Understanding globular cluster pollution through nuclear reactions

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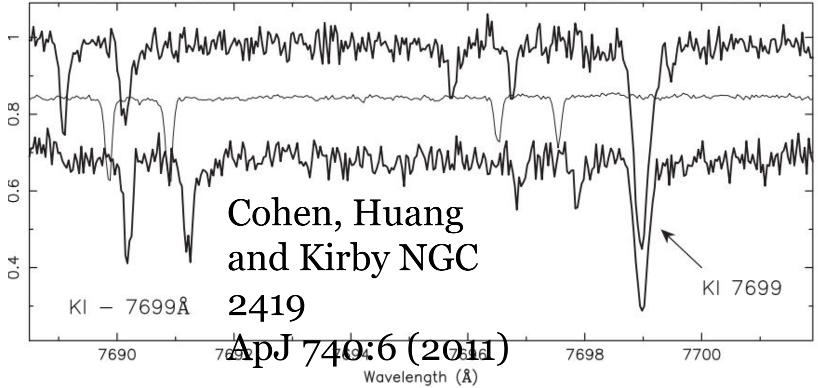
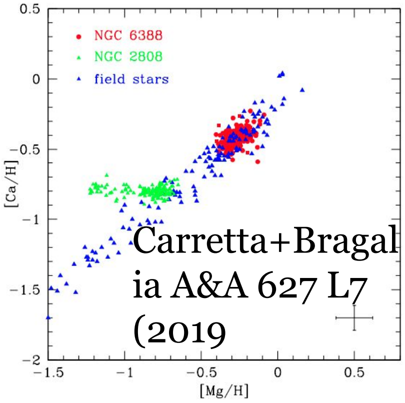
Reduce, reuse, recycle

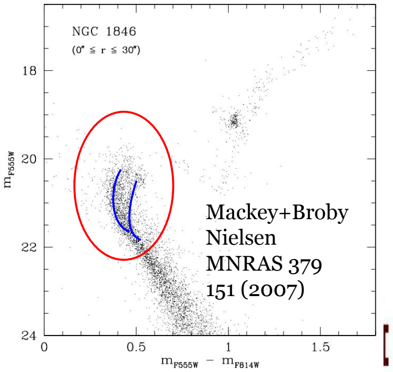
- Globular clusters are weird - originally thought to be a single generation of ancient stars but now strong evidence against that
- Currently observed stars are too cool to make the elements seen in their spectra - must originate from older stars but what were they?
- The temperature-density conditions are unclear because some nuclear reaction rates are unclear



Cohen, Huang and Kirby NGC 2419 ApJ 740:6 (2011)

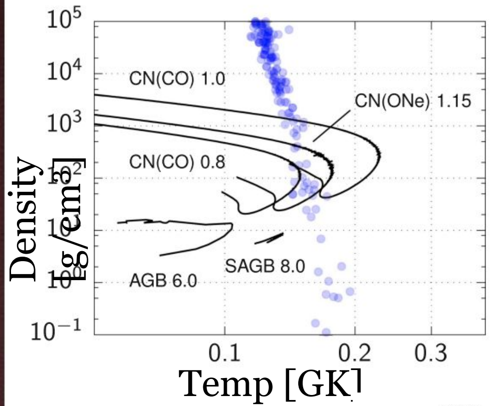


Carretta+Bragalia A&A 627 L7 (2019

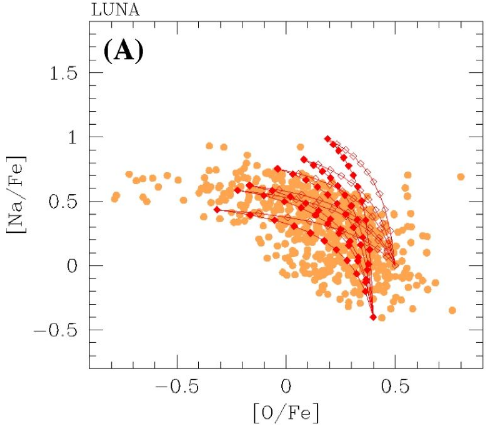


Mackey+Broby Nielsen MNRAS 379 151 (2007)

Critical reactions for GC pollution



Dermigny and Iliadis
ApJ 848:14 (2017)



