Nuclear Astrophysics with Gammasphere and GRETINA

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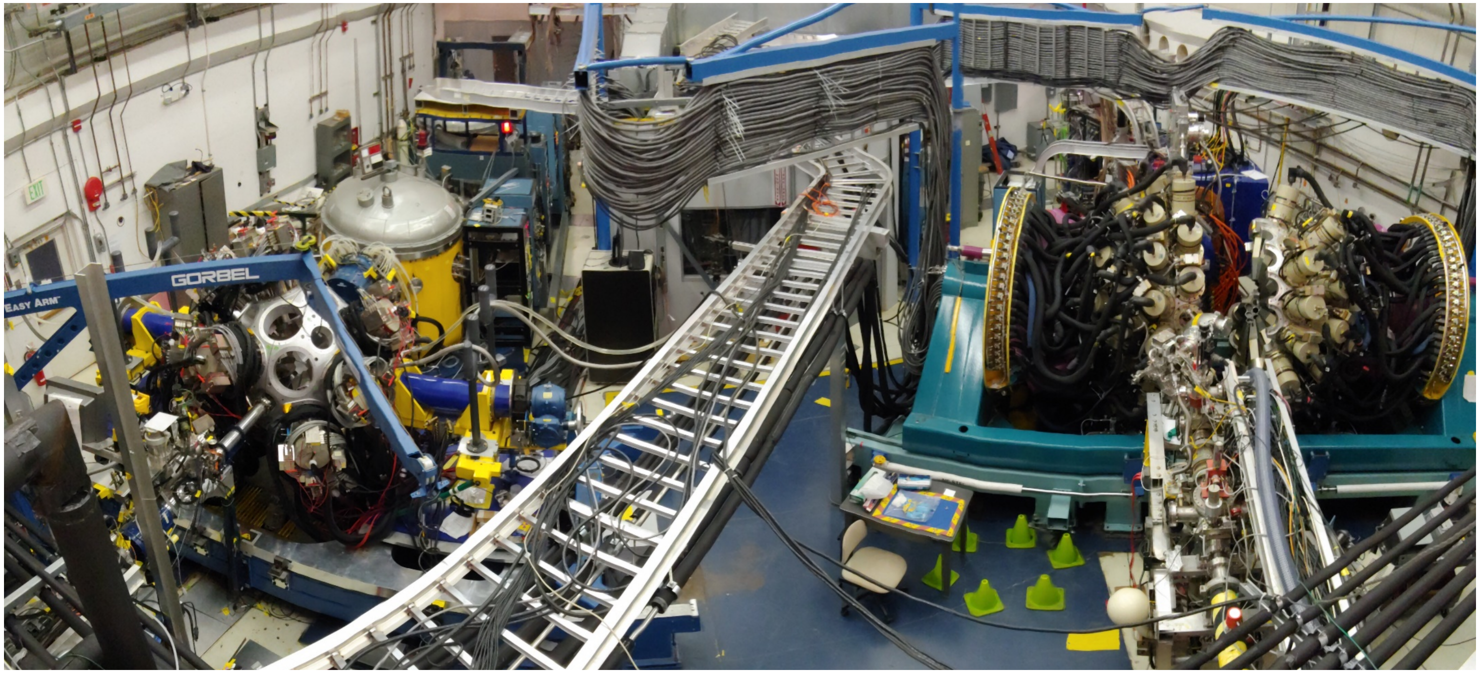
Workshop on Nuclear Astrophysics Opportunities at ATLAS, 2019



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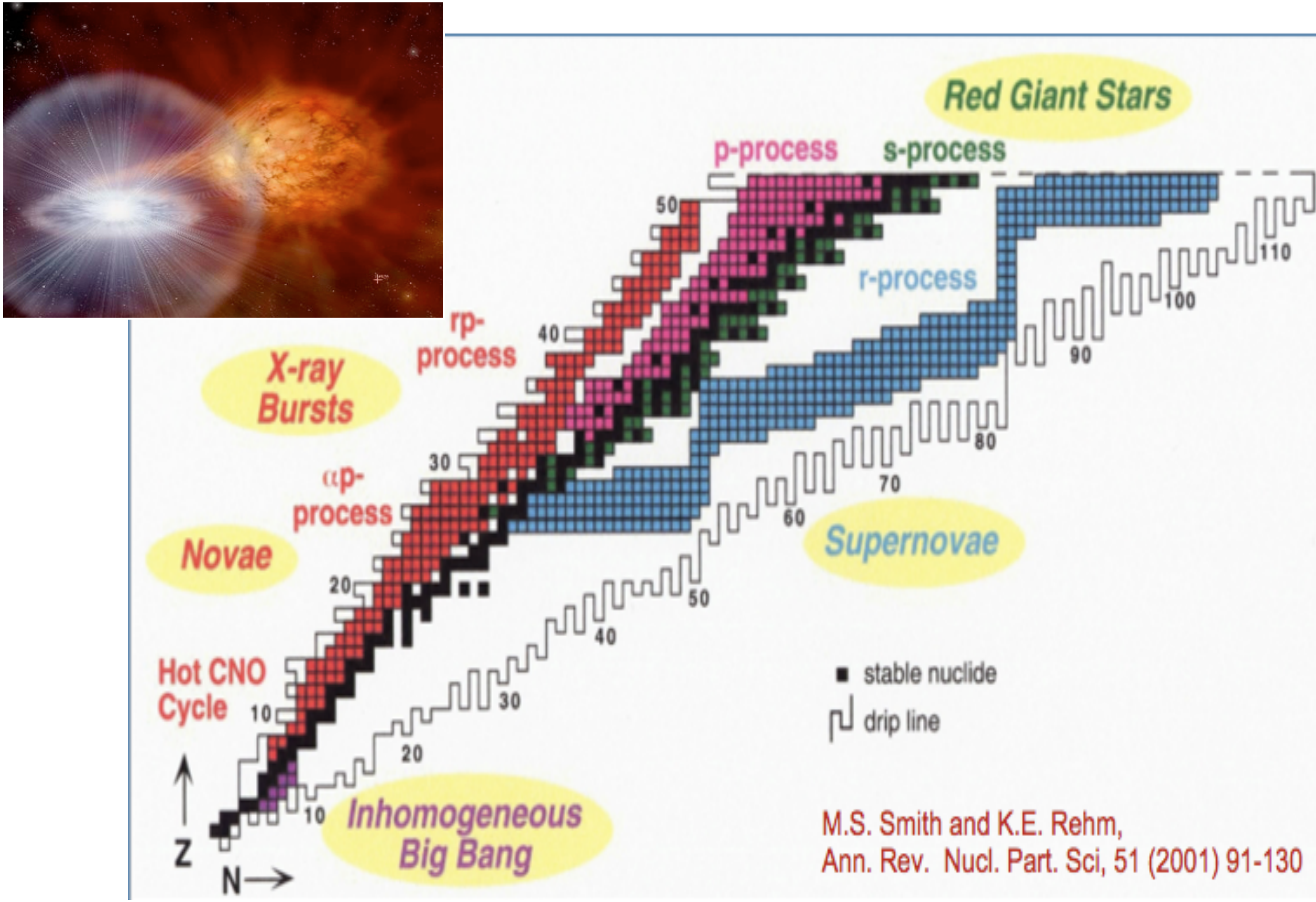
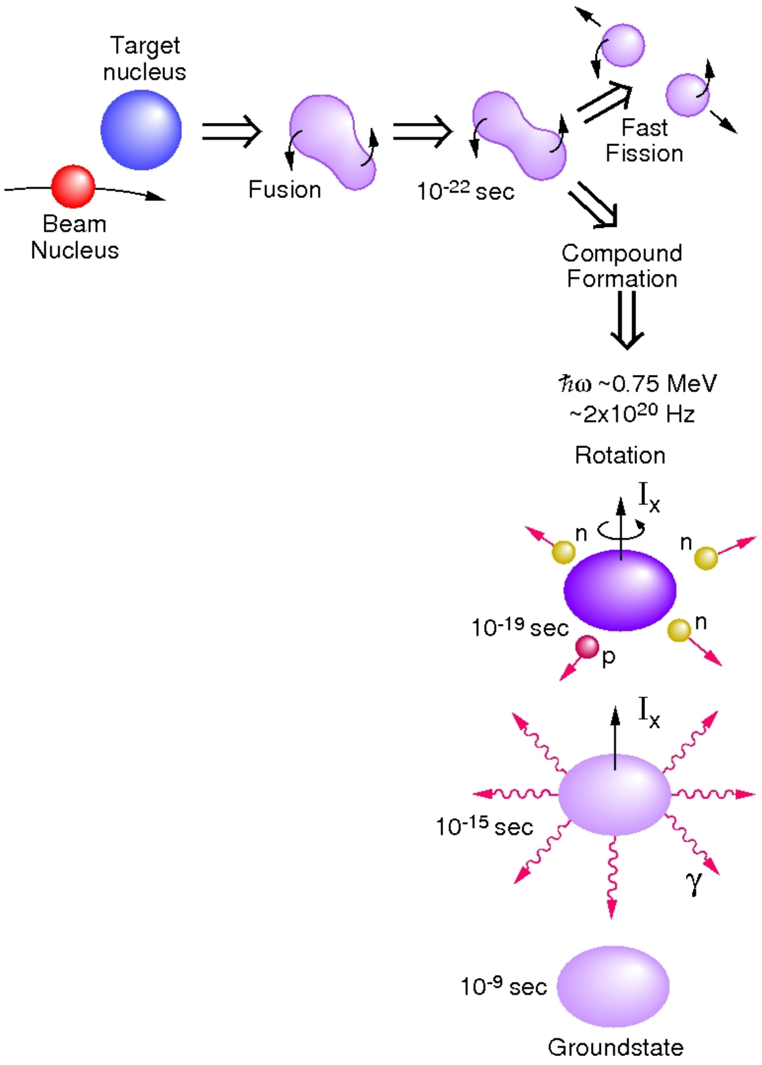
Astrophysical Motivation



Indirect Measurements : Gamma-ray Spectroscopy (1)

Modern γ-ray spectroscopy techniques provide the means to obtain **precise resonance energies** and **spin-parity assignments**.



