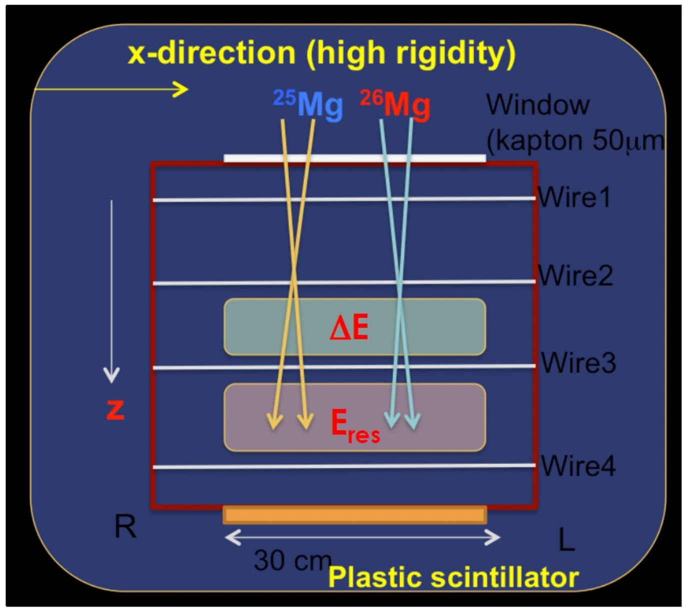




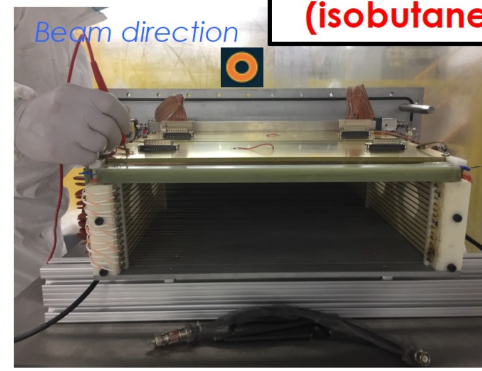
Note:
Ota's experiment was performed at θ_{lab}=0 (±2) °

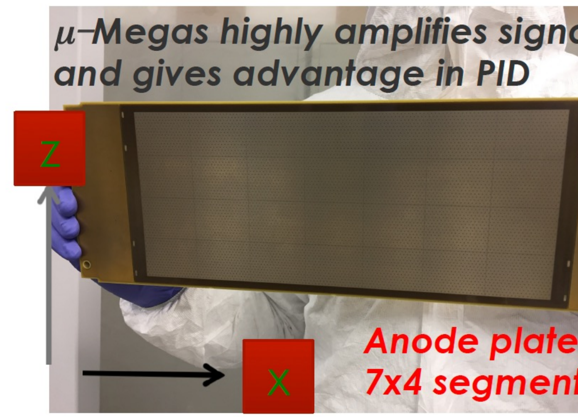
MDM focal-plane detector

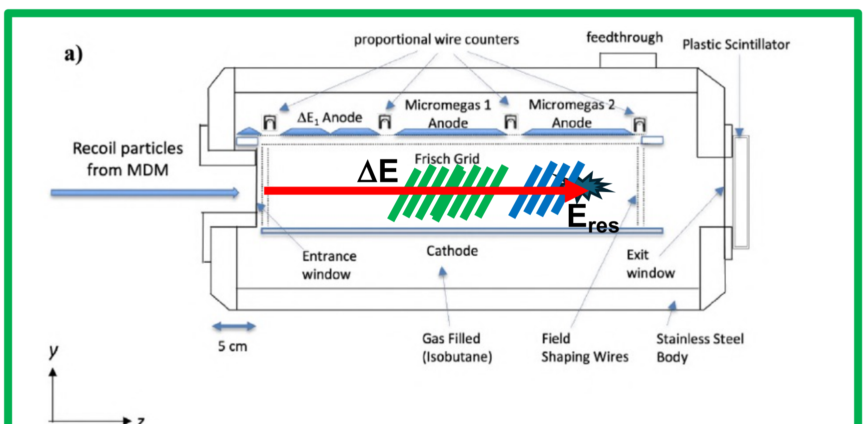
Oxford Ionization chamber (isobutane 35 torr)

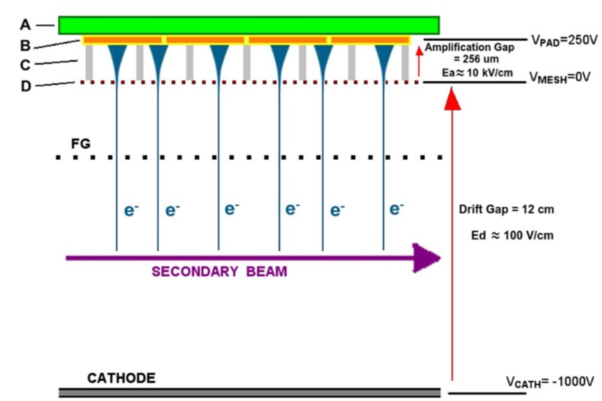


(isobutane 30 torr)



