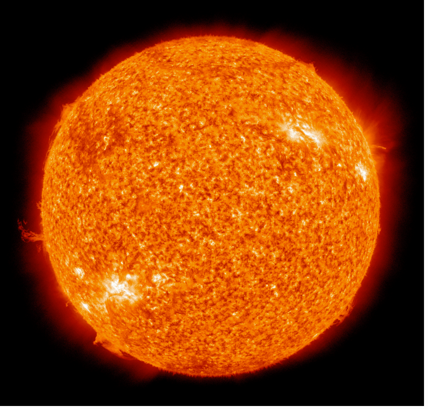
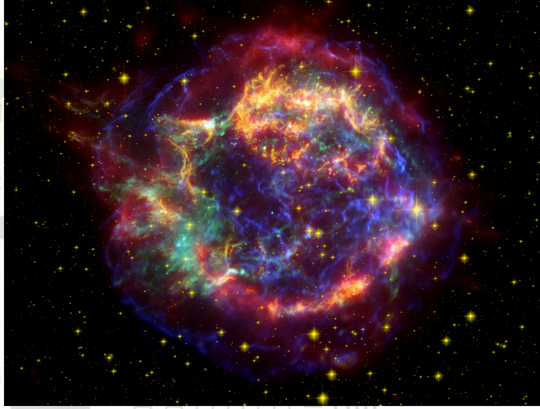
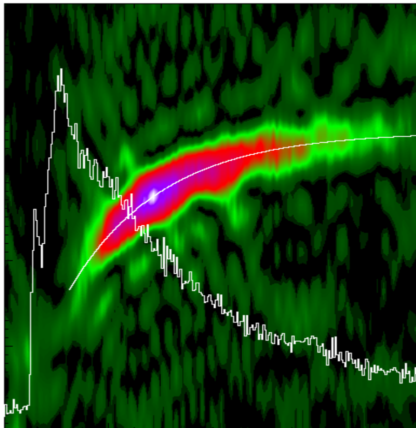




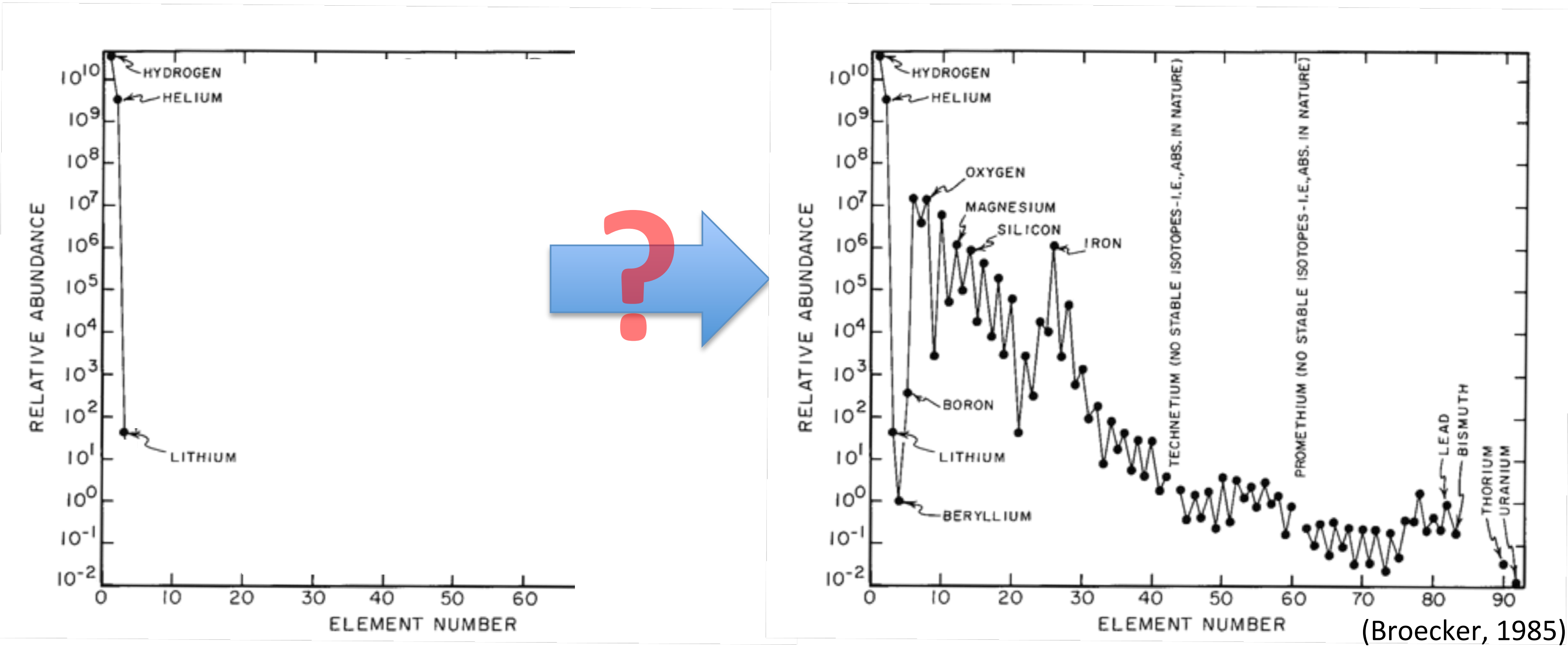
Nuclear Astrophysics: Experiment

Catherine M. Deibel

Louisiana State University



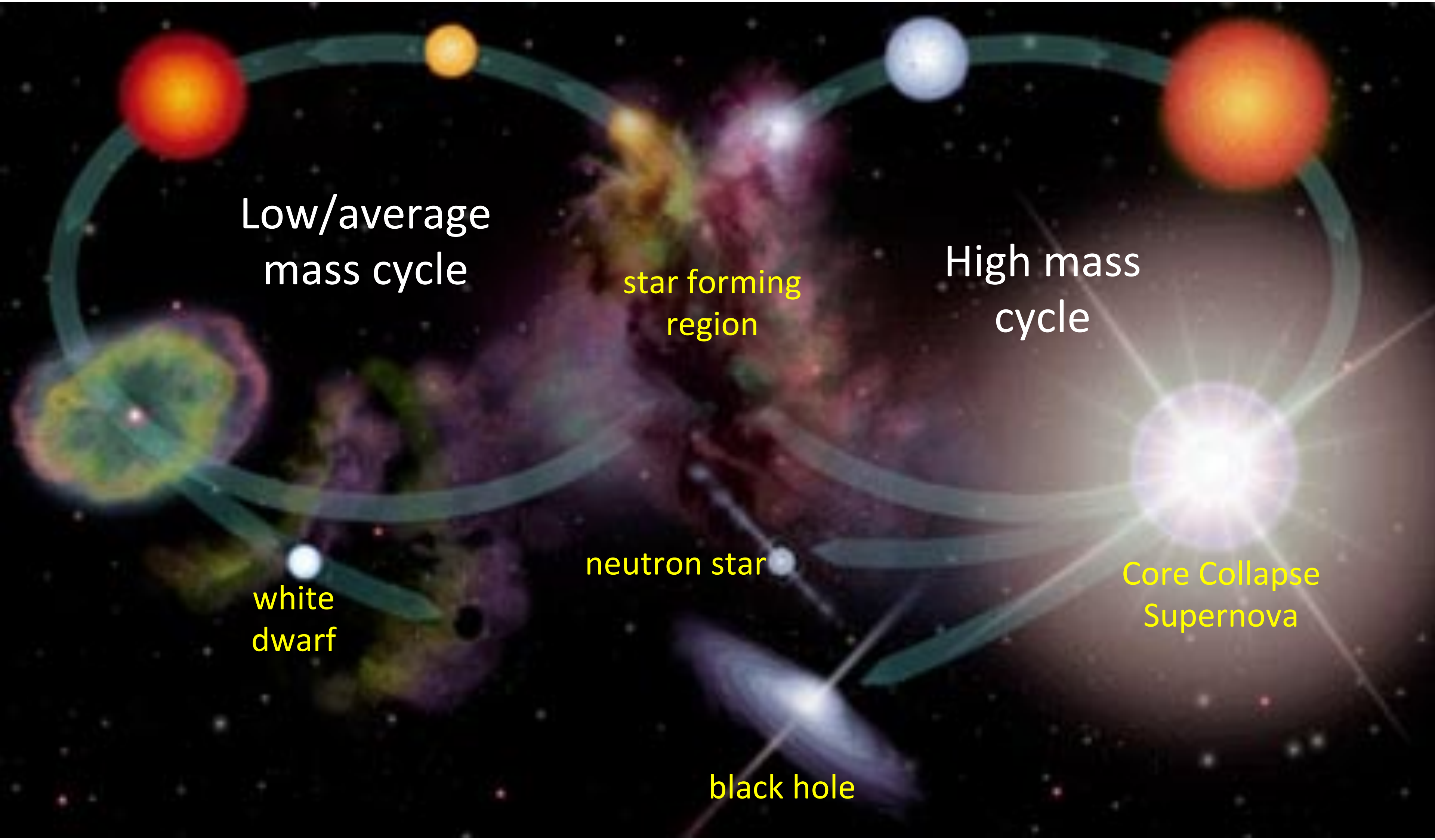
Solar Abundances: We are all Stardust!
. . . but how did we get here?



