Indirect experimental approaches to charged particle reactions in astrophysics

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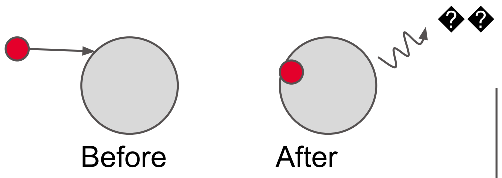
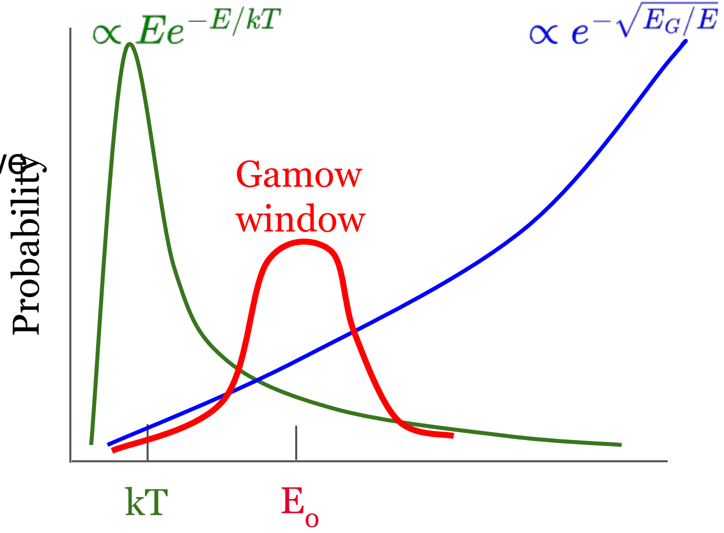
Nuclear reaction rates





Have a range of energies with which collisions take place and we need to take that into account

Distribution of energies: Maxwell-Boltzmann

How likely is it that a reaction takes place at each energy: cross section which depends strongly on the penetration through the Coulomb+angular momentum barrier

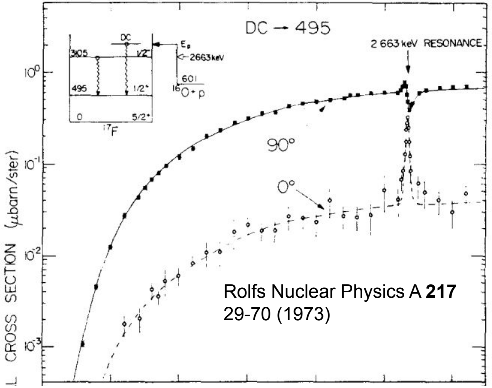
Add up (the probability of interaction at each energy) * (the probability of having two particles with that relative energy)

$$\langle \sigma v \rangle \propto \int E e^{-E/kT} \sigma(E) dE$$

Nuclear physics provides the cross sections - often depends on resonances so need to know their properties

Nuclear reaction rates

Resonance reactions - forming some excited “nearly bound” state in the compound nucleus for a while which can then decay into the reaction products



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

Cross section decreases worse than exponentially!

Resonances characterised by certain parameters: energy, spin and parity, partial widths (decay rates into different channels)

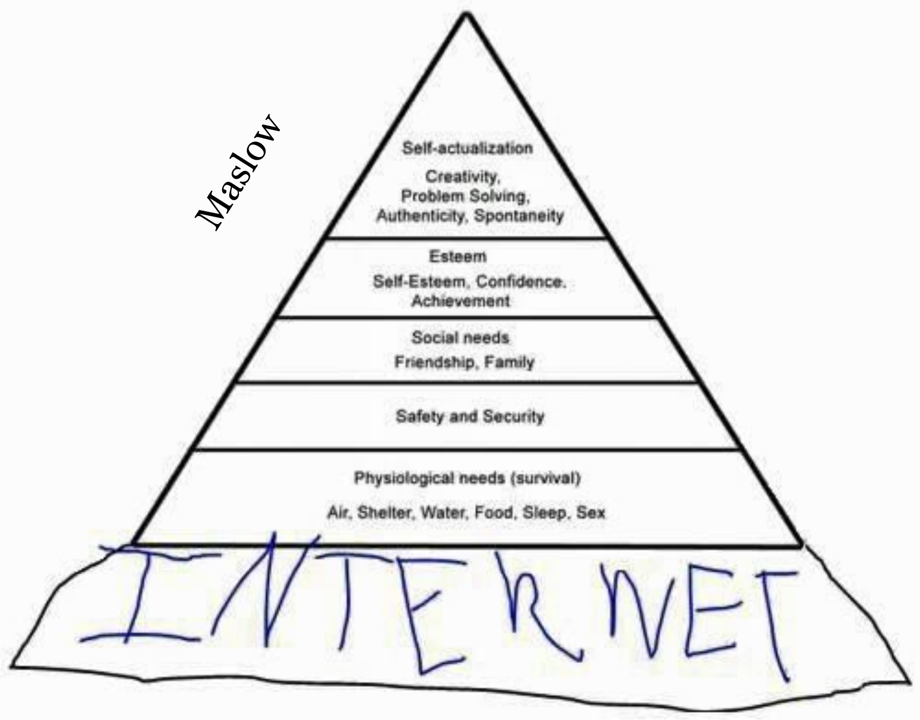
$$\sigma(E) \propto \frac{2J+1}{(2j_1+1)(2j_2+1)} \frac{\Gamma_i \Gamma_f}{(E-E_r)^2+\frac{\Gamma}{4}}$$

Need these data somehow and different data can help in different ways

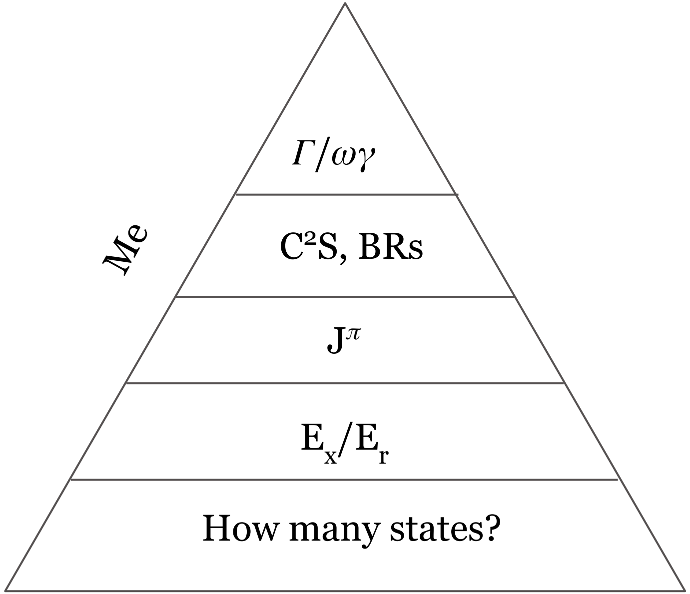
Direct capture into bound states also depend on similar quantities (energy, spin and parity, spectroscopic factor)

The Hierarchy Of Needs

Maslow



Me



$\Gamma/\omega\gamma$

C^2S, BRs

J^π

E_x/E_r

How many states?