A. Slemer++
MNRAS
465:44817 (2017)

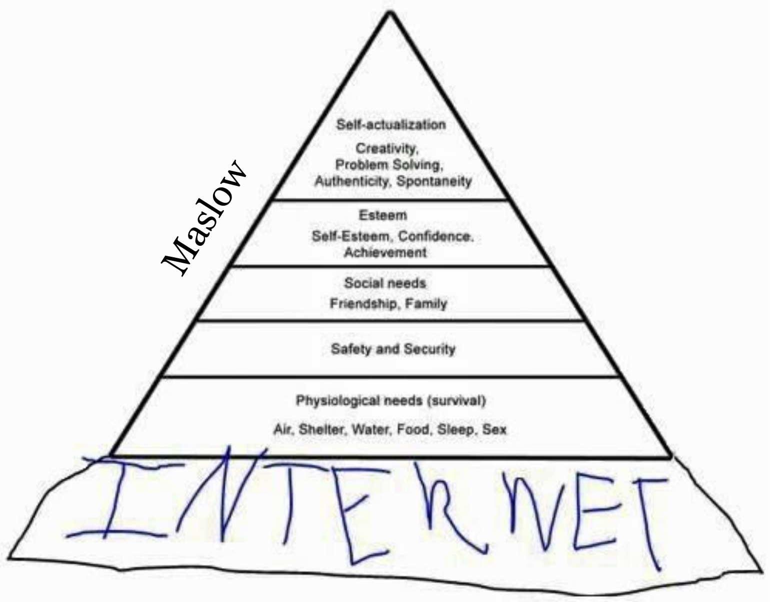
Hydrogen burning - abundance pattern gives information on the temperature+density conditions in the originating star

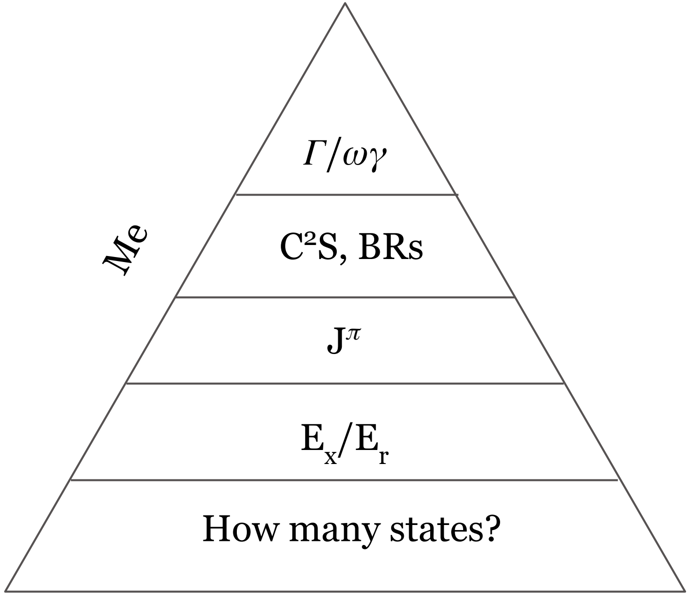
For Na-O anticorrelation: ^{22}Ne(p, γ)^{23}Na is the main source of uncertainty

For Mg-K anticorrelation:

(p,γ) reactions on ^{30}Si, ^{37}Ar, ^{38}Ar, ^{39}K

What do we need to know?





$$\sigma_r(E) \propto \frac{2J+1}{(2j_1+1)(2j_2+1)}\frac{\Gamma_{\mathrm{in}}\Gamma_{\mathrm{out}}}{(E-E_r)^2+\Gamma^2/4}$$

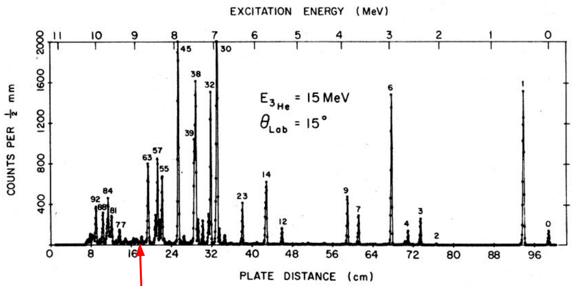
The various inputs required for getting the cross section and thus reaction rate are built up in the pyramid above

^{22}Ne(p,γ)^{23}Na and ^{23}Na(p,p')

In order to rule a state out as important, need very stringent measurements of low resonance strengths - check existence first!