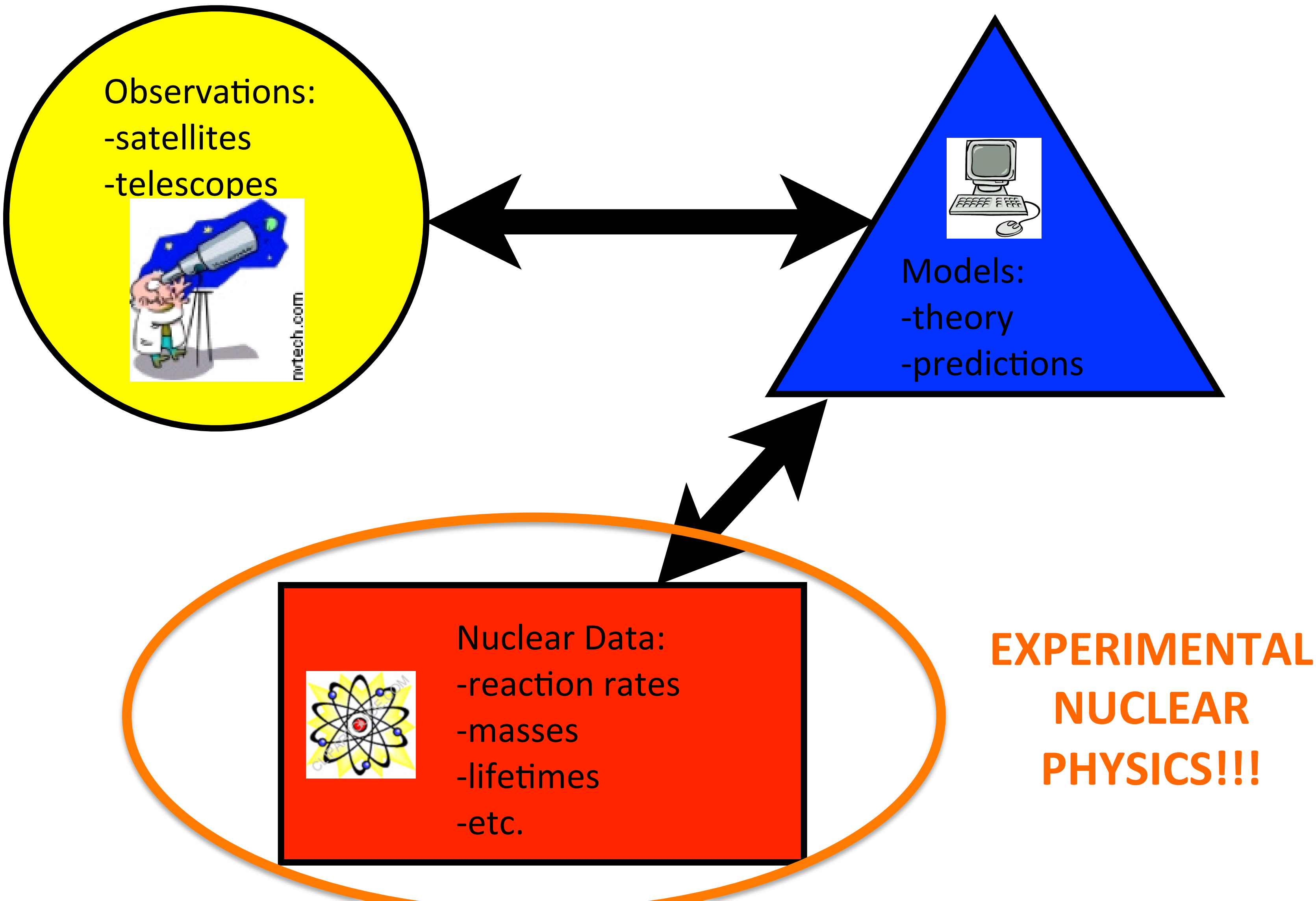
Big Bang Nuclei **Relative Solar Abundances**

1. **How did the elements form (nucleosynthesis)?**
2. **How to different stars evolve?**

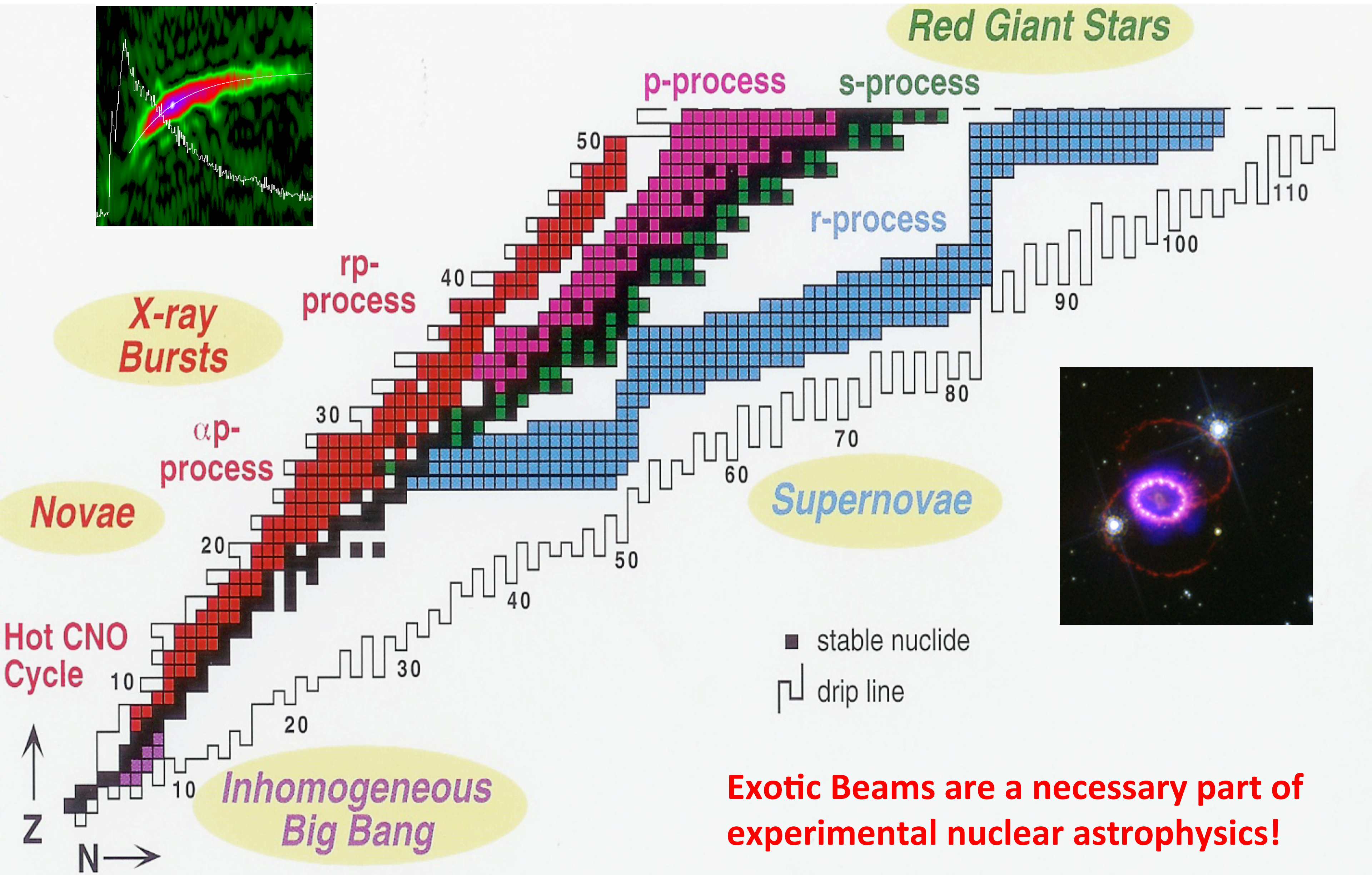
Stellar Life Cycle



Nuclear Astrophysics at a Glance

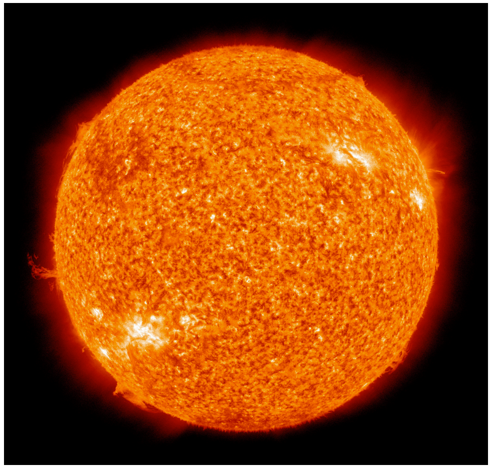


Nuclear Astrophysicist's Chart

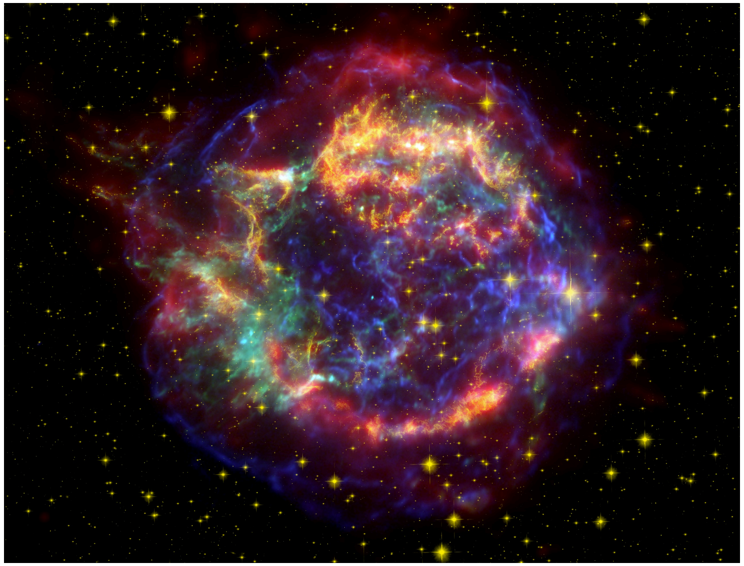


Exotic Beams are a necessary part of experimental nuclear astrophysics!