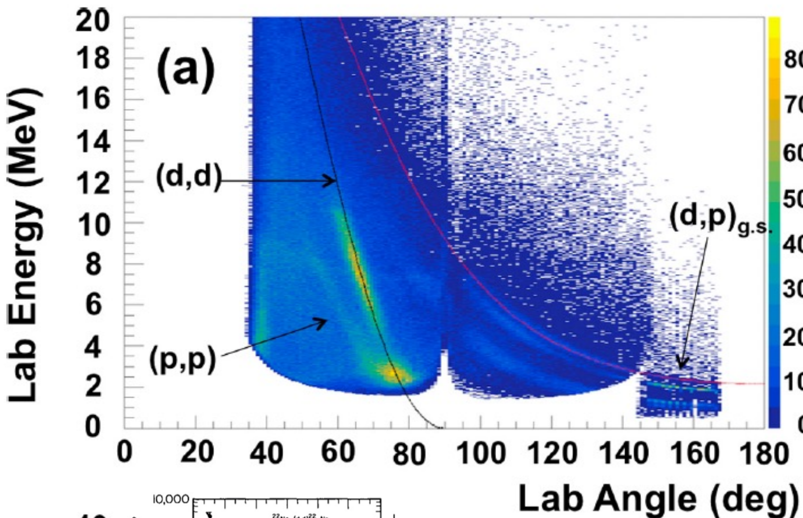


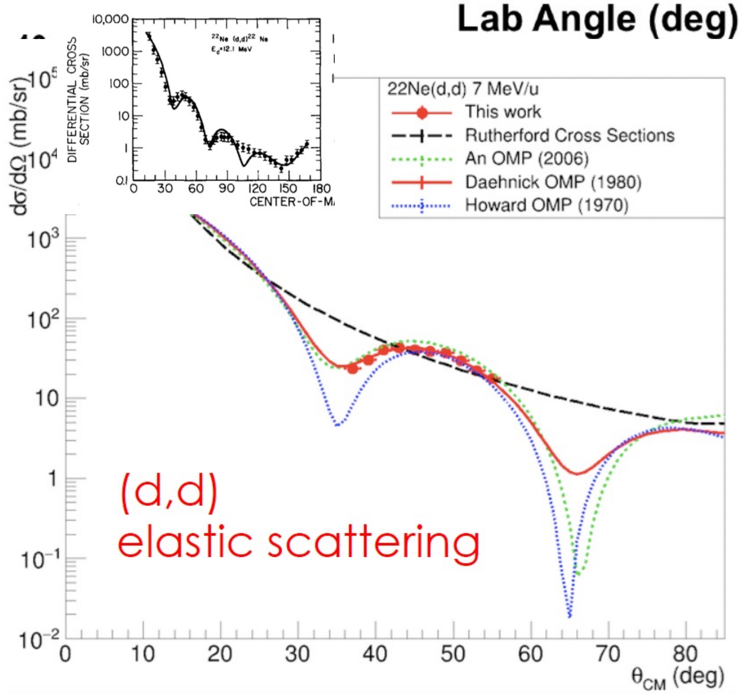




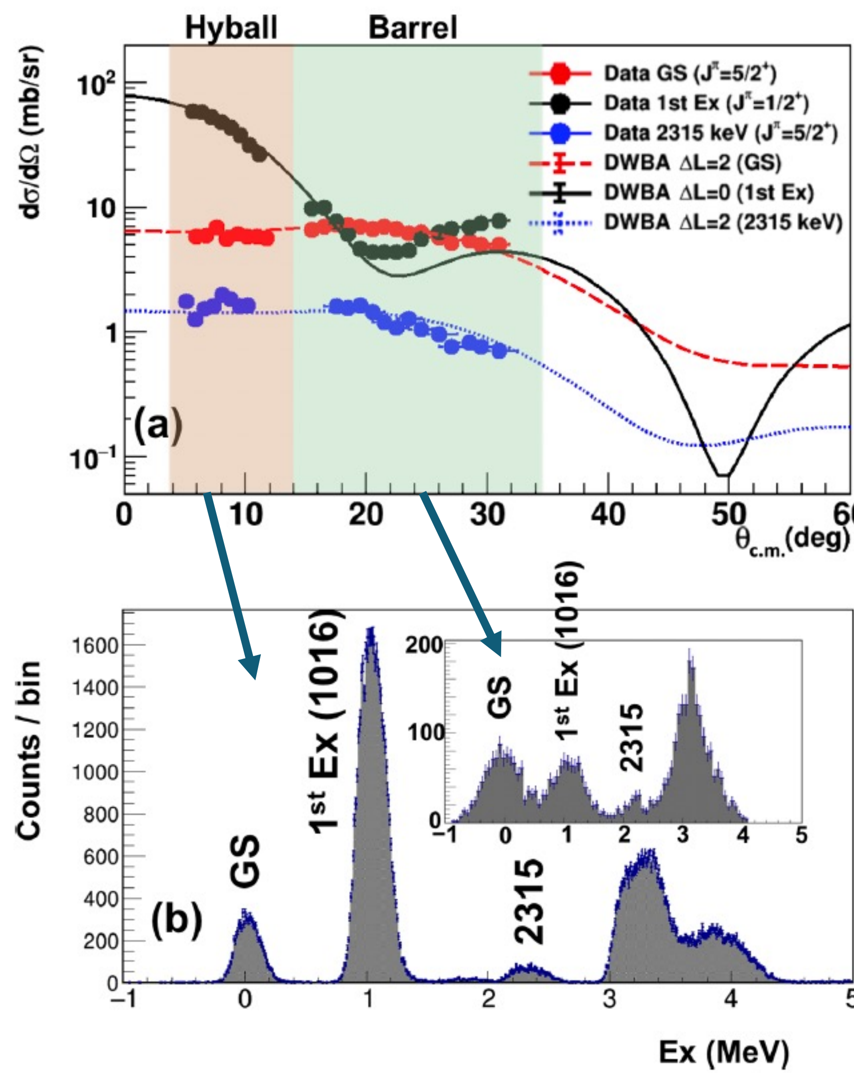
0

Benchmarking with $^{22}Ne(d,p\gamma)$



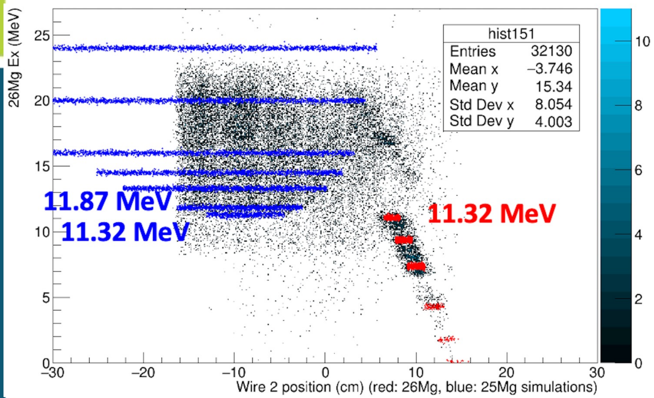


Obtained J^{π}, *S* reproduce literature

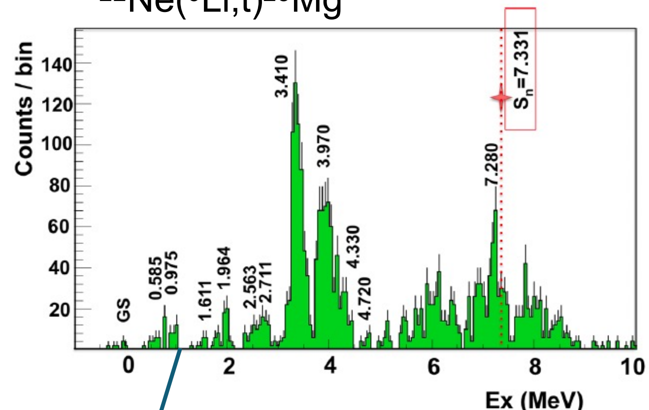


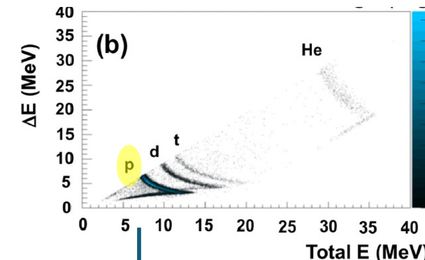
$^{22}Ne(^{6}Li,d)$

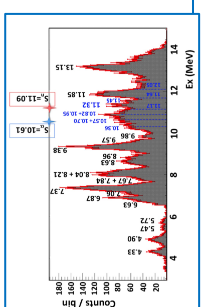
^{25}Mg has broader ***p*** due to n-evaporation

