Radiative capture on a nuclear isomer

– Direct measurement of the ^{26m}Al(p,γ)^{27}Si reaction at DRAGON

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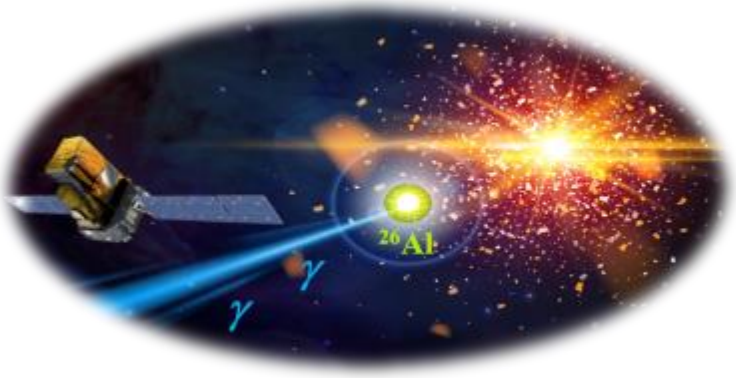
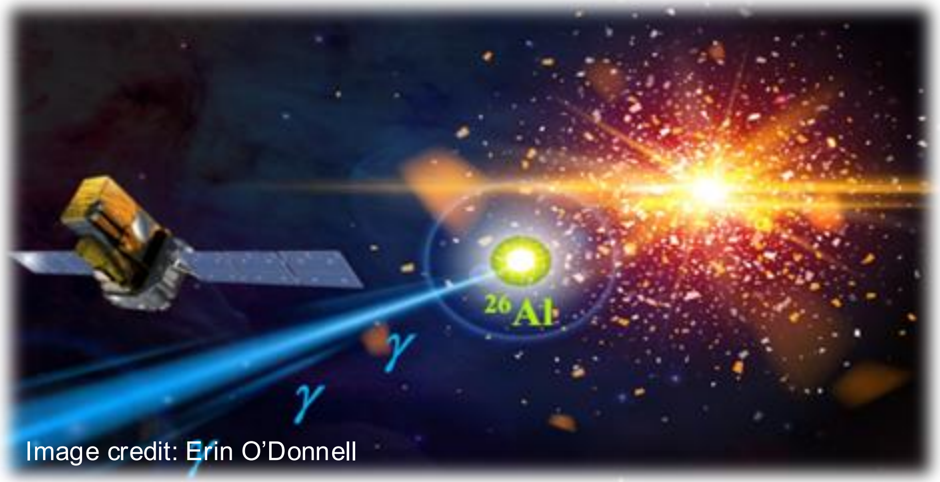
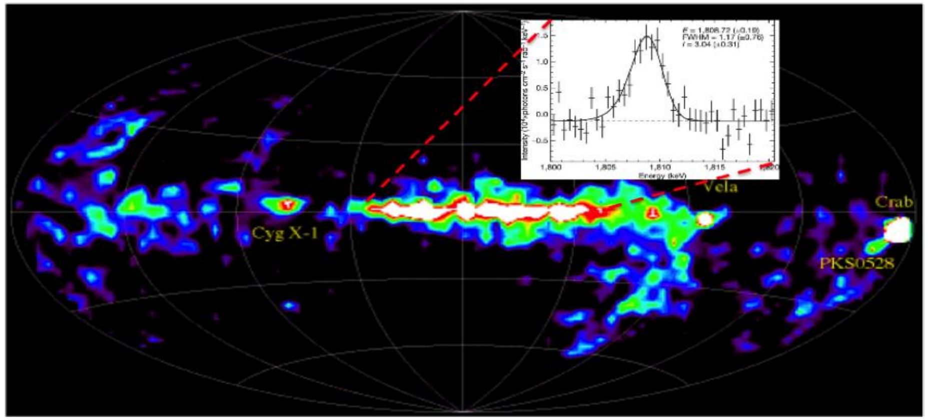


Cosmic γ-ray emitter ^{26}Al



The **radioisotope** ^{26}Al provides insight into the **nature of nuclear processes in stars** in the Milky Way.



- Relatively short half-life (0.72 Myr) provided first direct evidence of **active nucleosynthesis** in our Galaxy (1.809 MeV γ-ray)

➔ Tracer for **star formation!**

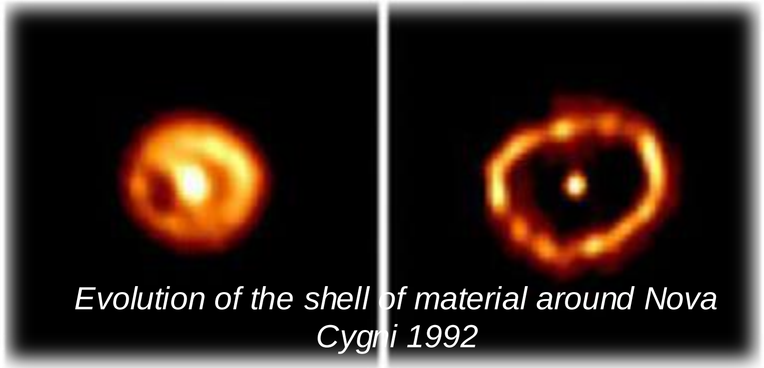
- ^{26}Mg isotopic excesses in **meteorites**

➔ Early Solar System

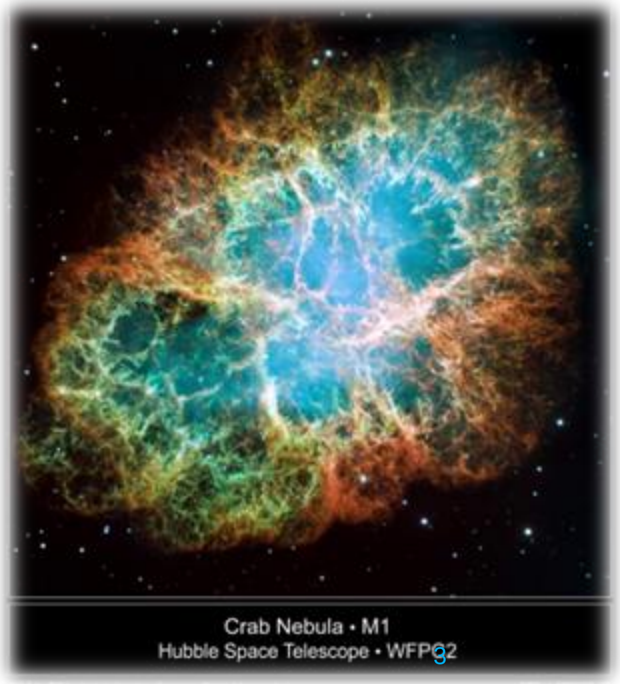
Identifying the main sources of ^{26}Al would have far-reaching implications:
- Circumstances & conditions of the solar system birth
- Strong constraints on the chemical evolution of the Galaxy

However, it's astrophysical origin is still under debate!

