Impact of the ^{26m}Al(p, γ) reaction to galactic ^{26}Al yield

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so let's get started...

Astronomer's Periodic Table — because I love this figure

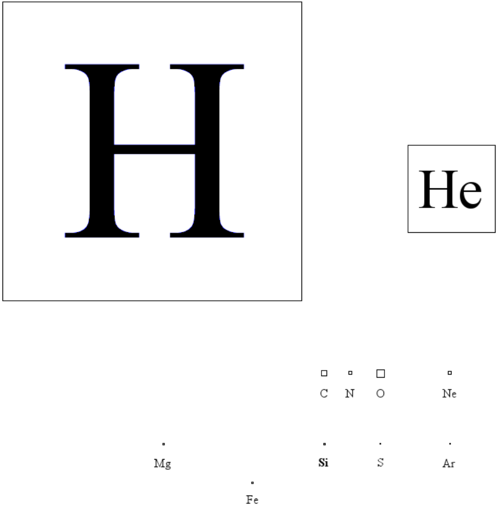

Figure: Baryonic mass of the universe >99% hydrogen and helium!

Inspired by Ben McCall, Jason Tumlins, and others from University of Chicago.

hydrogen is involved in the production and destruction of many elements including ^{26}Al. . .

Motivation

- **^{26}Al is critical because it is observed in our Galaxy!**
- Observation of Galactic ^{26}Al must answer two questions:
  - **How much** is observed?
  - **Where** is it observed?
- The observations raise questions for stellar models:
  - Can our models **reproduce** the observations?
  - Which **inputs** affect the **output** of ^{26}Al?
  - What is the relationship between I/O uncertainty?
  - Which model parameters (**input**) can we test?
- We should *reduce* the uncertainty for **inputs** to models
  - The sum of models overestimates ^{26}Al production
- Knowledge of reactions w/ ^{26m}Al is extremely limited
  - Can't be a target, and it's a tricky beam
  - Only isomer proton scattering was Brown *et al.* PRC 1995
  - ^{18m}F, $T_{1/2}$=163 ns, tagged γ-rays in coincidence
  - Good for that case, but *impossible* for most isomers!
  - A new method is needed!

so we can begin with the observations of γ-rays. . .

Basics of galactic ^{26}Al γ-rays

- ^{26g}Al ($J^{\pi} = 5^{+}$): long-lived radioisotope ($T_{1/2} = 0.72$ Myr)
  - Good timescale for stellar production and ejection
  - Unique signature via β-delayed γ-decay through 1.809 MeV 2^{+} state in ^{26}Mg
- 1.809 MeV γ-rays observed by satellite for 30+ years
  - 2.7 ± 0.7 $M_{\odot}$ ^{26}Al detected (Wang 2009)
  - 2.0 ± 0.4 $M_{\odot}$ ^{26}Al detected (Diehl 2016)
- Massive stars (WR & ccSNe) expected as the main source

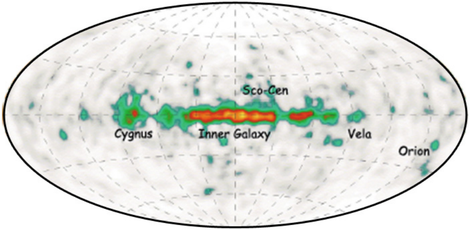

Figure: All-sky image of ^{26}Al γ-lines from COMPTEL.

is the ^{26}Al just local or part of the Galaxy...

SPI telescope on INTEGRAL: ^{26}Al over 9 years of data

- 1.809 MeV γ-ray from ^{26}Al decay is Doppler shifted!
  - This radioactivity is *a part of the Galaxy*

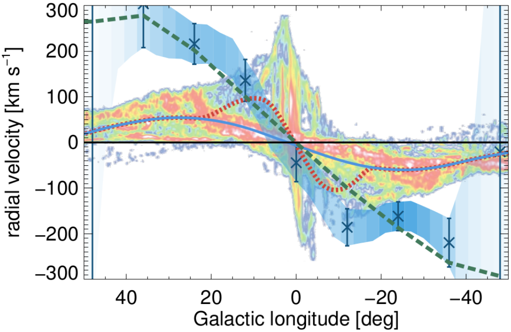

Figure: Longitude-velocity diagram of ^{26}Al γ-rays ($\times$ mark w/ error) and other objects (*i.e.* CO molecular lines) in the Galaxy. Dashed green line model includes spiral-arm sources.