Nuclei of interest produced in **fusion-evaporation reactions**, typical *1n* and *2n* evaporation channels of interest.

Challenging for astrophysical nuclei as key levels are **proton unbound** and (usually) **highly non-yrast**

Indirect Measurements : Gamma-ray Spectroscopy (2)

Here, we focus solely on resonant proton radiative capture reactions and low-energy resonances [i.e. (p,γ) and $E_r \le 500$ keV].

$$N_A\langle\sigma\upsilon\rangle = \frac{1.5399\times10^{11}}{(\mu T_9)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605E_r/T_9}$$

RESONANCE ENERGY

$$E_r = E_x - S_p$$

RESONANCE STRENGTH

$$\omega\gamma = \left(\frac{2J_r+1}{(2j_0+1)(2j_1+1)}\right)\frac{\Gamma_a\Gamma_\gamma}{\Gamma_a+\Gamma_\gamma} \approx \omega\Gamma_p$$

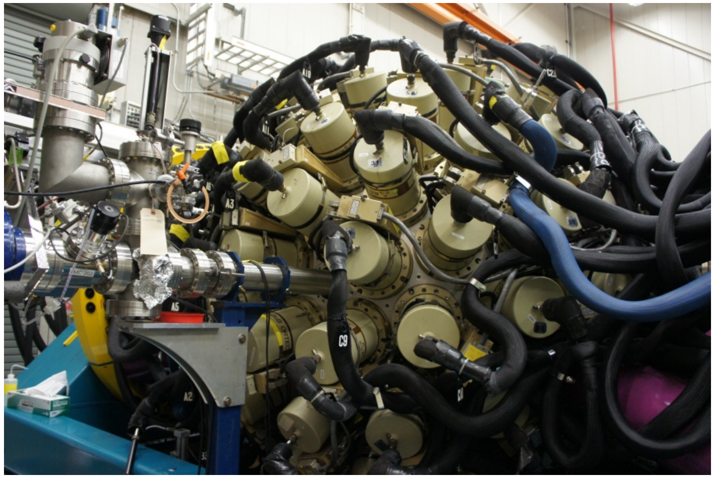
$$\Gamma_p = 2\cdot\frac{\hbar^2}{\mu R^2}\cdot P_l\cdot C^2S\cdot\theta_p^2$$

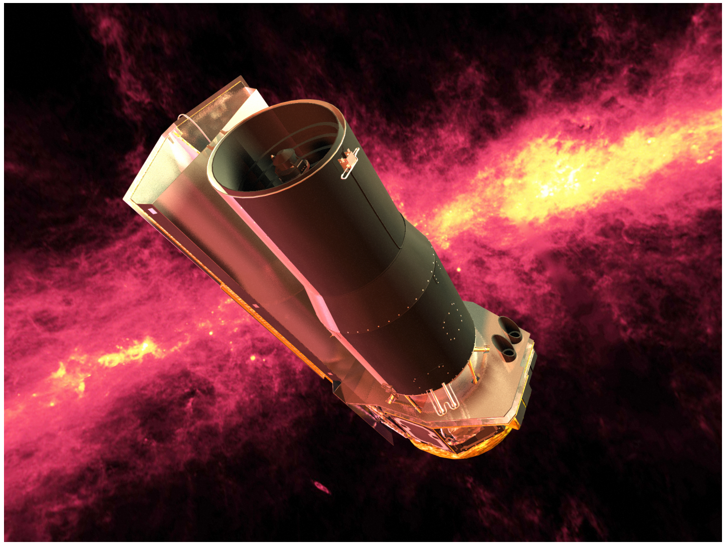
Measurements of Key Astrophysical Nuclei with Gammasphere

Programme of studying sd-shell nuclei with Gammasphere, e.g.

Destruction of the cosmic gamma-ray emitter ^{26}Al

- Low-lying resonances dominate the rate in Wolf-Rayet and AGB stars
- High-spin states in ^{27}Si key due to 5^+ ground state of ^{26}Al





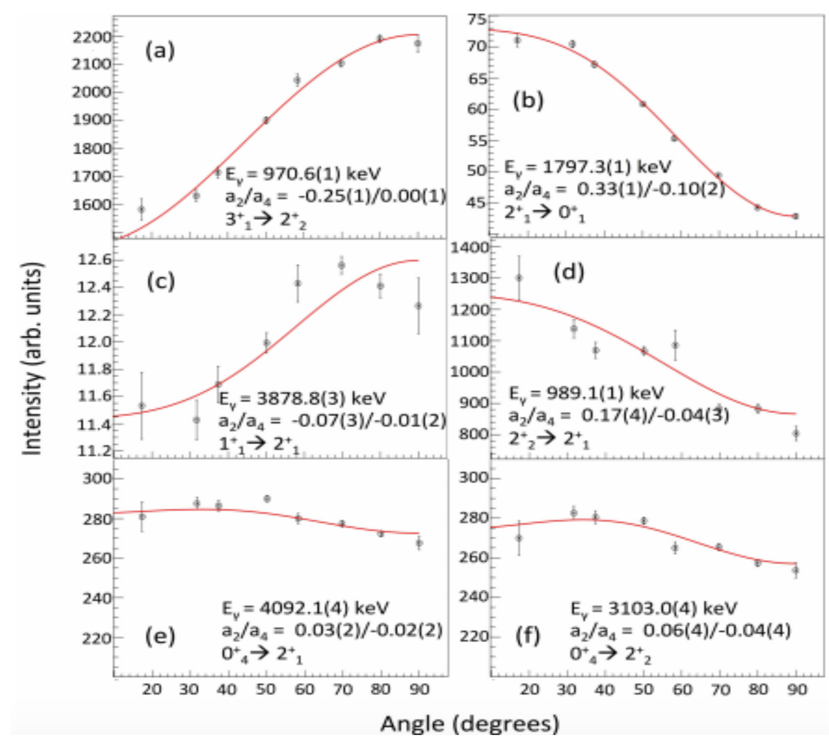
G. Lotay *et al.,* Phys. Rev. Lett **102,** 162502 (2009)
G. Lotay *et al.,* Phys. Rev. C **84,** 135802 (2011)

Measurements of Key Astrophysical Nuclei with Gammasphere

Programme of studying sd-shell nuclei with Gammasphere, e.g.

Level Structure of ^{26}Si

- The ^{25}Al(p,γ)^{26}Si reaction is a crucial link that bypasses the production of the ^{26}Al ground state.
- Important low-spin states populated with light-ion induced reactions.



D. Seweryniak Phys. Rev. C **75** 062801(R) (2007)

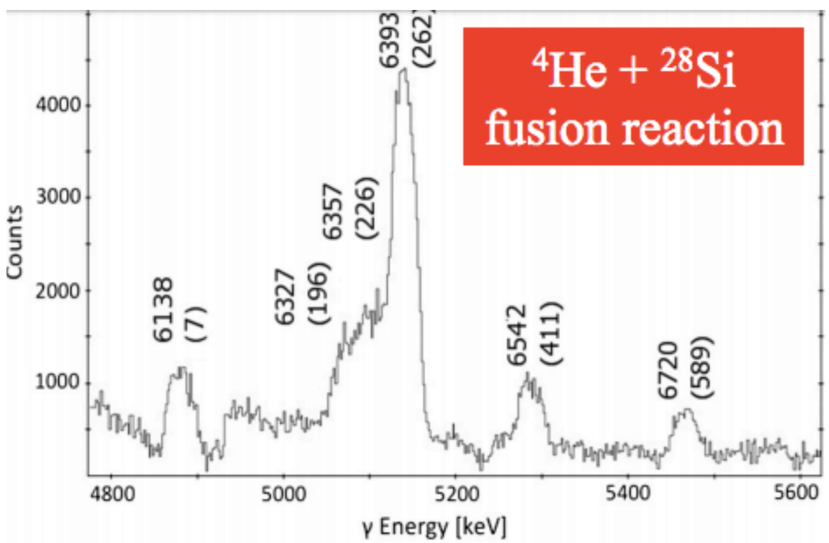
D. T. Doherty *et al.*, Phys. Rev. C **90** 035808 (2015)

Measurements of Key Astrophysical Nuclei with Gammasphere

Programme of studying sd-shell nuclei with Gammasphere, e.g.