The astrophysical origin of ^{26}Al



Evolution of the shell of material around Nova Cygni 1992

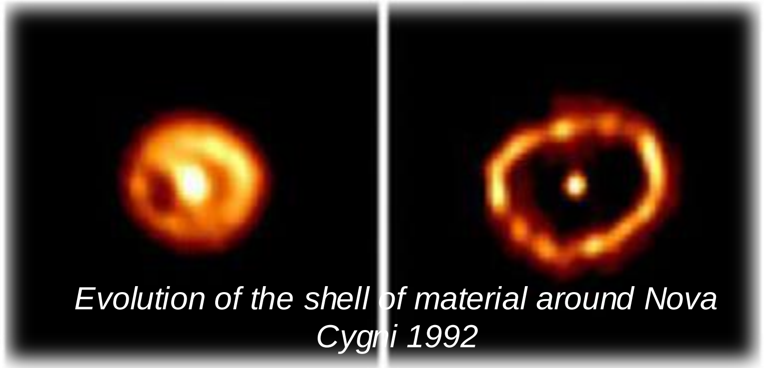


<u>Several stellar sites discussed:</u>

- Massive & very massive stars
  - Wolf-Rayet winds
  - & their final Core-Collapse Supernovae (CCSN)
- Winds of low- & intermediate-mass AGB stars
- Novae ejecta

- ^{26}Al/^{27}Al ratios in **presolar grains** suggest nova or AGB star origin [Bose & Starrfield, APJ. 873, 14 (2019)]
- Satellite missions ➔ massive stars and CCS [R. Diehl et al., Nature (London) 439, 45 (2006)]

The astrophysical origin of ^{26}Al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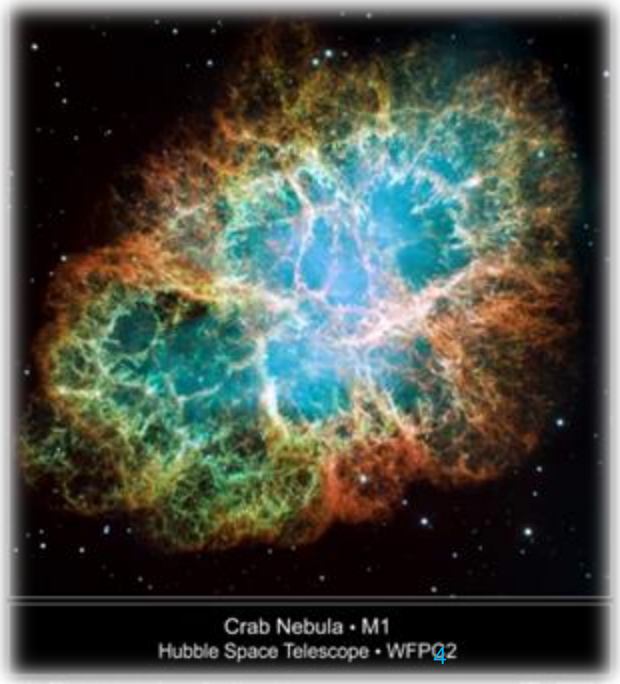

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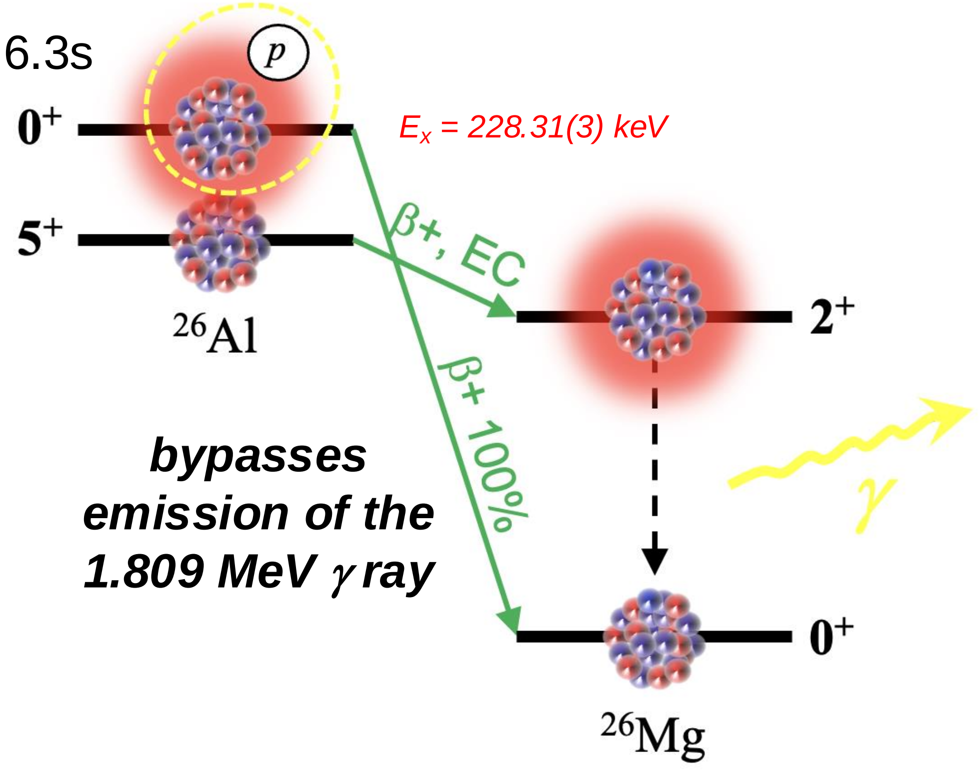
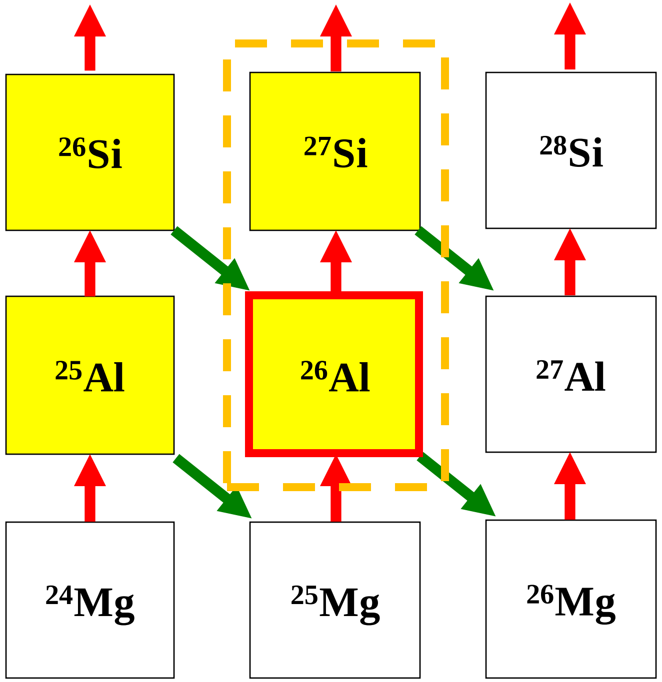
*"To properly interpret the large variety of astronomical and meteoritic data, it is crucial to understand both the **nuclear reactions involved** in the production of ^{26}Al in the relevant stellar sites and the physics of such sites!"*