Experimental Quantities to be Measured



- Quiescent (stable) burning:
  - reaction rates
  - lifetimes
- Explosive burning (e.g. *rp*-process nucleosynthesis: X-ray bursts, classical novae):
  - reaction rates: (p,γ), (α,p), fusion, etc.
  - lifetimes
  - masses



- *r*-process nucleosynthesis:
  - masses
  - β-decay lifetimes
  - P_n values
  - reaction rates: (n,γ)

Competition: What happens to a nucleus in a star?

Depends on:

1. **Properties of nucleus**
2. **Properties of stellar site**

***β* decay**

Particle capture:

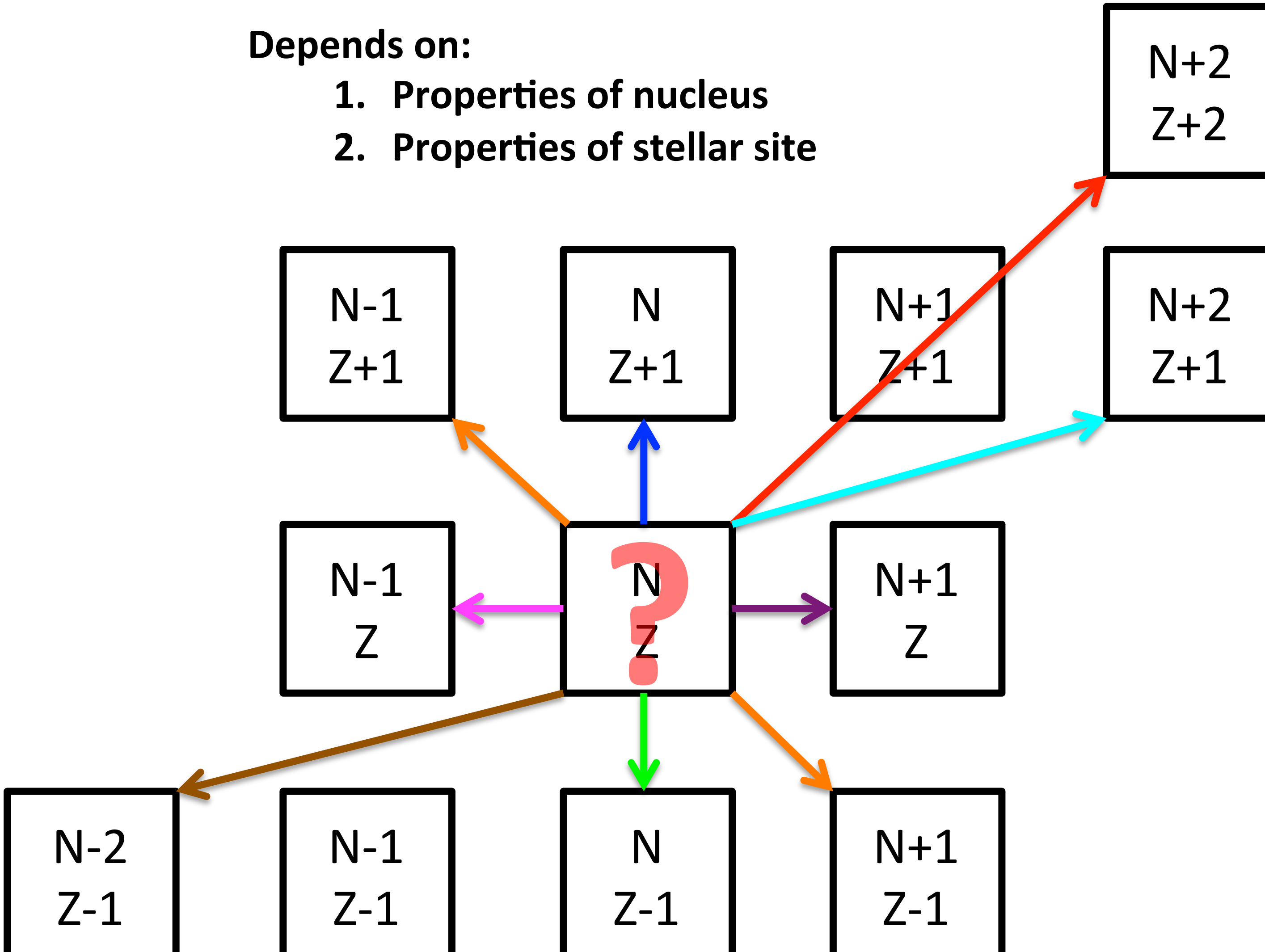
- **(p,γ)**
- **(n,γ)**
- **(α,γ)**

Photodisintegration:

- **(γ,p)**
- **(γ,n)**
- **(γ,α)**

Other reactions:

- **(α,p)**
- **(p,α)**
- ***β*-delayed emission**
- **fusion**
- **etc.**



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***β* decay**

Particle capture:

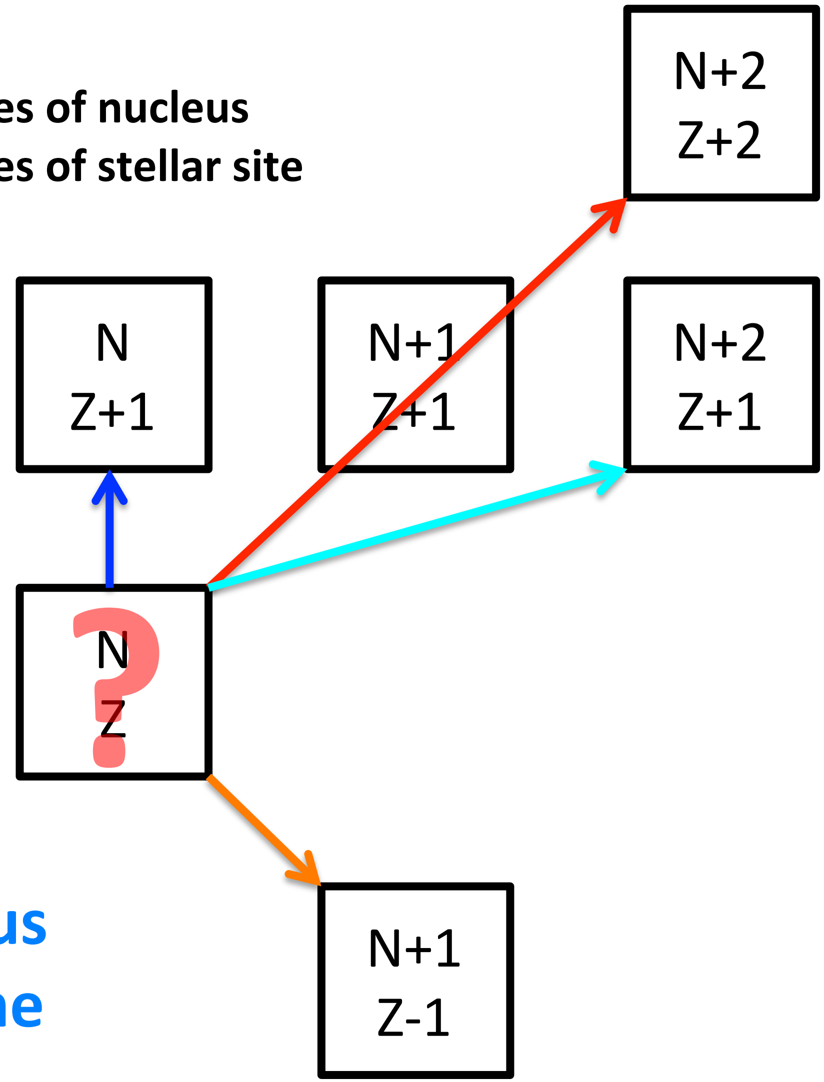
- **(p,γ)**
- **(n,γ)**
- **(α,γ)**

Photodisintegration:

- **(γ,p)**
- **(γ,n)**
- **(γ,α)**

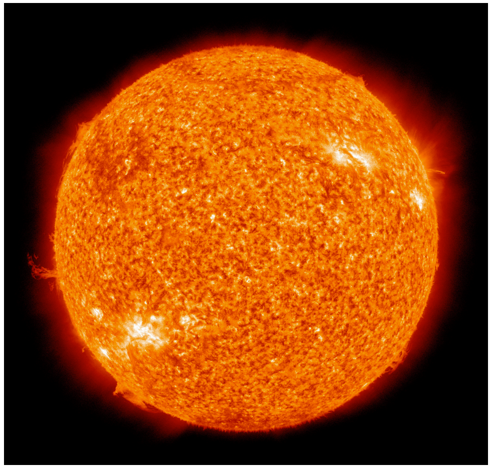
Other reactions:

- **(α,p)**
- **(p,α)**
- ***β*-delayed emission**
- **fusion**
- **etc.**



Several processes/ reactions on a nucleus can be possible in one stellar site!