What do we need to know?

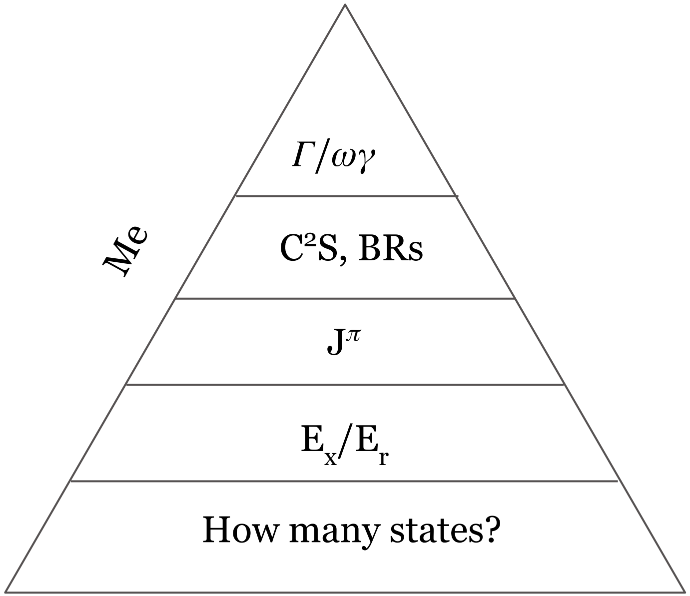
First problem is knowing whether states exist which could give rise to resonances! Deciding on if enough states are available to use statistical models, for example.

What are the energies of these resonances? Need to know excitation energies, masses, thresholds

Which resonances can contribute? Energy around the Gamow window? **Spin matters** - high angular momentum can rule the states out

Information on structure from transfer, branching ratios etc. Maybe we can estimate the contribution for these resonances from these reactions and guesstimate which are the important resonances?

Measuring partial widths, resonance strengths, cross sections



Me

$\Gamma/\omega\gamma$

C^2S, BRs

J^π

E_x/E_r

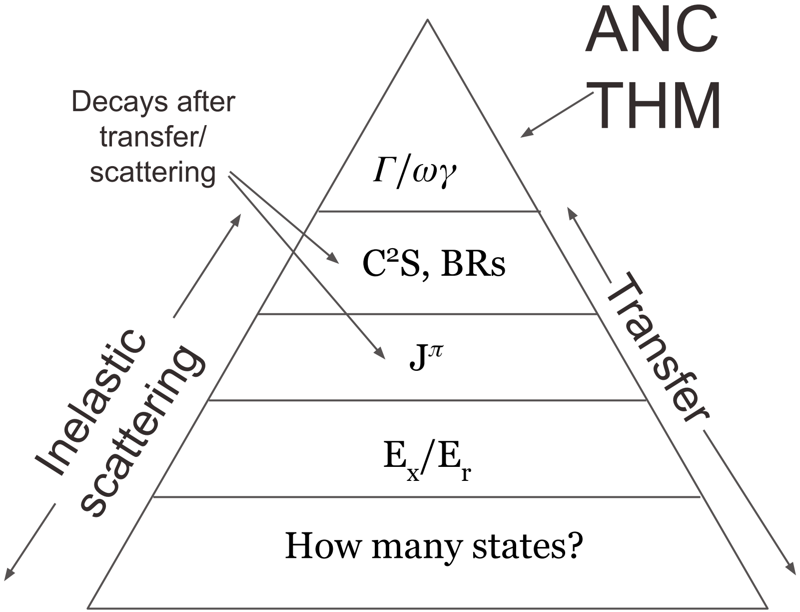
How many states?

How do we know these things?

Indirect methods can answer many of these problems

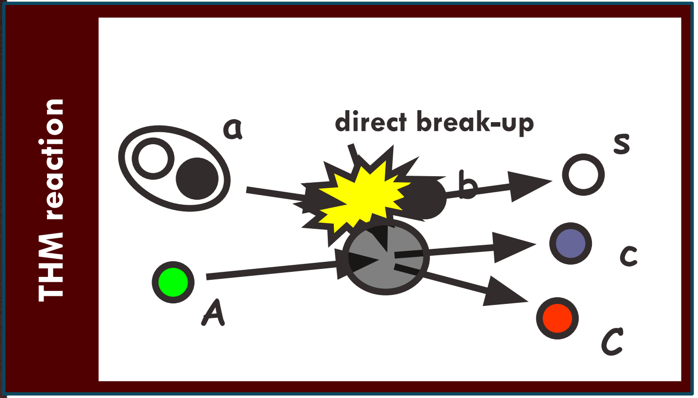
Can be sensitive to the higher quantities with powerful techniques to infer cross sections (ANC/THM)

Other reactions can be much simpler and aim at identifying levels, how many, properties



Thanks to Marco La Cognata :)

The Trojan Horse Method (THM): Basic Features



In the Plane Wave Impulse Approximation (PWIA):

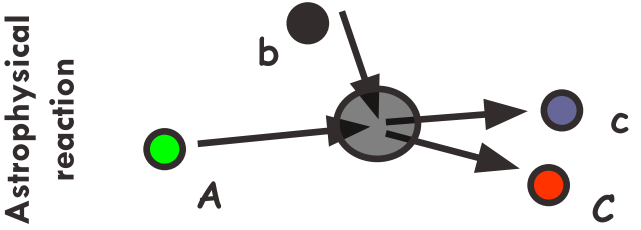
- **beam energy >> a = s ⊕ b breakup Q-value**
- **projectile wavelength k^{-1} << s – b intercluster distance**

+ plane waves in the entrance and exit channel

☐ **the 3-body cross section factorizes:**

$$\frac{d^3\sigma}{dE_C\,d\Omega_C\,d\Omega_c} \propto \mathrm{KF}\,|\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\mathrm{off}}$$

- KF kinematic factor
- $\varphi(-p_b)^2$ spectator momentum distribution



$$\frac{d\sigma}{d\Omega} = \sum_l P_l \frac{d\sigma_l^N}{d\Omega}$$

$d\sigma^{off}/d\Omega$ ☐ $d\sigma/d\Omega$ (on shell)

The penetration factor P_l has to be introduced

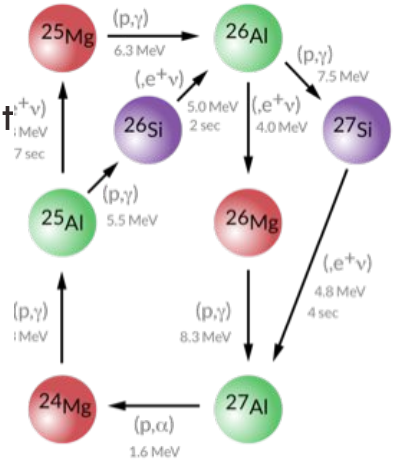
E.G. See RE Tribble et al. Rep. Prog. Phys. 77 (2014) 106901

Thanks to Marco La Cognata :)