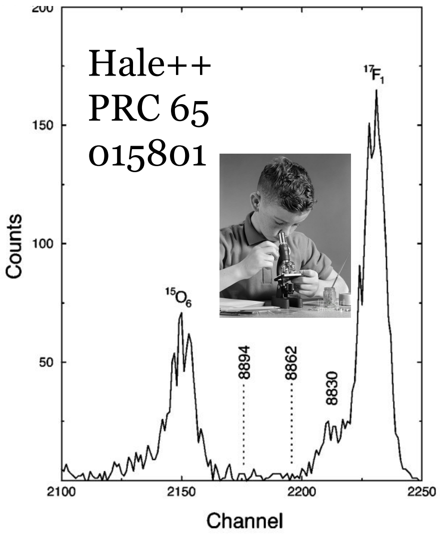
Resonance states from one previous measurement of ^{22}Ne(^{3}He,d)^{23}Na

We use ^{23}Na(p,p') with the Munich Q3D since this reaction is indiscriminate and should populate everything

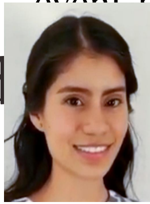


Powers++
PRC 4 2030

The states are around here(!) on the focal plane, and the experiment was done with emulsion plates which means no event-by-event selection etc



Hale++
PRC 65
015801



Diana Carrasco-Rojas
TREND student
UTEP+Cyc Inst.

Q3D Experiment

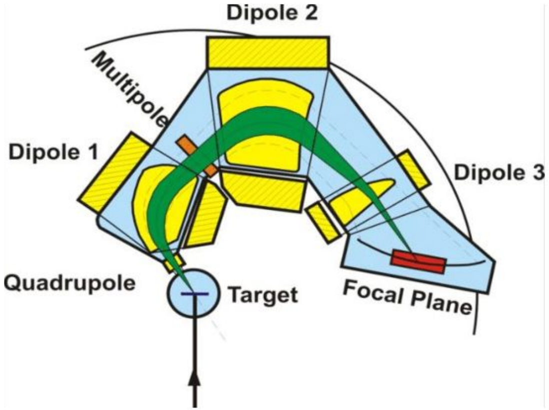
25-MeV ^{3}He on a $^{30}SiO_2$ target

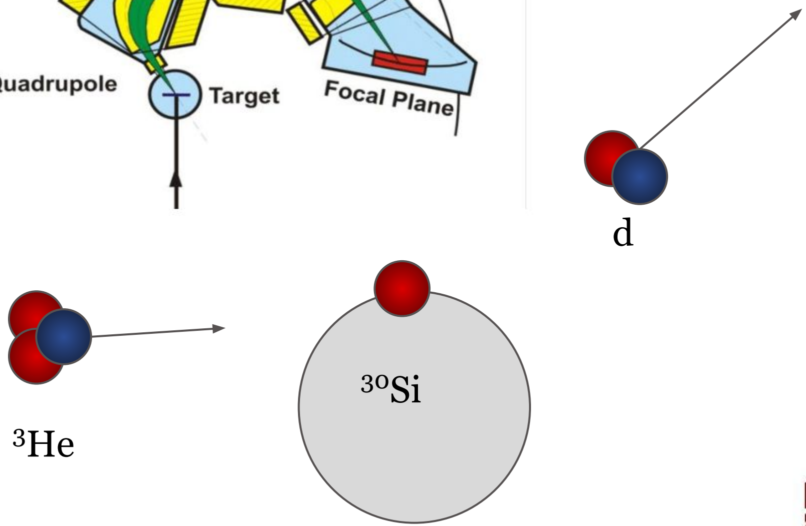
Populate states in ^{31}P

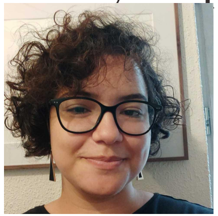
Get widths from the shape (for orbital angular momentum) and magnitude of the transfer cross section

Reduce uncertainties in the rate significantly

One remaining problem is the unknown spin-parity of the 149-keV resonance - there are some Gammasphere data which may help