Experimental Quantities to be Measured



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  - ➡ reaction rates
  - – lifetimes

- Explosive burning (e.g. *rp*-process nucleosynthesis: X-ray bursts, classical novae):
  - ➡ reaction rates: (p,γ), (α,p), fusion, etc.
  - – lifetimes
  - – masses

- *r*-process nucleosynthesis:
  - – masses
  - – β-decay lifetimes
  - – P_n values
  - ➡ reaction rates: (n,γ)

These quantities dictate:

- the reaction flow
- elemental abundances
- energy output
- evolution of star

. . . and us!

Reactions are important!! (Filomena)

Reaction *Rates*

- How often does a reaction A(*a*,*b*)B happen in a stellar plasma??

- What matters?
  - number density of target nuclei: N_A
  - number density of projectile nuclei: N_a
  - relative velocities (energies) of particles: v
  - reaction area for reaction: $\sigma(v)$

- Basic form of reaction rate: $$r = N_A N_a \underbrace{v\sigma(v)}$$

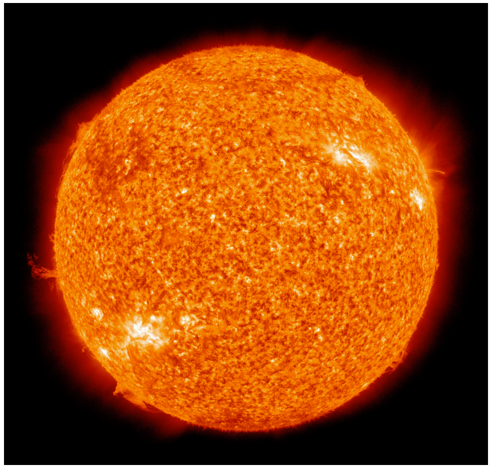
Velocity (Energy) dependence!!

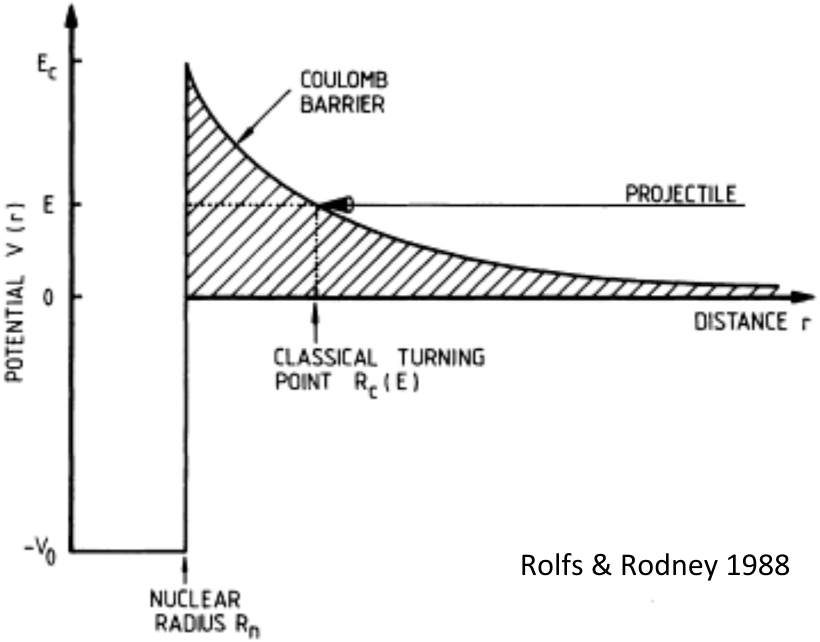
Charged Particle Reaction Rates

- Stars are hot . . . but not that hot!
- How much energy does a the average proton have in the sun?
  - 1 keV (E ~ kT)
- But the Coulomb repulsion between two protons is:

$$V_C = \frac{Z_1^2 Z_2^2 e^2}{r} = 550 \text{ keV}$$

- How do protons fuse in our Sun??
  - Tunneling!!
- Tunneling probability of 1 keV proton?
  - 8.9 x 10^{-10}!!!





Rolfs & Rodney 1988

Energy Distribution of Protons in Sun

- Of course, not every single proton has 862 eV of energy – there is some distribution $\phi(v)$
- This probability distribution
  - must normalize to unity
  - must be folded in with $v\sigma(v)$

$$\int_0^\infty \phi(v)\,dv = 1$$

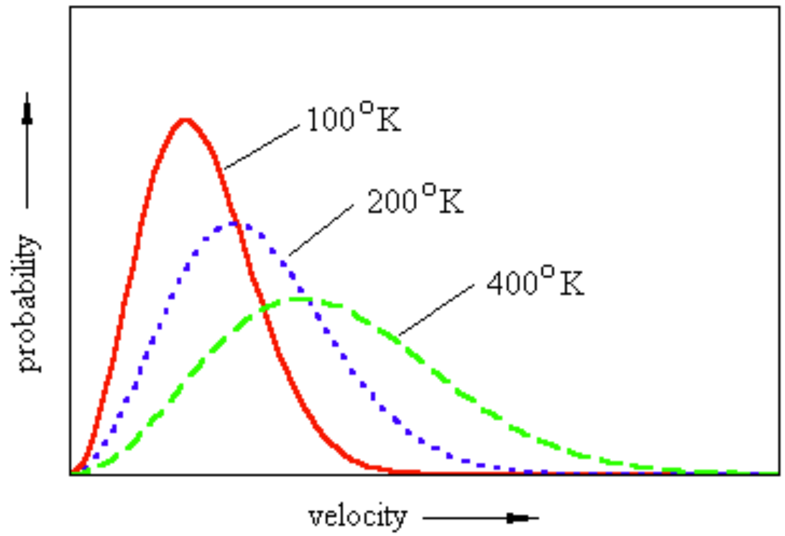
$$\langle \sigma v \rangle = \int_0^\infty \phi(v)\,v\sigma(v)\,dv$$

$$r = N_A N_a \langle \sigma v \rangle \left(1 + \delta_{Aa}\right)^{-1}$$

$$r = N_A N_a \langle \sigma v \rangle = N_A N_a \int_0^\infty \int_0^\infty \phi(v_A)\,\phi(v_a)\,v\sigma(v)\,dv_A\,dv_a$$

Energy Distribution of Particles in Plasma

- What type of energy/velocity distribution exists in a stellar plasma?
  - A. Gaussian distribution
  - B. Maxwell-Boltzmann distribution
  - C. Poisson distribution
  - D. Gamma distribution



Distribution for both species A and a:

$$\phi(v_{A,a}) = 4\pi v_{A,a}^2 \left(\frac{m}{2\pi kT}\right)^{3/2} \exp\left(-\frac{m v_{A,a}^2}{2kT}\right)$$

$$\phi(v) = 4\pi v^2 \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right)$$

$$\phi(V) = 4\pi V^2 \left(\frac{M}{2\pi kT}\right)^{3/2} \exp\left(-\frac{M V^2}{2kT}\right)$$

relative velocity (v); reduced mass (μ); center of mass velocity (V); total mass (M)

Reaction Rates

$$\langle \sigma v \rangle = \int_0^\infty \int_0^\infty \phi(v) v \sigma(v) dv \phi(V) dV$$

$$\langle \sigma v \rangle = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} \int_0^\infty v^3 \exp\left(-\frac{\mu v^2}{2kT} \right) \sigma(v) dv$$

In terms of center of mass energy, $E = 1/2\, \mu v^2$, we can rewrite the **reaction rate per particle pair** as:

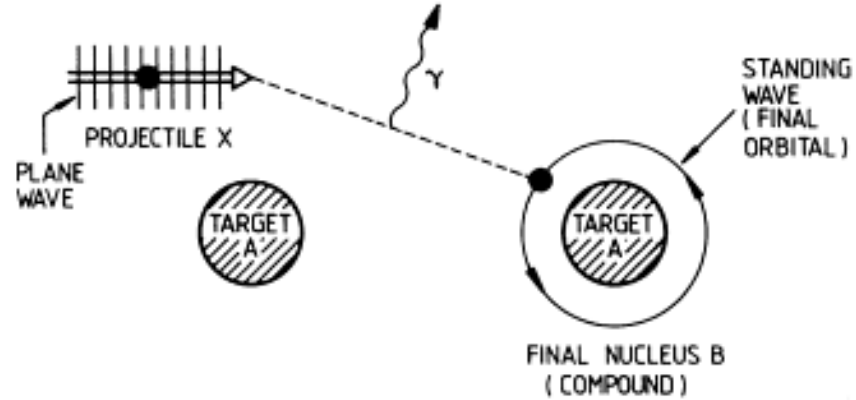
$$\langle \sigma v \rangle = \left(\frac{8}{\mu \pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty E \sigma(E) \exp\left(-\frac{E}{kT} \right) dE$$

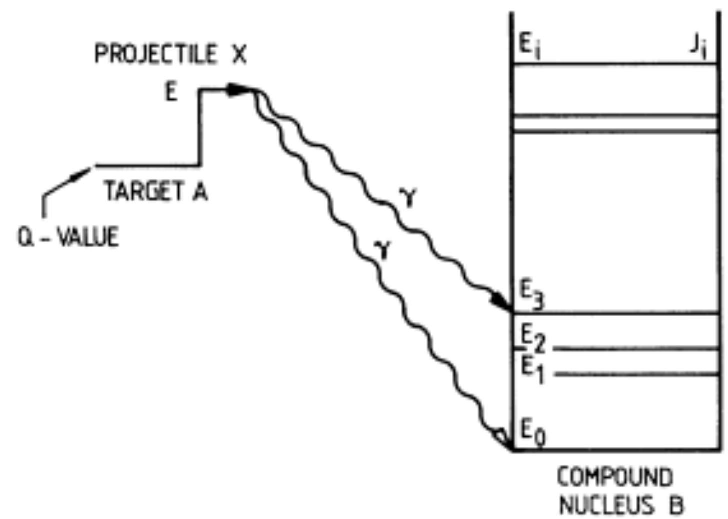
Notice:

1. The energy depend terms are all in the integral!!
2. Temperature dependence

Non-Resonant Reaction Rates

- Two types of reaction rates:
  - non-resonant
  - resonant
- Non-resonant reactions:
  - one-step process
  - can occur at any energy
  - electromagnetic process
  - cross section varies smoothly but drops quickly
  - measurements at low (stellar) energies are difficult!





