(Not) Understanding globular cluster pollution through nuclear reactions

Phil Adsley - padsley@tamu.edu

It's silly season and I'm leaning into that

Outline

What even are globular clusters?

Reaction rates - what is the role of nuclear physics?

Starting simple - ^{23}Na and the $^{22}Ne(p,\gamma)^{23}Na$ reaction rate

Making things more complicated - $^{30}Si(^{3}He,d)^{31}P$

Backwards and in heels - $^{39}K(p,\gamma)^{40}Ca$ with DRAGON

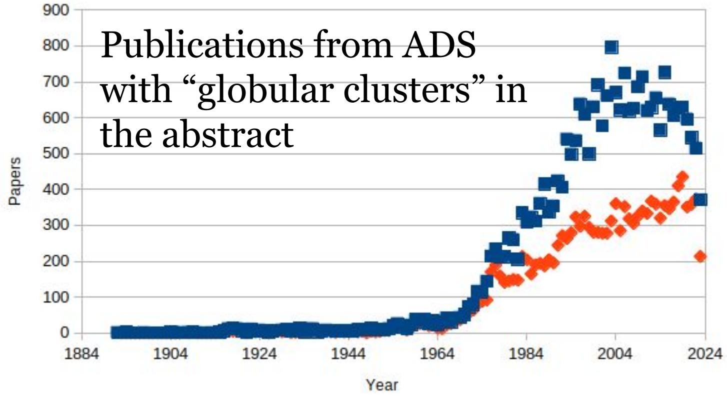
Globular Clusters

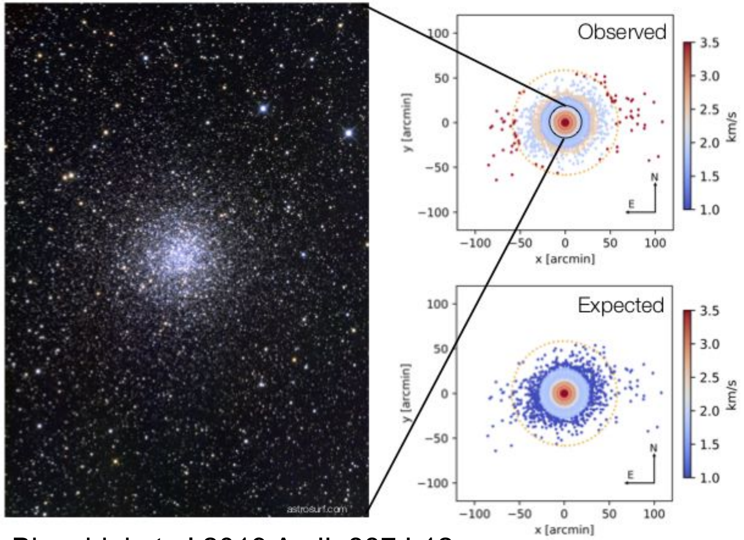
Tightly bound groups of stars

Their origins are somewhat mysterious (like every good protagonist)

Test beds of various models of galaxy formation, dark matter halos

Understanding how GC history will help to clarify how useful they are to test other things





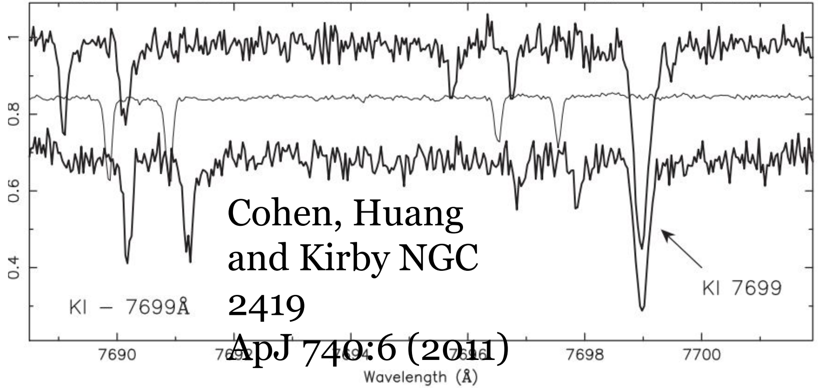
P. Bianchini et al 2019 ApJL 887 L12

Multiple GC stellar populations

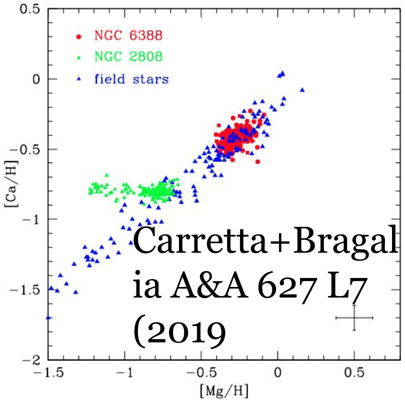
Globular clusters are weird - originally thought to be a single generation of ancient stars but now strong evidence against that

Currently observed stars are too cool to make the elements seen in their spectra - must originate from older stars but what were they?

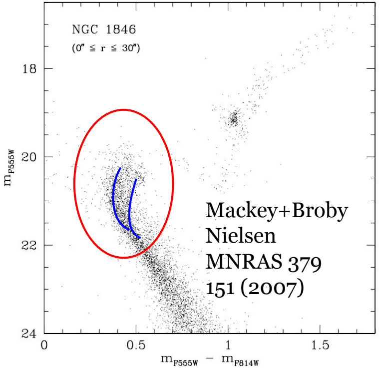
The temperature-density conditions are unclear because some nuclear reaction rates are unclear



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

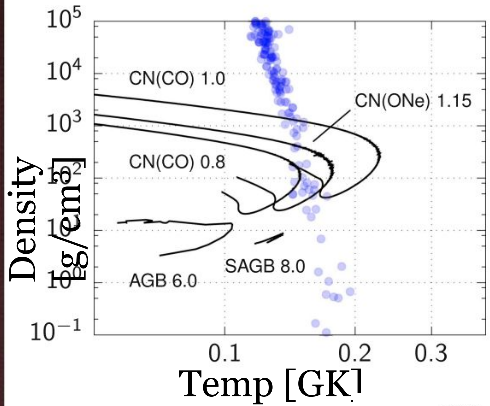


Carretta+Bragaglia A&A 627 L7 (2019

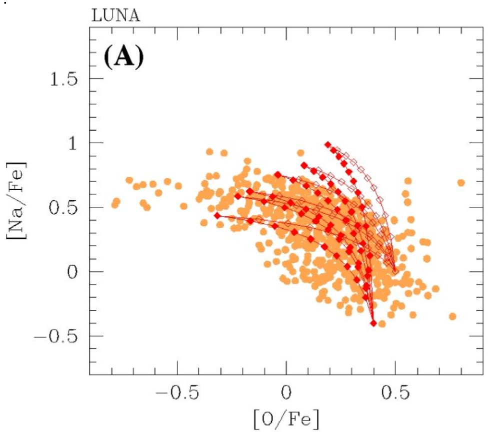


Mackey+Broby Nielsen MNRAS 379 151 (2007)

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: $^{22}Ne(p,\gamma)^{23}Na$ is the main source of uncertainty
- For Mg-K anticorrelation: (p,γ) reactions on ^{30}Si, ^{37}Ar, ^{38}Ar, ^{39}K

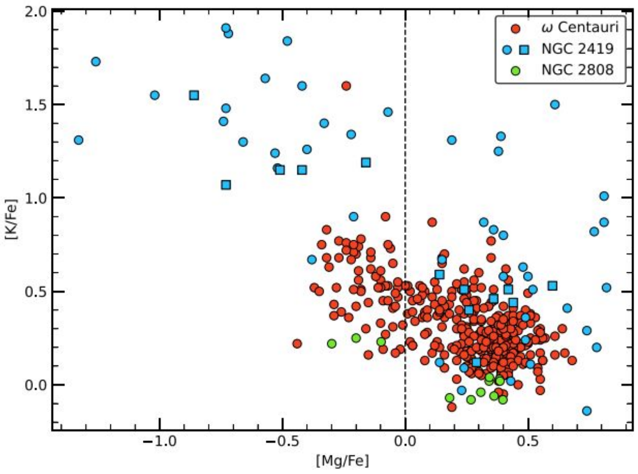
What can abundance anomalies tell us?