Djamila Sarah Harrouz
IJCLab

Q3D Experiment

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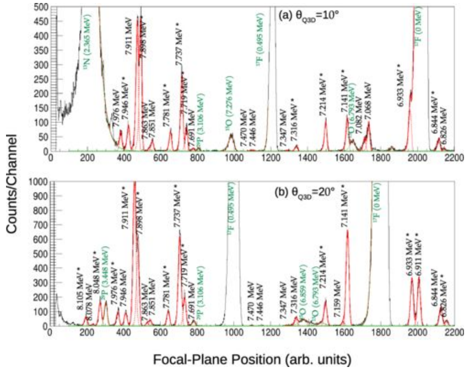
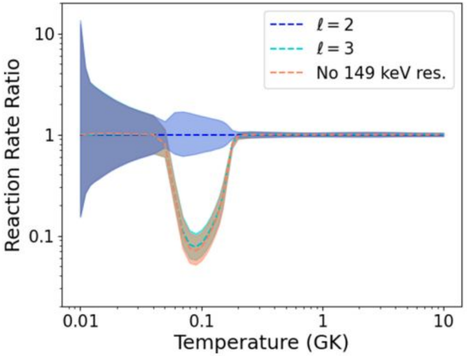
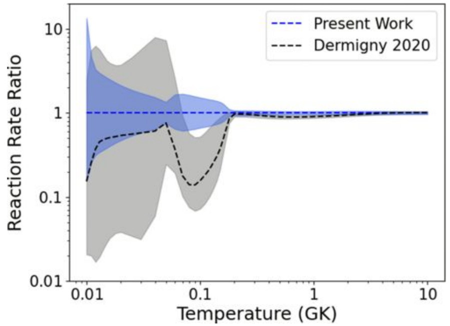
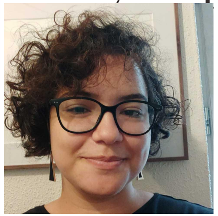


Harrouz++
Phys. Rev. C 105, 015805







Djamila Sarah Harrouz
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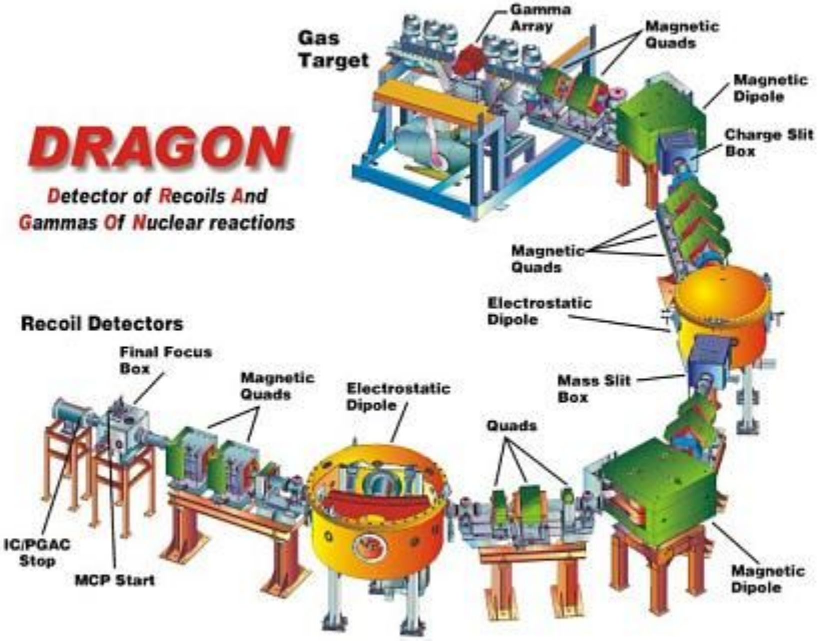
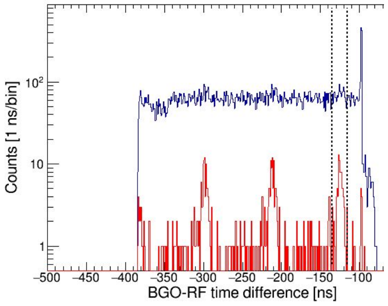
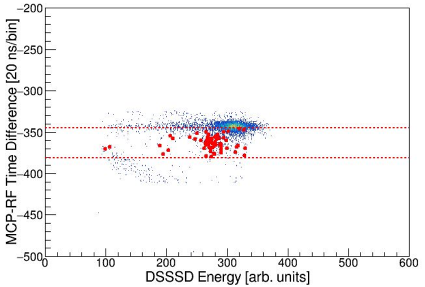
Measuring $^{39}K(p,\gamma)^{40}Ca$ with the DRAGON