Schematic of a non-resonant capture (direct capture) process: Rolfs and Rodney, 1988

Non-Resonant Reaction Rates

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- Non-resonant reactions:
  - one-step process
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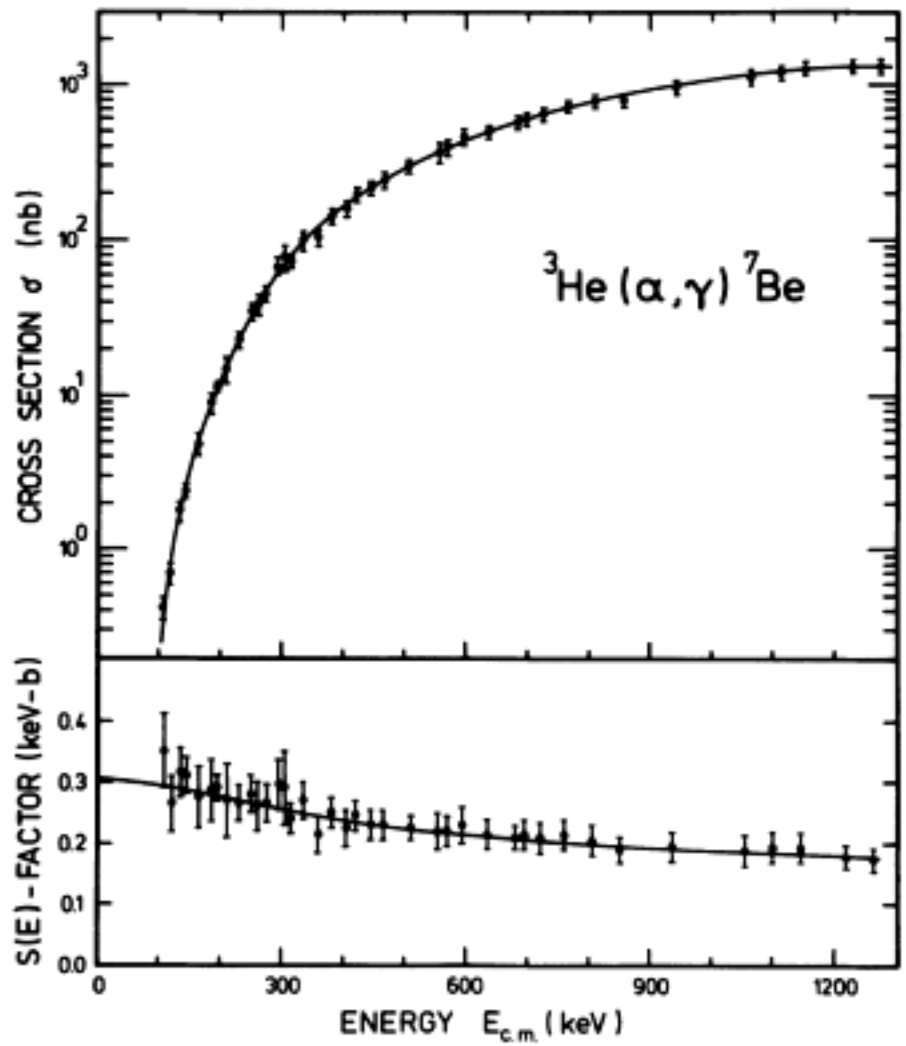
- Form of cross section??

$$\langle \sigma v \rangle = \left(\frac{8}{\mu \pi} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^{\infty} E \sigma(E) \exp\left(-\frac{E}{kT} \right) dE$$



Non-Resonant Reaction Rates

- Probability for tunneling where $R_c >> R_n$:

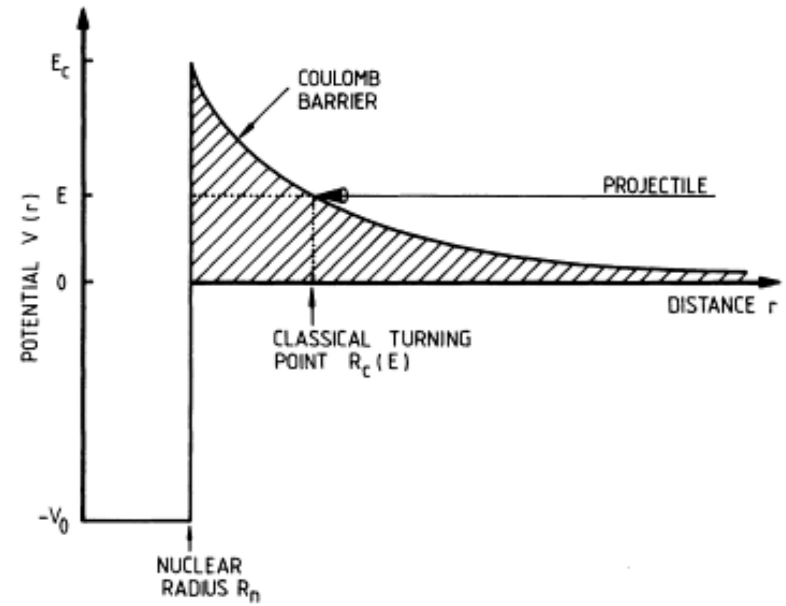
$$P = \exp(-2\pi\eta) \quad \text{where} \quad \eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

- The cross section is also proportional to 1/E, and can be written as:

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E)$$

- ***S*(*E*) is the astrophysical *S*-factor** and contains all strictly nuclear effects

- The *S*-factor varies much less rapidly and can be extrapolated to stellar energies – THIS is often what we are after!



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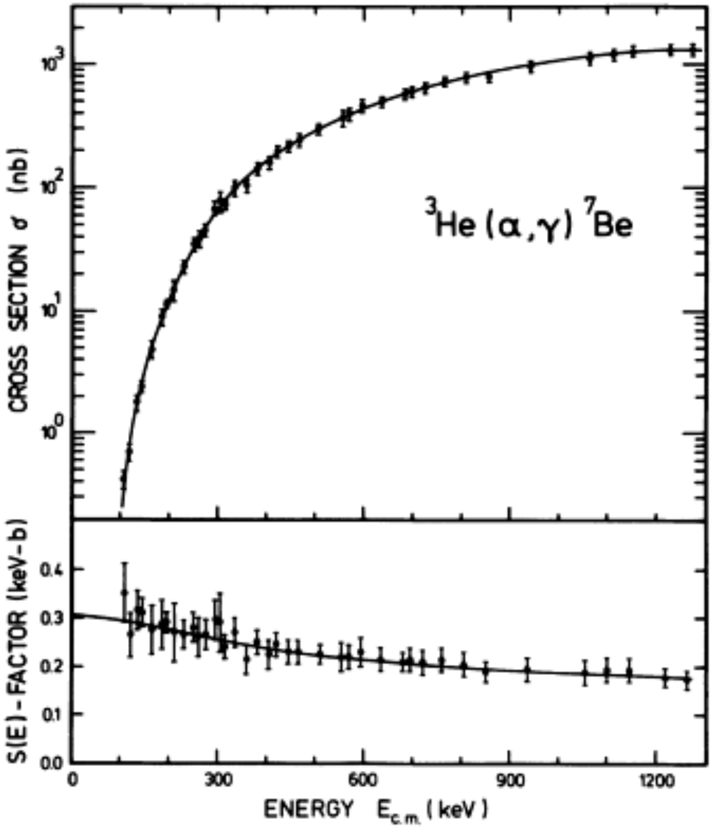

Non-resonant reaction rate:

$$\langle \sigma v \rangle_{NR} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E)\exp\left(-\frac{E}{kT} - \sqrt{\frac{E_G}{E}}\right) dE$$

We can **expand *S*(*E*)** around zero energy and get these values from the fit to the data!