IN THEORY, we can identify the polluting side in GCs from the abundance pattern

However, there are some mutual inconsistencies - NGCs 2419 and 2808 and ω Centurai have Mg/K anti-correlation but Na is destroyed at the temperatures at which K is produced so these can't be made in the same site

Bastian and Lardo: "it is not clear if [K abundances are] a promising window into the MP phenomenon, or instead pathological cases that confuse the issue"

The Astrophysical Journal Letters, 928:L11 (7pp), 2022 March 20



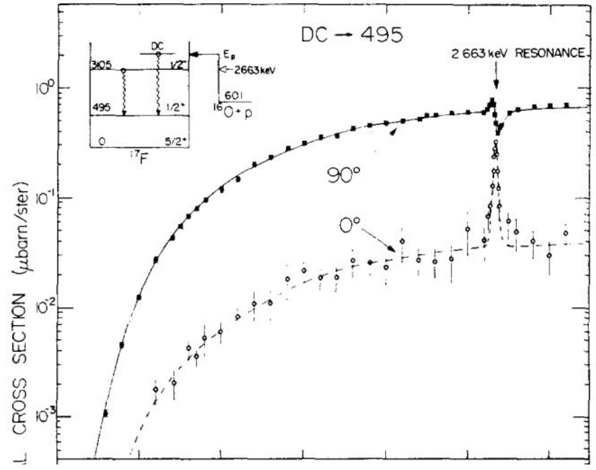
What do we need to know?

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

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

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

$$\Gamma = 2\gamma^2 P_\ell(E,\eta)$$



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

Nuclear data inputs

Some information about nuclear physics in here!

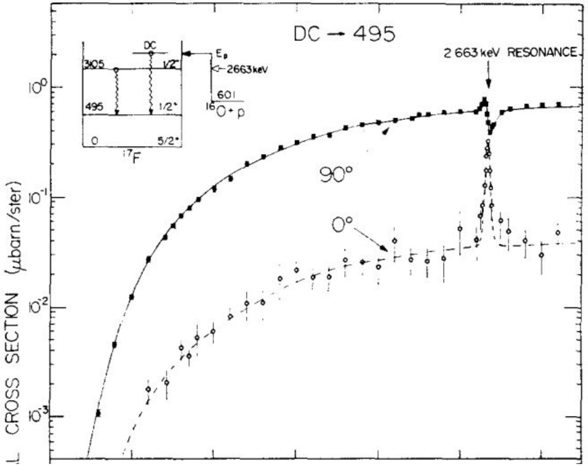
Where are the resonances? What are the spins? Widths? Widths depend strongly on L

Lots to find out - need to be systematic about it

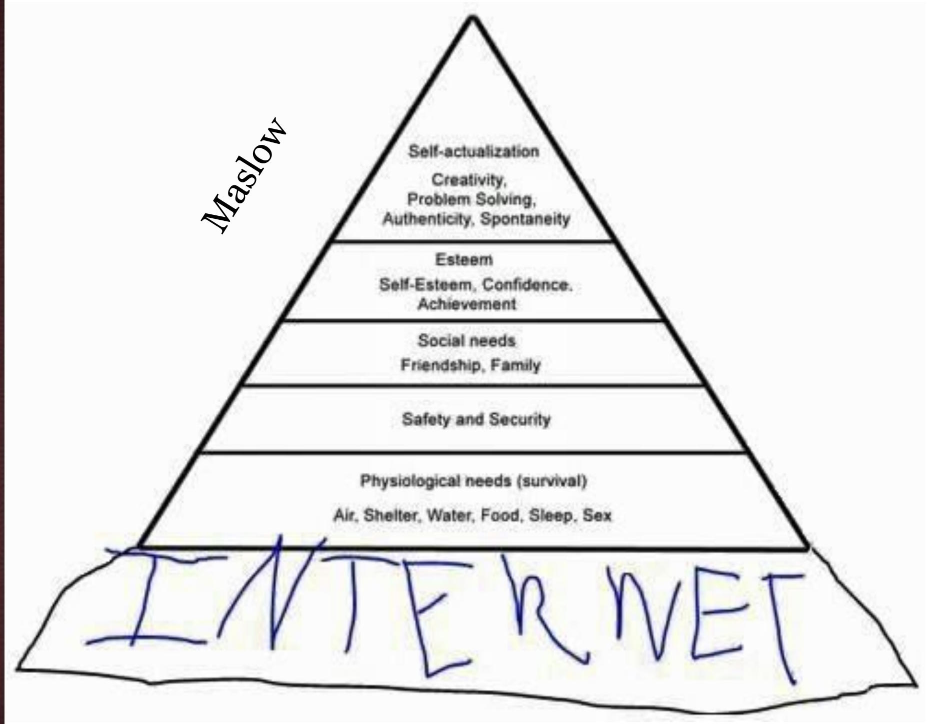
$$N_A\langle\sigma v\rangle \propto \omega\gamma e^{\frac{-11.605E_r}{T_9}}$$

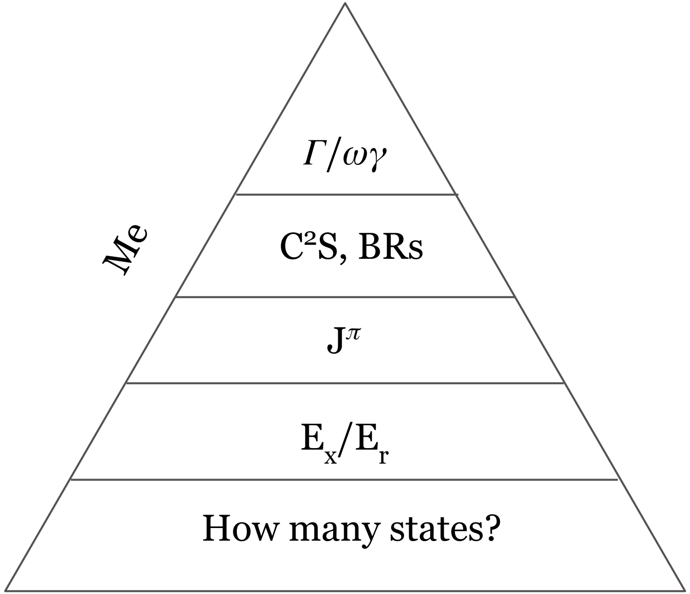
$$\omega\gamma = \frac{2J+1}{(2j_1+1)(2j_2+1)}\frac{\Gamma_1\Gamma_2}{\Gamma_1+\Gamma_2}$$

$$\Gamma = 2\gamma^2 P_\ell(E,\eta)$$



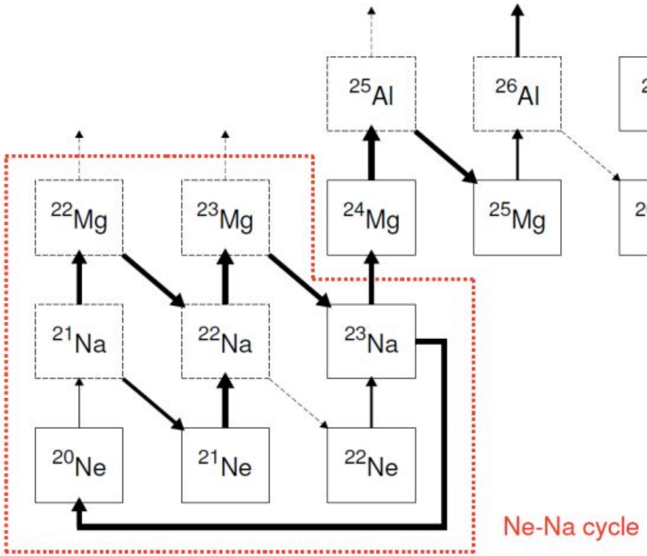
What do we need to know?