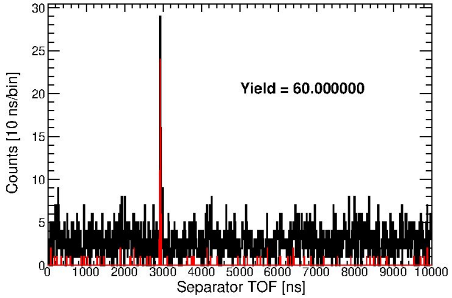


- ^{39}K beam onto the windowless gas target of the DRAGON
- $^{39}K(p,\gamma)^{40}Ca$ reaction
- γ rays detected in BGO array
- ^{40}Ca recoils selected by the separator
- Hit gas ionisation chamber+DSSSD at the focal plane

Experimental Observables







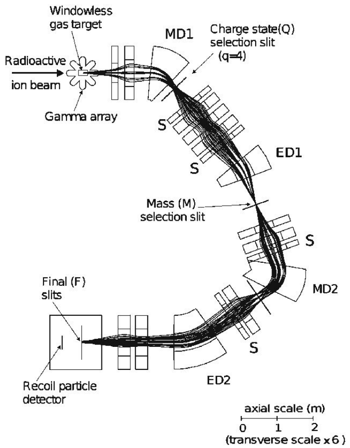
- Identify ^{40}Ca recoils (and exclude ^{39}K leaky beam) by times of flight
- BGO-DSSSD timing
- Accelerator RF-BGO timing
- Energy at the focal plane vs time difference
- Can use these gates to reduce the background in the separator time-of-flight from ^{39}K leaky beam

Current status for $^{39}K(p,\gamma)^{40}Ca$

Analysis almost finished (promise)

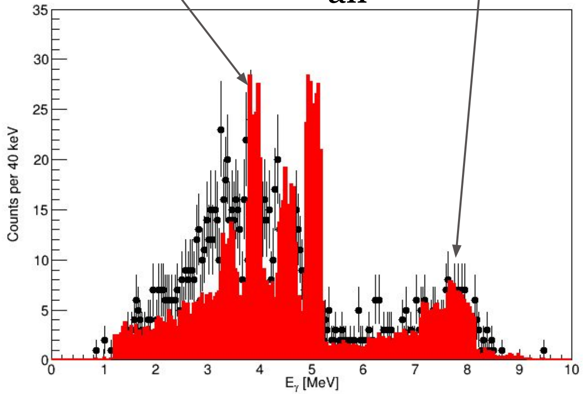
BGO spectra simulations in progress to get final separator efficiency values - turns out that the listed branching ratios for these states are trash - have some new data!

Waiting for charge-state distributions but Ca beam problems so there will be some delay in final results

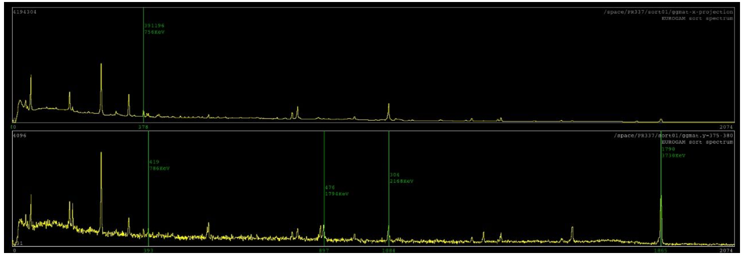


This part is still wrong

These transitions are not listed in the literature at all



Shiny ^{40}Ca data with gate on 756-keV in lower plot



Summary

Globular clusters are confusing and understanding nuclear reaction rates will make them less confusing

There are a variety of nuclear reactions which can be used to improve knowledge of reaction rates

Boring reactions like (p,p’) at low energy are rather useful and we should do more of them - pyramids are built from the bottom

We’re closing in on having well-constrained rates for half of the reactions of important for globular clusters

THE CLAUDE LEON FOUNDATION

Collaborators

PHYSICAL REVIEW C **105**, 015805 (2022)

Editors' Suggestion

Experimental study of the ^{30}Si(^{3}He, d)^{31}P reaction and thermonuclear reaction rate of ^{30}Si(p, γ)^{31}P