$^{26m}Al(p,\gamma)^{27}Si$ – Destruction of ^{26}Al

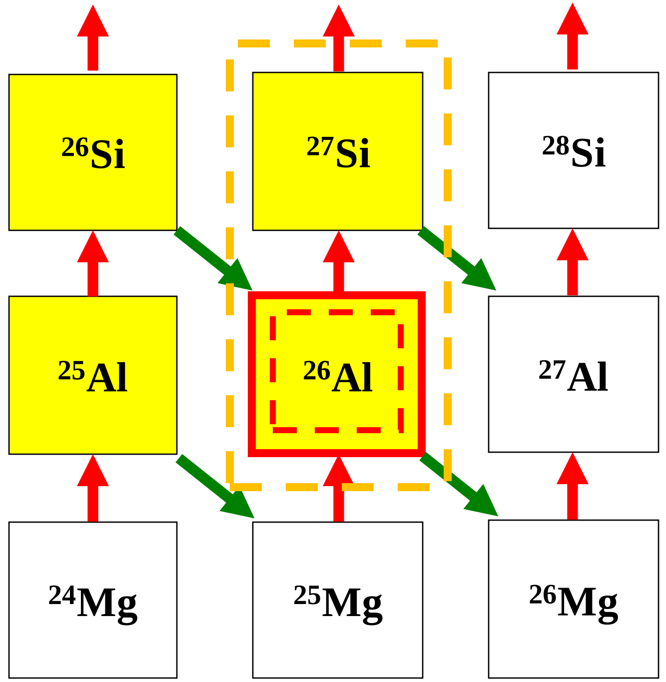
- *Need to understand* ***production & destruction of ^{26}Al*** *in stellar scenarios!*
- Exp. have focused on reactions on nuclear g.s



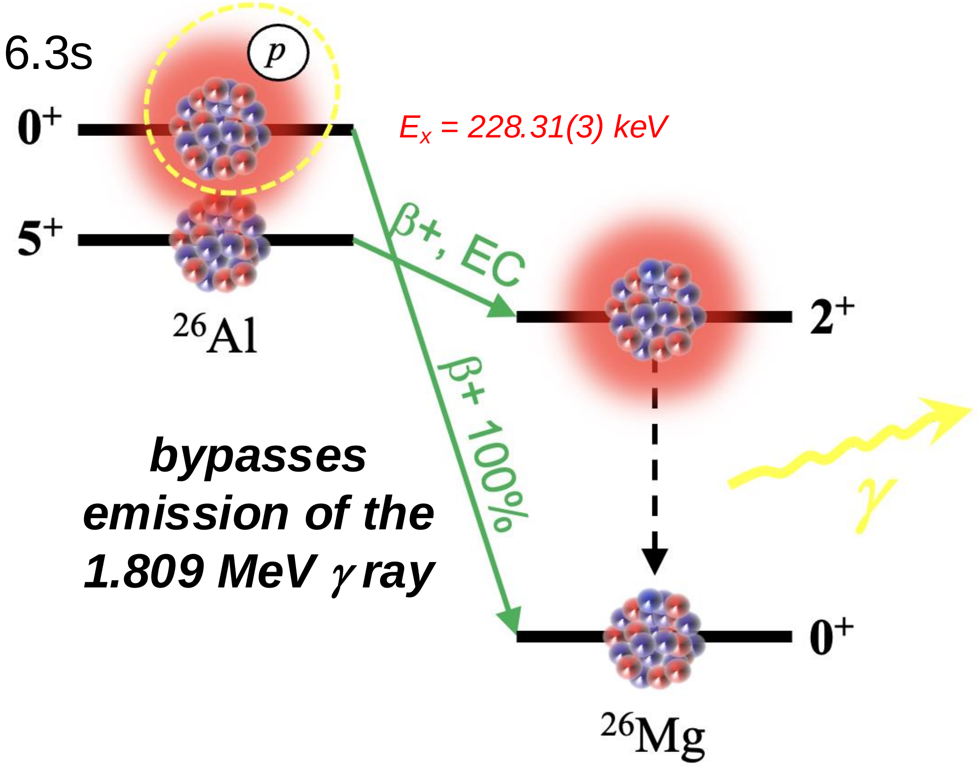


^{26m}Al(p,γ)^{27}Si – Destruction of ^{26}Al

*Nucleosynthesis of ^{26}Al is **complicated by the presence of an isomer** (E_x = 228.31(3) keV)*



Can act as entirely separate nuclei!



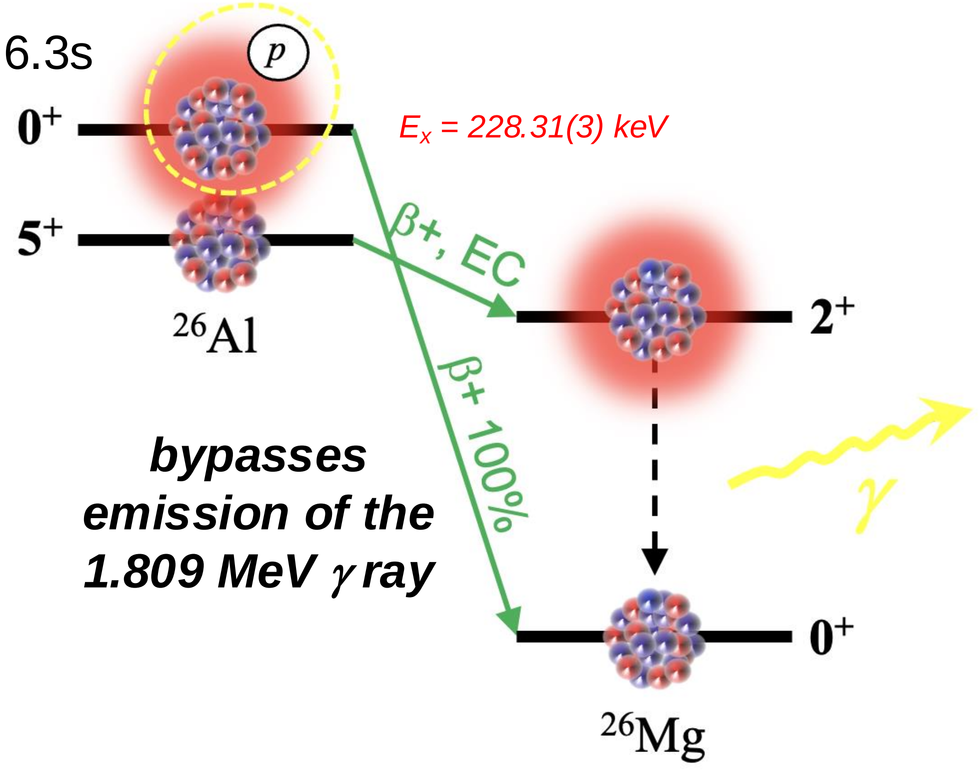
bypasses emission of the 1.809 MeV γ ray