Measurement of the ^{27}Al(p,α)^{24}Mg reaction

MgAl cycle in massive stars

It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei

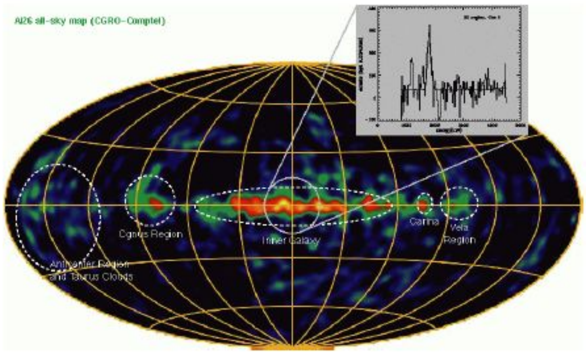


Mg-Al Cycles

^{26}Al/^{27}Al abundance ratio

- ^{26}Al abundance is used to estimate the number of Galactic neutron stars and, therefore, of neutron star mergers (sources of GW)

The ^{26}Al/^{27}Al is generally estimated, so it is influenced by ^{27}Al abundance predictions



Thanks to Marco La Cognata :)

Advantages (and disadvantages!) from the use of the THM

From

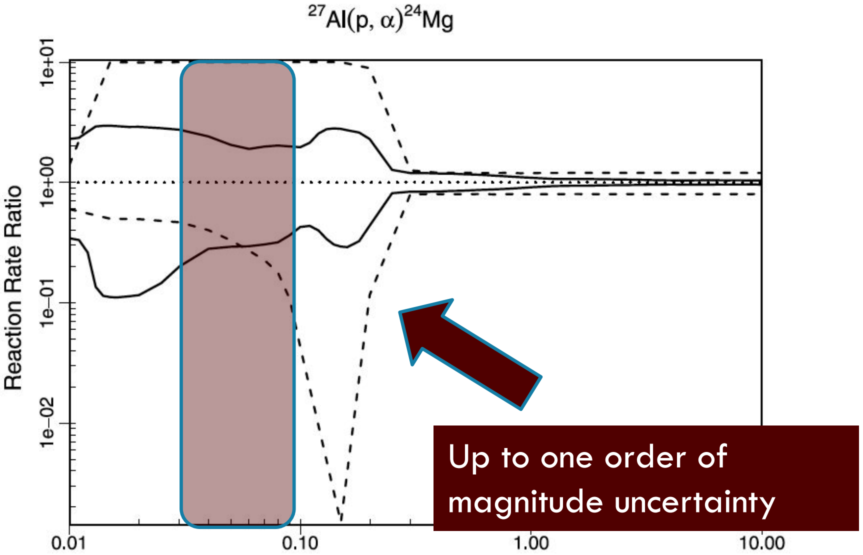
$A+a(b\oplus s) \rightarrow c+C+s$ @ 10-60 MeV

$A + b \rightarrow c + C$ @ 5-20 keV

By selecting the QF contribution

Though $E_A \gg V_{Coul}$ it is possible to measure at the Gamow peak since:

$$E_{c.m.}=E_{A-x}-Q_{x-s}$$



Up to one order of magnitude uncertainty

The most recent review [Iliadis et al. (2010)] shows that for most low-energy (and most influential!) resonances only an upper limit is known

Additional advantages:

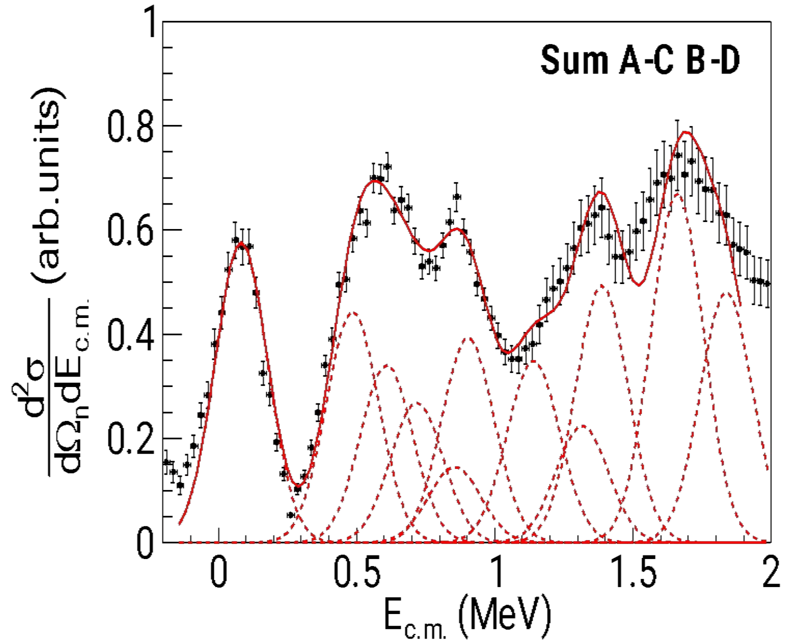
- reduced systematic errors due to straggling, background…
- magnifying glass effect

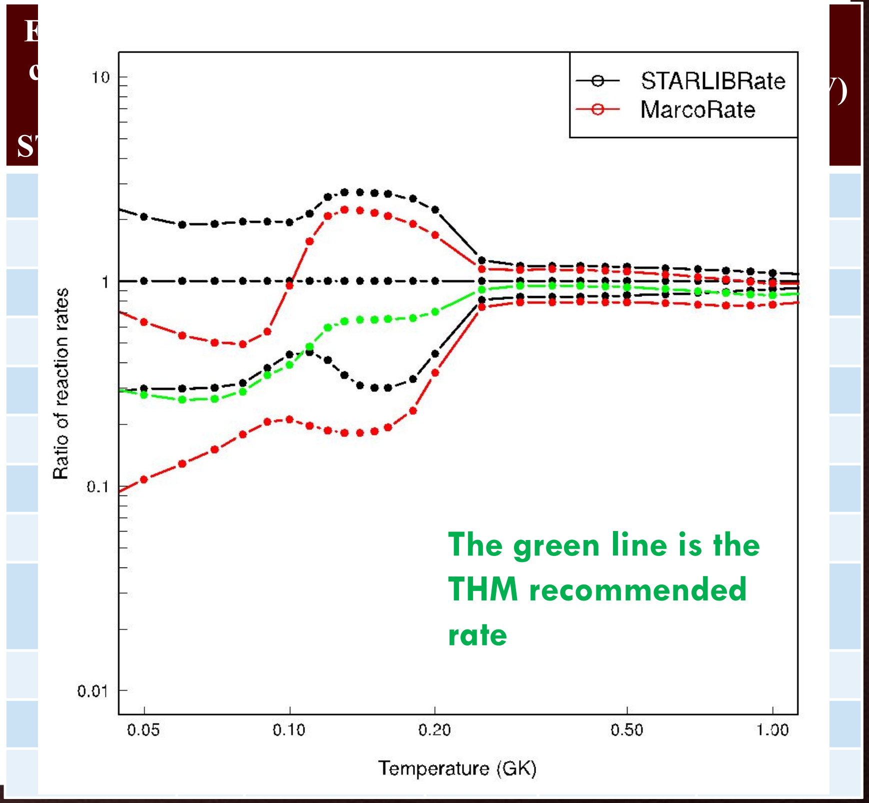
But…

- off-shell cross section deduced
- no absolute units

Thanks to Marco La Cognata :)