$^{22}Ne(p,\gamma)^{23}Na$ through $^{23}Na(p,p')^{23}Na$

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



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

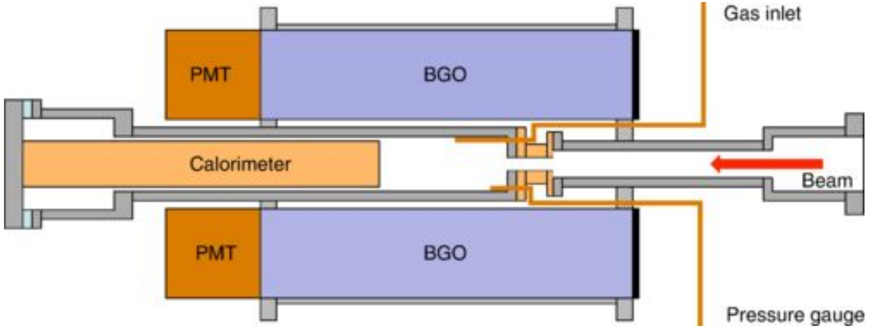
- Destroys ^{22}Ne and makes ^{23}Na
- ^{23}Na is the only stable sodium isotope so the [Na/O] anticorrelation must depend on ^{23}Na
- Need to know how ^{23}Na is made (this reaction) and destroyed (^{23}Na+p reactions to ^{20}Ne and ^{24}Mg)
- Hot Bottom Burning one possible site for sodium production - want the rate down to 70 MK

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

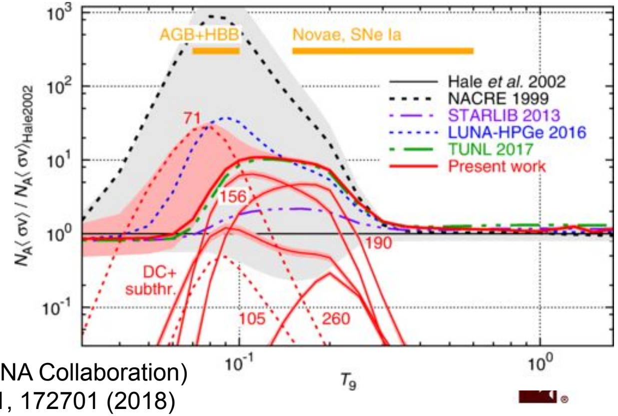
LUNA have done amazing work on direct measurements

One main source of uncertainty is whether a low-energy resonance exists (and its strength if it does)

The evidence for its existence is ~~really really bad~~ inconclusive

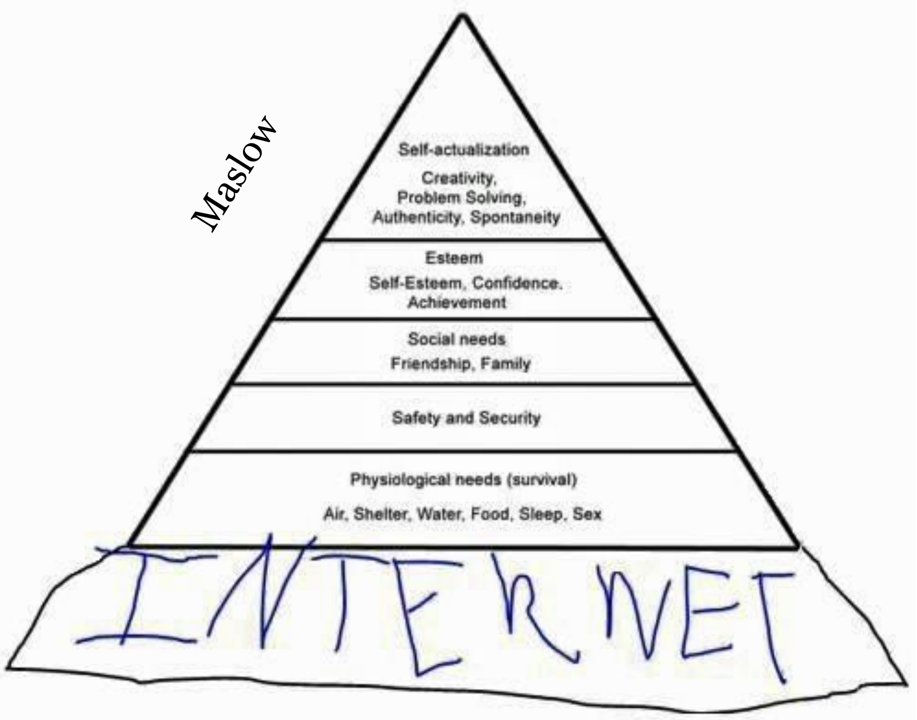


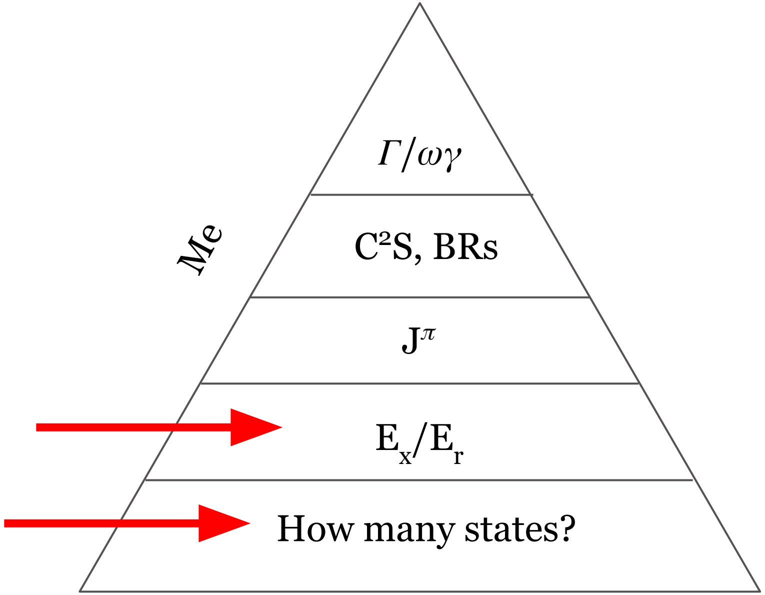
These are proton bombarding energies



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

What do we need to know?