- Proton capture reactions on ^{26m}Al impact all **observational signatures** of ^{26}Al in our universe (directly or indirectly)
- 447-keV resonance thought to **dominate** the entire ^{26m}Al(p,γ) rate for T > 0.3 GK

^{26m}Al(p,γ)^{27}Si – Destruction of ^{26}Al

*Nucleosynthesis of ^{26}Al is **complicated by the presence of an isomer** (E_x = 228.31(3) keV)*

Little exp. information is available on the rate of the ^{26m}Al(p,γ)^{27}Si reaction



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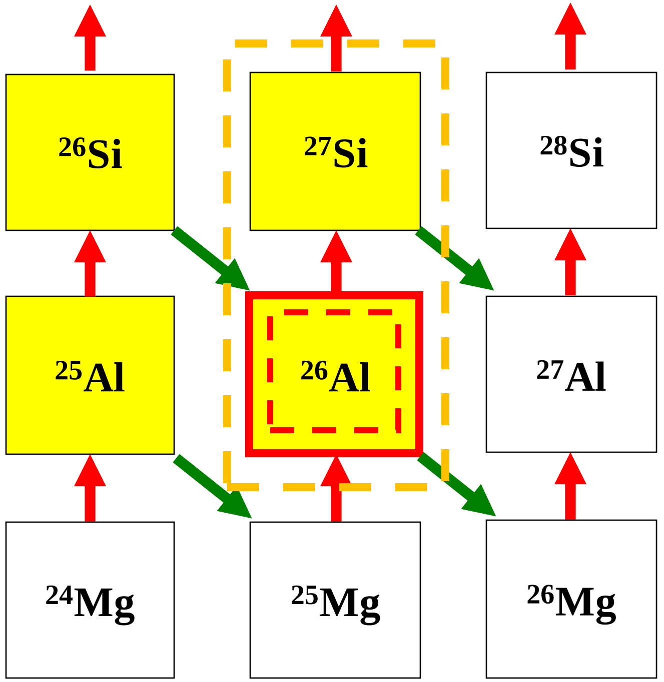


➔ Need to measure proton capture on excited quantum state of ^{26}Al

EXPERIMENTAL CHALLENGE!

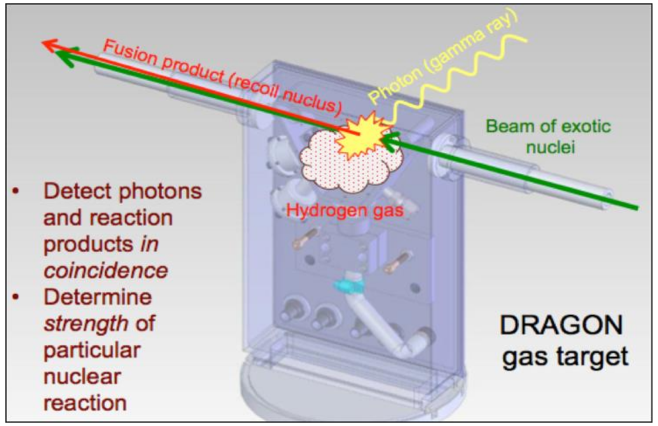
DRAGON – Detector of Recoils and Gammas of Nuclear Reactions