Kretschmer, K., Diehl, R., Krause, M., Burkert, A., Fierlinger, K., Gerhard, O., Greiner, J. & Wang, W., Kinematics of massive star ejecta in the Milky Way as traced by ^{26}Al, A&A **559** (2013) A99

what is the ^{26}Al yield calculated from various stellar models. . .

Can models reproduce the observed galactic ^{26}Al mass?

- All models (summed together) may make too much, now!
- 2.7 ± 0.7 $M_\odot$ ^{26}Al estimated (Wang 2009)
- 2.0 ± 0.4 $M_\odot$ ^{26}Al estimated (Diehl 2016)
  - State-of-the-art work gives a smaller value
  - (Of course, the galactic mass did not change in only 7 years)
- Limongi & Chieffi (2006) can reproduce the ^{60}Fe/^{26}Al ratio
  - Massive stars, both WR and SN phases
- Estimation of nova contribution to ^{26}Al doubled recently
  - That was by reducing only the $^{25}\mathrm{Al}(\mathrm{p},\gamma)^{26}\mathrm{Si}(\beta^+)^{26\mathrm{m}}\mathrm{Al}$ rate!
  - José, Hernanz & Coc (1997): 0.4 $M_\odot$
  - Bennett *et al.* (2013): 0.8 $M_\odot$ or 40% total
- Mowlavi & Meynet (2000) AGB stars: ≤ 0.4 $M_\odot$
  - Shows up to factor 10 difference from $^{26\mathrm{g}}\mathrm{Al}(\mathrm{p},\gamma)$ rate choice
- Siess & Arnould (2008) SAGB stars: ≤ 0.3 $M_\odot$
- **Destruction of ^{26}Al needs to be studied more!**

preliminary results from deep-sea sediment don't need explosive contributions. . .

Preliminary results: $^{60}Fe/^{26}Al$ from deep-sea sediment

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and we have a poor, lonely isomer to think about. . .

What is the effect of ^{26m}Al(p, γ) in models?

- How is ^{26m}Al(p, γ) treated in a sensitivity study?

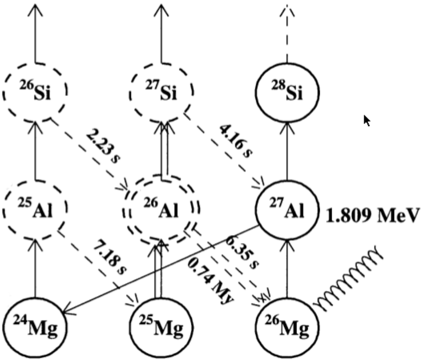
"There can be no doubt that [the ^{26m}Al(p, γ)] rate is highly uncertain at present [. . .] too much experimental information is still lacking (i.e., missing levels, spectroscopic factors, proton partial widths, and resonance strengths) in order to estimate this rate reliably over the temperature range of interest. More measurements are clearly in order. In the absence of a more reliable estimate, we approximated in this work the ^{26m}Al(p, γ)^{27}Si rate by the (experimental) ground state rate. Our assumption is a starting point for exploring the effects of ^{26m}Al(p, γ)^{27}Si reaction rate variations."

Iliadis, C., Champagne, A., Chieffi, A. & Limongi, M., The Effects of Thermonuclear Reaction Rate Variations on ^{26}Al Production in Massive Stars: A Sensitivity Study, ApJS **193** (2011) 16

what's the big deal about treating them the same, they are both aluminium twenty six. . .