Level structure of ^{31}S and key resonances for ONe novae

- Gateway reaction for the production of heavy elements in ONe nova explosions
- New states identified when employing a light-ion projectile
- Suggested the dominance of negative parity states



D. G. Jenkins *et al.*, Phys. Rev. C **73**, 065802 (2006)

D. T. Doherty *et al.*, Phys. Rev. Lett **108** 262502 (2012) and Phys. Rev. C **89** 045804 (2014)

Measurements of Key Astrophysical Nuclei with Gammasphere

As well as a host of other studies

- The ^{23}Na-^{23}Mg mirror pair and astrophysical implications (Jenkins PRC 2013)
- ^{30}S of interest for both Classical Novae and X-ray bursts (Lotay PRC 2012)
- Neutron unbound states in ^{26}Mg relevant to the ^{22}Ne(α,n) reaction for the s-process (Lotay, Doherty, Seweryniak EPJA Lett *Accepted*)
- Plus data under analysis for key isotopes ^{26}Al, ^{30}P, ^{60}Zn …

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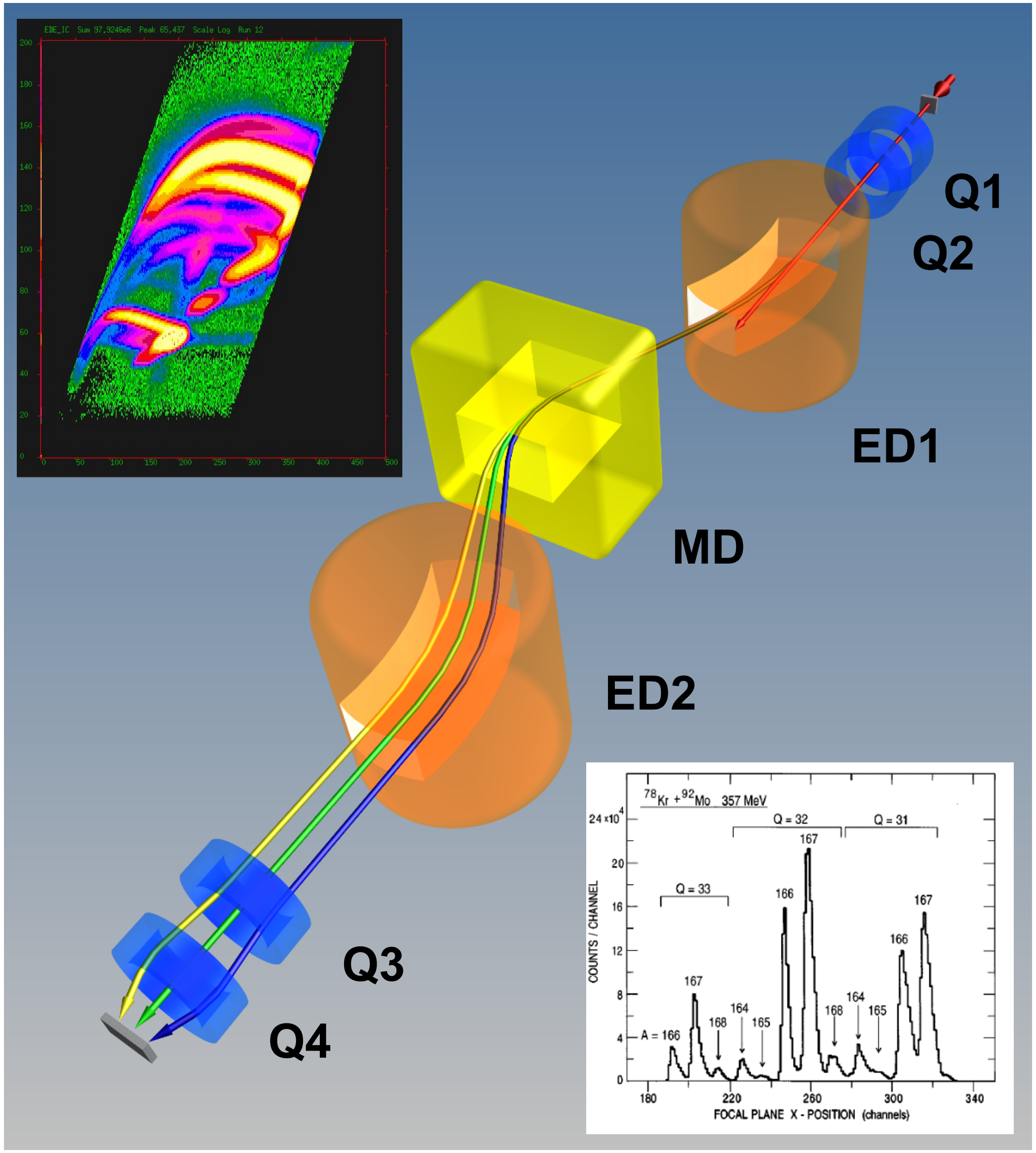
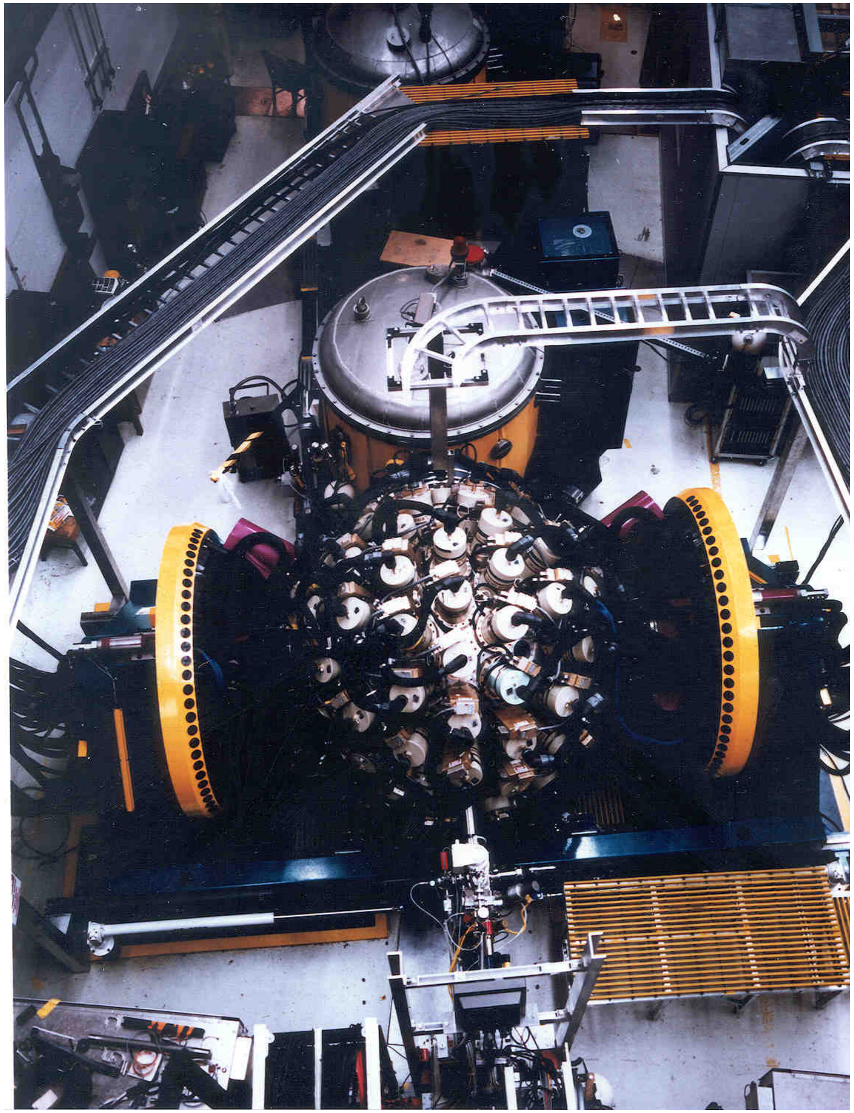
However, in many cases additional channel selectivity is required

Argonne Fragment Mass Analyzer (FMA)

Mass resolution:
 dM/M ~1/350
Angular acceptance:
8 msr (max)
Energy acceptance:
 DE/E= +/-20%
M/Q acceptance:
D(M/Q)/(M/Q) = 10%
Flight path 8.2m
Max(Br)=1.1 Tm
Max(Er)=20 MV
Can be rotated off 0 degrees
Can be moved along the axis
Different focusing modes



GAMMASPHERE + FMA

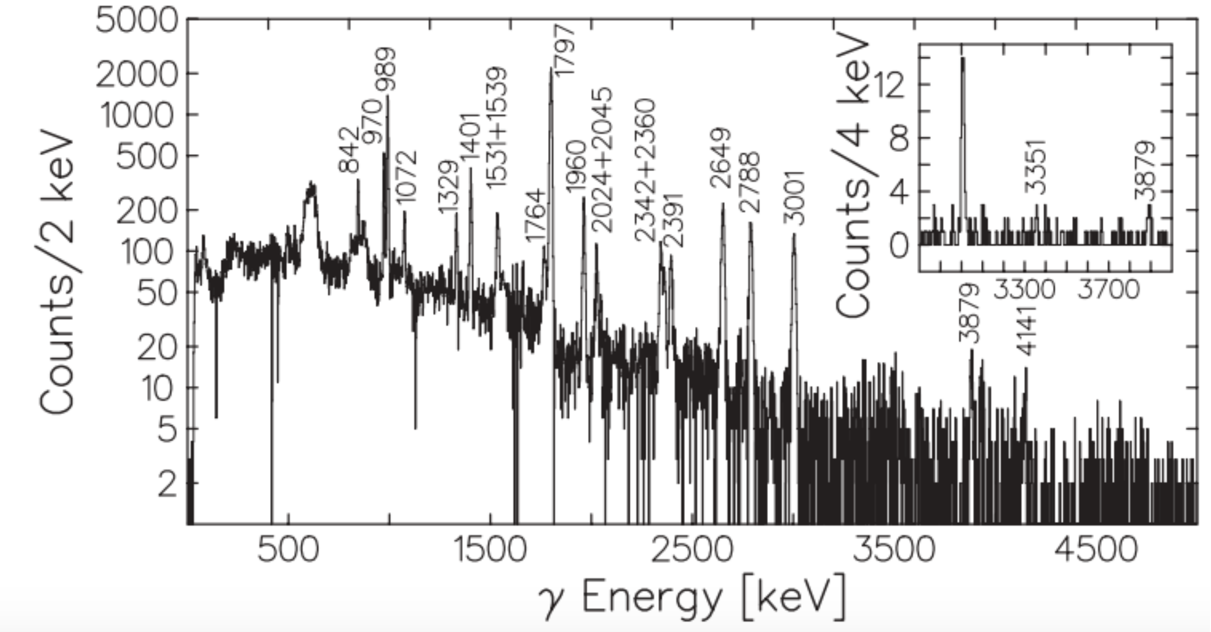


Important component of the experimental program at ATLAS since its commissioning in 1992 (~200 papers)