Gamow Energy:

$$E_G = \left[(2\mu)^{1/2} \pi e^2 Z_1 Z_2 / \hbar\right]^2$$

Non-Resonant Reaction Rates

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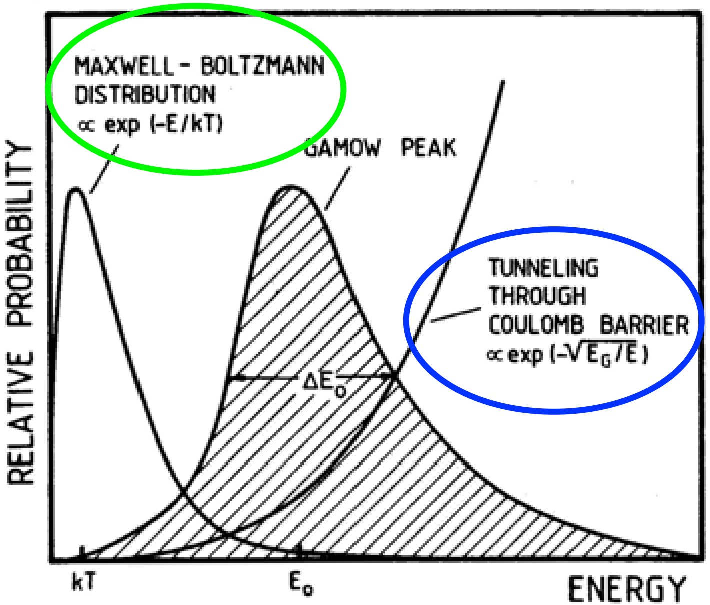
Gamow Energy: $E_G = \left[(2\mu)^{1/2}\pi e^2 Z_1 Z_2/\hbar\right]^2$

Reaction rate folds together the **Maxwell-Boltzmann distribution** and the **Nuclear cross section**



Rolfs & Rodney 1988

Gamow Window

$$\langle \sigma v \rangle_{NR} = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{kT} - \sqrt{\frac{E_G}{E}}\right) dE$$

Gamow Energy:

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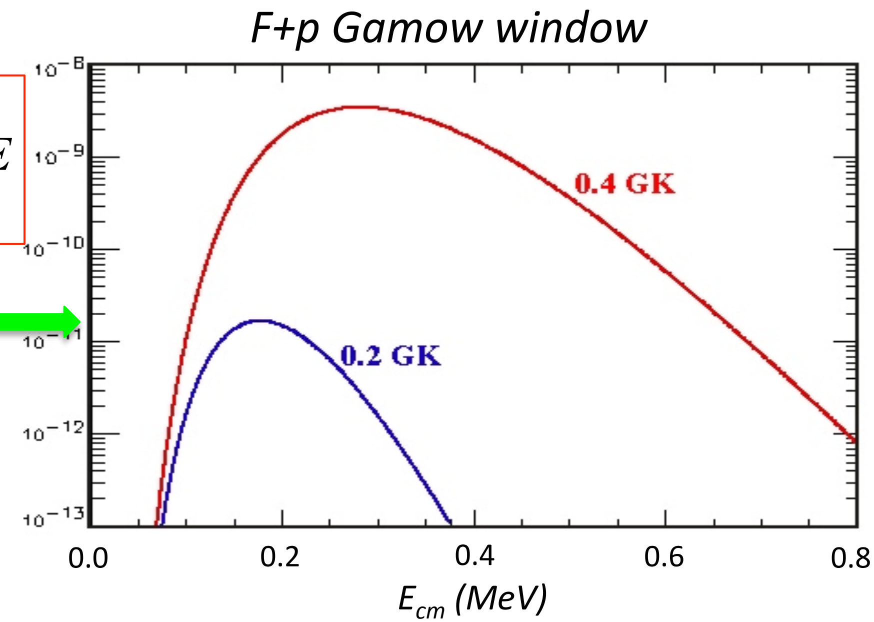
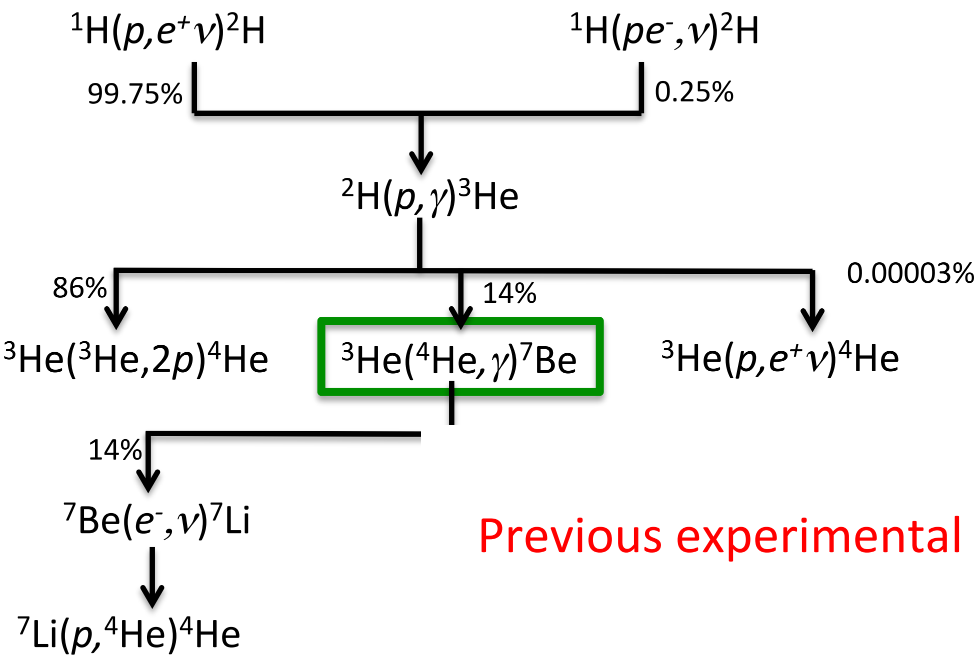
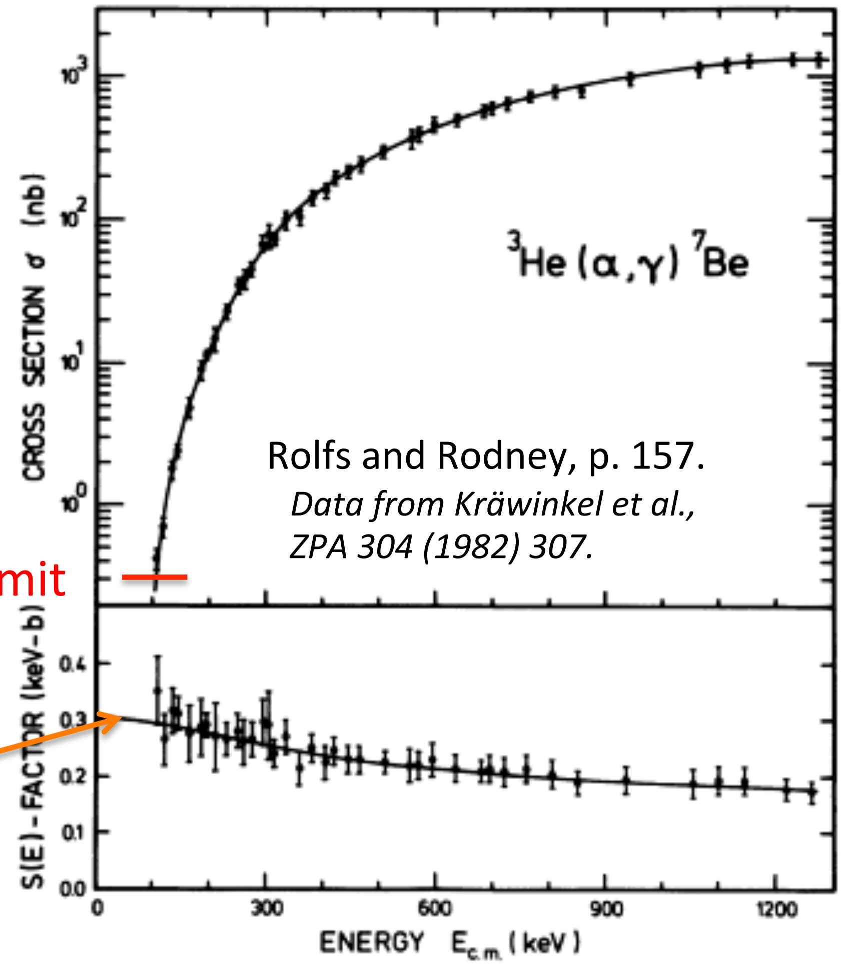


Reaction	*site*	*T (10^6 K)*	*kT (keV)*	*r_{turn} (fm)*	*r (fm)*	*E_0 (keV)*
p+p	sun	15	1.3	1100	2.5	6
p+^{14}N	CNO	30	2.6	3900	4.3	42
α+^{12}C	red giant	190	16	1060	4.8	300
p+^{17}F	nova	300	26	500	4.5	230
α+^{30}S	x-ray burst	1000	86	500	5.9	1800
^{3}He+^{4}He	big bang	2000	170	33	3.8	580

Direct Measurement of $^3He(\alpha,\gamma)^7Be$



***pp* chain**



Previous experimental limit

Need σ here for sun

Important for:

The sun (ν production)

Big Bang (Li production)