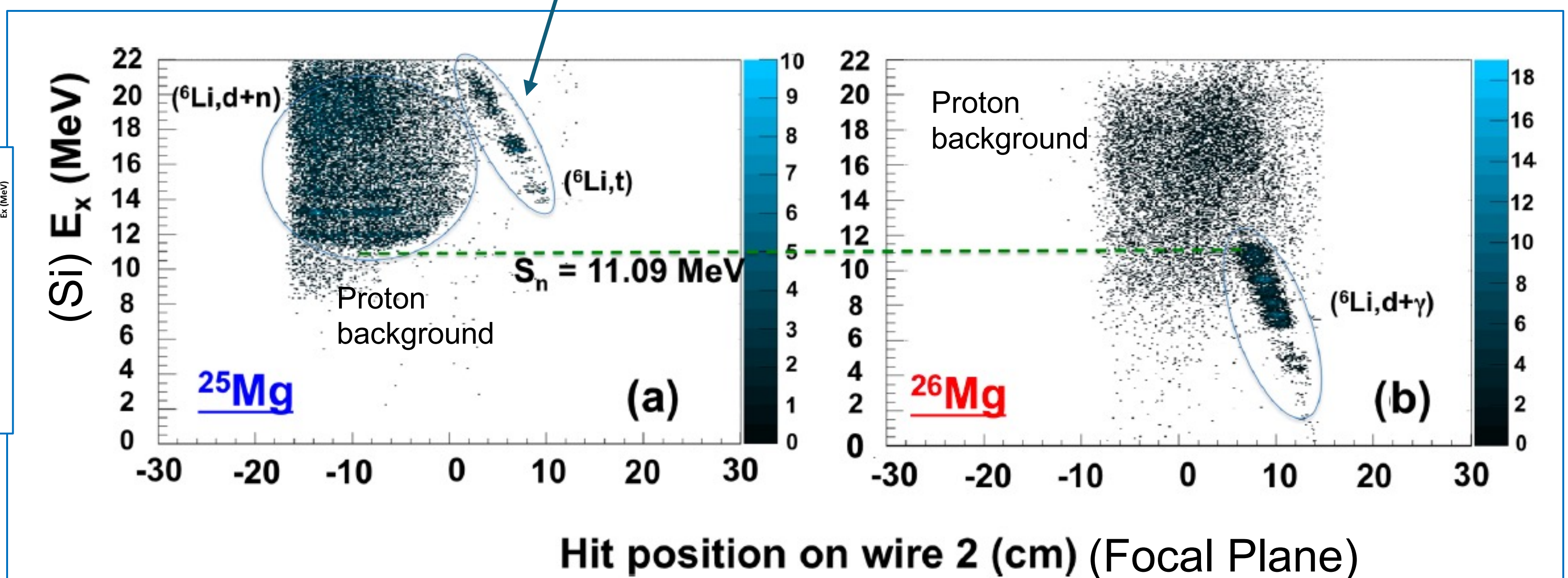


$^{22}Ne(^{6}Li,t)^{25}Mg$

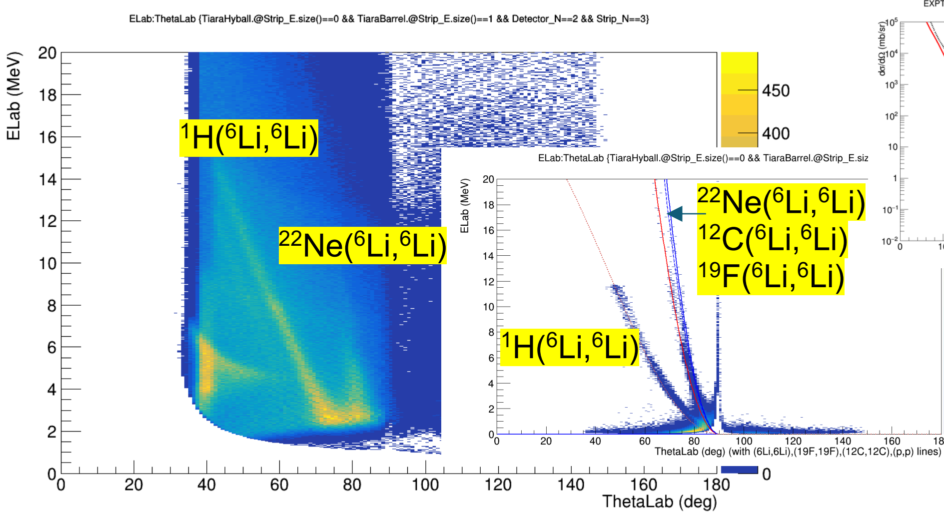


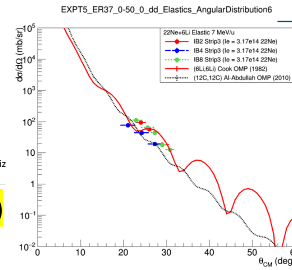






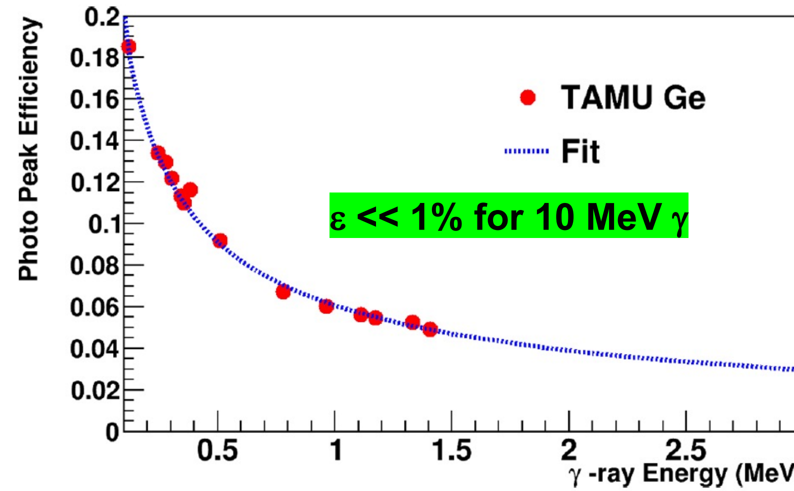
Some details (looking back…)





gave the correct beam intensity (3 nA)

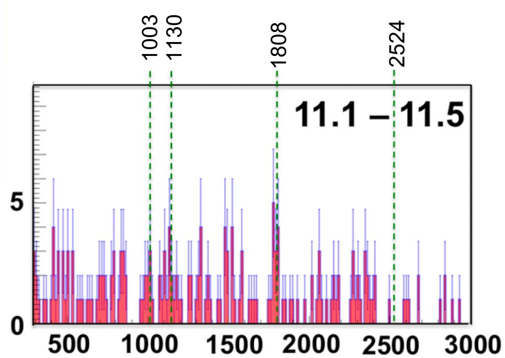
- Small count rates (slow DAQ)
- BGO could have helped γ-spectrum

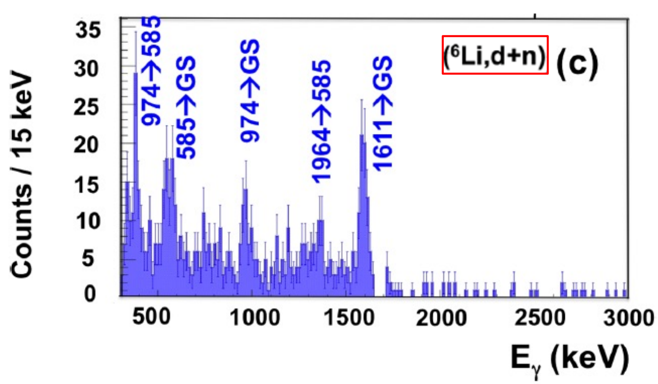


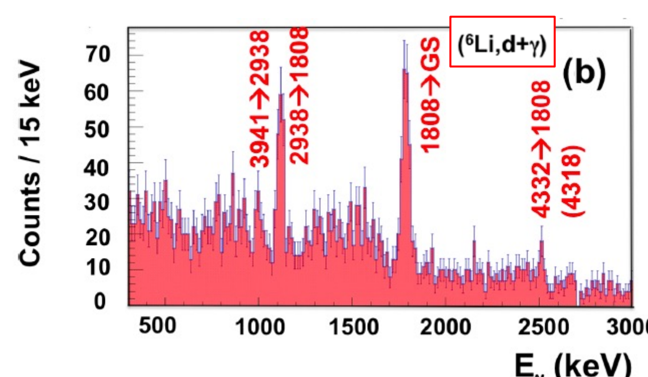
^{22}Ne(^{6}Li,^{6}Li) elastic is contaminated from F and C in targets

→ no beam normalization, no absolute σ

~150 singles counts
(γ efficiency ~6%)