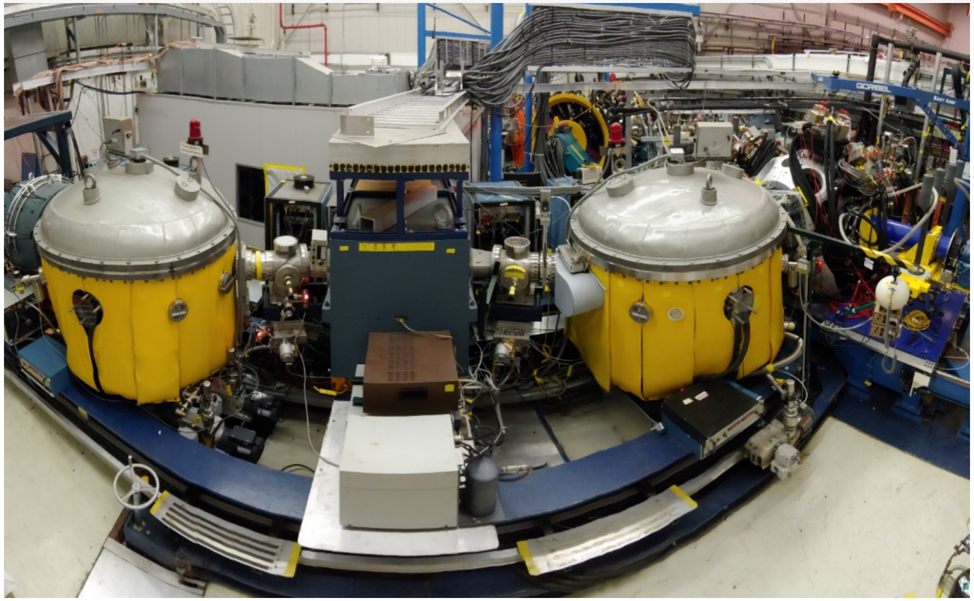
- Proton drip-line
  - Proton emitters
  - new α emitters
  - In-beam γ rays
- ^{101}Sn
- Transfermium nuclei: No, Lr, Rf
- Transfer on **^{56}Ni and ^{44}Ti**
- …

Fusion-evaporation, deep-inelastic, transfer reactions

Nuclear Astrophysics with GAMMASPHERE + FMA



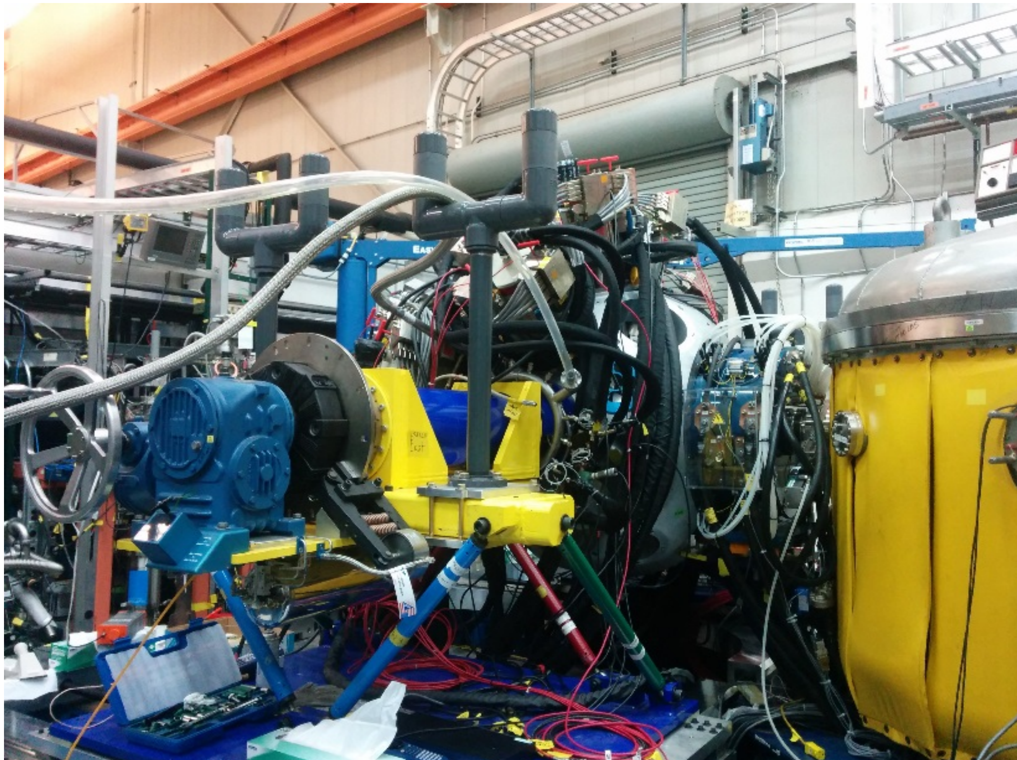
Spectrum obtained in coincidence with ^{26}Si residues



Limited FMA efficiency

- modest solid angle – 2-8 msr
- small M/Q acceptance – 7%

Nuclear Astrophysics with GRETINA + FMA

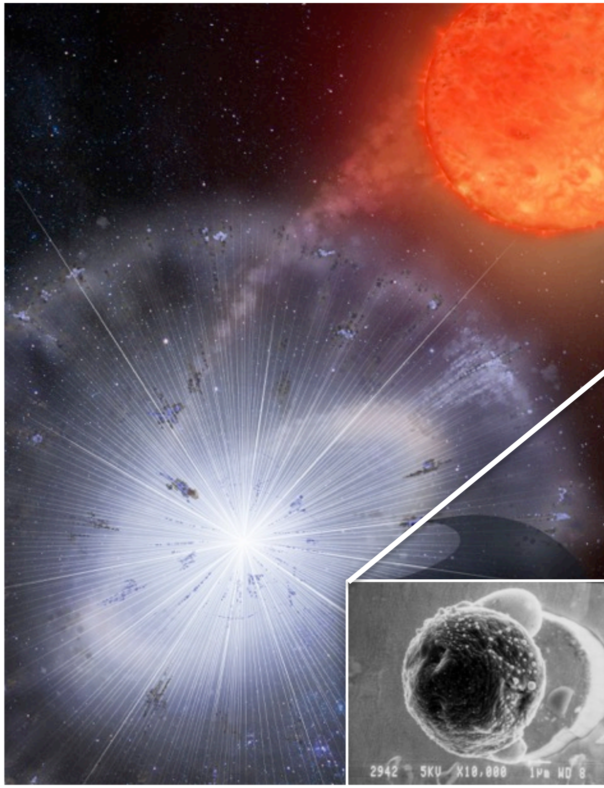


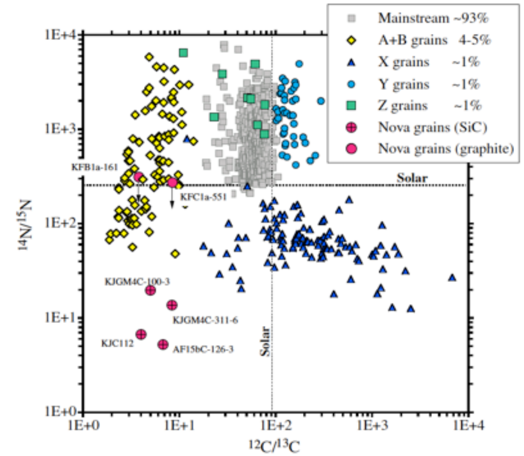
New FMA entrance quadrupole doublet

Solid angle **~10-12 msr** for FMA/Gretina compared to **~2 msr** with FMA/GS

=> **Key for weak channels**

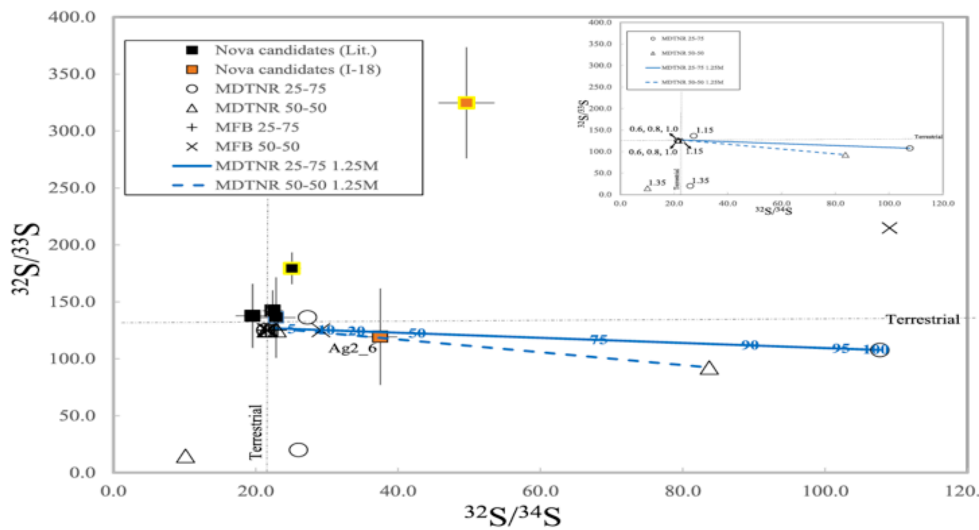
Astronomical Observations – Presolar Grains