From the $^{2}H(^{27}Al,\alpha^{24}Mg)n$ yield to the $^{27}Al(p,\alpha)^{24}Mg$ strengths





The green line is the THM recommended rate

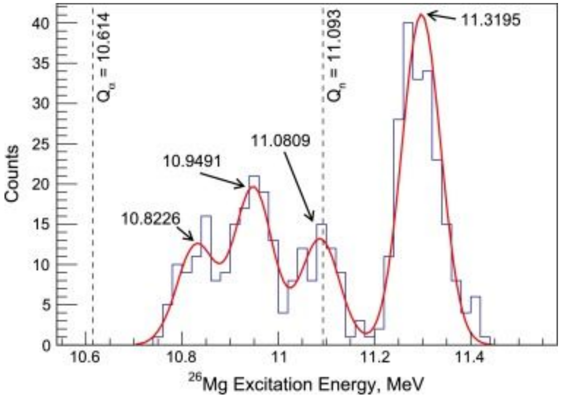
ANC and Transfer measurements

Partial widths depend on nuclear wavefunction at the surface

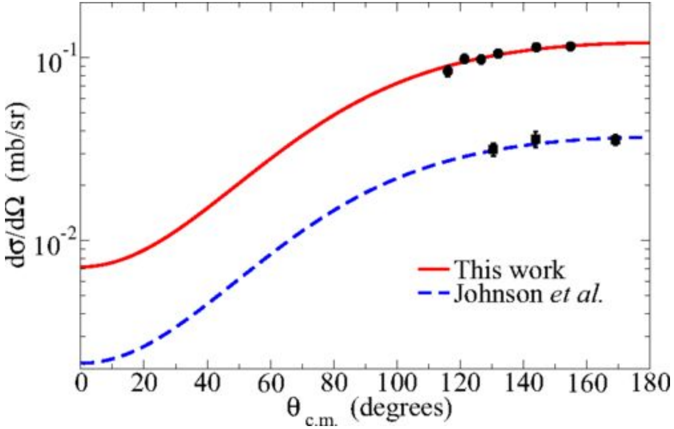
Conventional transfer reactions give this but with dependence on optical models

Go to very low energy →minimise model dependence because just the tail

Difficulties:
-low statistics as small cross sections
-strong energy dependence so model sensitivity replaced by experimental one



Jayatissa++
PLB 802
135267



M. L. Avila++
Phys. Rev. C 91, 048801

Transfer - the ^{39}K(^{3}He,d) reaction at TUNL

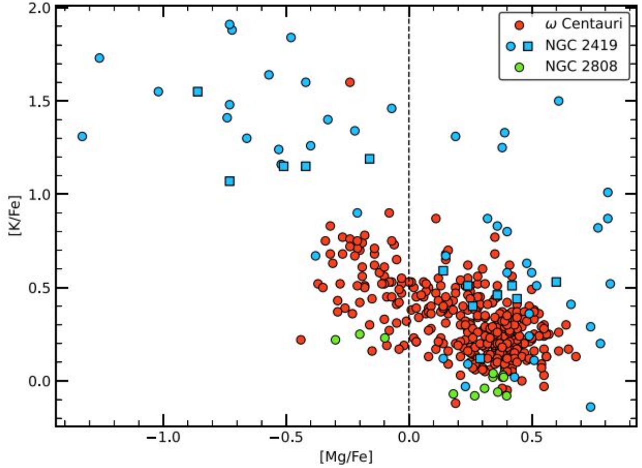
NGC 2419 shows Mg-K anticorrelation - unclear the polluting site for the globular clusters

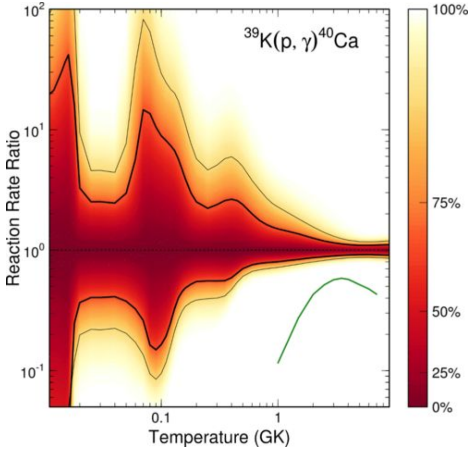
^{39}K(p,γ)^{40}Ca destroys ^{39}K - key uncertainty identified in sensitivity studies

Previous studies identified a wide range of plausible reaction rate within the astrophysically relevant region

Need better constraints on this - resonance strength depends on the proton width so measure this! :)

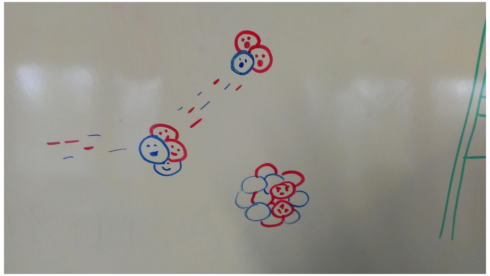
THE ASTROPHYSICAL JOURNAL LETTERS, 928:L11 (7pp), 2022 March 20

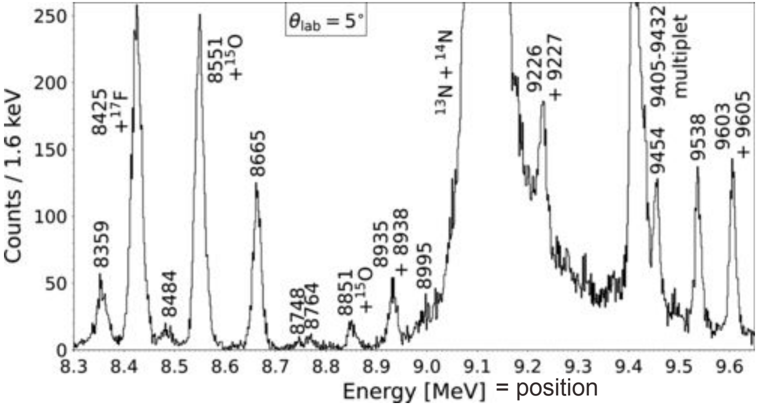




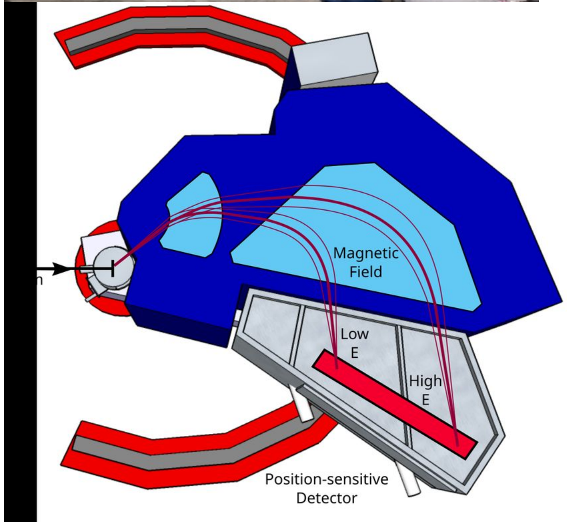
R. Longland, J. Dermigny, and C. Marshall
Phys. Rev. C 98, 025802 – Published 23 August 2018