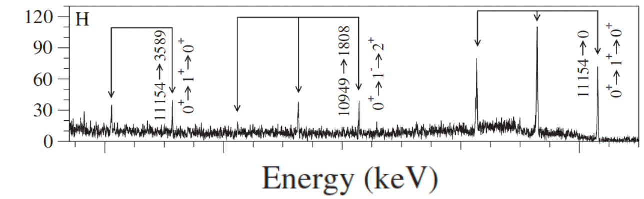


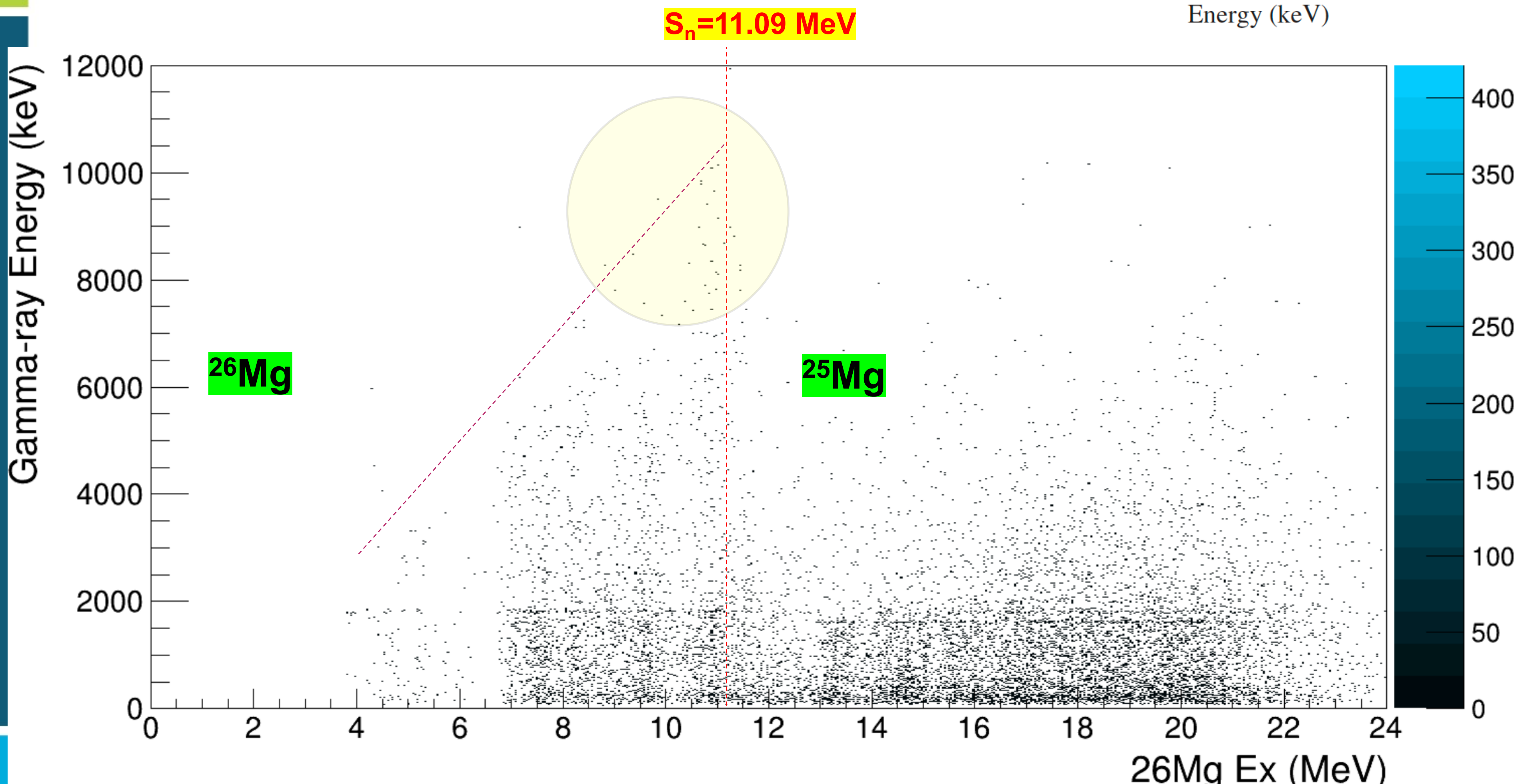




E_x-E_γ plot for $^{22}Ne(^{6}Li,d)$

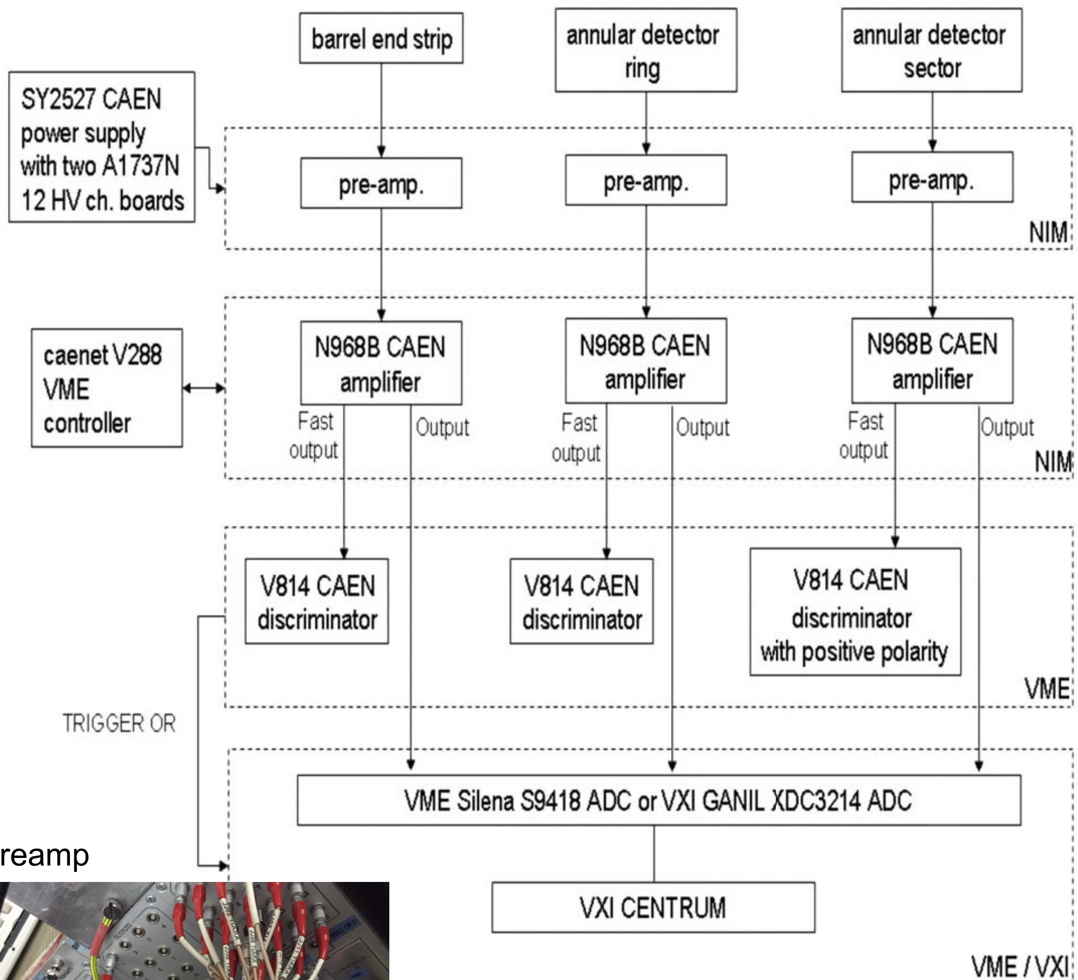
Longland et al., PRC 2009

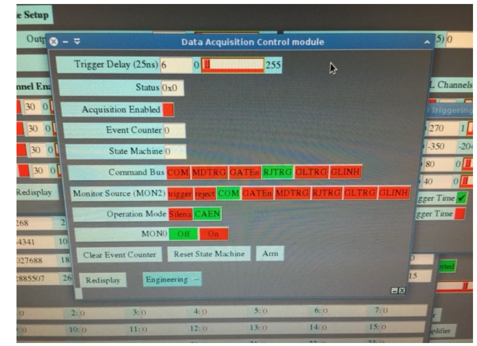


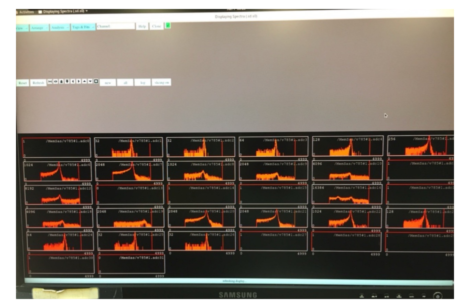


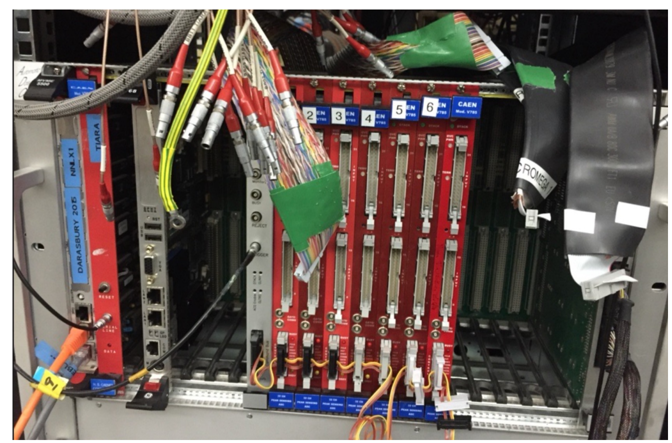
TIARA DAQ (analog…thus slow)

NIM + VME; master triggered by Si. coincidence by TAC

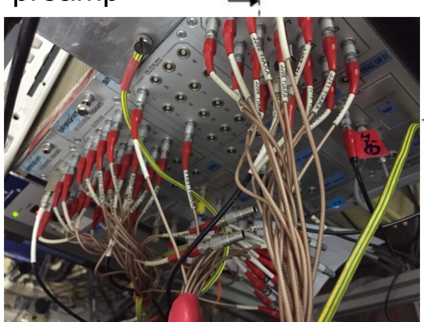