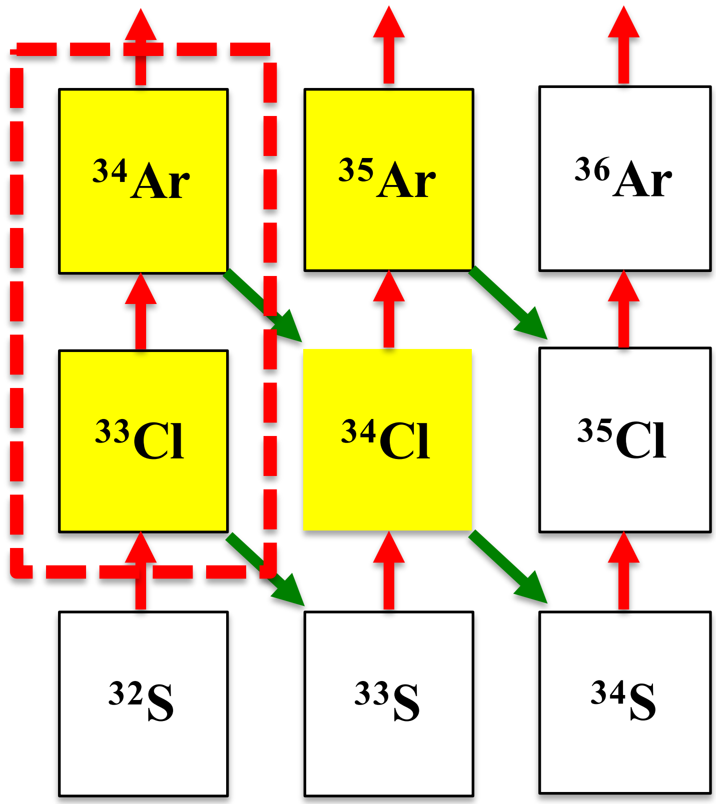


Discovery of presolar grains has provided a versatile tool to study nucleosynthesis.

In order to utilize the latest data, it is necessary to accurately identify the origin of presolar grains using markers (e.g. ^{30}Si)



Novae Nucleosynthesis



Proton captures on stable sulfur isotopes well-studied [A. Parikh *et al.*, PLB **737**, 314 (2014) & S. Gillespie *et al.*, PRC **96**, 025801 (2017)]

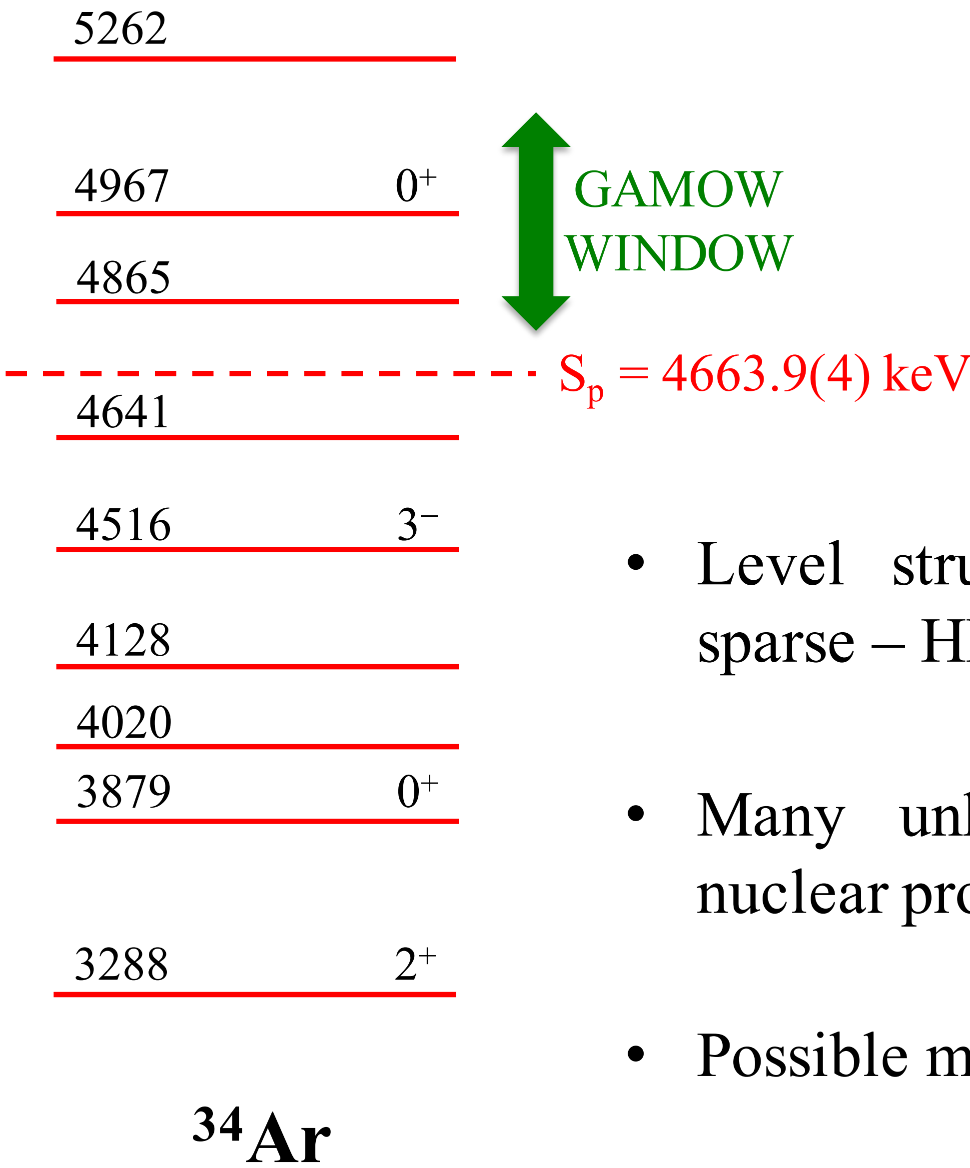
However, proton capture rates on unstable chlorine isotopes are almost entirely unknown – HF (10^4 uncertainty)

C. Iliadis *et al.*, Astrophys. J. Suppl. Ser. 142, 105 (2002).

VARIED 175 REACTIONS THROUGH THEIR ASSOCIATED UNCERTAINTIES

Uncertainties in the ^{33}Cl(p,γ)^{34}Ar reaction were found to result in ^{33}S and ^{34}S abundance variations of ~18 and ~3, respectively

Previous Studies of ^{34}Ar



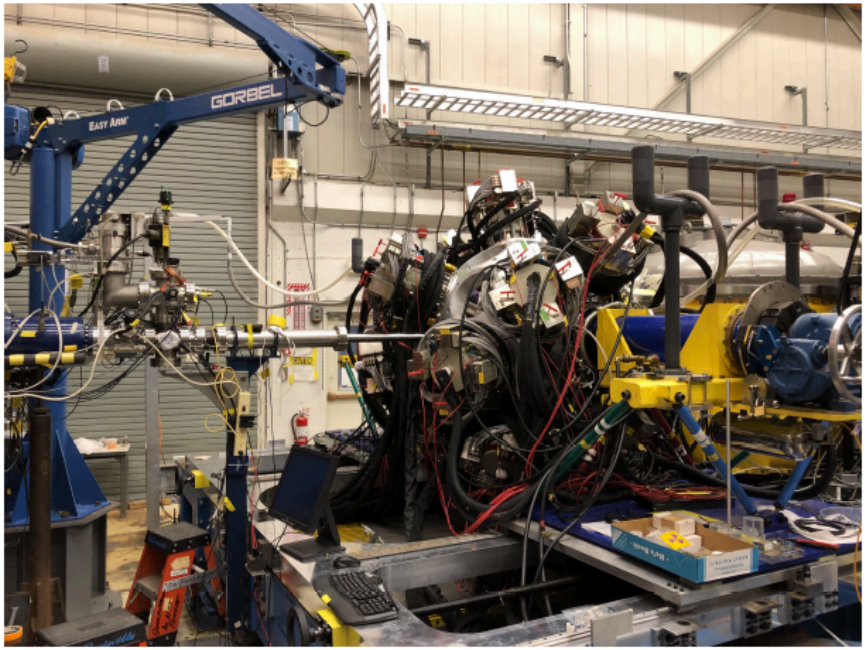
^{32}S(^{3}He,*n*) – [R.A.I. Bell *et al.*, NPA 222, 477 (1974)]

^{36}Ar(*p,t*) – [A.M. Long *et al.*, PRC 97, 054613 (2018)]

- Level structure of ^{34}Ar is relatively sparse – HF clearly inappropriate
- Many unknowns in relation to the nuclear properties of excited states
- Possible missing levels