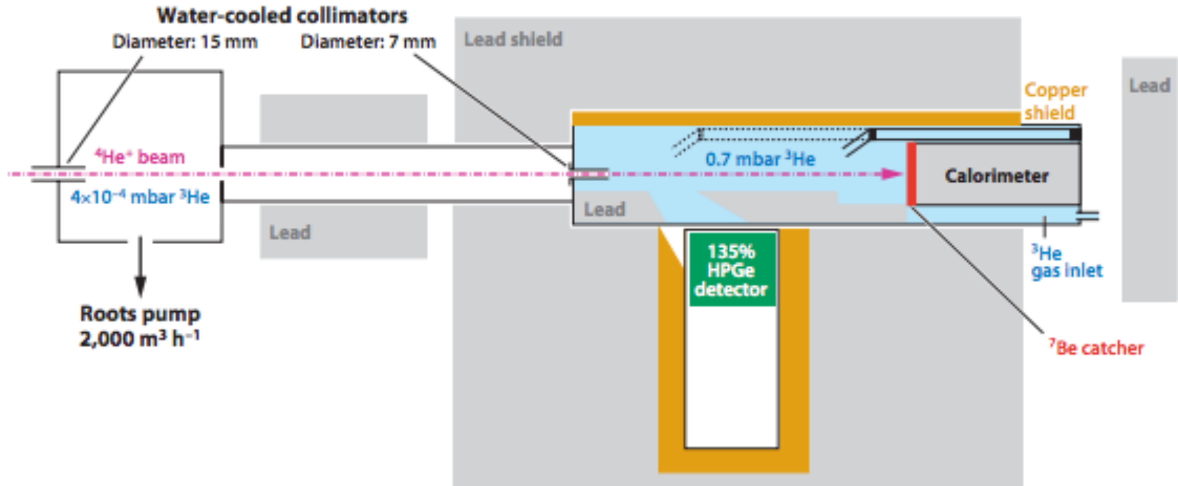
$$\sigma \equiv \frac{S}{E} e^{-\sqrt{E_G / E}}$$

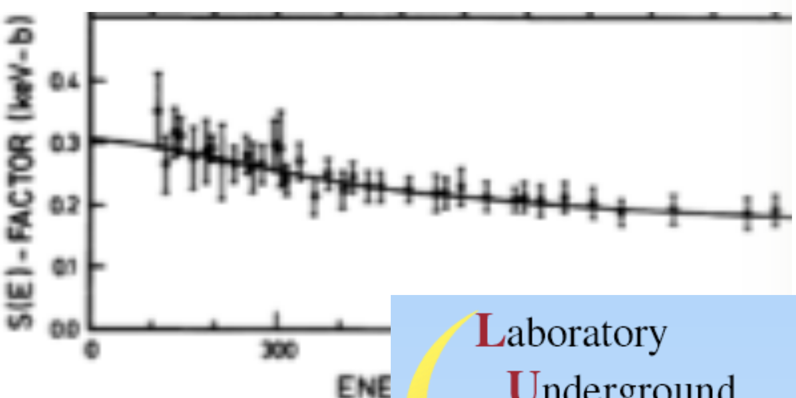
How to get down to lower energies i.e. lower cross sections?

- High intensities
- Low background

Measurement of $^3He(\alpha,\gamma)^7Be$ @ LUNA

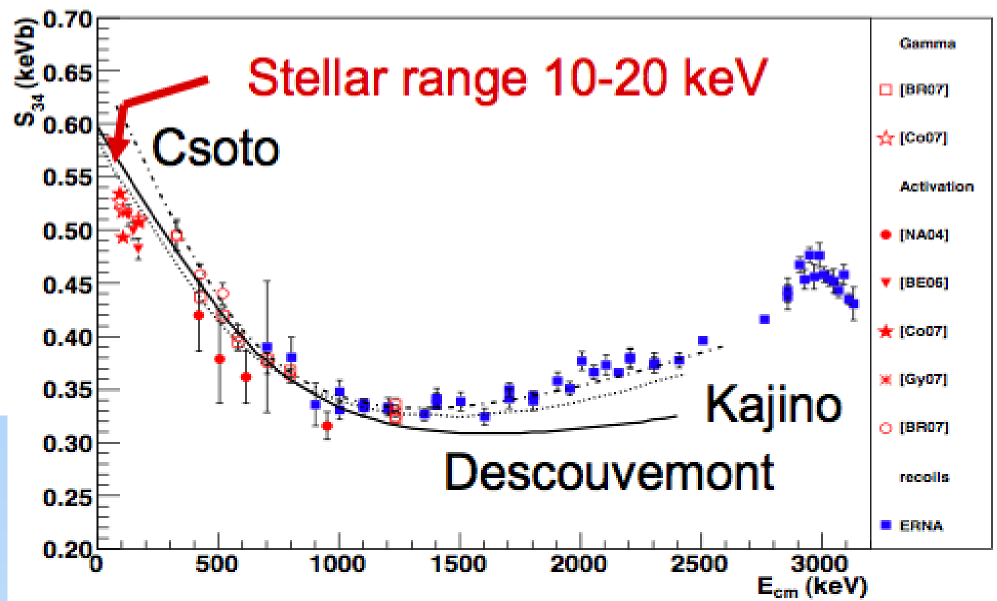
- Laboratory deep underground (Gran Sasso mine)
- Can perform direct measurements at very low background
- High Intensity Beams
  - 100's μA – 1 mA