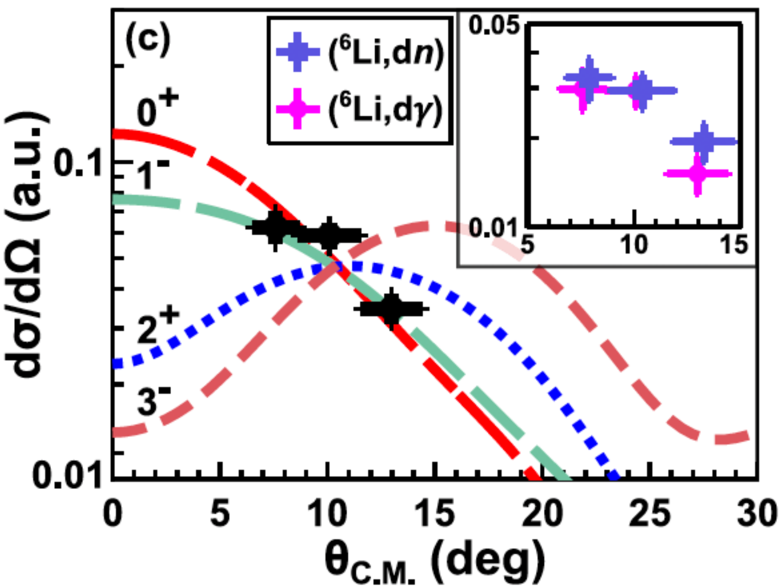


preamp

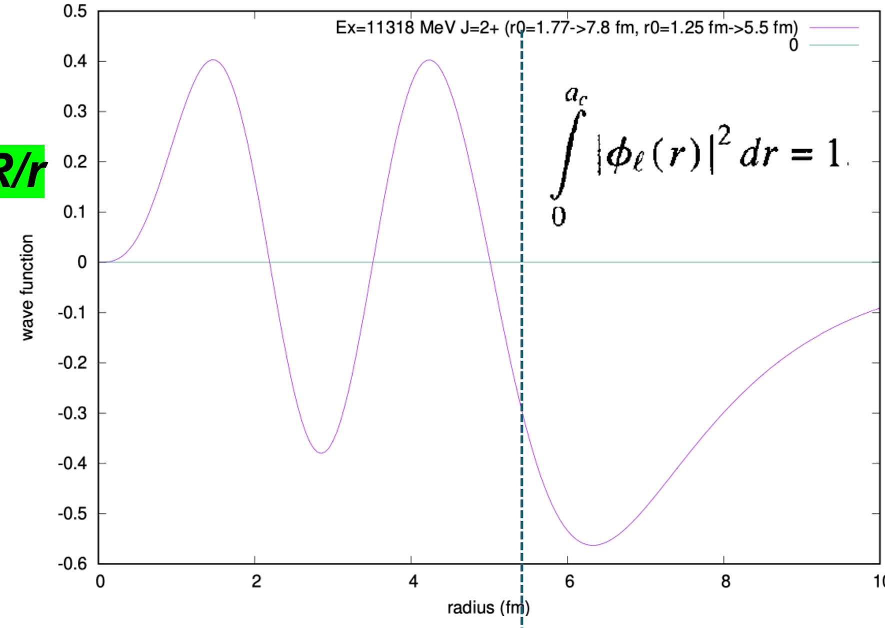


Digital one is now published in S. Ota et al., NIMA (2024)

S_α to $\omega\gamma$

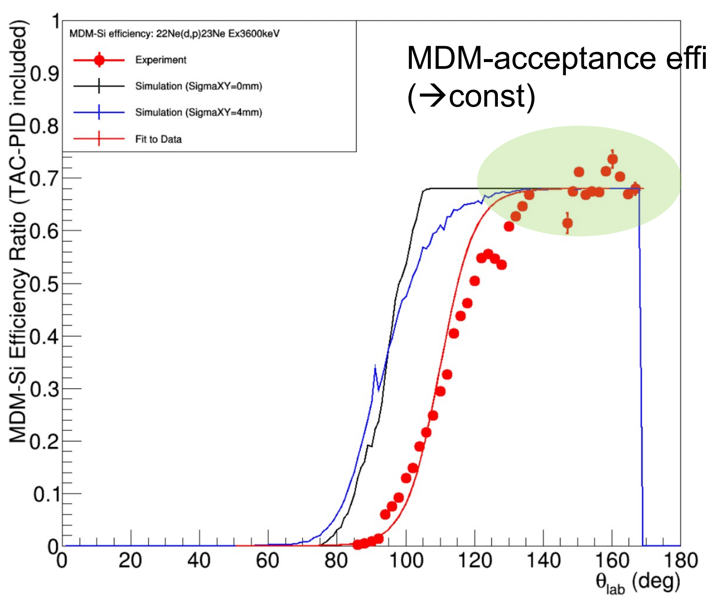


R/r



$$\int_0^{a_c} |\phi_\ell(r)|^2\, dr = 1.$$

Channel radius α_c



MDM-acceptance efficiency; ±2° (→const)

$$\Gamma_{\lambda c} = 2\frac{\hbar^2}{M_c a_c^2} P_c C^2 S \theta_{\mathrm{sp}}^2.$$