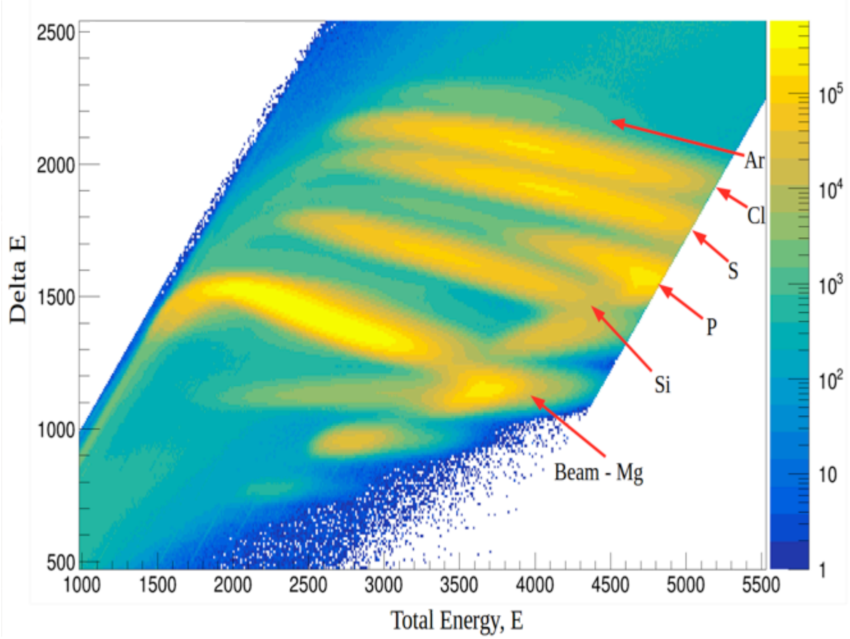
Gamma-ray Spectroscopy Study of ^{34}Ar @ ANL

- Used 95 MeV beam of ^{24}Mg ions produced by the Argonne ATLAS accelerator to bombard a ~200 μg/cm^2 thick target of ^{12}C target to populate excited states in ^{34}Ar via ^{12}C(^{24}Mg,2*n*)