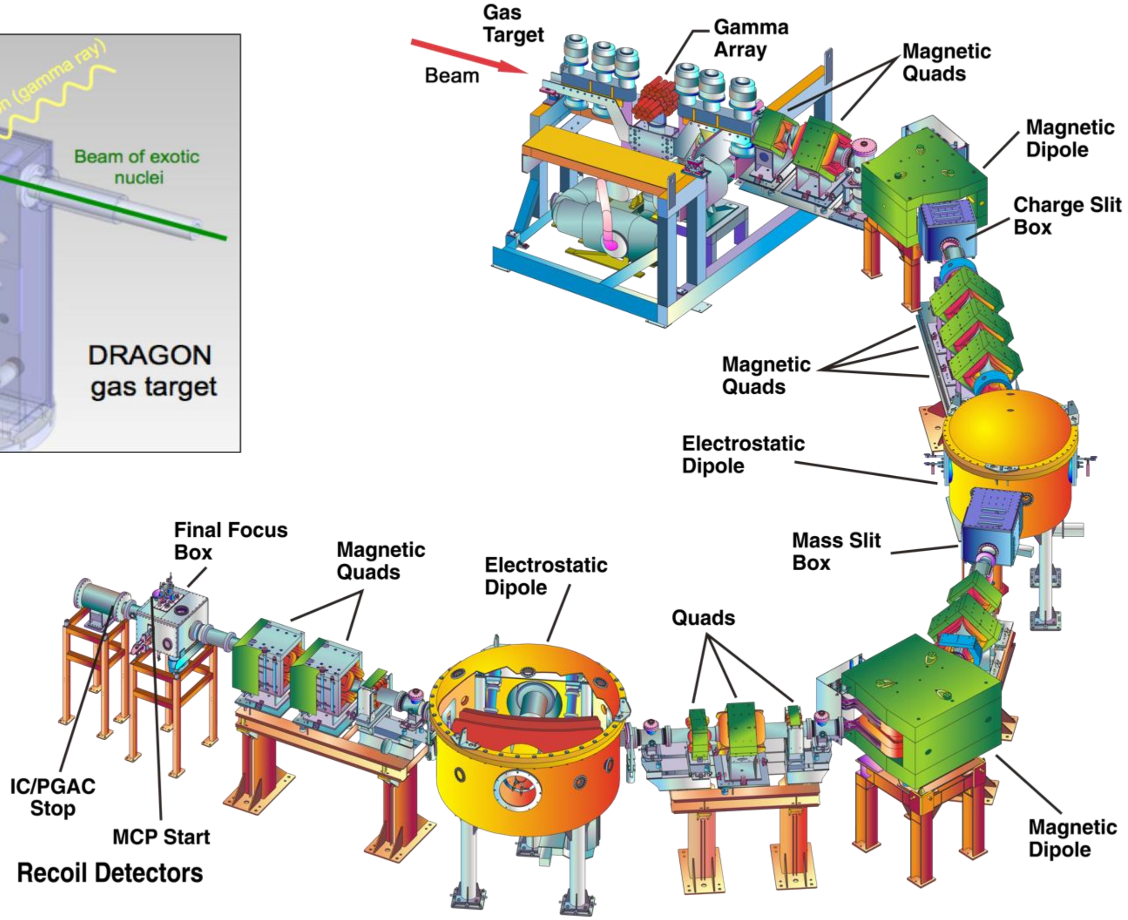
① Windowless gas target

② BGO γ-detection array

③ MEME mass separator

④ Recoil detection system





$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion

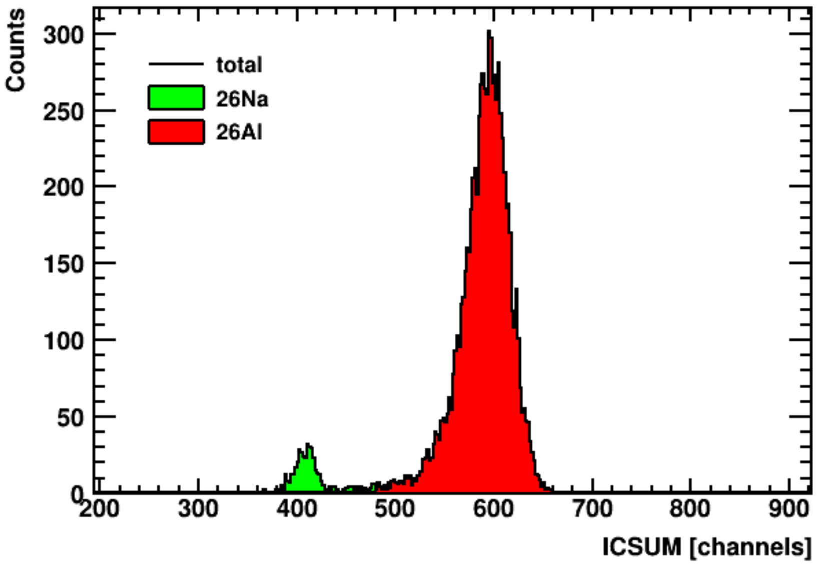
$$N_A\langle\sigma v\rangle = 1.54\times 10^{11}(\mu T)^{-3/2}\,\omega\gamma \times \exp\left(-11.605\frac{E_R}{T_9}\right)$$

- **Coincidence measurement:** Prompt γ-rays, PID cuts & TOF
- **suppression factor** of ~10^{15} for p-capture & ~5×10^{17} for α-capture

Experimental details

Beam composition

- p+ beam (70 μA) impinged on HP SiC target
- Incoming beam **composed of ^{26m}Al, ^{26g}Al, ^{26}Na**
- ^{26}Na easily separated



Total beam on target for 447 keV measurement:

- 6.21(2)E+14 incident ^{26}Al g.s. beam ions
- 7.5(2)E+10 incident ^{26m}Al beam ions

Data collection

- Collected 50 hrs of data at **$E_{c.m.}$ = 447 keV** at 5 T, q = 7+
- Covered energy range from $E_{c.m.}$ = 439 keV to 456 keV in target (E_{center} = 447 keV)
- Measured ωγ of **g.s.** resonance at **$E_{c.m.}$ = 369 keV**, q = 6+ as reference
- **Charge state distributions** were measured for ^{26}Al and ^{28}Si in hydrogen
- IC + MCPs for recoil detection

Normalization

All measurements of cross sections/resonance strength require knowledge of the number of particles incident on the target

- Faraday Cup readings cannot distinguish between beam components
- ➔Isomeric component was identified by its associated β+ decay to the ^{26}Mg g.s.
- Beam deposited on left mass slit downstream of ED1
- Emitted positrons are “guided” up a horn at the center of two NaI scintillators positioned 180 degrees to each other.
- Allows for β+ detection via annihilation in the horn and subsequent detection of 511 keV coincidence photons.

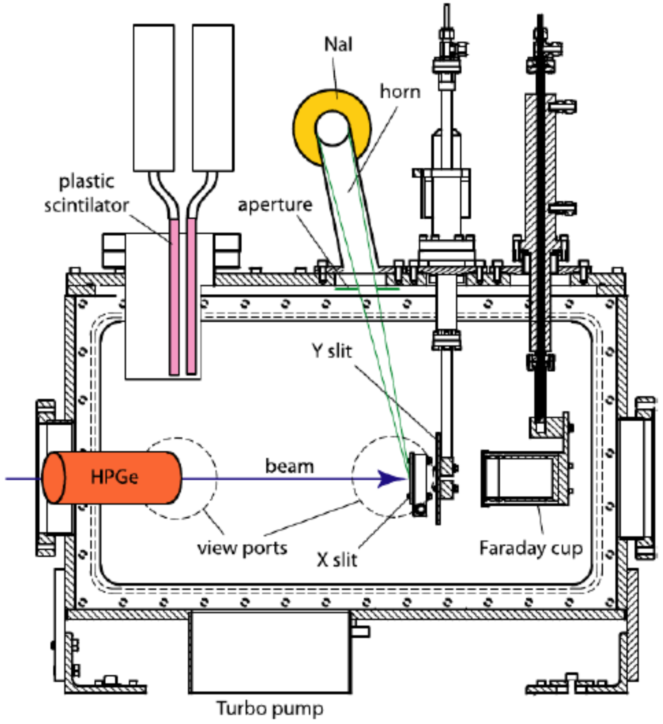
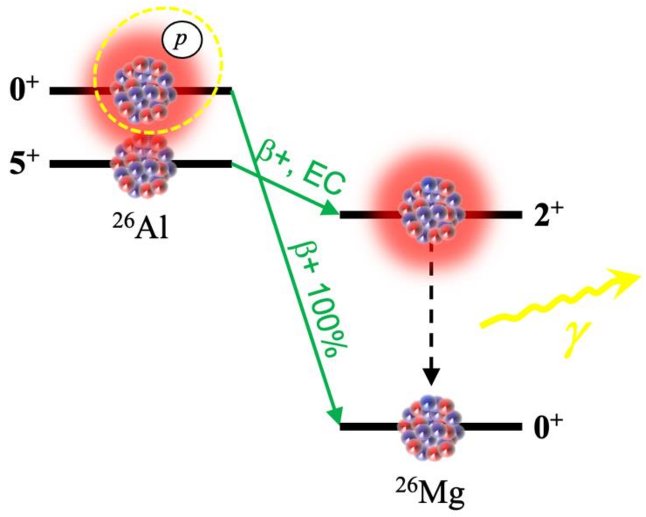


Figure from C. Vockenhuber et al. – NIMB 266, 4167 (2008)