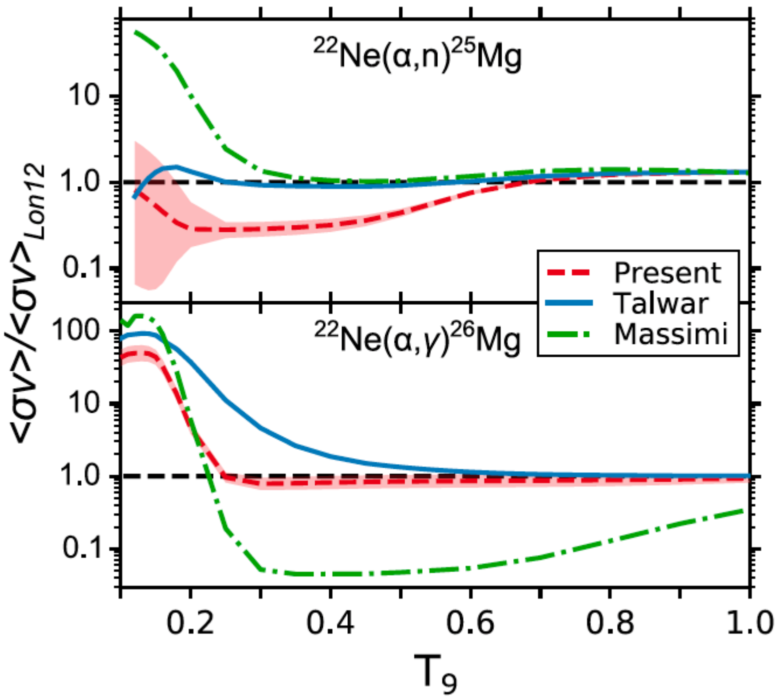
$$\theta_{\mathrm{sp}}^2 = \frac{a_c}{2}\phi_\ell^2(a_c)$$

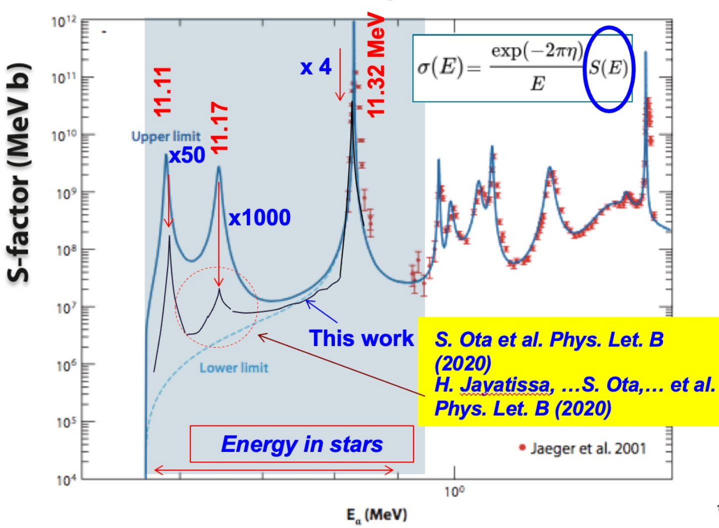
$$\boxed{\omega\gamma_{(\alpha,\gamma)} = (2J+1)\cdot\frac{\Gamma_\alpha \cdot \Gamma_\gamma}{(\Gamma_\alpha + \Gamma_\gamma + \Gamma_n)}}$$

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

$$\omega\gamma = (2J+1)\Gamma_\alpha = \omega\gamma_{(\alpha,n)} + \omega\gamma_{(\alpha,\gamma)}$$