Transfer - the ^{39}K(^{3}He,d) reaction at TUNL



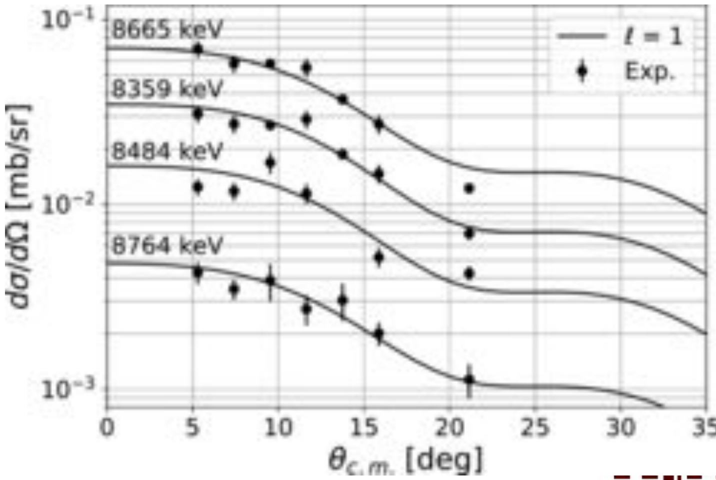


^{3}He beam from the TUNL tandem



Outgoing particles momentum-analysed in the Split Pole

Get both energy and differential cross section (L, J, C^{2}S->Γ_p) at the same time!



Transfer - the ^{39}K(^{3}He,d) reaction at TUNL

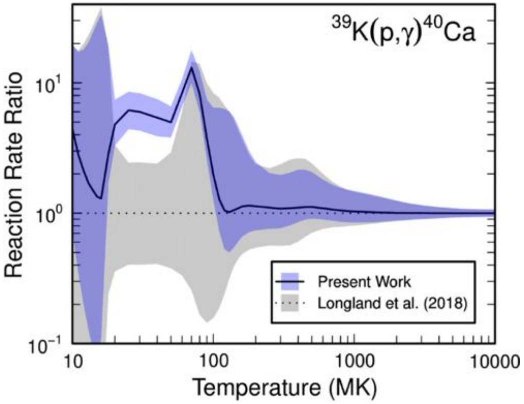
Not the only study of this reaction:

0.156 vs 0.004 meV for the 335-keV resonance(!)

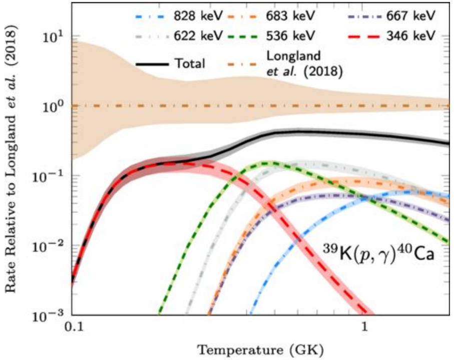
Why?

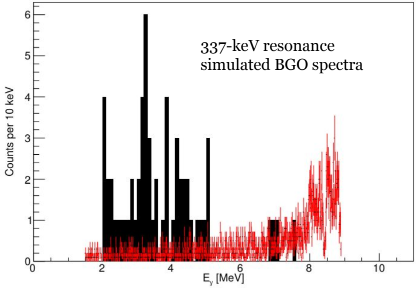
DRAGON experiment suggests only weak branching directly to ground but assumed = 1 in Scholz

Lessons: better γ-ray decay data is useful even if not directly applicable to resonance strengths

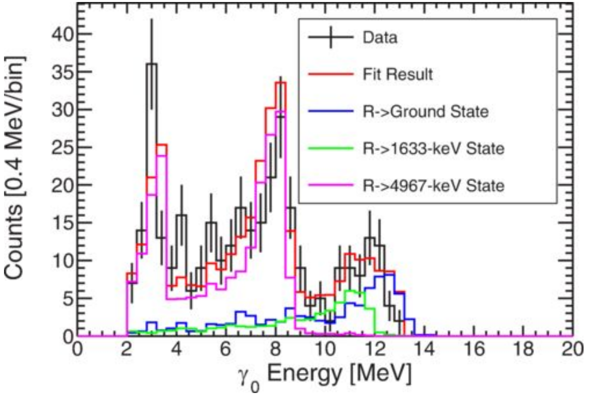


Scholz++ PRC 107 065806 (2023)
Notre Dame

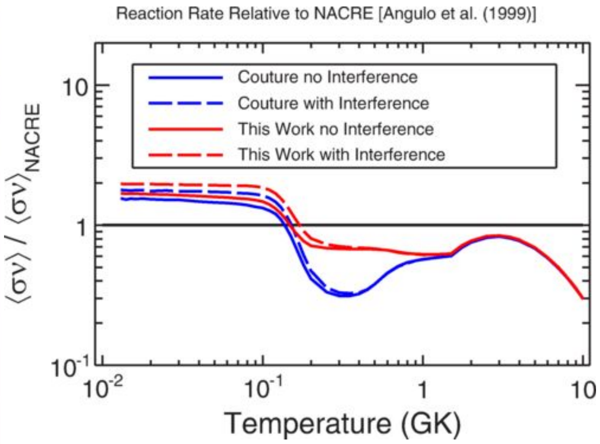




This isn’t an isolated problem! ^{19}F(p,γ)^{20}Ne with DRAGON and JUNA



M Williams++ Phys. Rev. C 103, 055805

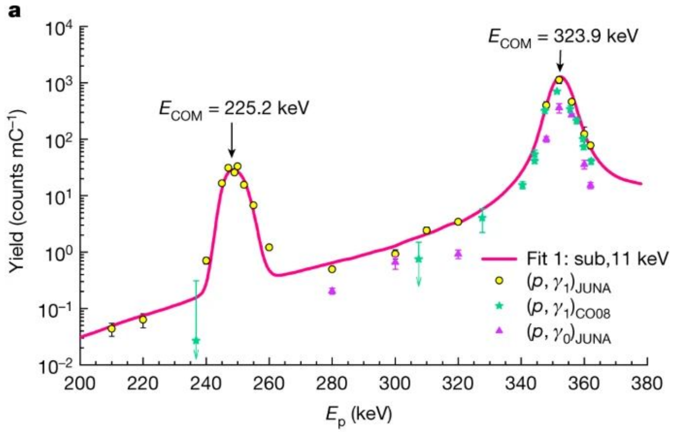


^{19}F(p,γ) of interest for CNO breakout in the earliest stars

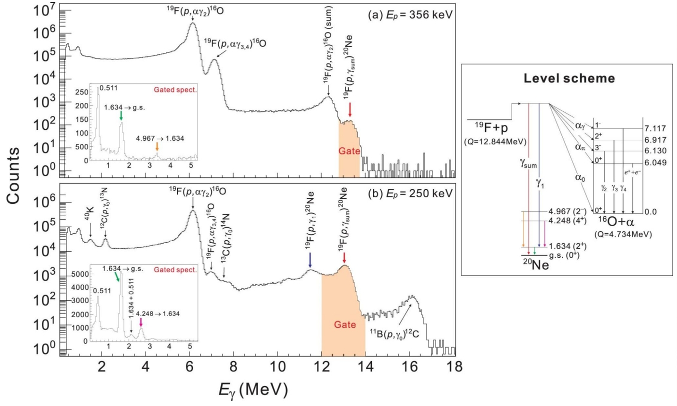
Previous measurements at Notre Dame only sensitive to 2γ cascades