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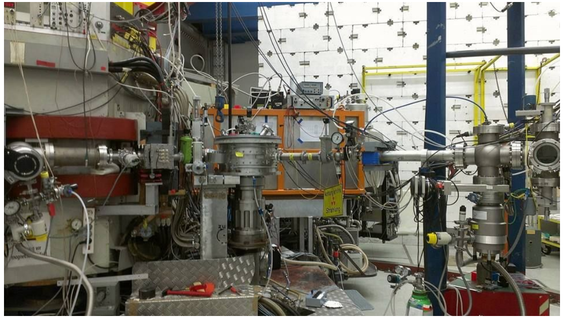

In loving memory of the Munich Q3D and the beer vending machine in the lab

Searching for possible resonance states in ^{22}Ne(p,γ)^{23}Na

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Probing historic pollution of globular clusters: a direct measurement of the ^{39}K(p,γ)^{40}Ca reaction rate with the DRAGON

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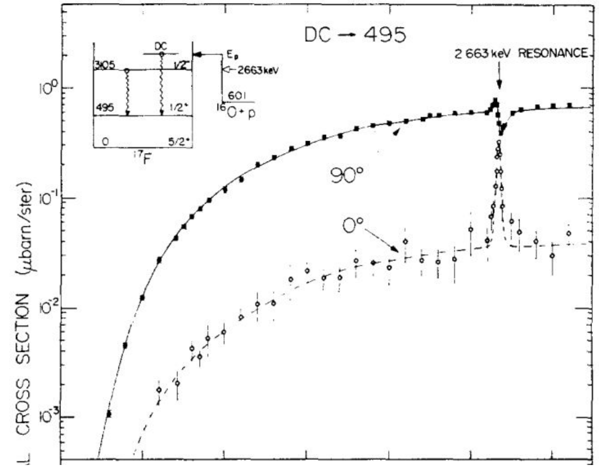
(Dated: September 7, 2022)

What do we need to know?

- Need reaction rates to constrain the physical conditions of previous stars
- Reaction rates dominated by narrow resonances
- Need energy, spin/parity, proton widths/resonance strengths
- Resonance strength = area under the curve for narrow resonances

$$\langle \sigma v \rangle = \int E\sigma(E)\exp\left(-\frac{E}{kt}\right)dE$$

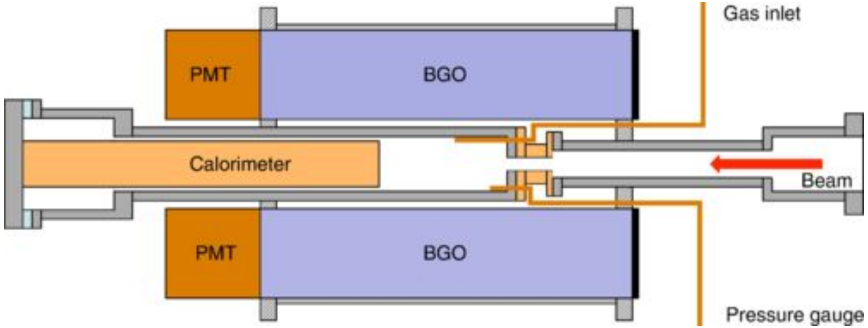
$$\sigma_r(E) \propto \frac{2J+1}{(2j_1+1)(2j_2+1)}\frac{\Gamma_{\text{in}}\Gamma_{\text{out}}}{(E-E_r)^2+\Gamma^2/4}$$



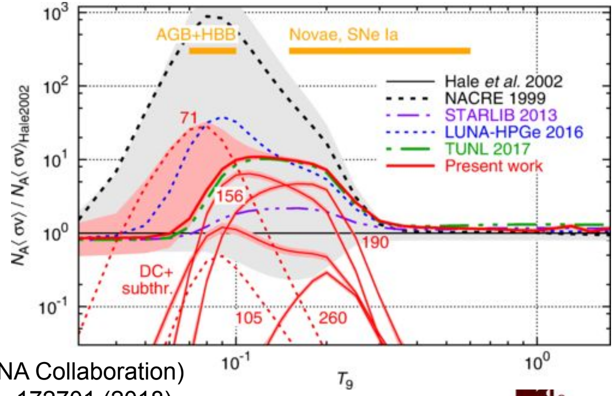
Rolfs Nuclear Physics A **217** 29-70 (1973)

Status of $^{22}Ne(p,\gamma)^{23}Na$

- LUNA+LENA have done amazing work on direct measurements
- One main source of uncertainty is whether two low-energy resonances exist (and what their strengths are if they do)
- The higher (E_r = 100 keV) has been ruled out as unimportant but the lower (E_r=65 keV) is still a problem