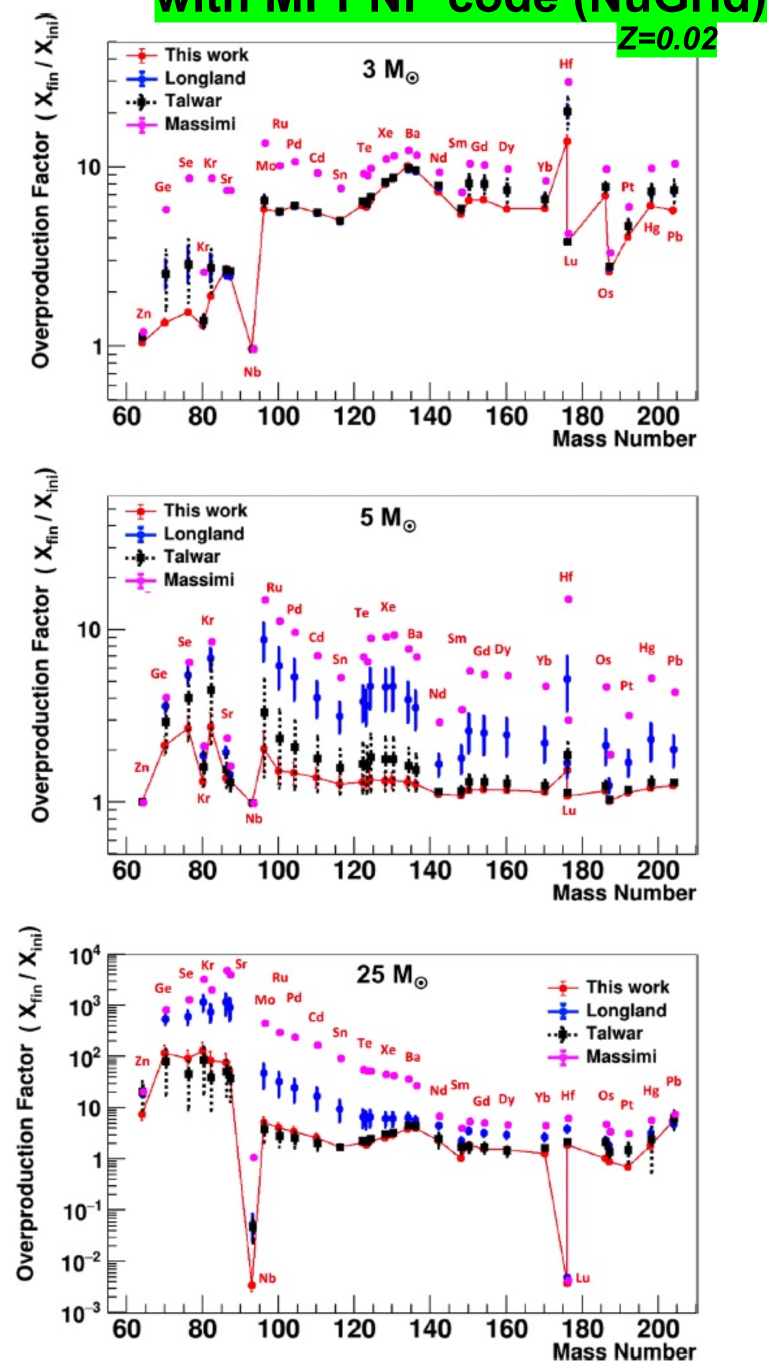
Final reaction rates





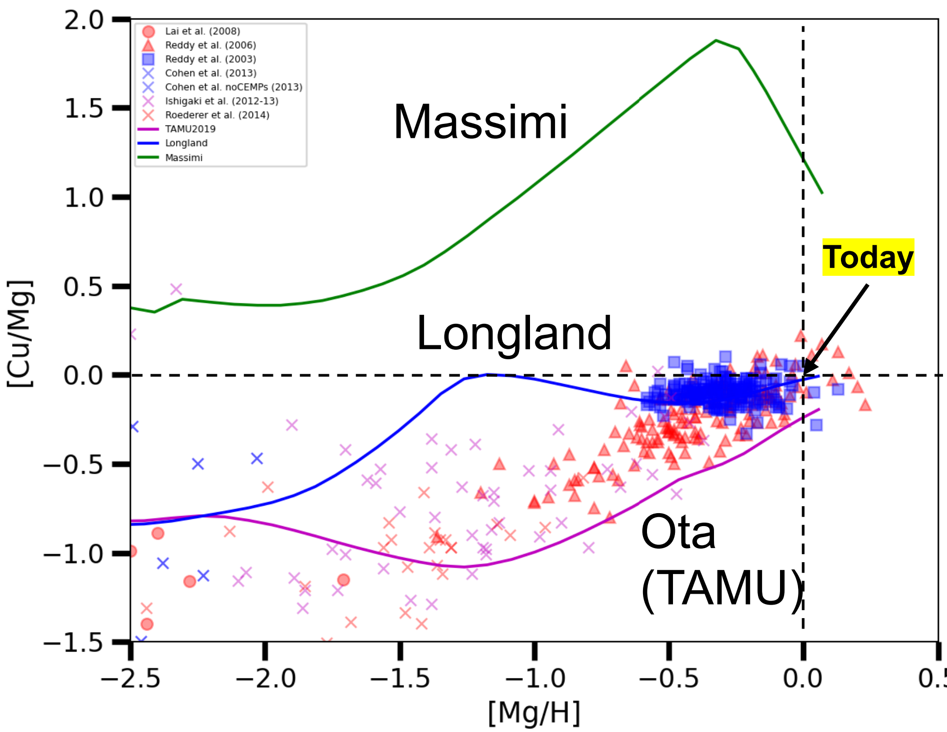
S. Ota et al. Phys. Let. B (2020)
H. Jayatissa, …S. Ota,… et al. Phys. Let. B (2020)

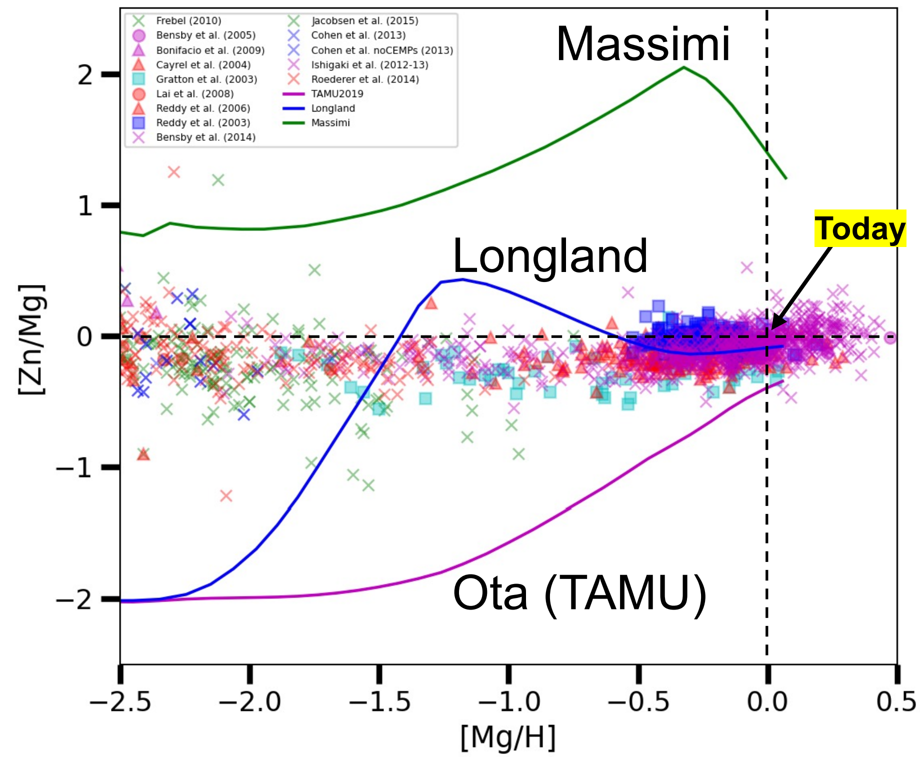
with MPPNP code (NuGrid)
Z=0.02



Sensitivity of Galactic Chemical Evolution (GCE) to ^{22}Ne + α reactions

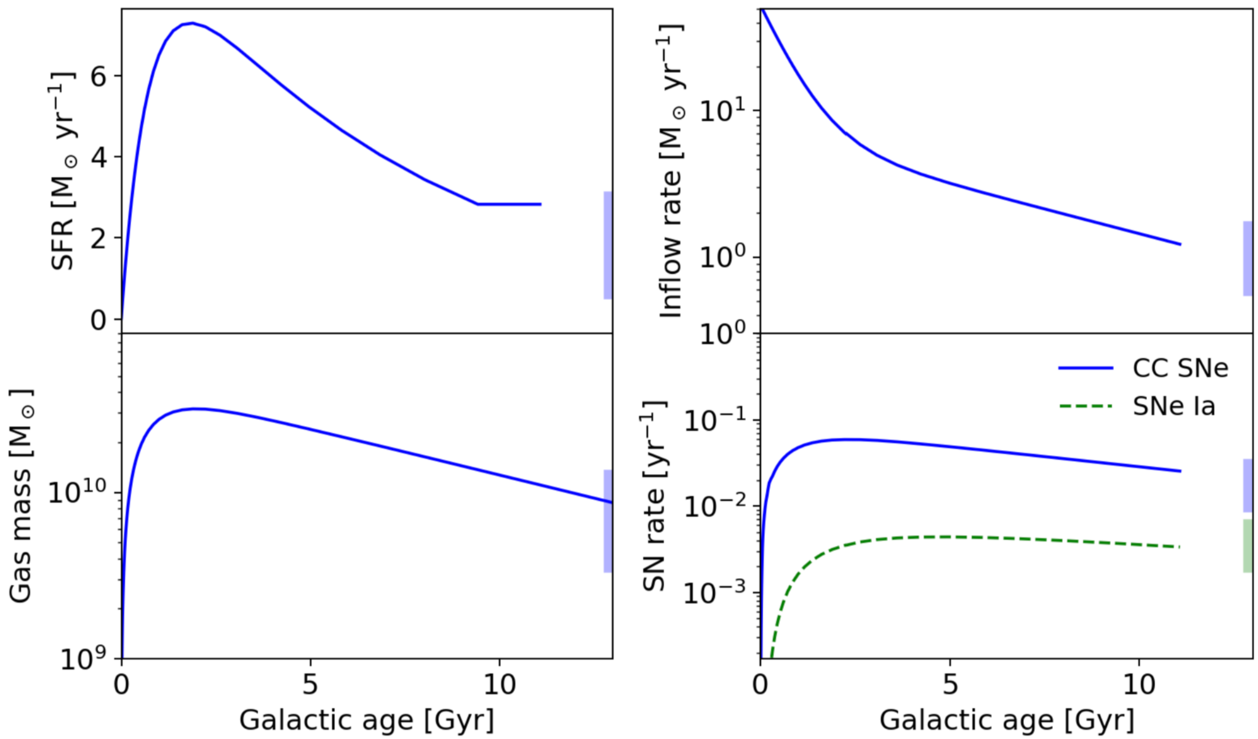
With OMEGA code (NuGrid)
S. Ota, E. Kotar, J. Millman, and M. Pignatari

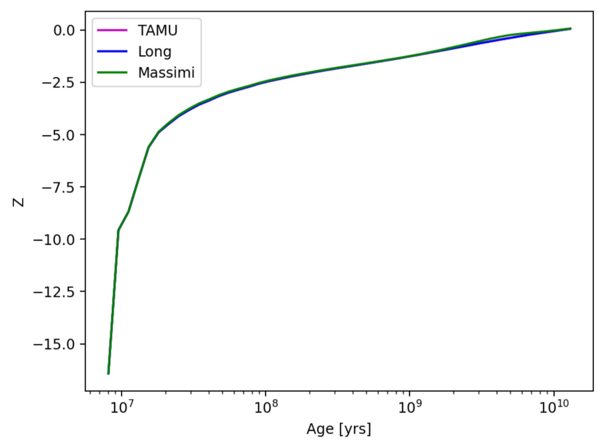




M=1 to 25 M$_\odot$, using GCE models by OMEGA (NuGrid collaboration)
[particularly more focused on massive stars (>8 M$_\odot$)]

GCE parameters used





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The Impact of Modeling Assumptions in Galactic Chemical Evolution Models

Benoit Côté[1,2,3,6], Brian W. O'Shea[2,3,4,5], Christian Ritter[1,3,6], Falk Herwig[1,3,6], and Kim A. Venn[1]

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Chemical evolution of fluorine in the Milky Way

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Summary

- $^{22}Ne(^{6}Li,d)$ experiments were performed at 7 MeV/u and Sub-Coulomb barrier energy with MDM spectrograph at TAMU.