DRAGON (left) and JUNA (right) both found significant ground-state decay branches - doubled the rate at important temperatures

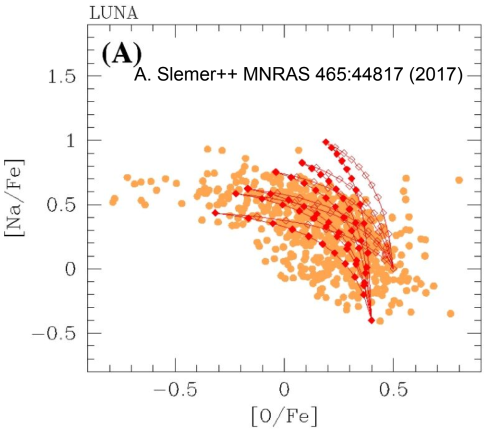
Is it realistic to expect to get enough counts to fit γ-ray decay spectra for RIB experiments with DRAGON for future measurements?



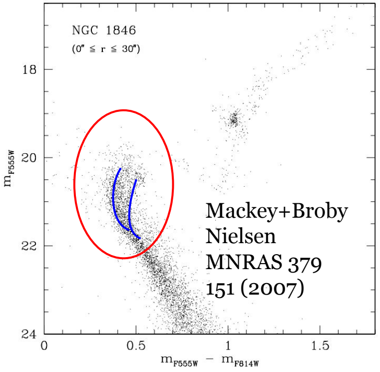
Zhang++ Nature 610 656-660 (2022)



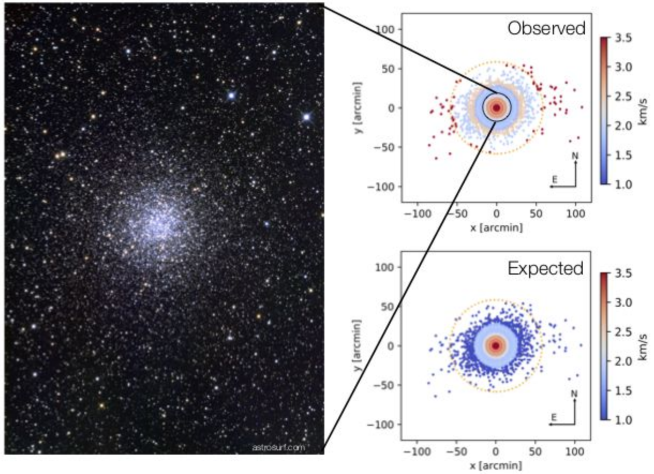
The ^{22}Ne(p,γ) reaction: why do we care?



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



Mackey+Broby Nielsen MNRAS 379 151 (2007)



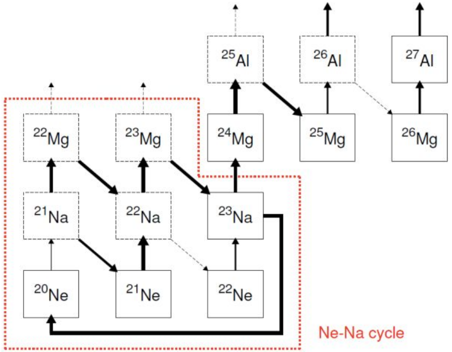
P. Bianchini et al 2019 ApJL 887 L12

Globular clusters are known to have multiple stellar populations but their histories are unclear

We like GCs as ways of tracing the history of galaxies, used as test bed for e.g. dark matter halos

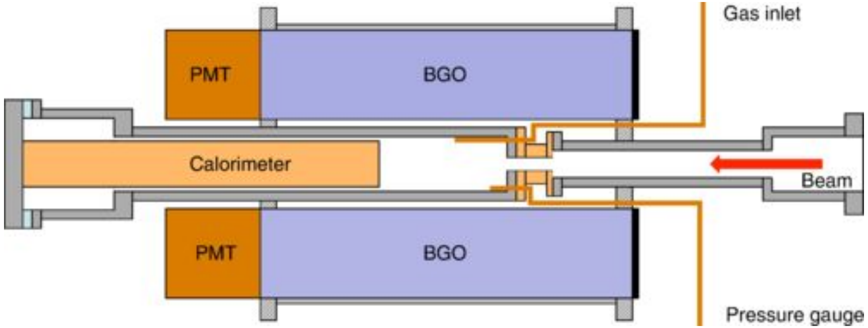
If we can understand the history of GCs then we may be able to understand how they and their host galaxies were formed

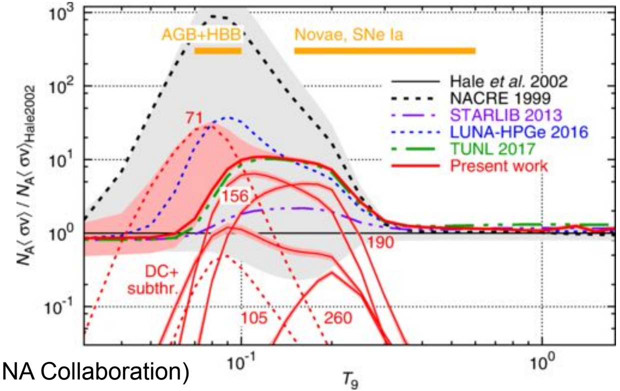
See abundance anomalies, e.g. Na-O anticorrelation, ^{22}Ne(p,γ) makes ^{23}Na



Federico Ferraro 2018 J. Phys.: Conf. Ser. 940 012041

The ^{22}Ne(p,γ) reaction: before





These are proton bombarding energies

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

What we we know about ^{22}Ne(p,γ)? Really quite a lot!