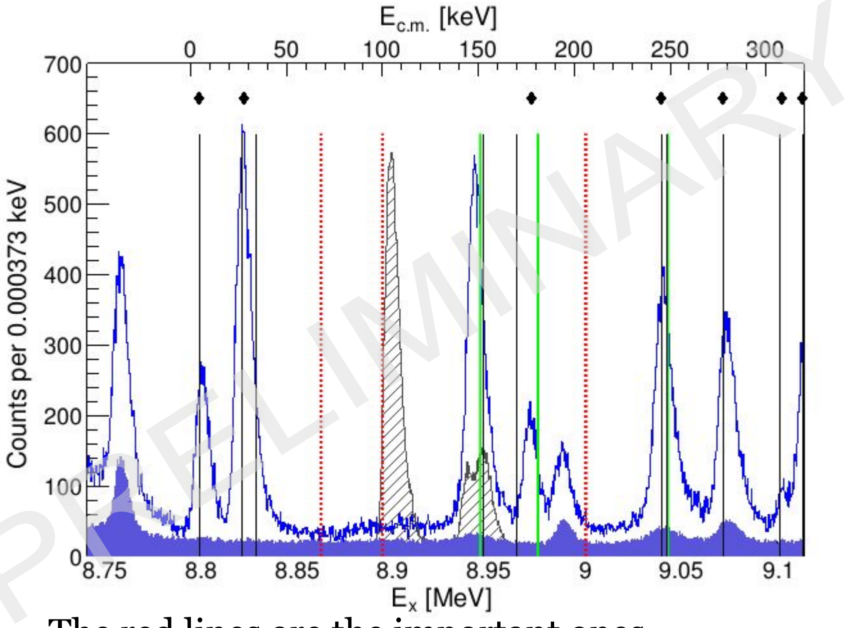
These are proton bombarding energies



F. Ferraro et al. (LUNA Collaboration) Phys. Rev. Lett. 121, 172701 (2018)

The states do not exist

Lindsay Lohan



The red lines are the important ones - tentative ^{23}Na states that we don't see

(Yes, that is a Mean Girls reference)

From our $^{23}Na(p,p')$ data, we see that there is no strength at E_r = 65 and 100 keV

Strong evidence against these resonances existing - we suggest omitting them in future

Proving a negative is hard but between this and the previous transfer study we see no support for the existence of the states

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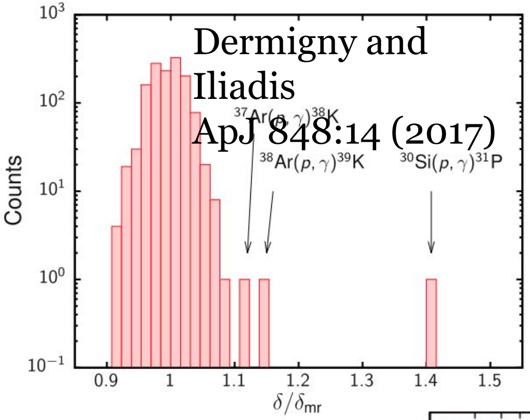
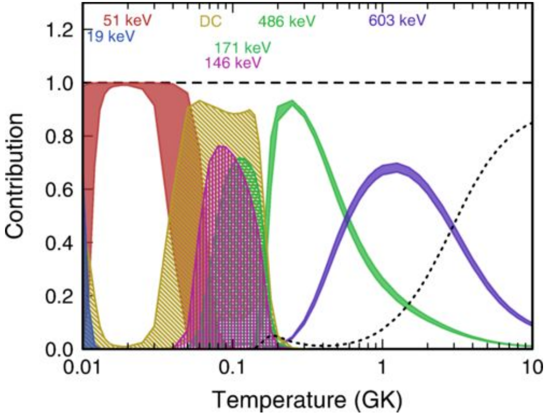
$^{30}Si(p,\gamma)^{31}P$



Dermigny and Iliadis ApJ 848:14 (2017)



Dermigny++ Phys. Rev. C 102, 014609 (2020)

- This reaction is one of the most impactful in defining the temperature of the polluting site
- Direct and indirect measurements of this reaction were performed
- Direct measurement @ DRAGON
- Indirect $^{30}Si(^{3}He,d)^{31}P$ experiment with the Munich Q3D