^{26}Al yield is complicated by an isomeric state

- ^{26m}Al with $E_{ex} = 228$ keV; $J^{\pi} = 0^{+}$; $T_{1/2} = 6.346$ s
  - Bypasses 1.809 MeV γ-ray emission
- Thermal transitions link ^{26g}Al and ^{26m}Al
- ^{25}Mg(p, γ) can populate both ^{26g,m}Al
- ^{25}Al(p, γ)^{26}Si β-decays to ^{26m}Al

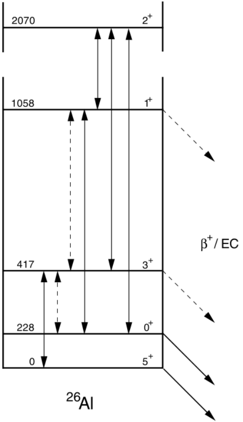


José, J., Coc, A. & Hernanz, M., Nuclear Uncertainties in the NeNa-MgAl Cycles and Production of ^{22}Na and ^{26}Al during Nova Outbursts, ApJ **520** (1999) 347–360

makes you want to take a hot bath. . .

^{26g,m}Al are linked in hot astrophysical plasmas

- Transitions induced by **thermal photons**
- Many detailed investigations in the past
  - Ward & Fowler (1980):
    - Distinct species below 0.4 GK
    - Thermal equilibrium above 0.4 GK
  - Coc *et al.* (2000)
  - Runkle, Champagne & Engel (2001):
    - Is there equilibrium?
    - Communication below 0.4 GK
  - Gupta & Meyer (2001)
- ^{26g,m}Al linked, but treated separately
- ^{26m}Al important at high temperatures
- What are the **nuclear** rates with ^{26m}Al?
- Q: Understanding the situation would
  - Ⓐ Probe astrophysical plasmas.
  - Ⓑ Complicate my life.
  - Ⓒ All of the above.



yeah okay but what is known experimentally. . .

Experimental knowledge of ^{26m}Al(p, γ)^{27}Si resonances

- β-delayed proton-decay of ^{27}P
  - Ognibene *et al.* (1996)
  - 4 resonances observed and assigned ($1/2^+$, $3/2^+$)
- $^{27}\mathrm{Al}(^3\mathrm{He}, \mathrm{t})^{27}\mathrm{Si}^*(\mathrm{p})^{26\mathrm{m}}\mathrm{Al}$ and $^{28}\mathrm{Si}(^3\mathrm{He}, \alpha)^{27}\mathrm{Si}^*(\mathrm{p})^{26\mathrm{m}}\mathrm{Al}$
  - Deibel *et al.* (2009)
  - Observed over 20 levels with $3 - 5$ keV resolution
  - Γ_p/Γ measured for several states to ^{26m}Al
    - Systematic error of 34(19)%, no absolute values
- In-beam γ-spectroscopy via $^{12}\mathrm{C}(^{16}\mathrm{O}, \mathrm{n})^{27}\mathrm{Si}^*$
  - Lotay *et al.* (2009)
  - Excitation energies, J^π, τ for levels near ^{26m}Al threshold
  - High angular momentum with heavy-ion beam ... but $J = 0$
- No proton partial widths known!
- Very limited J^π information for higher-energy resonances
- Proton elastic scattering complements existing studies

but why should anyone care about all these quantum numbers...

Narrow-resonance stellar reaction rate formulation

To calculate $^{26\mathrm{m}}\mathrm{Al}(\mathrm{p},\gamma)$ reaction rate $\langle\sigma\nu\rangle_{(\mathrm{p},\gamma)}$:

$$\langle\sigma\nu\rangle_{(\mathrm{p},\gamma)} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \omega\gamma \exp\left(-\frac{E_r}{kT}\right);$$