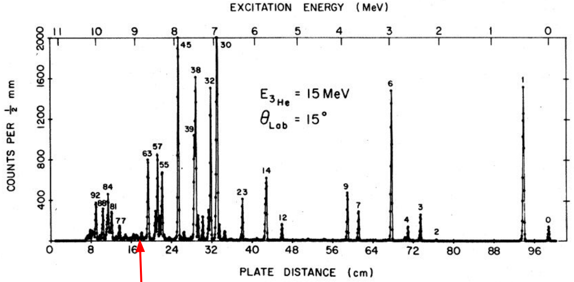


^{22}Ne(p,γ)^{23}Na and ^{23}Na(p,p')

In order to rule a state out as important, need very stringent measurements of low resonance strengths - beating LUNA is hard!

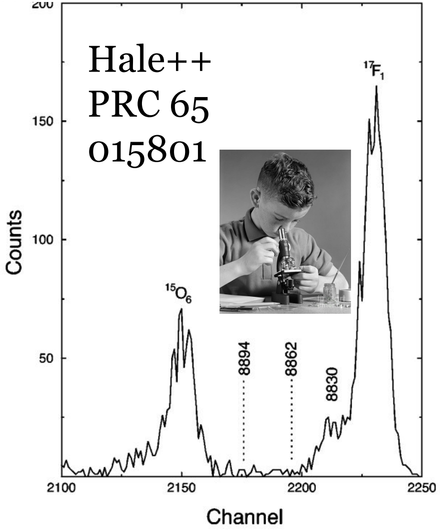
^{22}Ne(^{3}He,d)^{23}Na measurements - one found these states, one didn't

Need to look for these resonances in as non-selective a way as possible



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

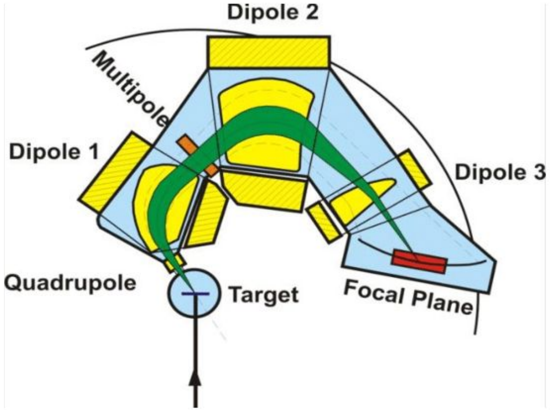
Experimental details

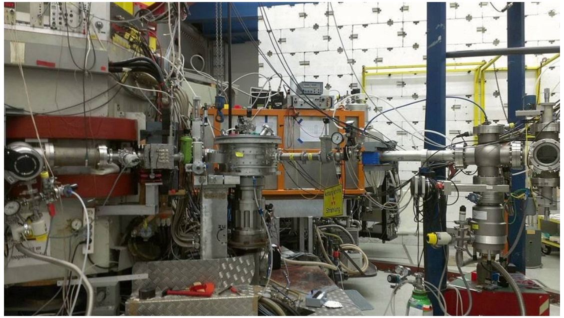
14-MeV proton beam on a NaF target

Background data taken with carbon target, also LiF (for F) and SiO_2 (for O)

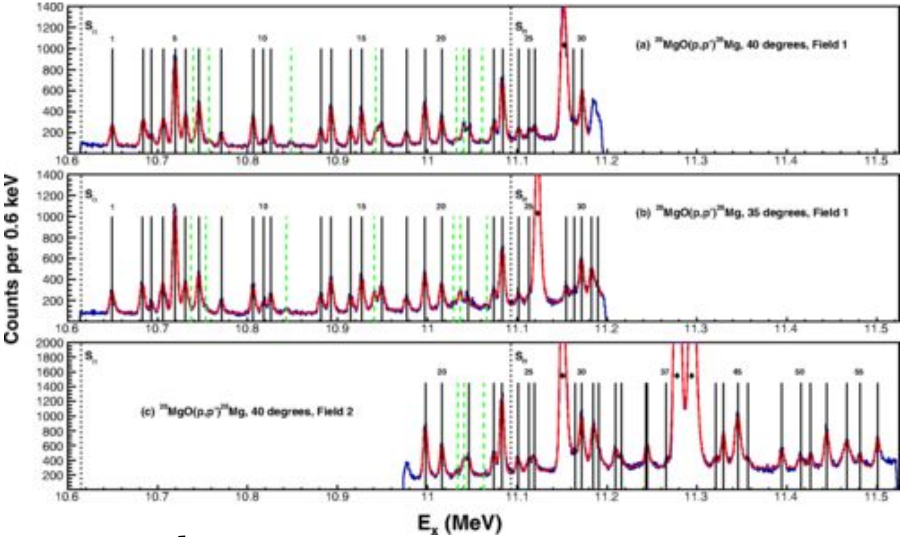
Protons detected at the focal plane: position = E_x

Excellent energy resolution of ~8 keV FWHM





Why use proton scattering?

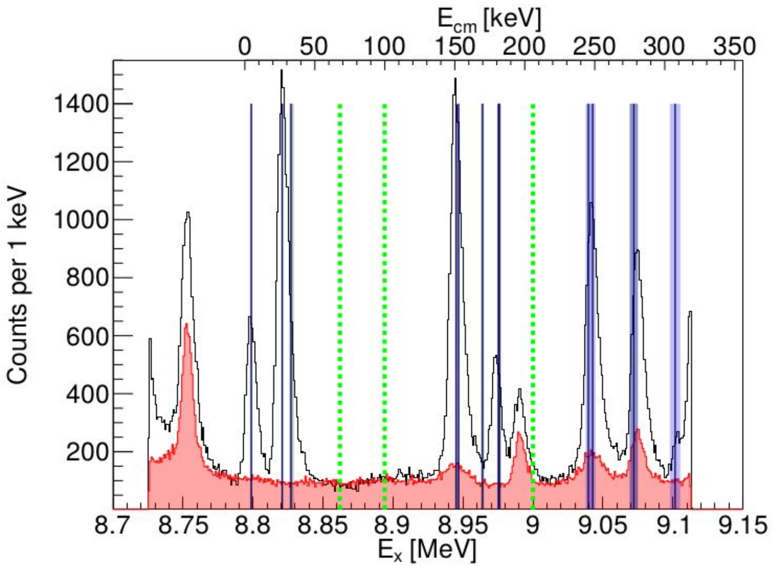


PA++ Phys. Rev. C 97, 045807

Studying ^{26}Mg - resolved discrepancies between (α,α'), (γ,γ') and fusion-evaporation by showing that there are three states just above E_x = 10.8 MeV

- Proton scattering at these energies is fairly indiscriminate!
- Other reactions (α or γ scattering, resonance reactions, transfer) are selective which is great *if* you want to be selective
- In this case we want to know how many states there are and where without any/much selection

The states do not exist



The green 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

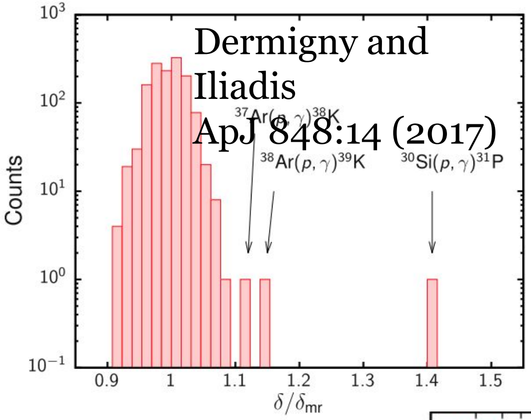
Proving a negative is hard but between this and the previous transfer study we see no support for the existence of the states

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

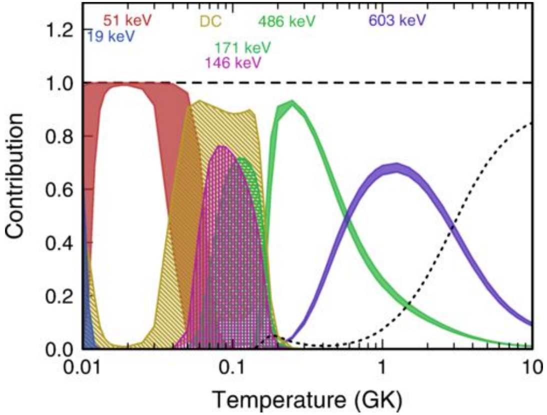
Matt Williams
I wonder where he is now?