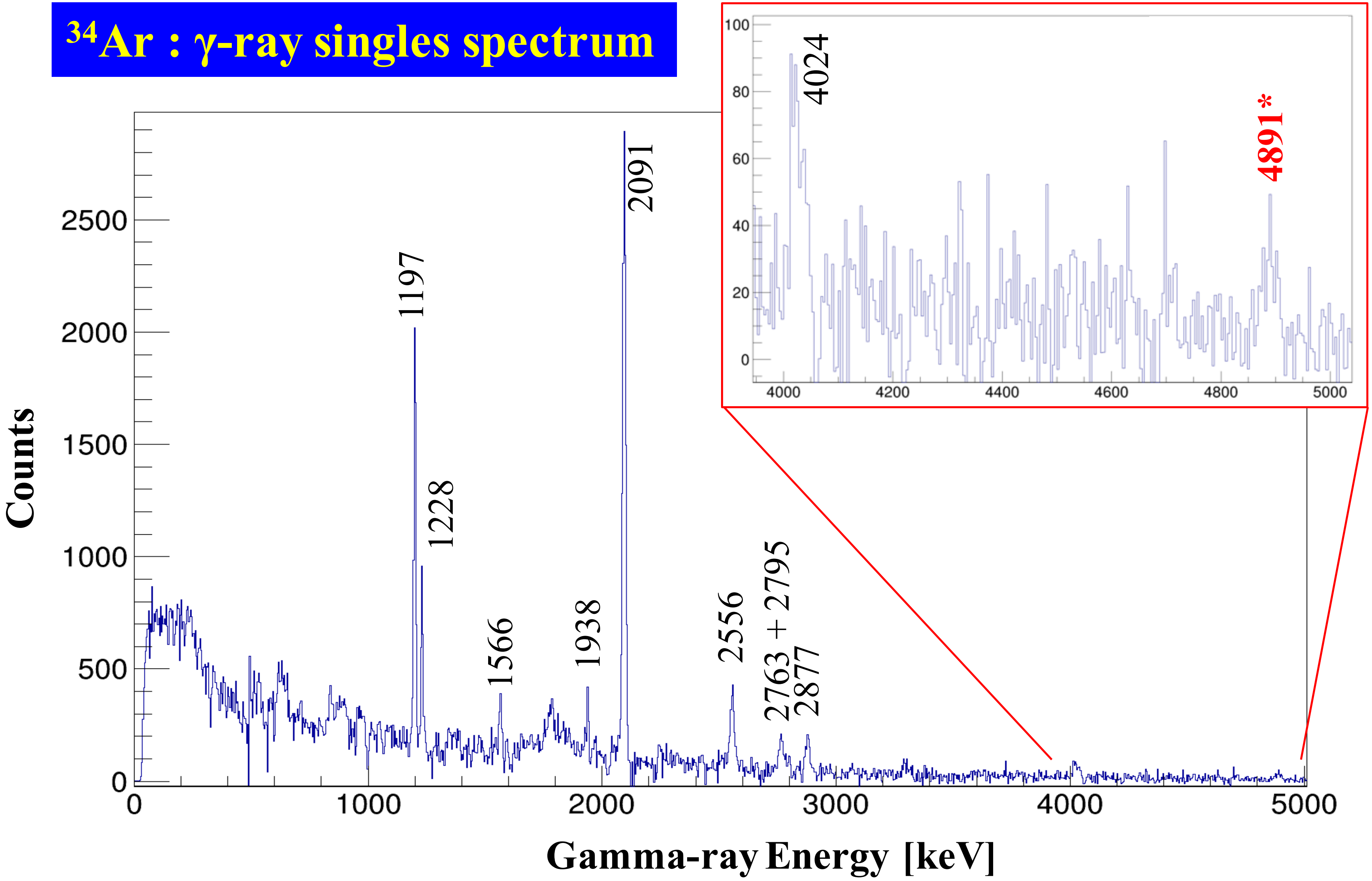


The Argonne Fragment Mass Analyser used to Transmit *A* =34 recoils

GRETINA γ-ray tracking array used to detect prompt γ rays at the target position



Gamma-ray Spectroscopy Study of ^{34}Ar @ ANL



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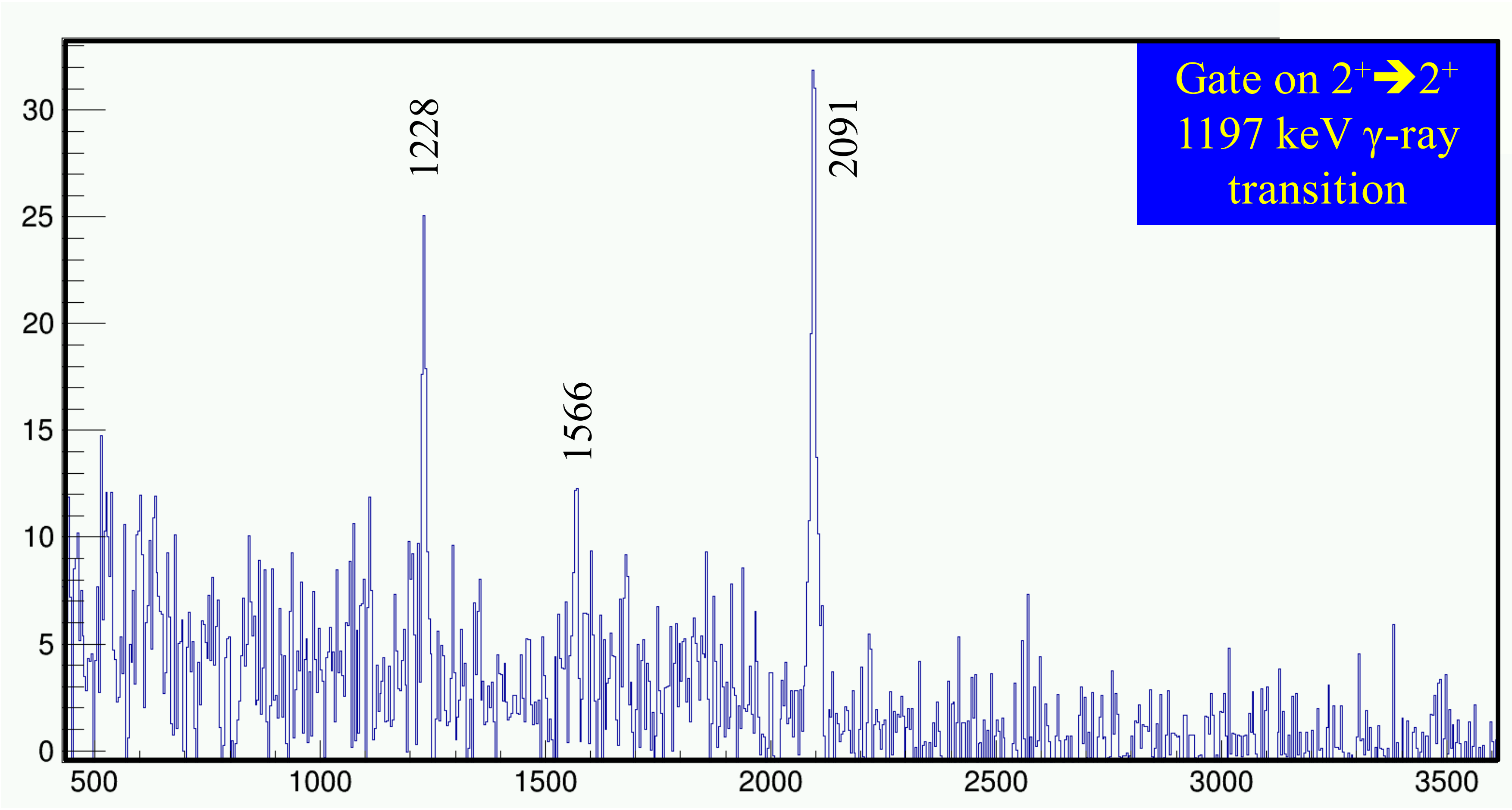
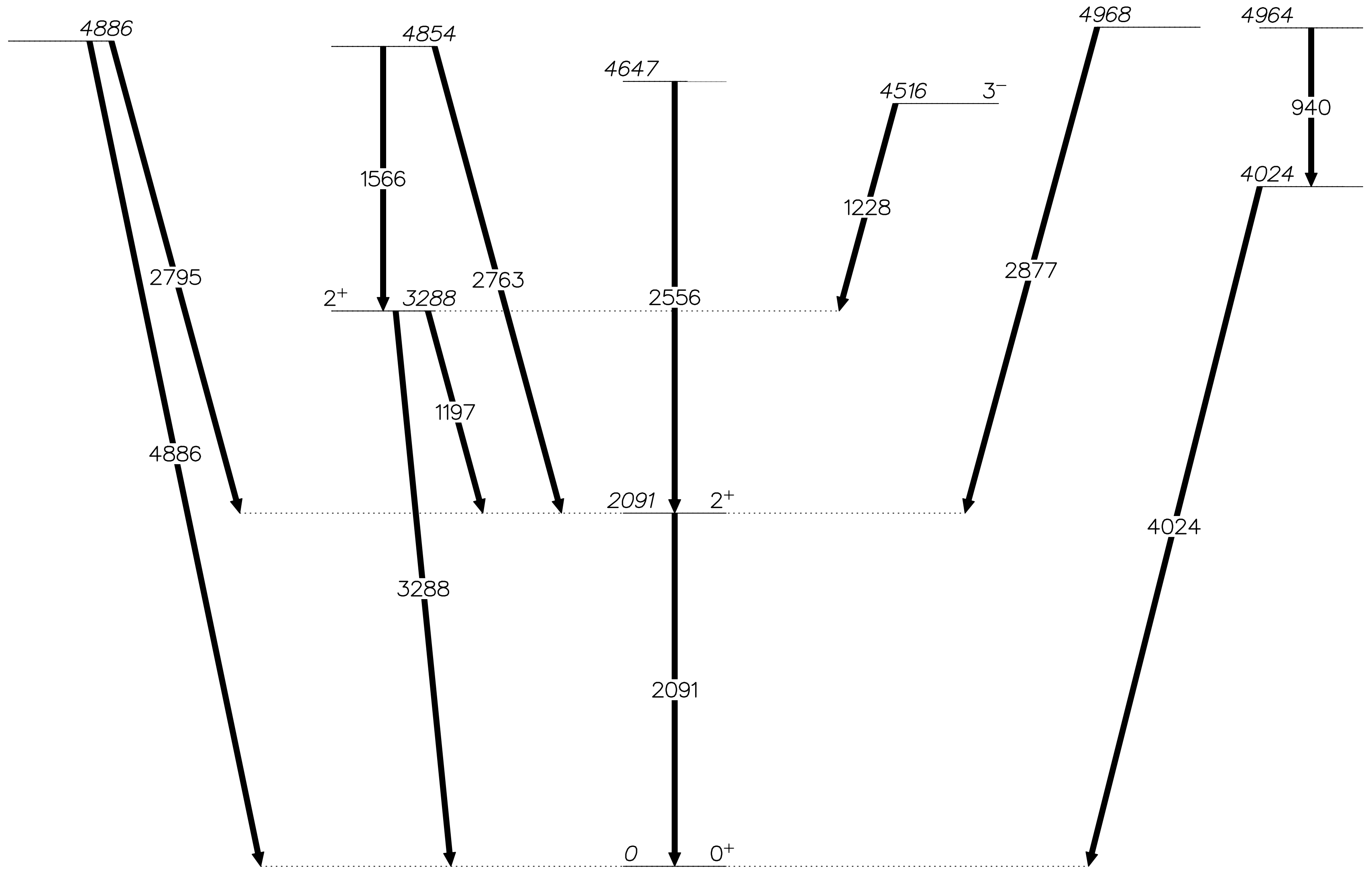
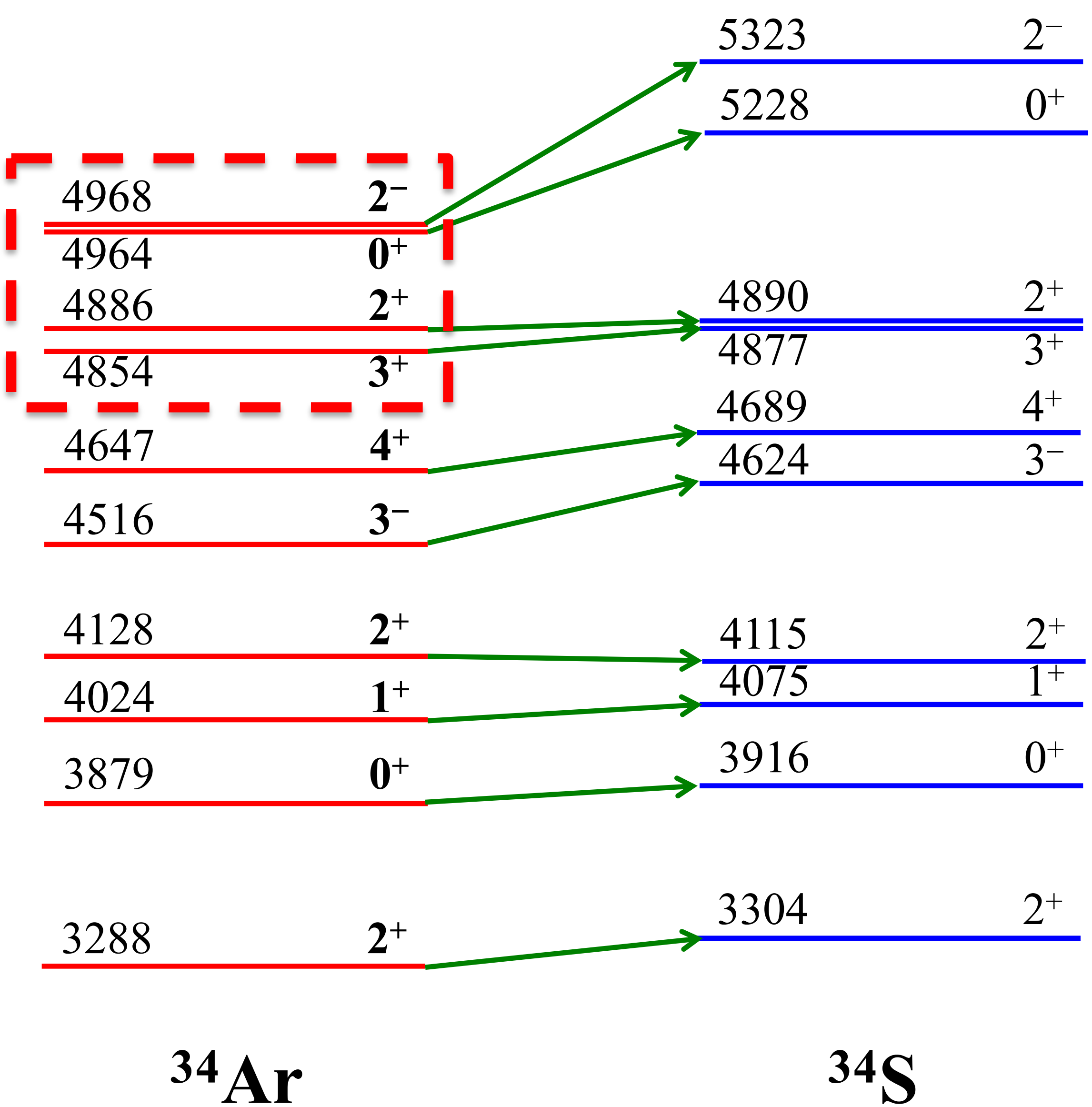


Partial Level Scheme of ^{34}Ar



Mirror Nucleus Comparisons

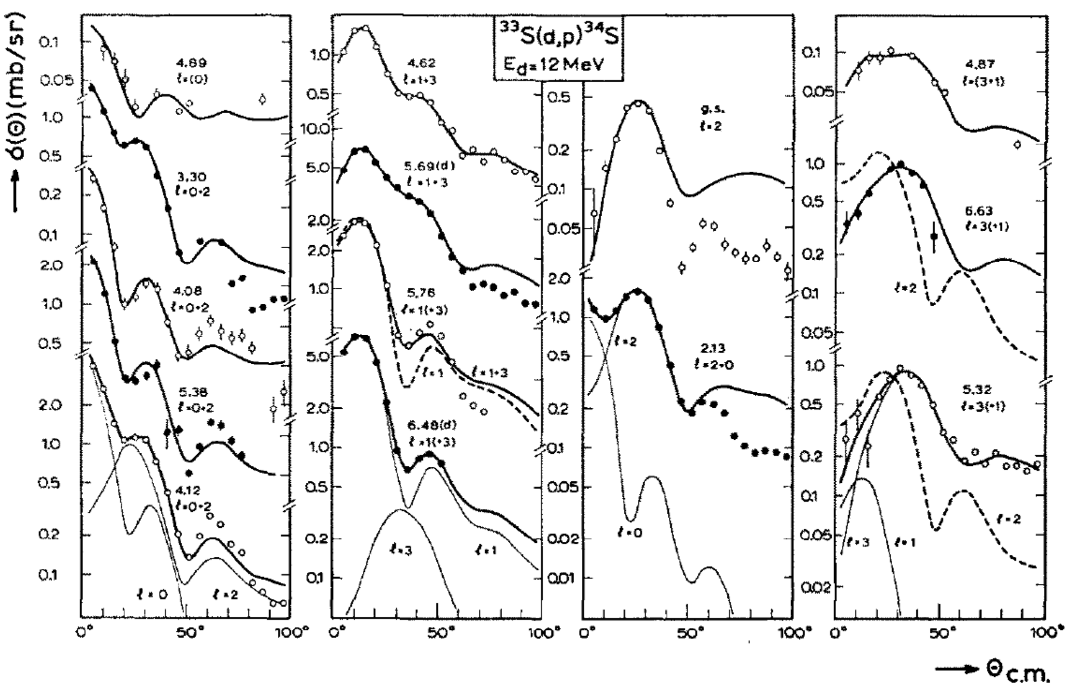


Mirror Nucleus Comparisons

- We can also obtain the resonance strengths from the mirror nucleus ^{34}S

$$Strength = \frac{(2J_R + 1)}{(2J_T + 1)(2J_P + 1)} \cdot C^2 S \cdot \Gamma_{s.p.}$$