the reduced width γ is defined as

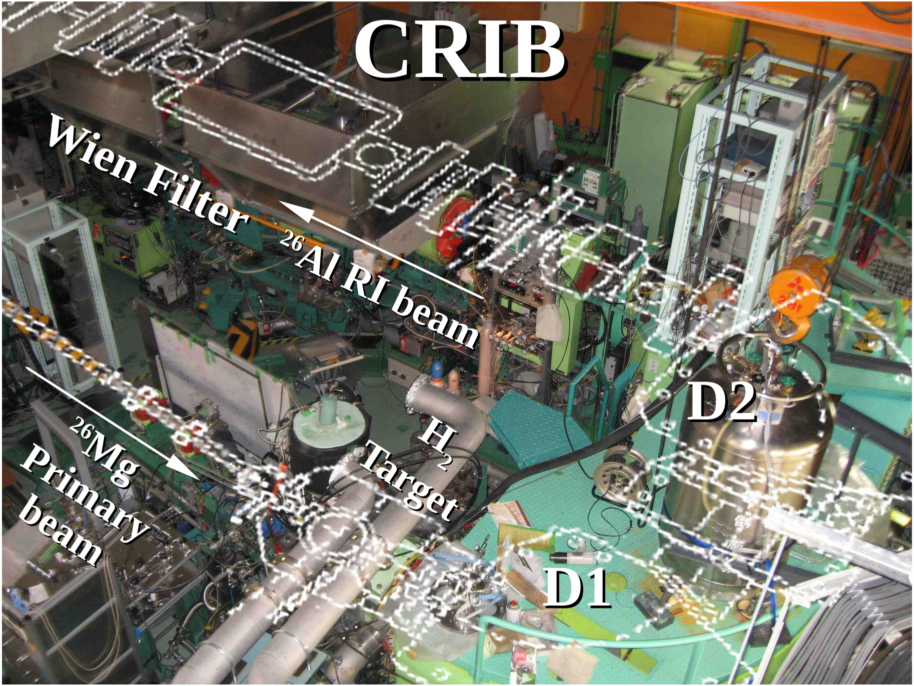
$$\gamma \equiv \frac{\Gamma_i \Gamma_j}{\Gamma_i + \Gamma_j} \approx \Gamma_i \quad \text{iff} \quad \Gamma_i \ll \Gamma_j,$$

and the spin-factor ω is defined as

$$\omega \equiv \frac{2J_r + 1}{(2J_{^{26\mathrm{m}}\mathrm{Al}} + 1)(2J_\mathrm{p} + 1)} = J_r + \frac{1}{2}.$$

Besides some constants, we just need to know the resonance energy E_r, spin J_r, and widths Γ_p & Γ_γ. **Most of these can be determined by $^{26\mathrm{m}}$Al+proton resonant elastic scattering, which we measured.**

the abstract said this was an experimental talk. . .


CRIB
Wien Filter
26Al RI beam
26Mg
Primary
beam
H2
Target
D2
D1

Experimental conditions: beams and targets

- Primary beam: $^{26}Mg^{8+}$ from ^{nat}Mg in ion source
  - Energy: 6.65 MeV/u (173 MeV)
    - Sometimes degraded further with 2.5 μm Havar foil
  - Intensity: $25 \sim 50$ pnA
- Secondary beam: $^{26}Al^{13+}$
  - Production reaction: $^{1}H(^{26}Mg, ^{26}Al)n$
  - Target: cryogenic H_2 gas (0.5 to 1.0 mg cm^{-2})
    - 130 to 290 Torr at 90 K
  - Intensity: 1.5×10^5 pps (average)
  - Purity: 93% (average)
  - Energies on target: 68, 83, and 90 MeV
- Secondary targets:
  - CH_2 (7.5 mg cm^{-2}) as proton target
  - ^{nat}C (10.6 mg cm^{-2}) for background subtraction
  - Thick targets to stop ^{26m}Al β^+ particles...
    - 1 cm plastic, aluminium blocks
- Multiple $^{26g,m}Al$ purity ratios

and I keep teasing you by not explaining how this experiment is feasible...

Beautiful Rutherford scattering with ^{26g}Al

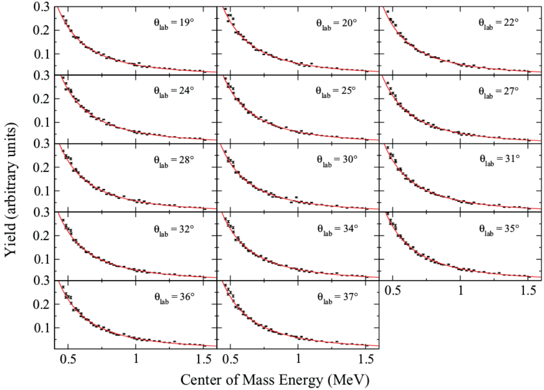


Figure: There don't seem to be any strong proton resonances with the ground state. Can you say background subtraction?