^{30}Si(p,γ)^{31}P through ^{30}Si(^{3}He,d)^{31}P

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



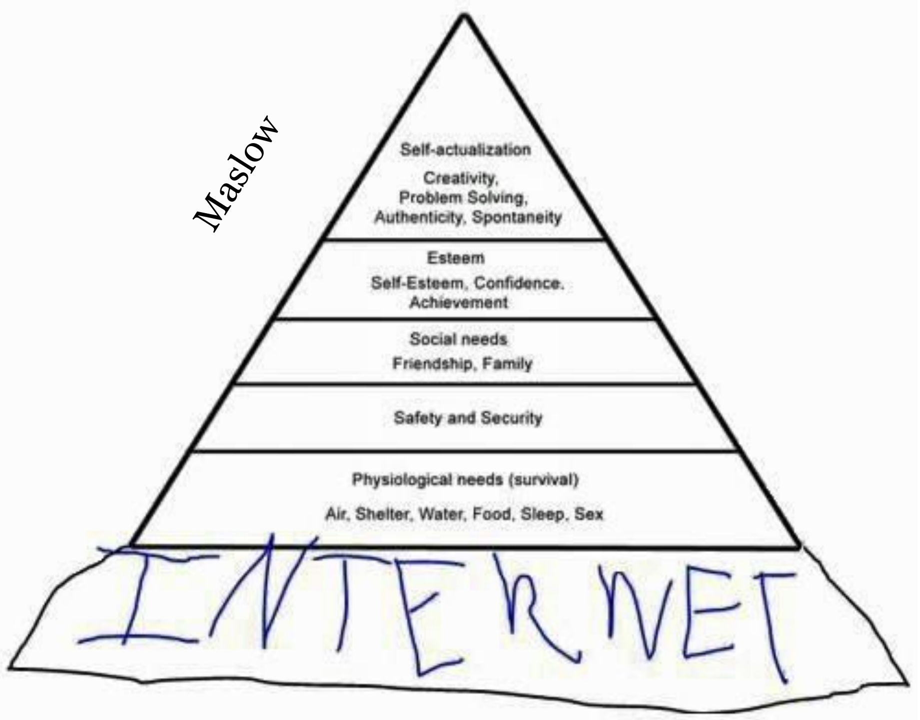
Dermigny and Iliadis
ApJ 848:14 (2017)

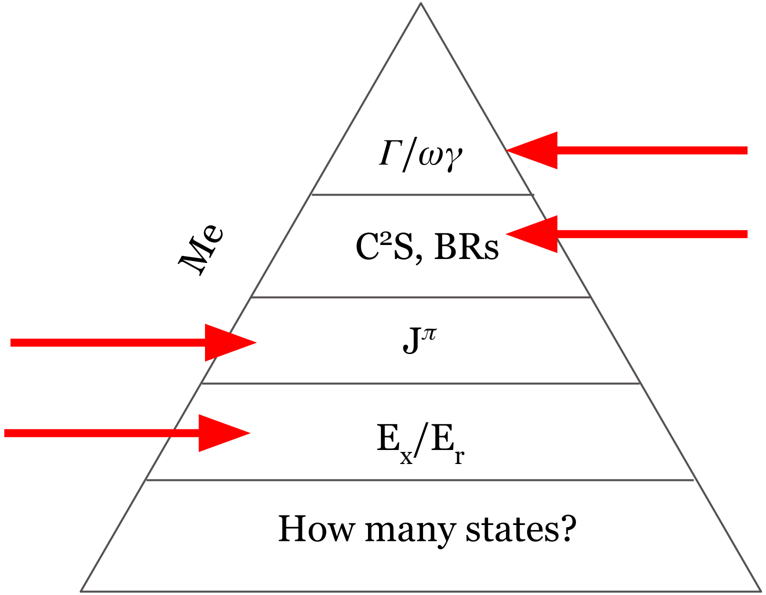


Dermigny++
Phys. Rev. C 102, 014609 (2020)

- This reaction is one of the most impactful in defining the temperature of the polluting site in GCs
- Bottleneck in moving from ~Mg to ~Ca
- 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

What do we need to know?





Q3D Experiment

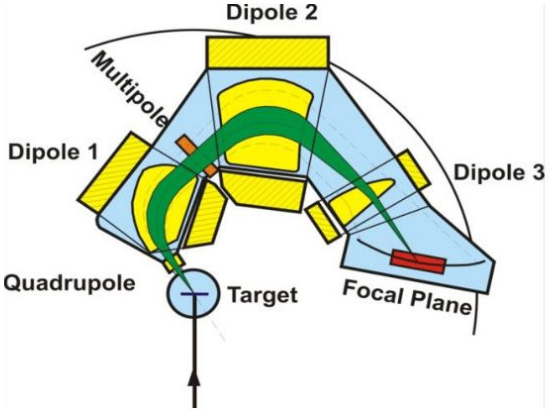
25-MeV ^{3}He on a $^{30}SiO_2$ target

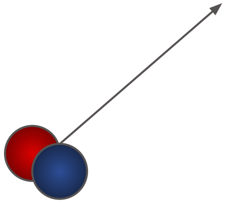
Populate states in ^{31}P

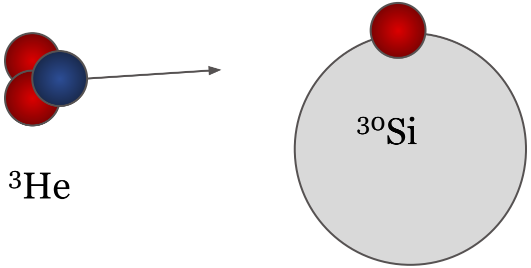
Again, from the focal-plane position get E_x

Resonance strengths at low E_{cm} depend mostly on the proton widths

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







Djamila Sarah Harrouz
IJCLab

How can transfer reactions help us?