PROTON SPECTROSCOPIC FACTOR



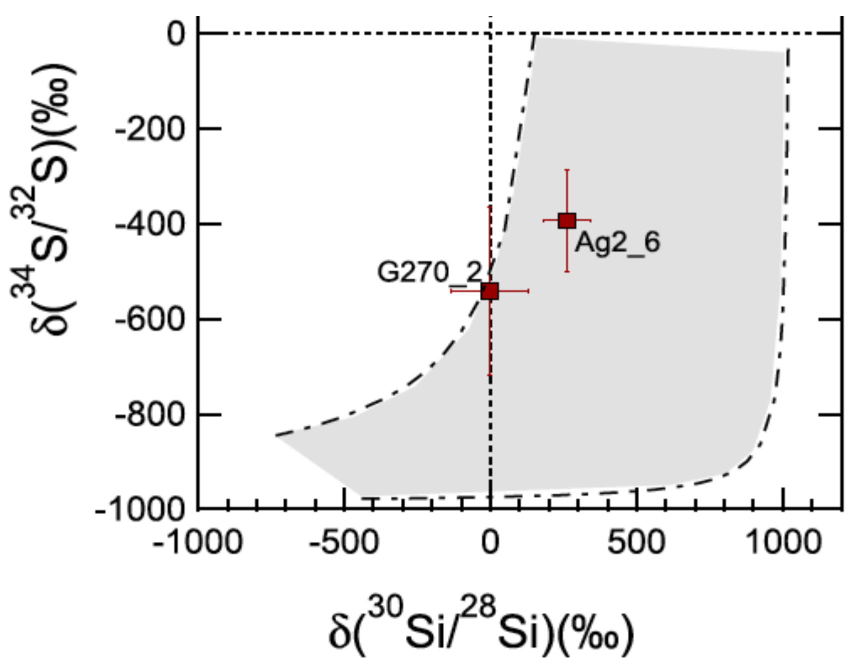
ADOPT NEUTRON SPECTROSCOPIC FACTORS of mirror analog states obtained via ^{33}S(d,p)^{34}S transfer

$^{33}Cl(p,\gamma)^{34}Ar$ Stellar Reaction Rate

E_x [keV]	E_r [keV]	J^π	l_p	$\omega\gamma$ [meV]
4631	-	4^+	2	-
4854	190	3^+	2	$\sim 6 \times 10^{-8}$
4886	222	2^+	0	$\sim 2 \times 10^{-4}$
4964	300	0^+	2	$\sim 3 \times 10^{-6}$
4968	304	2^-	1	$\sim 6 \times 10^{-3}$

A number of resonances identified. Analysis has reduced uncertainties in the astrophysical $^{33}Cl(p,\gamma)^{34}Ar$ reaction rate by ~3 orders of magnitude

Preliminary analysis indicates that rate is significantly lower than expected and points to 2 specific presolar grains as being likely nova candidates



Final answer relies on ^{34}S abundances. Stay tuned for LNL experiment $^{36}Ar(d,t)^{35}Ar$ [July??]

Future Perspectives and More Exotic Cases

GRETINA coupled to the FMA represents an extremely powerful tool for studying exotic astrophysical nuclei close to the proton drip line.

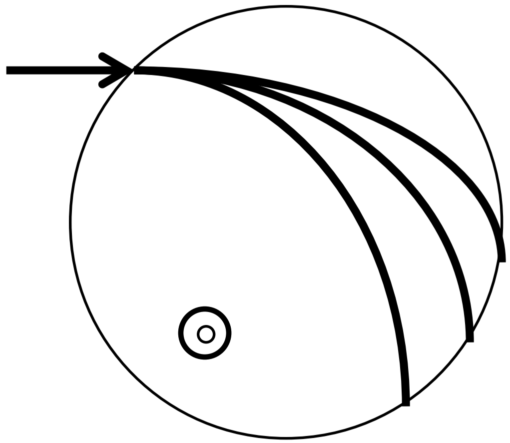
For extra selectivity

- **RDT studies with betas** (extremely difficult)
- **New focal plane detectors** (Bragg detector, MRToF)

Other separators..

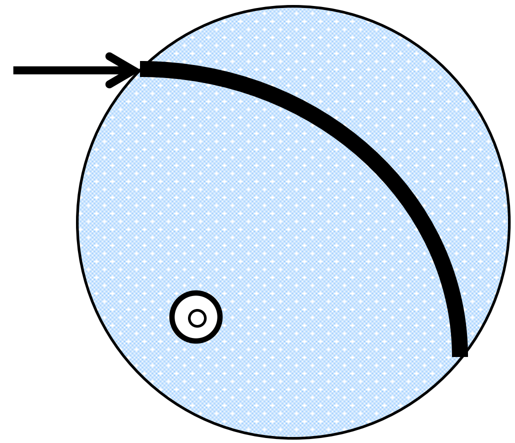
Gas-Filled separator - Principle of Operation

vacuum



$B\rho_i = p/q_i$

gas



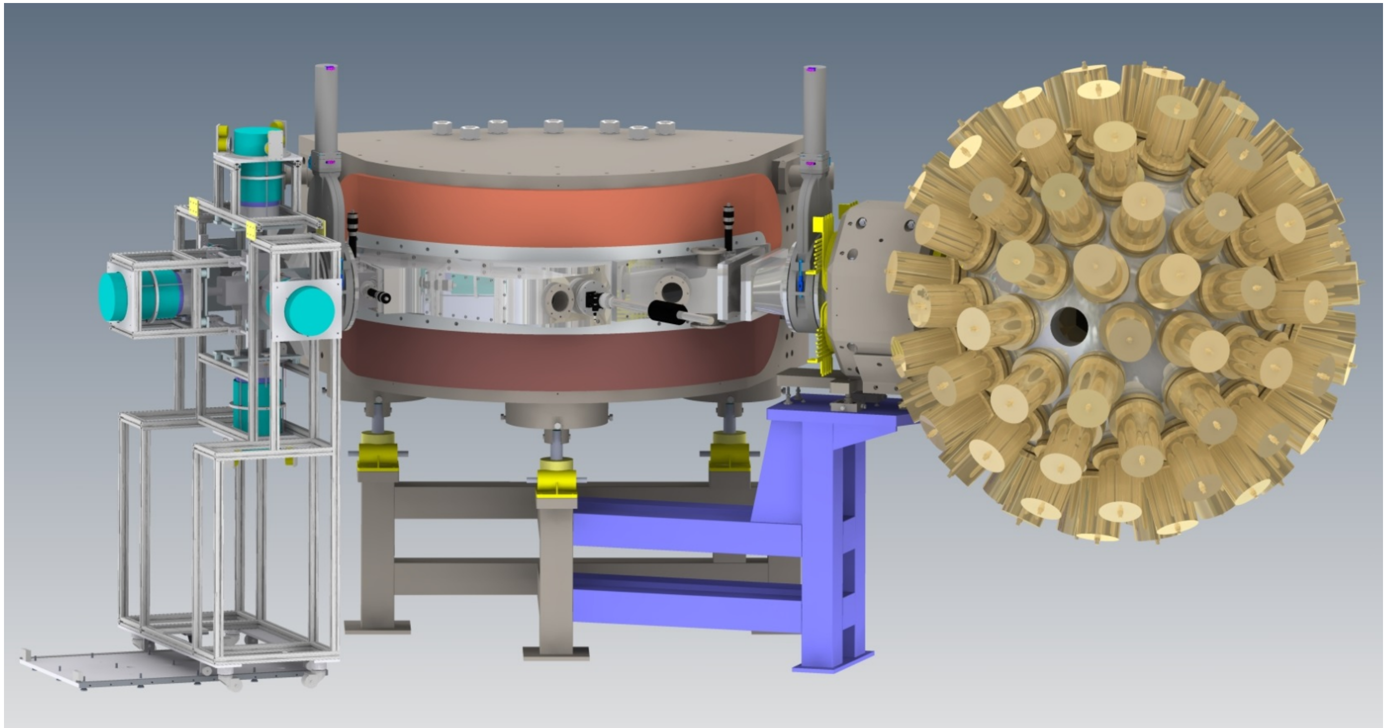
$B\rho = p/q_{ave}$

$q_{ave} \sim (v/v_0)\ Z^{1/3}$

$B\rho \sim 0.0227\ A/Z^{1/3}$ [Tm]

Charge-state focusing

AGFA Features – 1st gas-filled separator optimised for spectroscopy



Large solid angle

Large target-separator distance - prompt γ-ray spectroscopy with a 4π Ge array

Compact focal plane – efficient decay spectroscopy

Short flight path – short-lived activities

AGFA and Gammasphere

With thanks to

Adam Kennington, Gavin Lotay, Darek Seweryniak

Thank you very much for your attention

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