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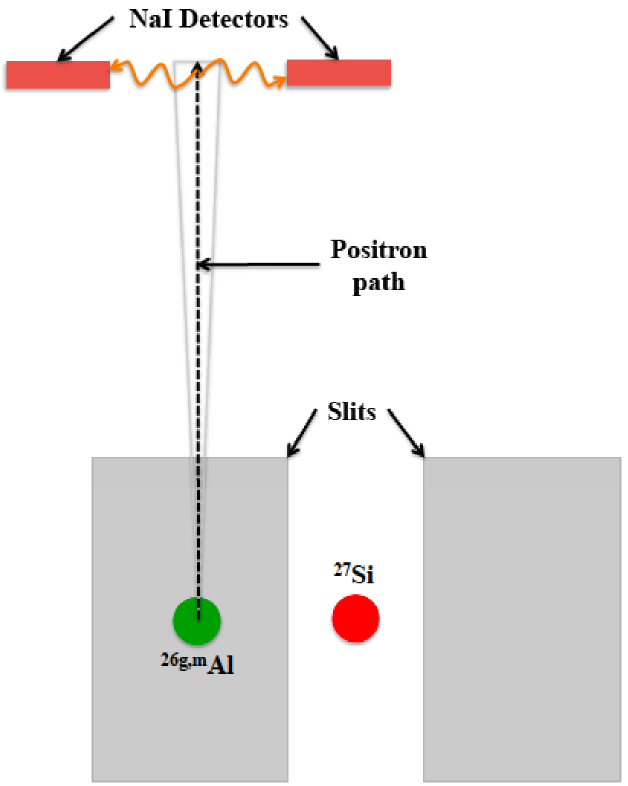
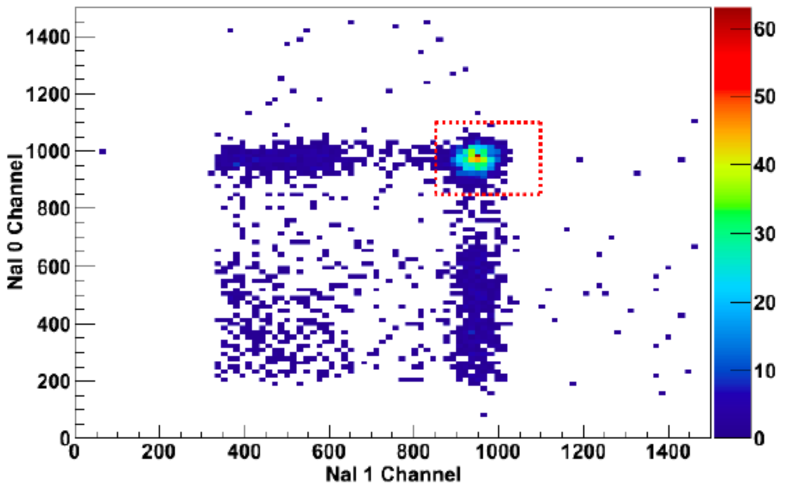
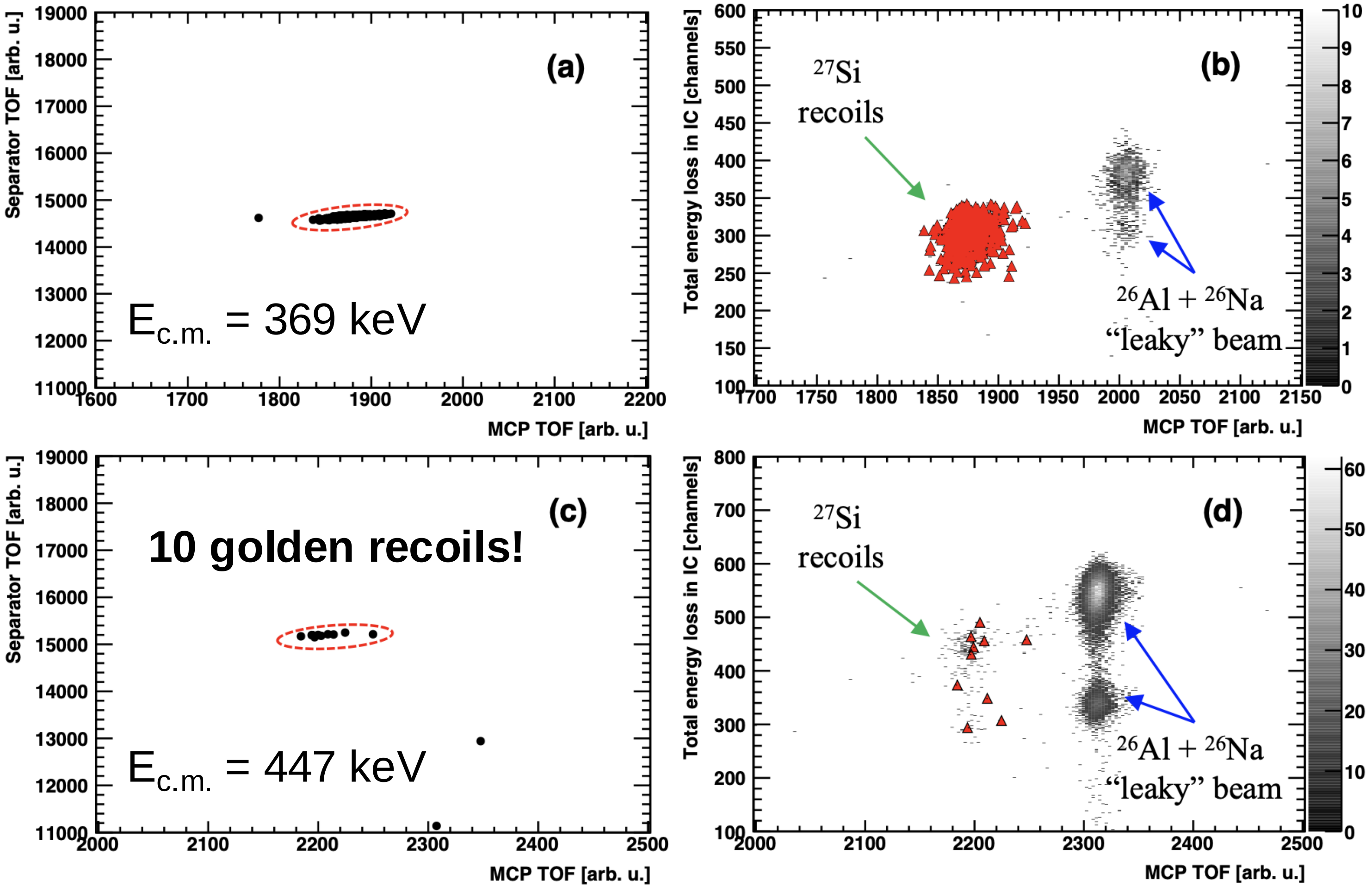
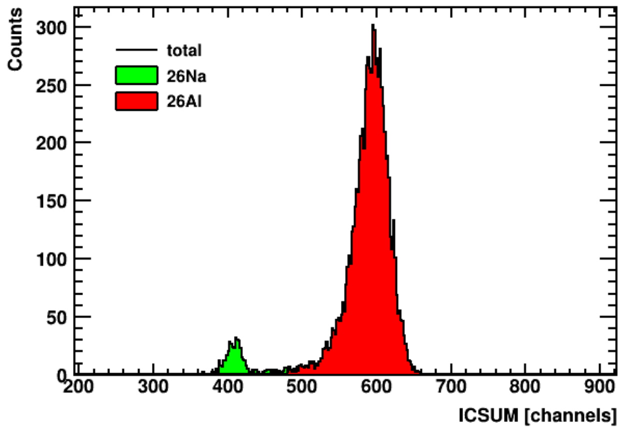