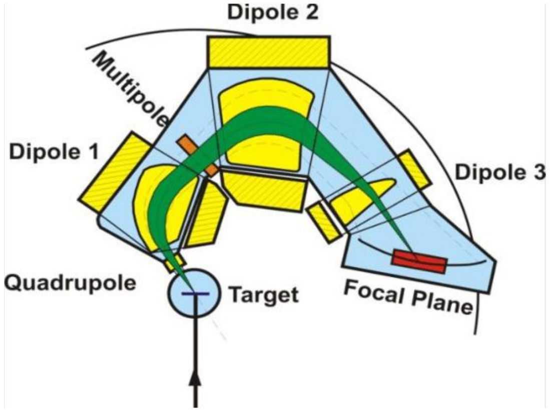
LUNA, the underground lab at Gran Sasso have done lovely work on the reaction

The major uncertainty which remains is the presence of a 71-keV resonance (65 keV in the centre-of-mass)

If this resonance exists, it can enhance the reaction rate by more than a factor of 10 in the relevant temperature region

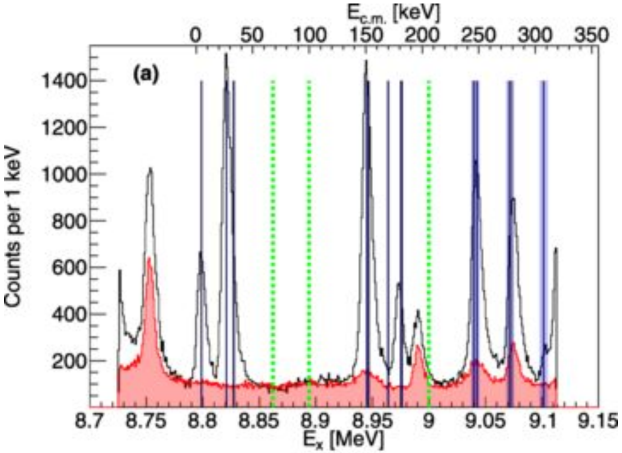
We want ~10% uncertainty so we need to do an experiment which is 100x more selective than LUNA(!)

The ^{22}Ne(p,γ) reaction: searching for possible resonance states



Green: missing ^{23}Na states

Vertical lines: known states with boxes for uncertainties

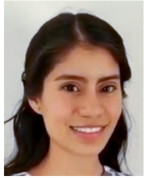


Maybe LUNA are looking for a state that doesn't exist?

Use proton scattering to populate states without any strong selectivity to structure to answer a very simple question:

Can we see a state in ^{23}Na at an energy corresponding to the 65-keV resonance?

Answer: no, and we think that the state probably doesn't exist! (Which, to be fair, everyone else seems to agree with but ruling it out was hard.)

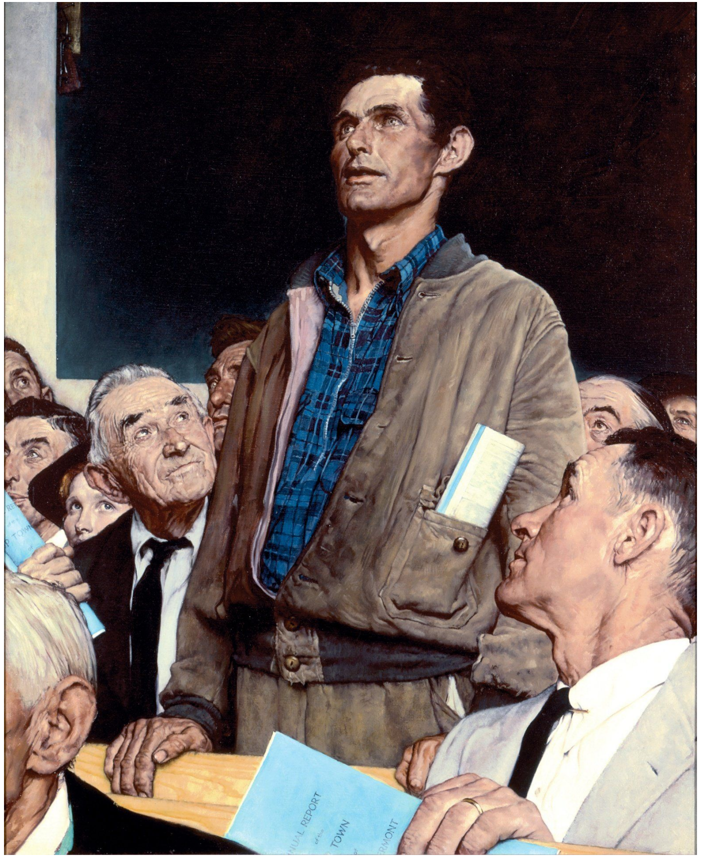


Diana Carrasco-Rojas
TREND student
UTEP+Cyc Inst.
Now PhD student at
MD Anderson

Matt Williams
Rutherford Fellow,
University of Surrey UK

…and now, the manifesto!

Even with the excellent experiments at LUNA, JUNA, LENA, OFLA (Other Four-Letter Acronyms), we need indirect measurements



Guides for direct experiments

-ID impactful resonances
-accurate resonance energies
-sanity check on direct resonances: does that resonance exist?

Interpretation

-enough resonances for statistical methods?
-ancillary data such as γ-ray decay branching
-target the most relevant physical quantity directly

Need to provide resources

-tools like magnetic spectrometers+tandems *vital* to these efforts
-beamtime for “boring” measurements in support of “shiny” experiments
-evaluations to ID the important physics data outstanding
-Theory/computational support

Things wot I missed

One of the difficulties of giving these talks is that I can really only feature a few studies but other interesting (to me) examples of indirect experiments giving vital information on important reactions at this conference include(d)…

Francois de Oliveira Santos' and Louis Wagner's talks on ^{22}Na(p,γ) and the lifetime of states in ^{23}Mg

Sifundo Binda on ^{38}K(p,γ)^{39}Ca using the ^{40}Ca(p,d)^{39}Ca reaction

Roberta Spartà on the THM (she explains it much better than I can!)

Nicolas de Séréville on ^{15}O(α,γ)

Elia Pilotto's talk on the lifetime of states in ^{15}O

Wanja Paulsen's talk on the γ branching ratio of the Hoyle state

Probably others which I now regret leaving off when I made this slide

Acknowledgements and Thanks

Matt Williams

Diana Carrasco-Rojas

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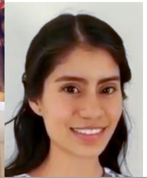
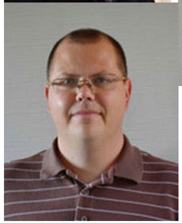
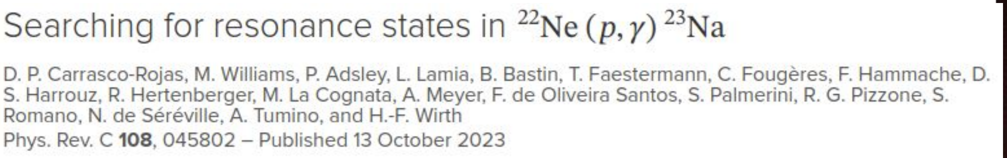
Richard Longland

Richard “James” deBoer

Heshani Jayatissa



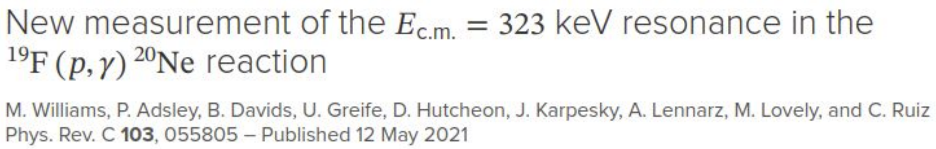




Searching for resonance states in $^{22}\mathrm{Ne}\,(p,\gamma)\,^{23}\mathrm{Na}$