Transfer cross sections are sensitive to the orbital angular momentum transferred and the spectroscopic factor

Calculate the proton width by using this relationship

If you do the calculations consistently between the DWBA and the partial width, the systematic error is still huge but smaller :)

$$\left[\frac{d\sigma}{d\Omega}\right]_{\mathrm{exp}} = C^2 S \left[\frac{d\sigma}{d\Omega}\right]_{\mathrm{DWBA}}$$

$$\Gamma = 2P_\ell(E,R)\frac{\hbar^2 R}{2\mu} C^2 S |\phi(R)|^2$$

Barrier penetration

Some boring constants

The scaling factor for the wavefunction

The size of the single-particle wavefunction at the nuclear surface

Q3D Experiment

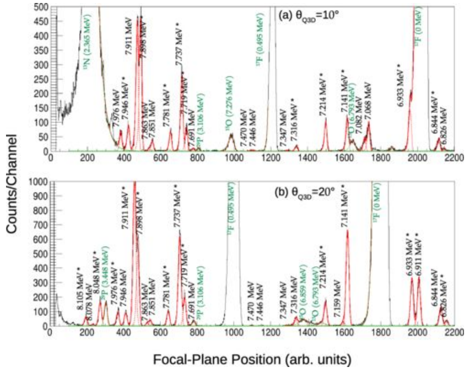
25-MeV ^{3}He on a $^{30}SiO_2$ target

Populate states in ^{31}P

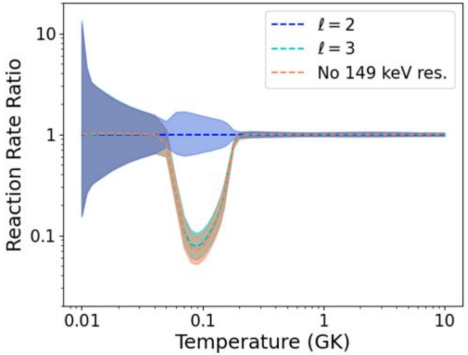
Get widths from the shape (for orbital angular momentum) and magnitude of the transfer cross section

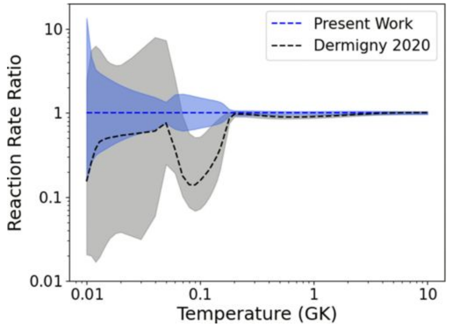
Reduce uncertainties in the rate significantly

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



Harrouz++
Phys. Rev. C 105, 015805





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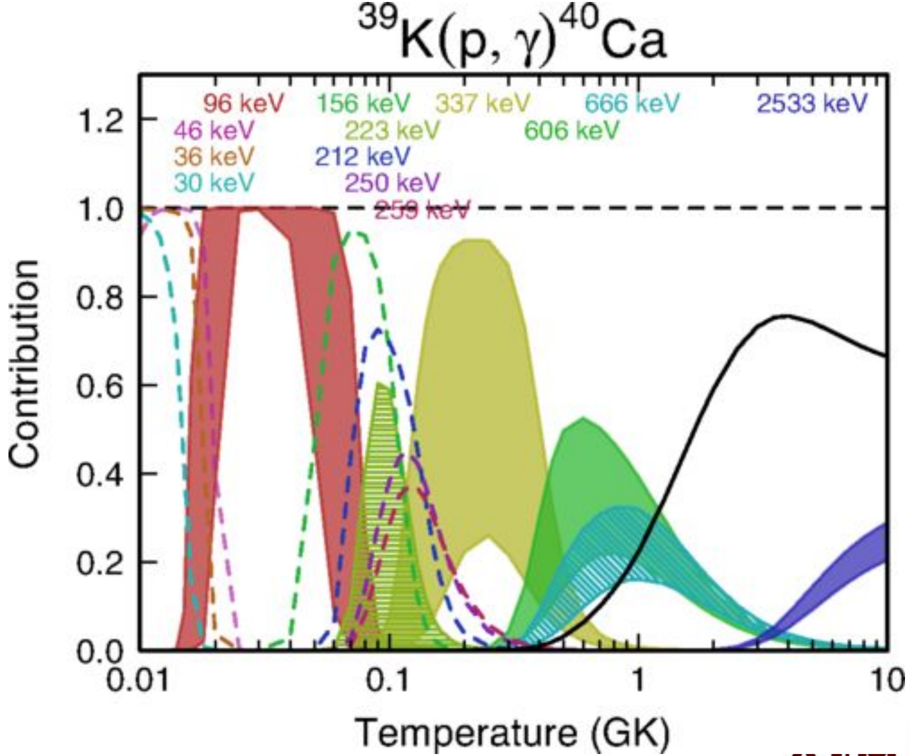
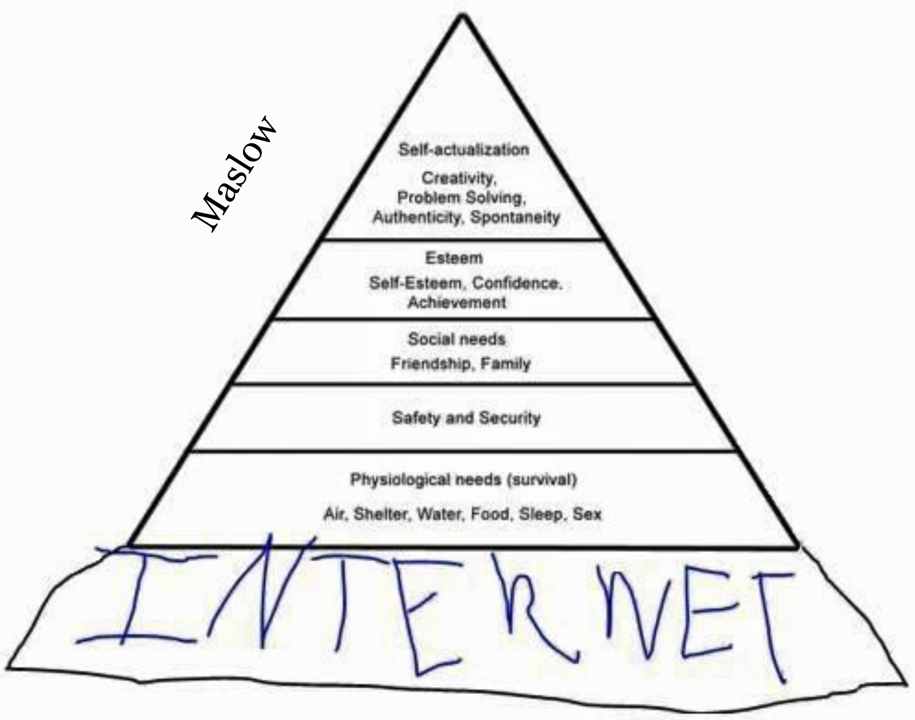
$^{39}K(p,\gamma)^{40}Ca$

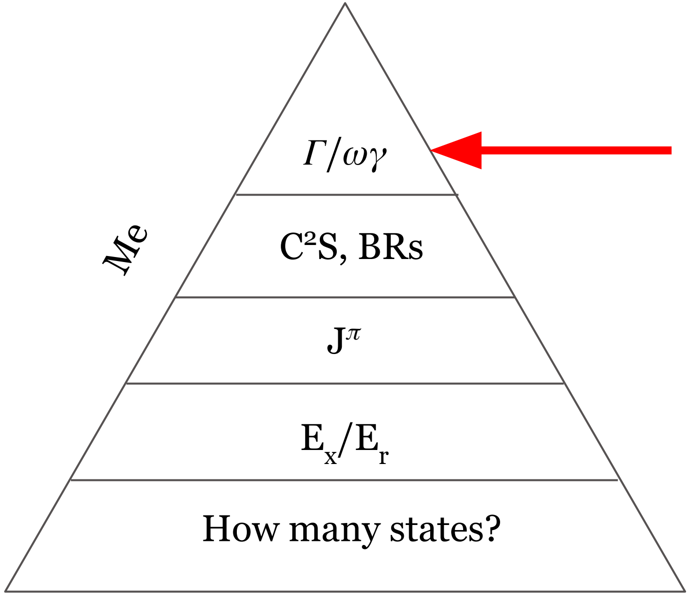
Rate evaluation

- Reaction destroys K - higher rate = less K left over
- R. Longland, J. Dermigny, and C. Marshall (PRC 98, 025802) performed a rate evaluation based on known ^{40}Ca nuclear data
- 337-keV resonance is the critical one, 606 and 666 also important