Pittman, S. T., Bardayan, D. W., Chae, K. Y., Chipps, K. A., Jones, K. L., Kozub, R. L., Matei, C., Matos, M., Moazen, B. H., Nesaraja, C. D., O'Malley, P. D., Pain, S. D., Parker, P. D., Peters, W. A., Shriner, J. F., Jr. & Smith, M. S., ^{26}Al+p elastic and inelastic scattering reactions and galactic abundances of ^{26}Al, *Physical Review C* **85** (2012) 065804

as for our beam. . .

Cocktail beam at the RI optimization focal plane

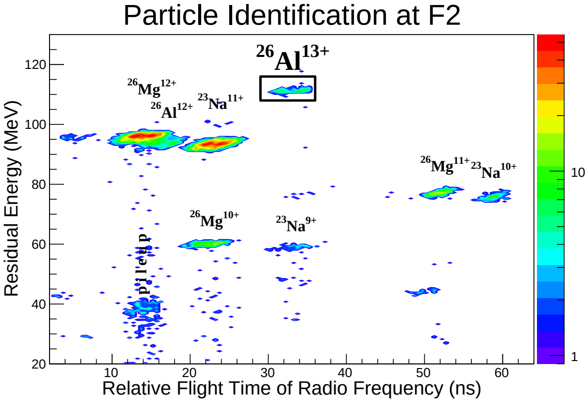


Figure: Flight time vs. residual energy. ^{26}Al^{13+} is clearly separated. Main contaminant ^{23}Na. This is illustrative (not optimized).

and at the experimental focal plane...

Cocktail beam at the experimental focal plane

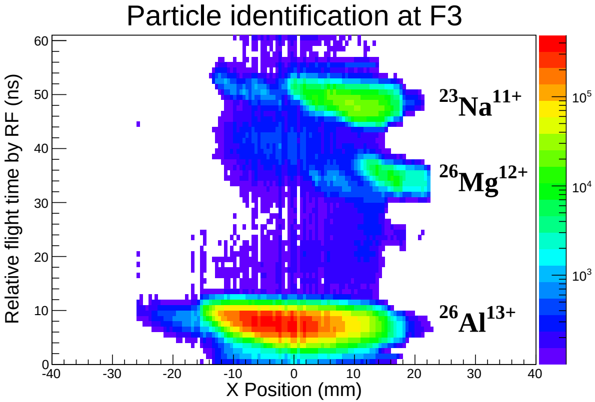


Figure: Position vs. flight time. $^{26}Al^{13+}$ is clearly separated. The only contaminants are *stable isotopes*.

Thick target inverse kinematics method

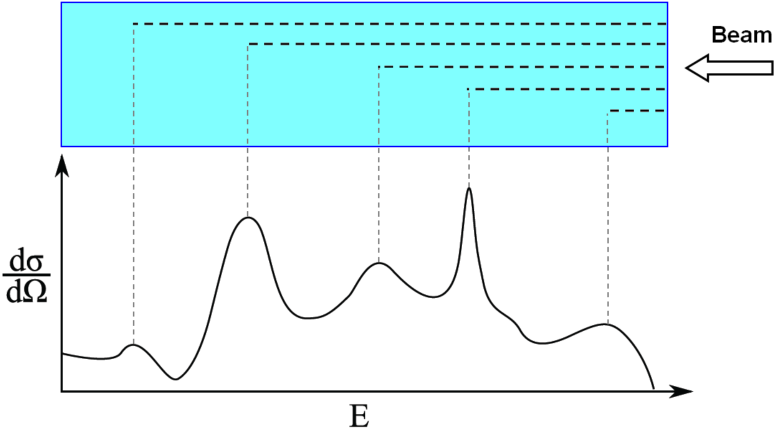


Figure: Thick target: excitation function with a single beam energy, and good statistics. Inverse kinematics (heavy beam on light target): kinematic focusing, measurement near $\theta_{cm} \sim 180^\circ$ is possible.