- Ex=11.32 MeV resonance strength could be much weaker than the formerly believed strength, which has a critical impact on s-process stellar abundances.

- The reduced strength is primarily because of the reduced branching ratio Γ_n/Γ_γ =1.14 (26) from 3-4. If this disagrees with direct measurements, the populated resonance by α-transfer may be different

- Ex=11.17 MeV resonance is likely negligible

- Ex=11.12 MeV resonance is negligible as well

- From GCE's point of view, we confirmed the current $^{22}Ne(\alpha,n)$ rate's uncertainties have a large impact → LUNA & Notre Dame new data are exciting.

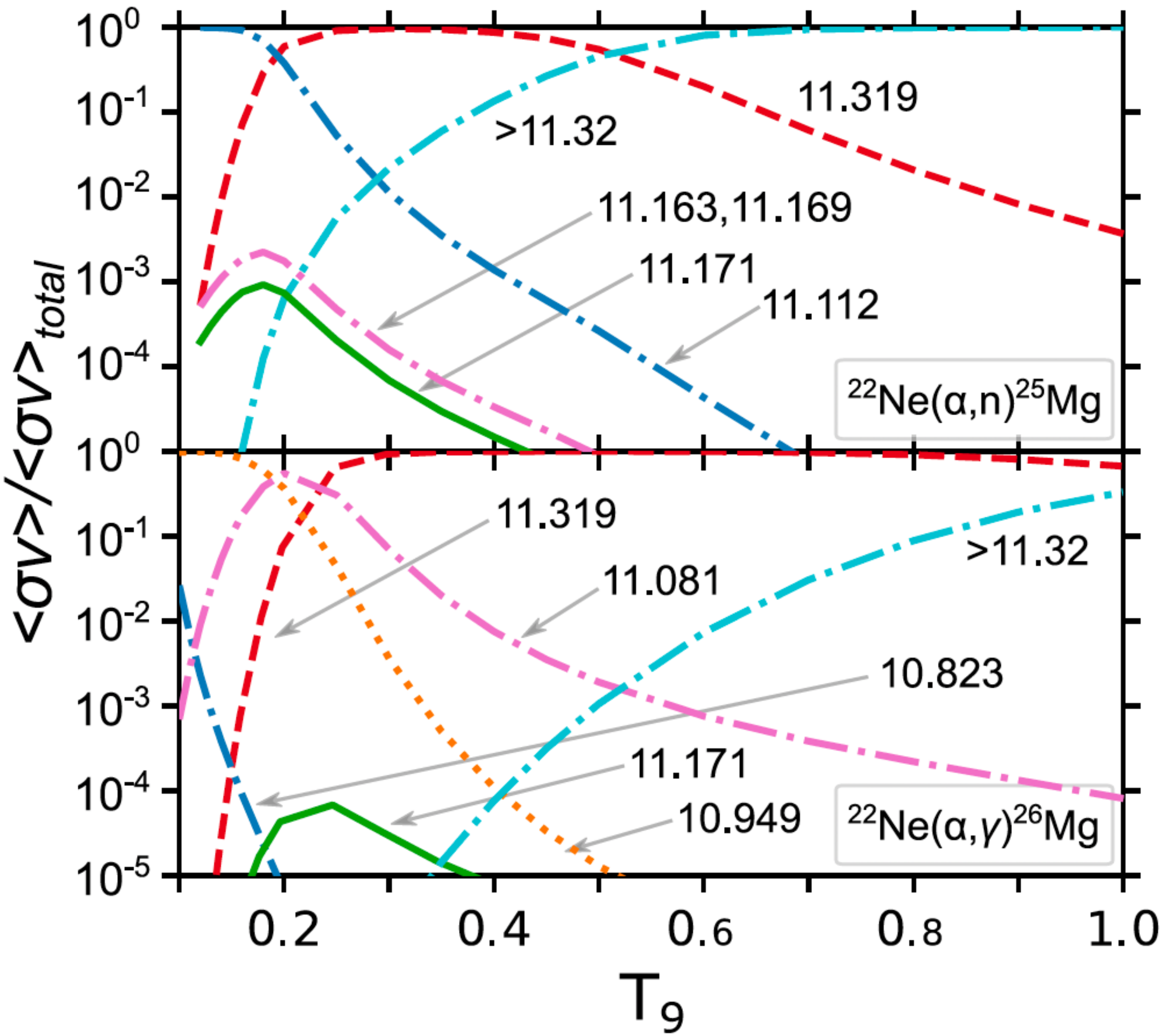
Thank you!

Brookhaven National Laboratory

Table 3
Resonance properties adopted for the Monte Carlo rate calculations.

E_x (MeV)	J^π	Γ_n/Γ_γ	Γ_α (eV)
10.8226(30)[a]	2^+ [a]	0	$2.1 \pm 0.3(\text{stat}) \pm 0.4(\text{sys}) \times 10^{-22}$ [d,g]
10.9491(8)[a]	1^- [a]	0	$3.0 \pm 0.3(\text{stat})^{+0.8}_{-0.6}(\text{sys}) \times 10^{-14}$ [d,g]
11.0809(40)[a]	2^+ [a]	0	$5.7 \pm 0.7(\text{stat})^{+1.4}_{-1.2}(\text{sys}) \times 10^{-11}$ [d,g]
11.112(6)[b]	2^+ [b]	1530(67)[b,e]	$< 2.2 \times 10^{-10}$ [f]
11.163(2)[b]	2^+ [b]	1896(137)[b,e]	$< 1.3 \times 10^{-11}$ [d,h]
11.169(1)[b]	3^- [b]	588(36)[b,e]	$< 1.3 \times 10^{-11}$ [d,h]
11.171(1)[b]	2^+ [b]	0.2–6[b]	$< 1.3 \times 10^{-11}$ [d,h]
11.3195(25)[c]	0^+ [d]	1.14(26)[f]	$7.9(13) \times 10^{-5}$ [f]
>11.32	Resonance strengths and energies adopted from Ref. [12] for (α,n) and Ref. [13] for (α,γ).		

[a] Adopted from Ref. [43].
[b] Adopted from Ref. [21].
[c] Adopted from Ref. [14].
[d] Adopted from Ref. [42].
[e] Treated as negligible in the (α,γ) rate calculation.
[f] Adopted from the present work.
[g] A common (correlated) systematic uncertainty of $^{+25\%}_{-21\%}$ has been generated for each of these resonances.
[h] See text for a detailed explanation.



<σv>/<σv>total
11.319
>11.32
11.163,11.169
11.171
11.112
22Ne(α,n)25Mg
11.319
>11.32
11.081
10.823
11.171
10.949
22Ne(α,γ)26Mg
T9

TABLE I. Obtained spectroscopic factors for some low-lying states of ^{23}Ne observed in ^{22}Ne(d, p) reaction, compared with values from past measurements.

E_x (keV)	J^π	S (present)	S (Ref. [59])	S (Ref. [58])
GS	$5/2^+$	0.25(5)	0.22	0.24
1016	$1/2^+$	0.58(12)	0.70	0.40
2315	$5/2^+$	0.022(5)	0.05(1)	0.07