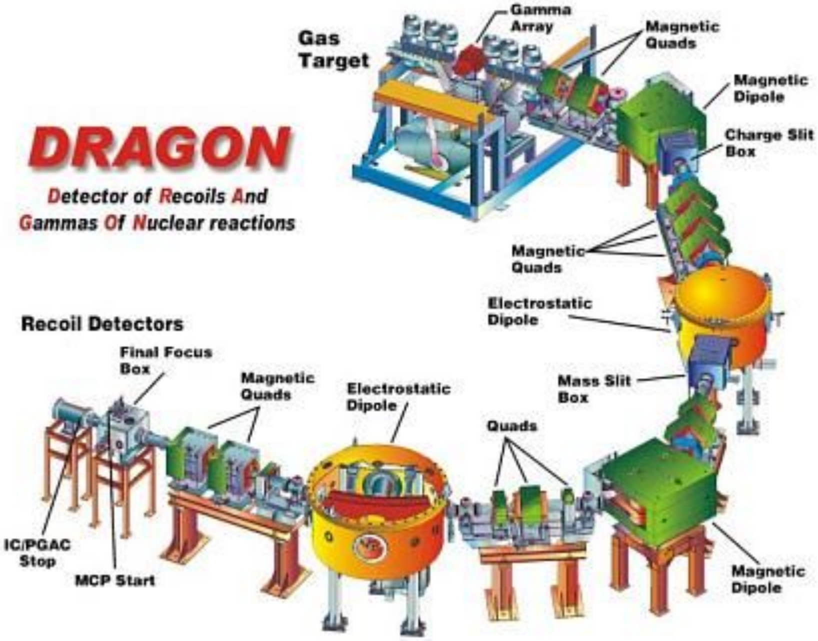


What do we need to know?



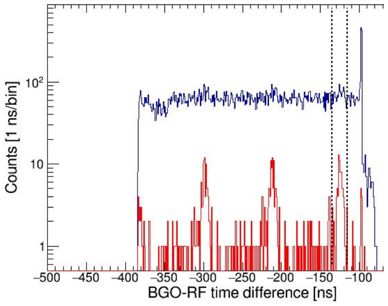


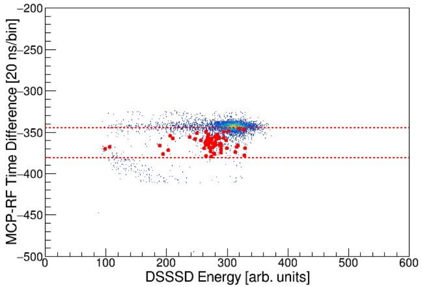
Measuring $^{39}K(p,\gamma)^{40}Ca$ with the DRAGON

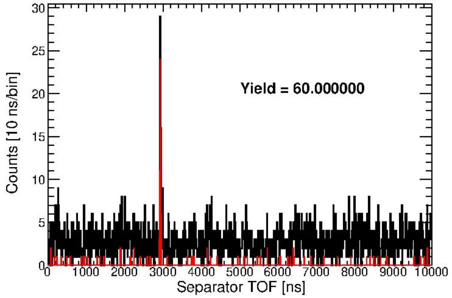


- ^{39}K beam onto the windowless gas target of the DRAGON
- $^{39}K(p,\gamma)^{40}Ca$ reaction
- γ rays detected in BGO array
- ^{40}Ca recoils selected by the separator
- Hit gas ionisation chamber+DSSSD at the focal plane

Experimental Observables







Identify ^{40}Ca recoils (and exclude ^{39}K leaky beam) by times of flight

BGO-DSSSD timing

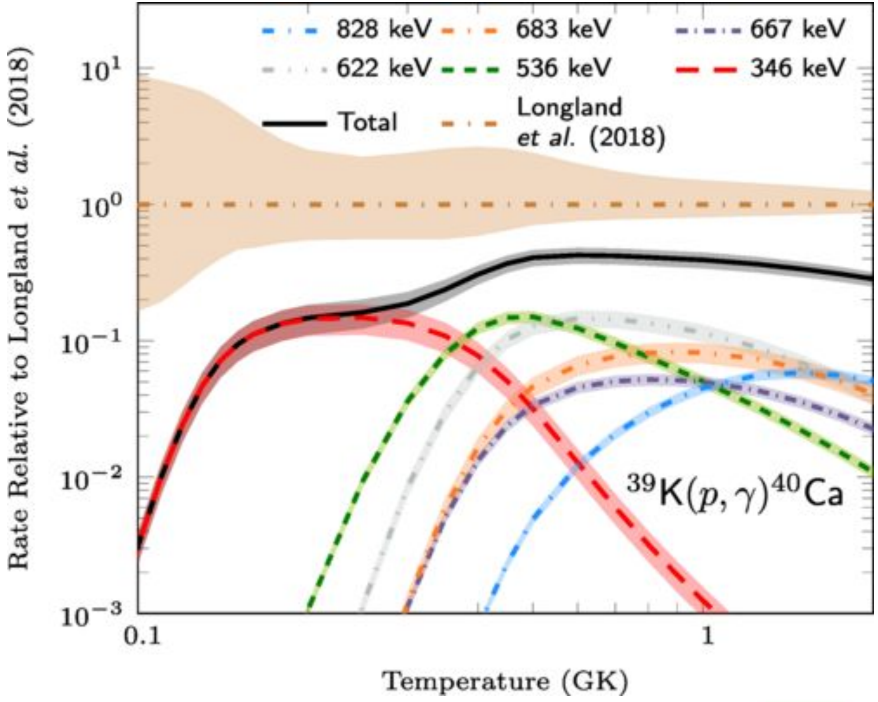
Accelerator RF-BGO timing

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

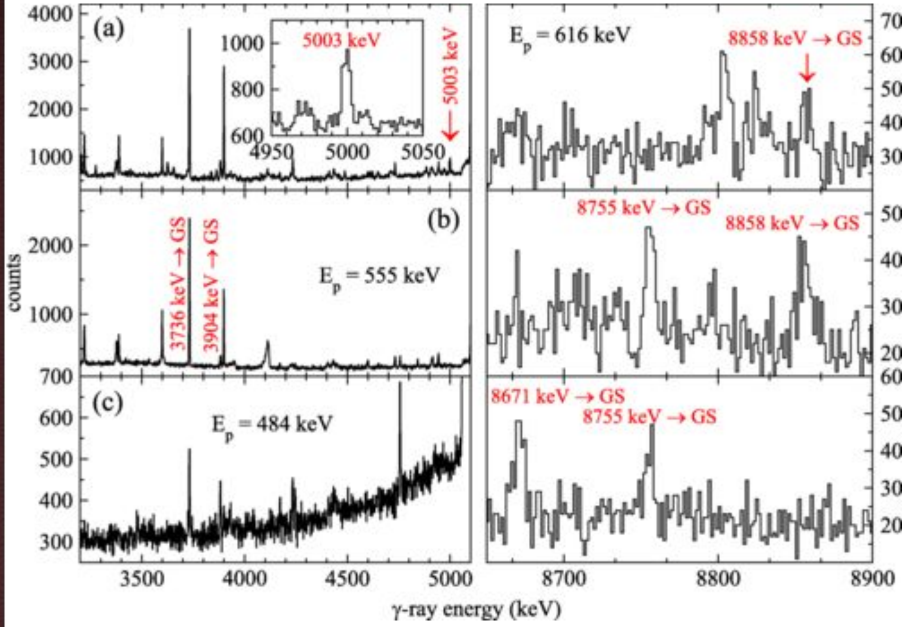
Recent Notre Dame results

- At this point, I need to mention another recent paper from ND
- Direct measurement of resonance strengths for this reaction in normal kinematics
- Resonance strengths are smaller that previous evaluation
- For E_r = 337 keV, imply that we should have had ~60 recoils *total* not 60 recoils *detected*



Scholtz, Phys. Rev. C 107, 065806
Again, E_r in the lab :(

Someone is wrong!