K.P. Artemov *et al.*, Sov. J. Nucl. Phys. **52**, 408 (1990).

we use a standard setup for elastic scattering. . .

Experimental setup for ^{26m}Al(p, p) measurement

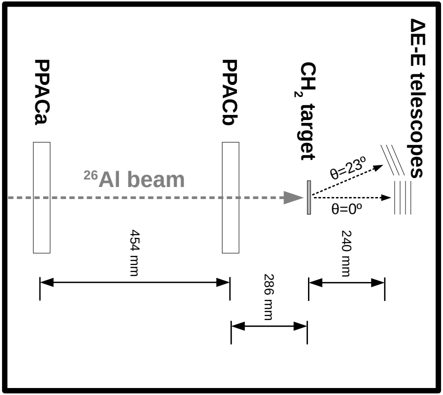


Figure: Beam is tracked by PPACs before impinging on and stopping in one of the targets. Scattered protons were detected by ΔE-E Si telescopes, the first layer is 75 μm with 16×16 strips and the other detectors 1.5 mm. An array of 10 NaI detectors was placed above the target to measure γ-rays (not depicted).

so how shall you be convinced that we can quantify the isomeric content...

Proof we made ^{26m}Al

- Pulsed the beam in regular tests, 12 s on — 12 s off
- Measured the β^+'s with the Si telescope
- (Also measured 511-keV γ's with NaI)

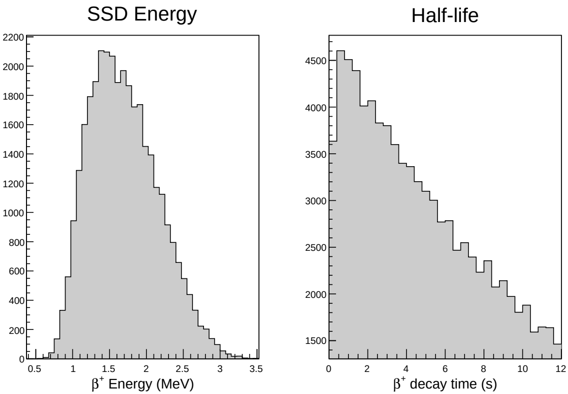


Figure: β^+ decay measurements: (a) Energy spectrum and (b) Decay timing. Both are consistent with ^{26m}Al.

and how about identifying scattered protons. . .

Identifying protons in Si telescope

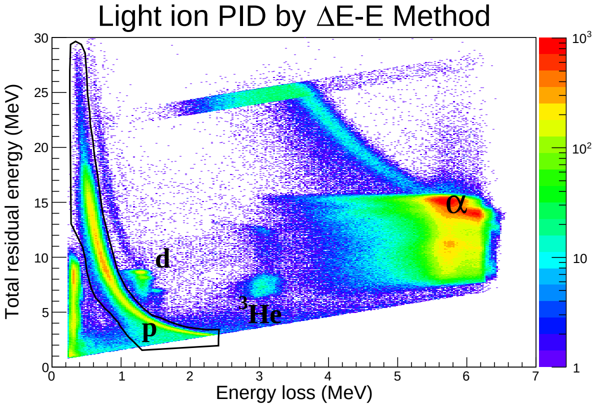


Figure: Energy loss from the 75 μm PSD and the sum of the residual light ion energy from the Si telescope. Several particle groups are seen and separated. A graphical cut for protons is shown.

but just knowing it is a proton is not enough. . .