D. P. Carrasco-Rojas, M. Williams, P. Adsley, L. Lamia, B. Bastin, T. Faestermann, C. Fougères, F. Hammache, D. S. Harrouz, R. Hertenberger, M. La Cognata, A. Meyer, F. de Oliveira Santos, S. Palmerini, R. G. Pizzone, S. Romano, N. de Séréville, A. Tumino, and H.-F. Wirth

Phys. Rev. C **108**, 045802 – Published 13 October 2023



New measurement of the $E_{\mathrm{c.m.}} = 323$ keV resonance in the $^{19}\mathrm{F}\,(p,\gamma)\,^{20}\mathrm{Ne}$ reaction

M. Williams, P. Adsley, B. Davids, U. Greife, D. Hutcheon, J. Karpesky, A. Lennarz, M. Lovely, and C. Ruiz

Phys. Rev. C **103**, 055805 – Published 12 May 2021

High Resolution Study of $^{40}\mathrm{Ca}$ to Constrain Potassium Nucleosynthesis in NGC 2419

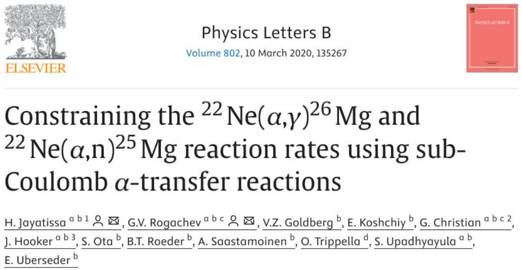
W. Fox, R. Longland, C. Marshall, and F. Portillo Chaves

Phys. Rev. Lett. **132**, 062701 – Published 8 February 2024

Measurement of $^{39}\mathrm{K}\,(p,\gamma)\,^{40}\mathrm{Ca}$ resonance strengths below 900 keV for nucleosynthesis in classical novae

Philipp Scholz, Richard J. deBoer, Joachim Görres, August Gula, Rebecca Kelmar, Khachatur Manukyan, Edward Stech, Wanpeng Tan, and Michael Wiescher

Phys. Rev. C **107**, 065806 – Published 20 June 2023



ELSEVIER

Physics Letters B

Volume 802, 10 March 2020, 135267

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

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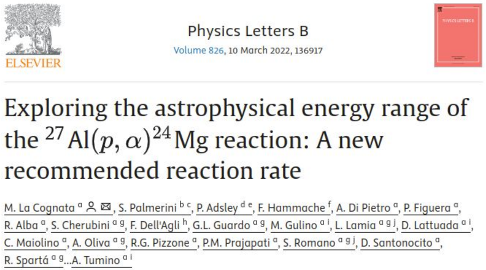

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Physics Letters B

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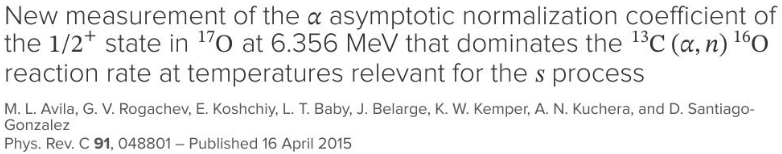
Exploring the astrophysical energy range of the $^{27}\mathrm{Al}(p,\alpha)^{24}\mathrm{Mg}$ reaction: A new recommended reaction rate

M. La Cognata [a], S. Palmerini [b c], P. Adsley [d e], F. Hammache [f], A. Di Pietro [a], P. Figuera [a], R. Alba [a], S. Cherubini [a g], F. Dell'Agli [h], G.L. Guardo [a g], M. Gulino [a i], L. Lamia [a g j], D. Lattuada [a i], C. Maiolino [a], A. Oliva [a g], R.G. Pizzone [a], P.M. Prajapati [a], S. Romano [a g j], D. Santonocito [a], R. Spartá [a g]...A. Tumino [a i]



New measurement of the α asymptotic normalization coefficient of the $1/2^+$ state in $^{17}\mathrm{O}$ at 6.356 MeV that dominates the $^{13}\mathrm{C}\,(\alpha,n)\,^{16}\mathrm{O}$ reaction rate at temperatures relevant for the s process

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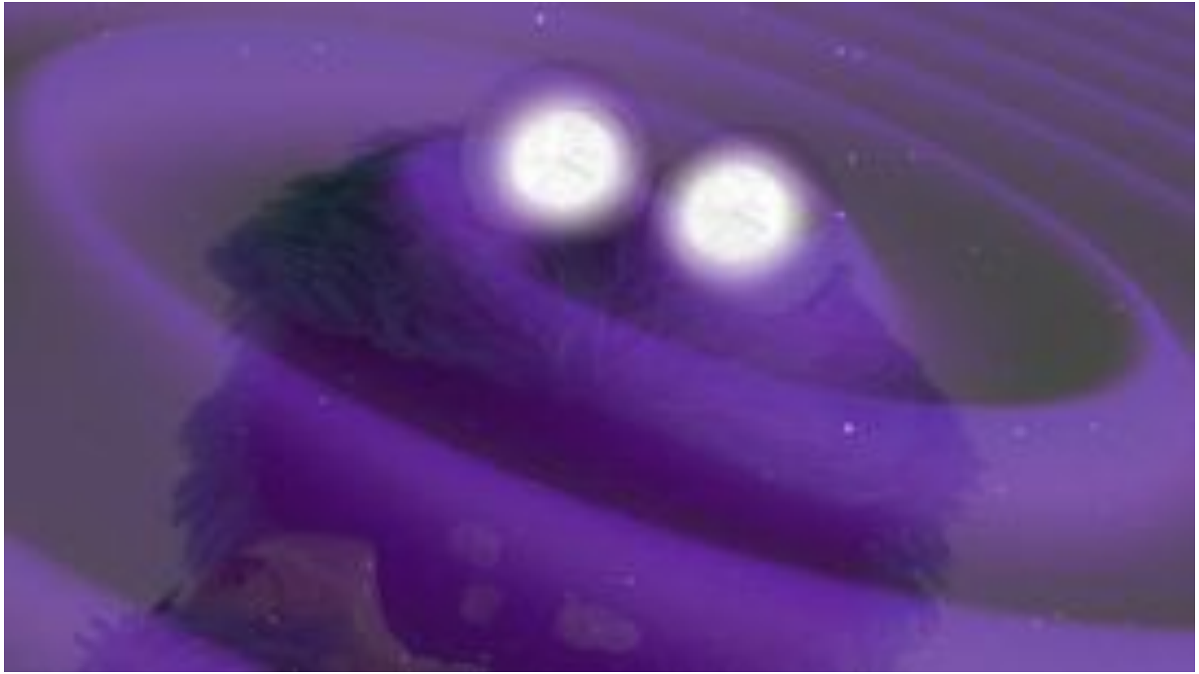

Any questions?