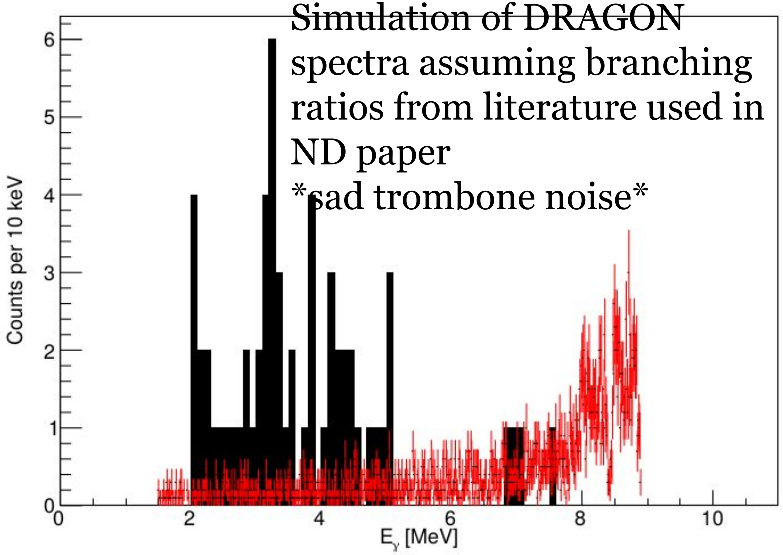


- Probably, and I think I know why it's them
- There's ^{41}K and ^{19}F in the targets with considerable background at lower energies
- They assume branching ratios from the literature which are inconsistent with the DRAGON results

What next?

Need to finish simulations of the γ decays to get the BGO efficiency but we don't know the decay branching

Also need to get charge-state fractions (but Ca is turning out to be a problem at TRIUMF with OLIS)



Simulation of DRAGON spectra assuming branching ratios from literature used in ND paper
sad trombone noise

Summary

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

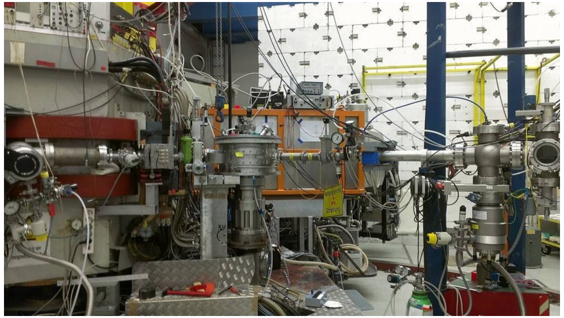
There are a variety of nuclear reactions which can be used to improve knowledge of reaction rates

Boring reactions like (p,p’) at lowish 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 - proton captures on ^{37,38}Ar need work

THE CLAUDE LEON FOUNDATION

Collaborators



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

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

D. S. Harrouz,[1] N. de Séréville,[1,*] P. Adsley,[2,3,†] F. Hammache,[1] R. Longland,[4,5] B. Bastin,[6] T. Faestermann,[7] R. Hertenberger,[8] M. La Cognata,[9] L. Lamia,[9,10] A. Meyer,[1] S. Palmerini,[11,12] R. G. Pizzone,[9] S. Romano,[9,10,13] A. Tumino,[9,14] and H.-F. Wirth[8]

[1]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[2]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[3]*iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa*
[4]*North Carolina State University, Raleigh, North Carolina 27695, USA*
[5]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[6]*Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DRF-CNRS/IN2P3, Boulevard Henri Becquerel, 14076 Caen, France*
[7]*Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[8]*Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[9]*Laboratori Nazionali del Sud–Istituto Nazionale di Fisica Nucleare, Via Santa Sofia 62, 95123 Catania, Italy*
[10]*Dipartimento di Fisica e Astronomia E. Majorana, Università di Catania, 95131 Catania, Italy*
[11]*Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, 06123 Perugia, Italy*
[12]*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, 06123 Perugia, Italy*
[13]*Centro Siciliano di Fisica Nucleare e Struttura della Materia (CSFNSM), 95123 Catania, Italy*
[14]*Facoltà di Ingegneria e Architettura, Università degli Studi di Enna, 94100 Enna, Italy*

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

D. P. Carrasco-Rojas,[1,*] M. Williams,[2,†] P. Adsley,[3,4,5,6,‡] L. Lamia,[7] B. Bastin,[8] T. Faestermann,[9] C. Foug'eres,[8] D. S. Harrouz,[10] R. Hertenberger,[11] M. La Cognata,[7] A. Meyer,[10] F. de Oliveira,[8] S. Palmerini,[12] R. G. Pizzone,[7] S. Romano,[7] N. de Séréville,[10] A. Tumino,[7] and H.-F. Wirth[11]

[1]*Department of Physics, University of Texas at El Paso, El Paso, TX 79968-0515, USA*
[2]*TRIUMF, Vancouver, BC V6T 2A3, Canada*
[3]*Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
[4]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[5]*iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa*
[6]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[7]*Laboratori Nazionali del Sud - Istituto Nazionale di Fisica Nucleare, Via Santa Sofia 62, 95123 Catania, Italy*
[8]*GANIL, CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France*
[9]*Physik Department E12, Technische Universität München, D-85748 Garching, Germany*
[10]*Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France*
[11]*Fakultät für Physik, Ludwig-Maximilians-Universität München, D-85748 Garching, Germany*
[12]*Dipartimento di Fisica e Geologia, Universit'a degli Studi di Perugia, Perugia, Italy*

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

Philip Adsley,[1,2,3,4,*] Matthew Williams,[5,6] Nicolas de Séréville,[7] Richard Longland,[8,9] Barry Davids,[6] Uwe Greife,[10] Fairouz Hammache,[7] Sarah Harrouz,[7] David Hutcheon,[6] Annika Lennarz,[6] Alison M. Laird,[5] François d'Oliveira Santos,[11] Athanasios Psaltis,[12] and Christopher Ruiz[6,13]

[1]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[2]*Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
[3]*iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa*
[4]*School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[5]*Department of Physics, University of York, Heslington, York, YO10 5DD, United Kingdom*
[6]*TRIUMF, Vancouver, BC V6T 2A3, Canada*
[7]*Institut de Physique Nucléaire d'Orsay, UMR8608, IN2P3-CNRS, Université Paris Sud 11, 91406 Orsay, France*
[8]*North Carolina State University, Raleigh, North Carolina 27695, USA*
[9]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[10]*Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA*
[11]*GANIL, CEA/DRF-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France*
[12]*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr. 2, Darmstadt 64289, Germany*
[13]*Department of Physics and Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada*

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