Identifying the scattered protons

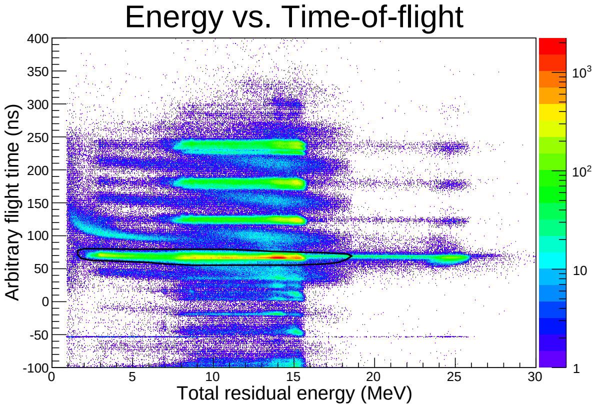


Figure: Residual light ion energy from the Si telescope against time of flight between PPACa and the Si telescope. The depicted gate shows the scattered protons.

Hayakawa, S., Kubono, S., Kahl, D., Yamaguchi, H., Binh, D. N., Hashimoto, T., Wakabayashi, Y., He, J. J., Iwasa, N., Kato, S., Komatsubara, T., Kwon, Y. K. & Teranishi, T., First direct measurement of the $^{11}C(\alpha, p)^{14}N$ stellar reaction by an extended thick-target method, *Physical Review C* **93** (2016) 065802

having all the scattered protons, what energies are important. . .

Gamow window for novæ

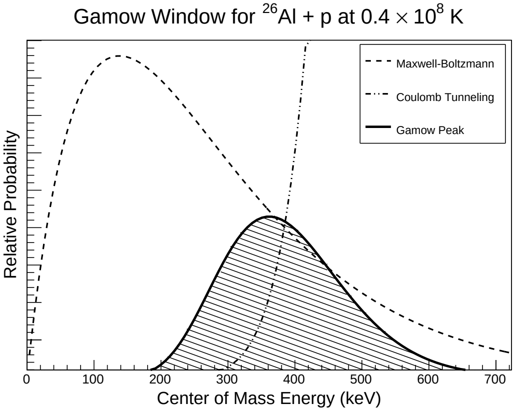


Figure: Peak energy is quite low, and proton elastic scattering will be challenged to see structure here.

but our experiment does have sensitivity. . .

Gamow window for supernovæ

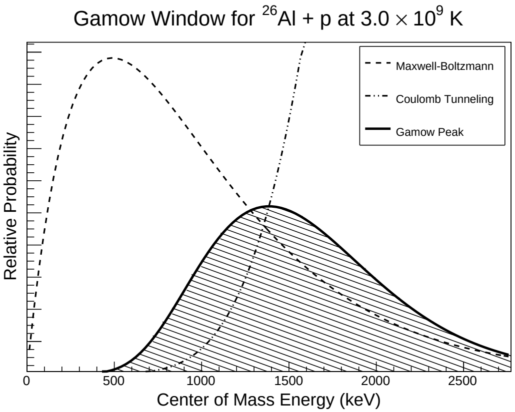


Figure: Peak energy is much higher, ideal for the elastic scattering method.

^{26}Al proton spectra — the method worked!

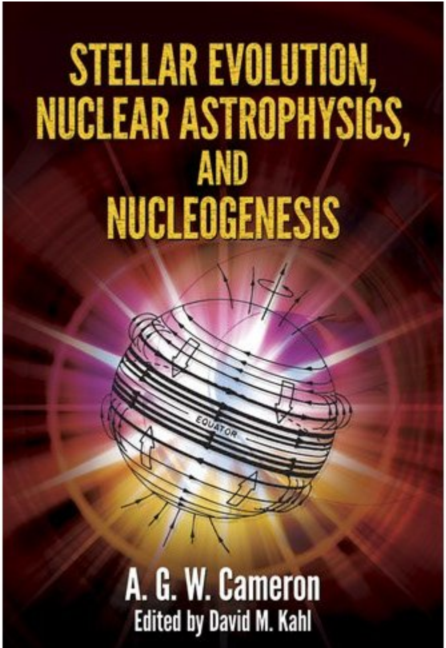
(slide is redacted for web publication)