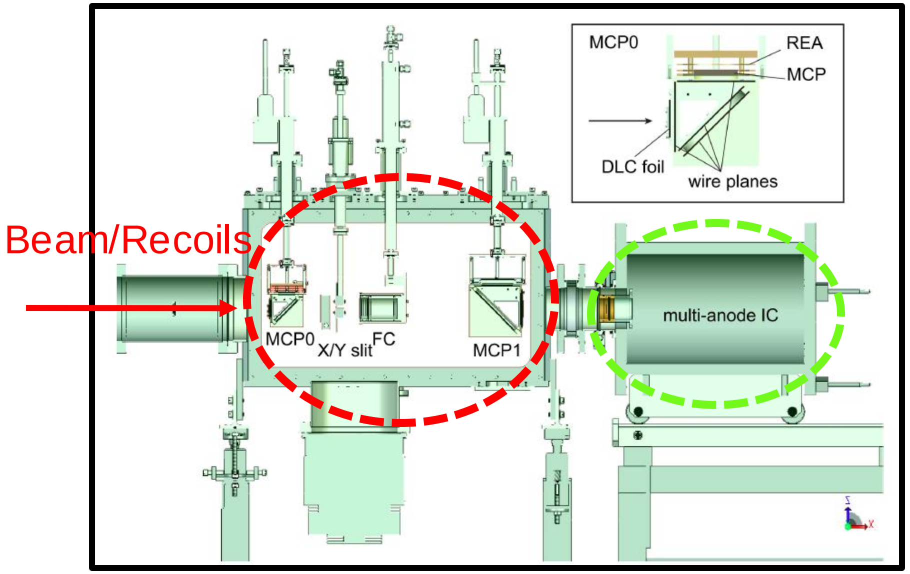
Particle Identification

Incoming beam composed of ^{26m}Al, ^{26g}Al, ^{26}Na





DRAGON end detector system



G. Lotay, A. Lennarz, C. Ruiz et. al., Phys. Rev. Lett. 128, 042701 (2022)

Used Ionization chamber & MCPs for recoil detection

Results

- **Reference** resonance: $\omega\gamma$(369keV) = 61 +/- 8(stat.) +/- 6(sys.) meV (singles & coincidence analysis in good agreement). **Good agreement** with previous measurements ➔ Verifies exp. methodology.
- **Off-resonance** measurements were taken at a beam energy of 484 A keV

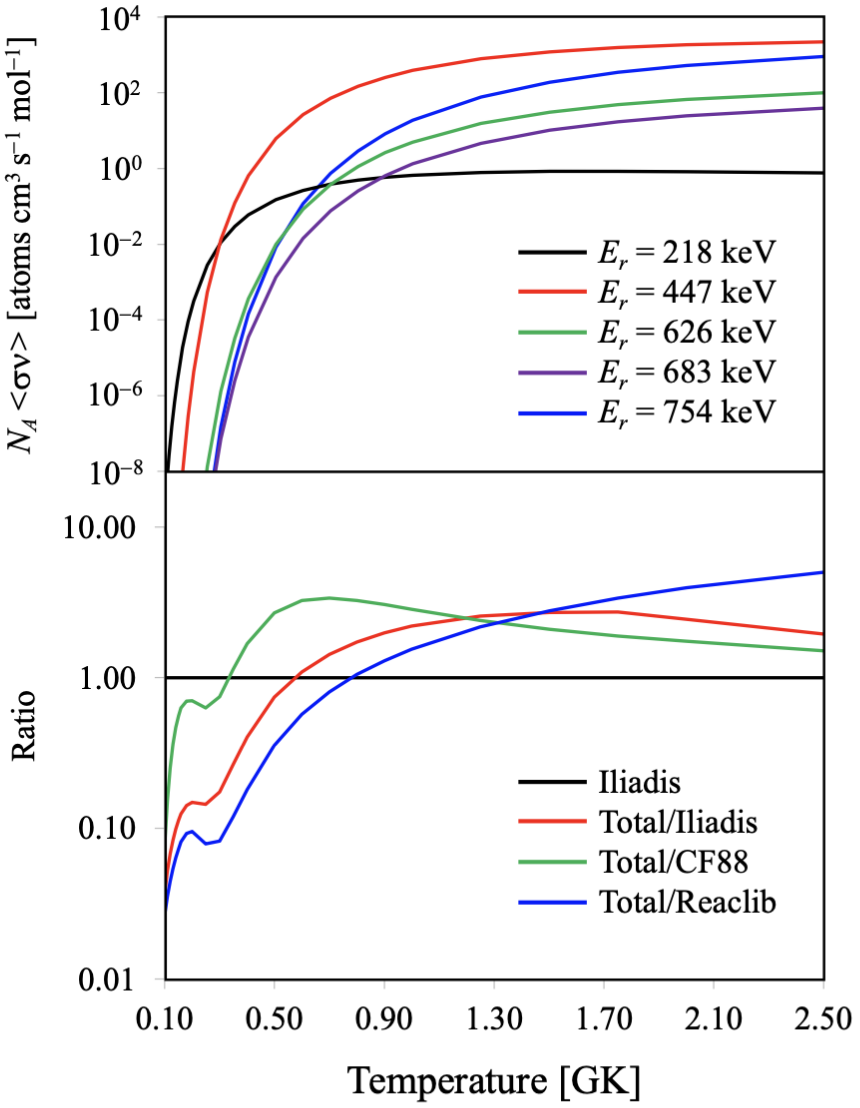
  ➔ **No coincident events** were observed in those data runs, confirming zero background counts in the region of interest.
- **Strength** for 447 keV resonance is **high!** Consistent with constraints given in Hallam, Lotay et al. (PRL126, 2021)

TABLE I: Summary of parameters used for the determination of resonance strengths. The values N_{inc} and N_{det} represent the number of incident particles and number of detected events, respectively, while the parameters η_{BGO}, η_{MCP}, $\eta_{trans.}$, η_{IC} and η_{CSF} correspond to the BGO array, MCP, transmission, ionization chamber and charge state fraction efficiencies.

Reaction	E_r [keV]	N_{inc}	N_{det}	η_{BGO}	η_{MCP}	$\eta_{trans.}$	η_{IC}	η_{CSF}	$\omega\gamma$ [meV]
$^{26g}Al + p$	369	$1.090(9) \times 10^{13}$	339(18)	0.83(8)	0.99(1)	0.77(1)	0.80(1)	0.40(2)	61 ±8 (stat.) ±6 (sys.)
$^{26m}Al + p$	447	$6.93(20) \times 10^{10}$	10(3)	0.64(6)	0.99(1)	0.77(1)	0.80(1)	0.37(2)	432 ±137 (stat.) ±51 (sys.)