Summary & Conclusions

- Galactic ^{26}Al directly constrains stellar models
  - Critical observation for stellar evolution
  - It seems ^{26}Al might be over-produced in models now
- The $^{26\mathrm{m}}\mathrm{Al}(\mathrm{p},\gamma)$ reaction rate is *highly uncertain*
- Short half-life of $^{26\mathrm{m}}$Al: most likely important in ccSNe
- We applied a novel technique to produce an isomeric beam
  - Background subtraction approach, like isobars in RIBs
  - Varied the purity by changing the production $E_{\mathrm{c.m.}}$
- Contrary to $^{26\mathrm{g}}\mathrm{Al}(\mathrm{p},\mathrm{p})$, $^{26\mathrm{m}}\mathrm{Al}(\mathrm{p},\mathrm{p})$ shows *large resonances*
- **These resonances may destroy ^{26}Al in ccSNe**
- This may be just what was needed in recent years
- Further work is still needed
  - Kinematic solution, R-Matrix fits to get quantum properties
  - (Γ_γ will control the strength…do you have an idea?)

if you're interested in what old textbooks say about the r-process …

Cameron's 1957 report – Republished and ≈$10



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^{26}Mg(p, n)^{26}Al cross sections – Skelton *et al.* (1987)

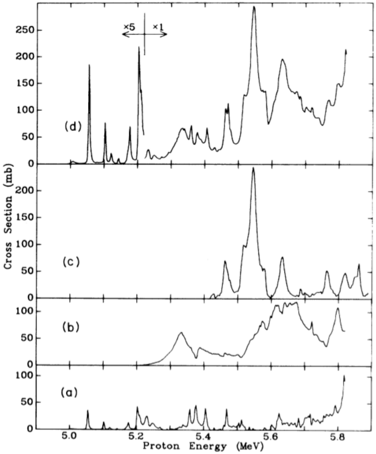

Figure: $\sigma(E)$ to populate the (a) ground, (b) isomeric, and (c) second excited states in ^{26}Al via the ^{26}Mg(p, n) reaction. The sum of all three cross sections are shown in (d).

Sources of background

- Beam-induced (*e.g.* upstream protons, C in CH_2, …)
  - Clear tracking and ID of ^{26}Al event-by-event with PPACs
  - Background runs with carbon foil
  - High-E protons vetoed with extra SSD layer at 0°
- ^{26g}Al contamination
  - Pittman *et al.* (2012): ^{26g}Al(p, p) only Coulomb scattering
    - Trivial to subtract knowing the ^{26g,m}Al ratio
  - Measure half-life to quantify purities in RIB test
  - Monitor 511 keV γ-rays with NaI in measurement
  - Produce ^{26g,m}Al beams with two purity hierarchies
    - Checks any systematic error in above purity determinations
- Inelastic scattering
  - Unexpected as Pittman *et al.* observed no contribution
  - Would proceed through the 2^{nd} excited state: 417 keV
  - NaI detectors can confirm the contribution is trivial
  - Pure-elastic scattering confirmed with angular distribution
- **The setup can control all sources of background!**

and the next experiment. . .

^{26m}Al yield calculation

- ^{26}Mg(p, n)^{26}Al $\sigma(E)$ known for $E_{cm} = 4.8 - 5.6$ MeV
  - Assume a ^{26}Mg beam current from natural Mg in ion source
- Optimize ^{26m}Al yield and purity at F0
  - Calculate ^{26}Mg E_{beam} and ^{26g,m}Al yield in 1 mm steps
  - Vary H_2 pressure in steps of 50 Torr
- Calculate transmission to F3 scattering chamber
  - Conservatively cut 50% to backward angles in CM frame
  - ^{26m}Al^{13+} charge-state fraction of 50% after C-stripper
    - Fully-stripped ^{26m}Al^{13+} required to avoid ^{26}Mg^{12+}
  - F1 $\Delta p/p = 0.5\%$ to cut yield according to ΔE (50%)
  - Wien filter transmission of 30%
- These very conservative yield estimates give 2×10^5 pps
- Measure ^{26g,m}Al ratio
  - By β-decay half-life during RIB test
  - By NaI array for 511 keV γ-rays during measurement