G. Lotay, A. Lennarz, C. Ruiz et. al., Phys. Rev. Lett. 128, 042701 (2022)

Conclusions – contribution to reaction rate



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➔ With present result for ωγ, **$E_{c.m.}$ = 447 keV resonance** governs entire ^{26m}Al(p,γ) stellar reaction rate over the peak temperature range (0.3-2.5GK) of classical novae & supernovae

- *But, keep in mind, strengths of resonances in ^{26m}Al + p with E_r > 447 keV remain uncertain*

➔ *could still increase the overall ^{26m}Al(p,γ) rate considerably at high temperatures!*

Summary

- Nuclei often exist in **excited quantum states**

➔ **Isomers** can act as entirely separate nuclei and **strongly influence the formation of chemical elements**

- Studying these reactions on earth represents a significant **experimental challenge**

➔ This needs to be overcome to fully understand many astronomical observations

➔ Astrophysical observations and their wide implications can only be addressed by understanding how stars and explosive scenarios produce ^{26}Al

- At DRAGON we have performed the **first ever direct study of excited state proton capture** at TRIUMF
- Measured key resonance in ^{26m}Al + p to investigate **origin of ^{26}Al**
- Strength of resonances with $E_r > 447$ keV is still uncertain ➔ Work must continue

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Thank you
Merci

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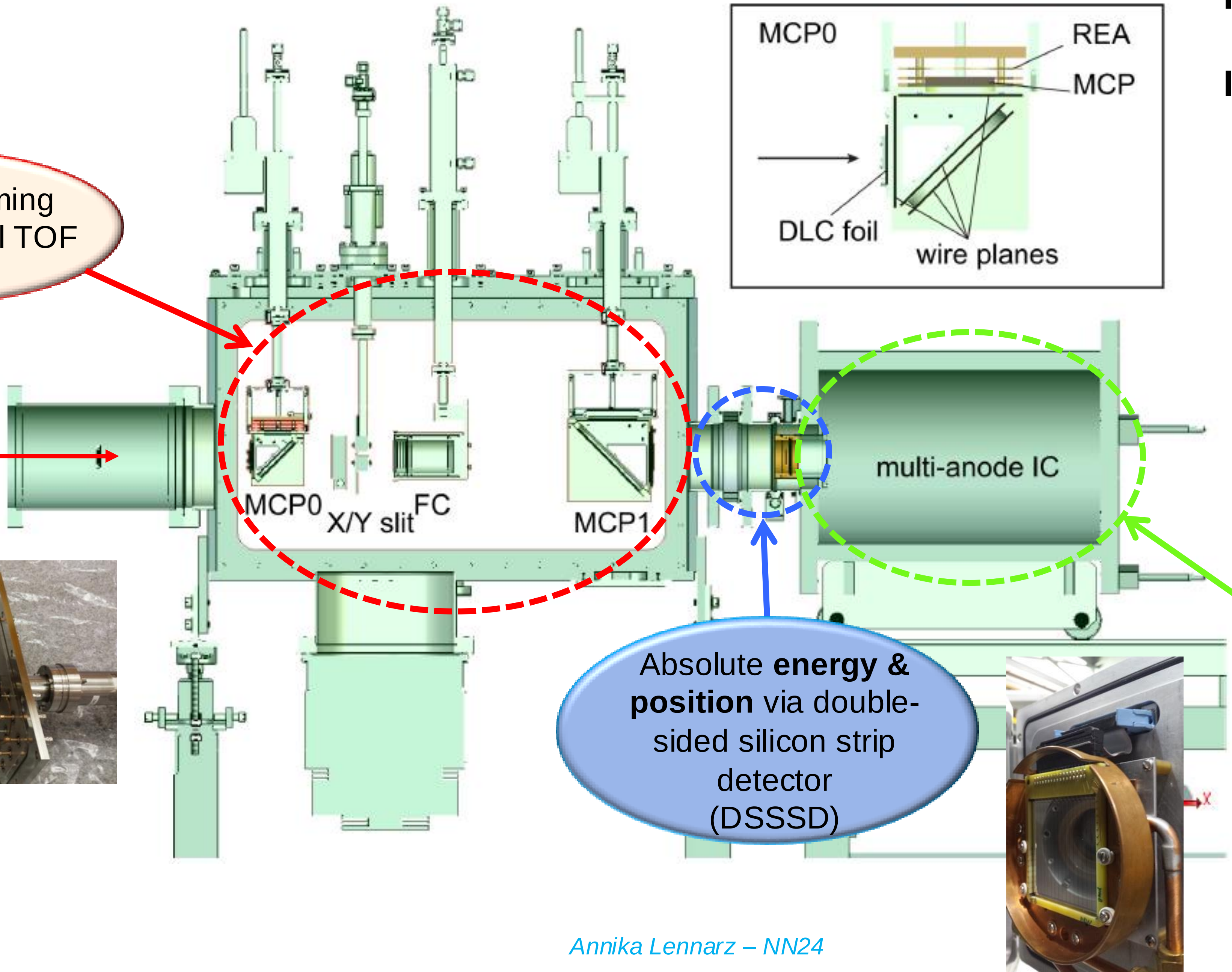
Discovery, accelerated

Particle Detection – End Detector Station

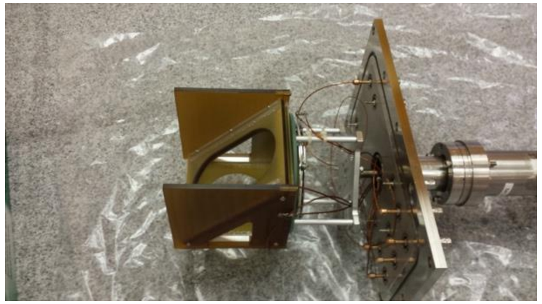
Interchangeable end detectors
IC, DSSSD or Hybrid
(Depending on reaction)

MCP based timing detector for local TOF

Beam/Recoils



- Particle ID
- Local TOF
- ΔE/E, Total E



Absolute **energy & position** via double-sided silicon strip detector (DSSSD)

ΔE-E in ionization chamber for **Z-identification**

Previous work

- States of relevance for the ^{26g}Al(p,γ)^{27}Si reaction have been studied extensively
- **<u>BUT:</u> Little experimental information** is available on the rate of the ^{26m}Al(p,γ)^{27}Si reaction
- **Difficulty in producing pure, isomeric ^{26}Al beams** to probe low-spin excited states in ^{27}Si.

2009: Deibel et al. used ^{27}Al(^{3}He,t)^{27}Si*(p)^{26}Al & ^{28}Si(^{3}He,α)^{27}Si*(p)^{26}Al to observe p-decays from excited states and found E_r = 445(4) keV

[Deibel et al., Phys. Rev. C80, 035806 (2009)]

2009/10: Lotay et al. performed spectroscopy study (Argonne) identifying low-energy ^{26m}Al + p states

➔ E_r = 447.7(6) keV, J = ½, + 4 more lower energy resonances.

➔ However, exact **strengths unknown!**

[G. Lotay et al., Phys. Rev. C80, 055802 (2009)]

Recent study by Hallam, Lotay et al. used concept of isospin symmetry to **mimic proton capture** on isomer via a ^{26}Si(d,p)^{27}Si transfer reaction study

➔ Stringent upper limits were placed on the spectroscopic factors of all resonant levels with E_r < 500 keV

➔ Estimated $\omega\gamma$(447-keV) ~ 385meV ➔ resonance is likely to **dominate** the entire ^{26m}Al(p,γ) rate for T > 0.3 GK

[S. Hallam et al., Phys. Rev. Lett. 126, 042701 (2021)]