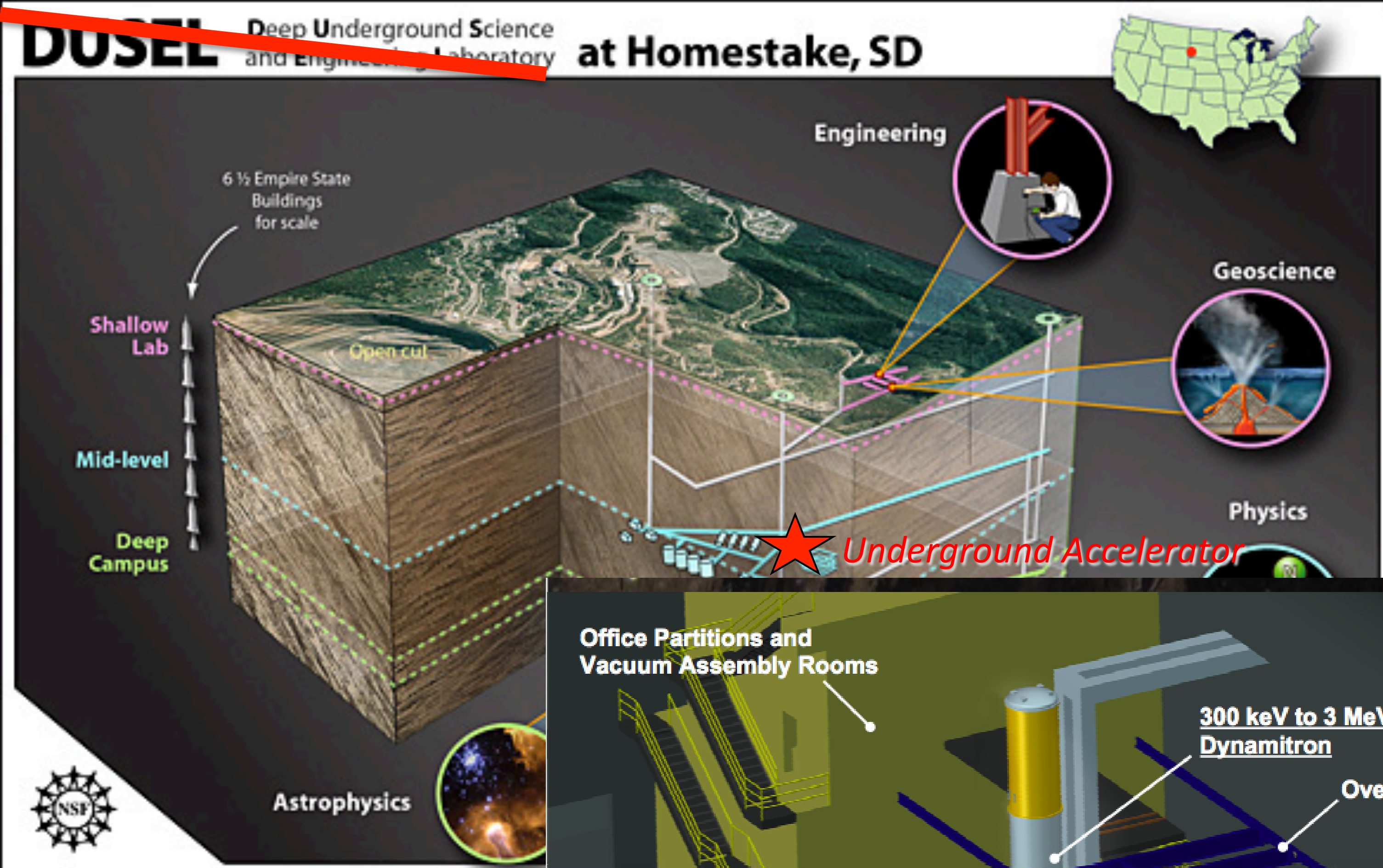




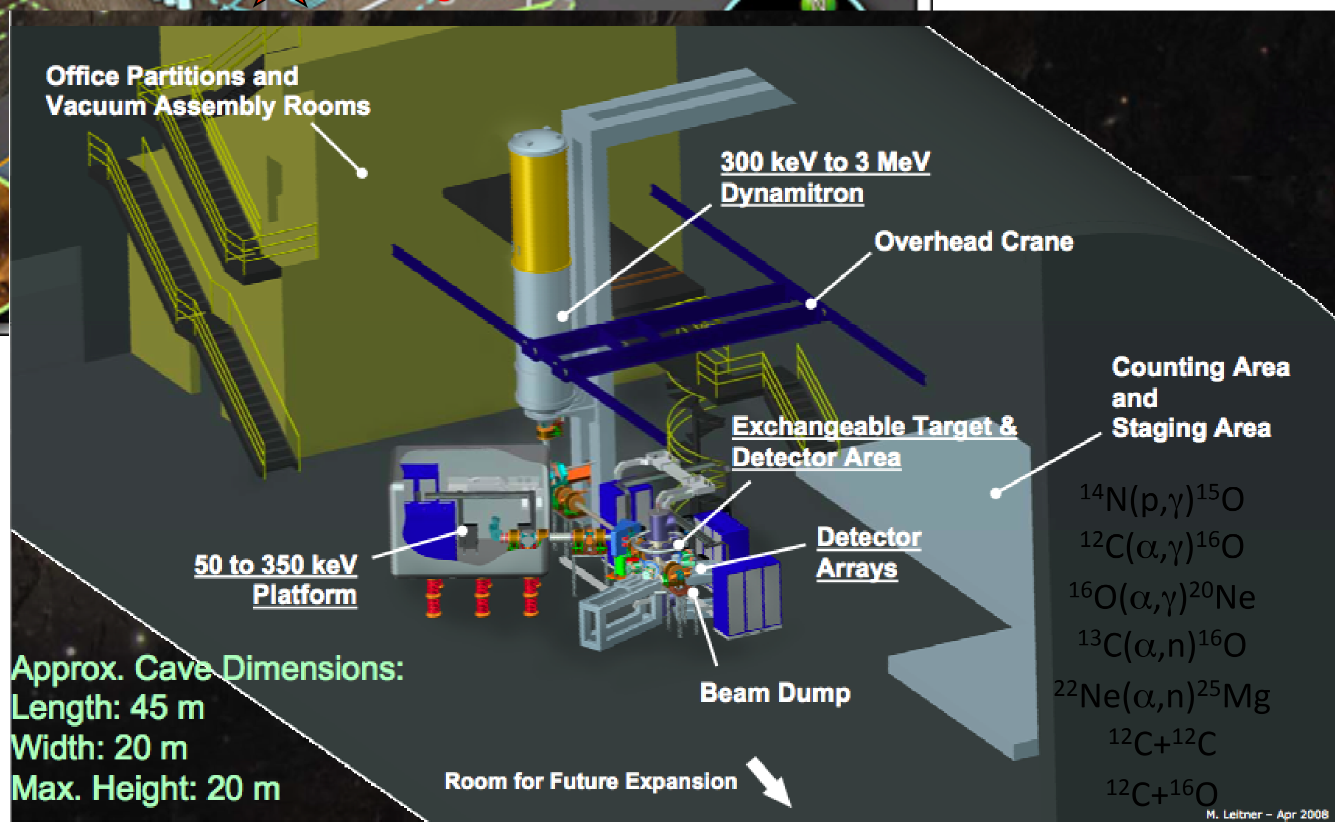
Laboratory
Underground
Nuclear
Astrophysics

New measurements



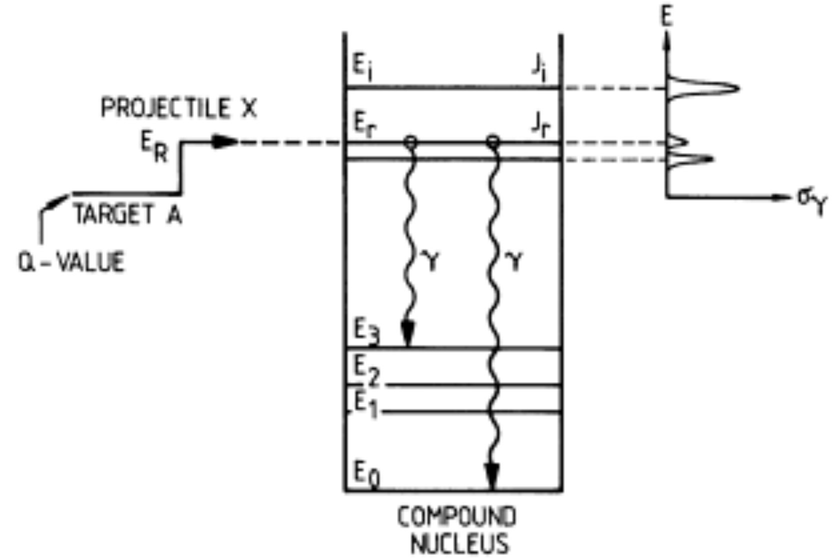

DUSEL Deep Underground Science and Engineering Laboratory
at Homestake, SD
Engineering
6 ½ Empire State Buildings for scale
Geoscience
Shallow Lab
Open cut
Mid-level
Physics
Deep Campus
Underground Accelerator
Astrophysics
NSF

DIANA


Office Partitions and Vacuum Assembly Rooms
300 keV to 3 MeV Dynamitron
Overhead Crane
Counting Area and Staging Area
Exchangeable Target & Detector Area
Detector Arrays
50 to 350 keV Platform
Beam Dump
Approx. Cave Dimensions:
Length: 45 m
Width: 20 m
Max. Height: 20 m
Room for Future Expansion
$^{14}N(p,\gamma)^{15}O$
$^{12}C(\alpha,\gamma)^{16}O$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$
$^{12}C+^{12}C$
$^{12}C+^{16}O$
M. Leitner – Apr 2008

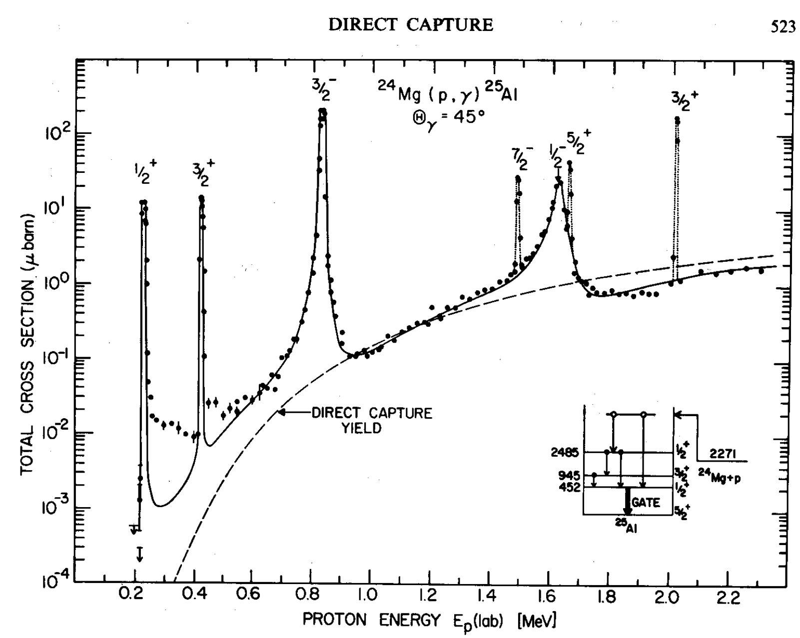
Resonant Reaction Rates

- Two types of reaction rates:
  - non-resonant
  - resonant



- Resonant reaction rates:
  - two-step process
  - creates excited state in compound nucleus
  - occur at specific (resonance) energies
  - vary dramatically over small energy ranges (resonances)
  - can have very high cross sections if beam energy satisfies:

$$E_R = E_x - Q$$



- From of cross section??

Resonant Reaction Rates

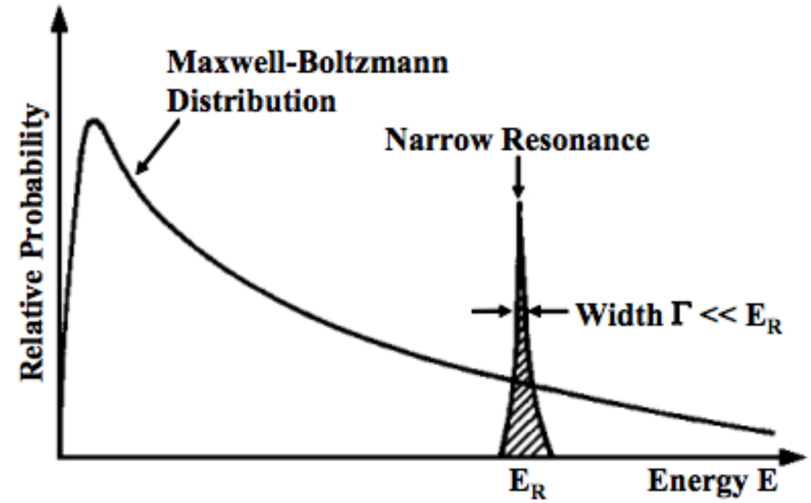
- Resonances can be narrow or broad
- Narrow resonances:
  - Width $\Gamma < 10\%$ of E_R
- Resonant phenomena occur in nature all the time!
  - e.g. damped oscillator

$$\frac{f}{(\omega - \omega_0) + (\delta/2)^2}$$

- Breit-Wigner cross section has this form:

$$\sigma_{BW}(E) = \pi \lambda\!\!\!^{-2} \frac{2J+1}{(2J_A+1)(2J_a+1)}(1+\delta_{Aa}) \frac{\Gamma_a \Gamma_b}{(E-E_R)^2 + (\Gamma/2)^2}$$

statistical factor



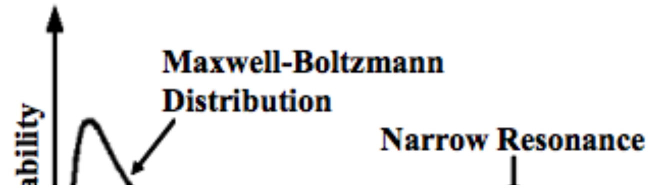
Rolfs & Rodney 1988

$$N_A \langle \sigma v \rangle = \frac{1.5399 \times 10^{11}}{(\mu T_9)^{3/2}} \sum_i (\omega\gamma)_i \, e^{-11.605 E_i / T_9}$$

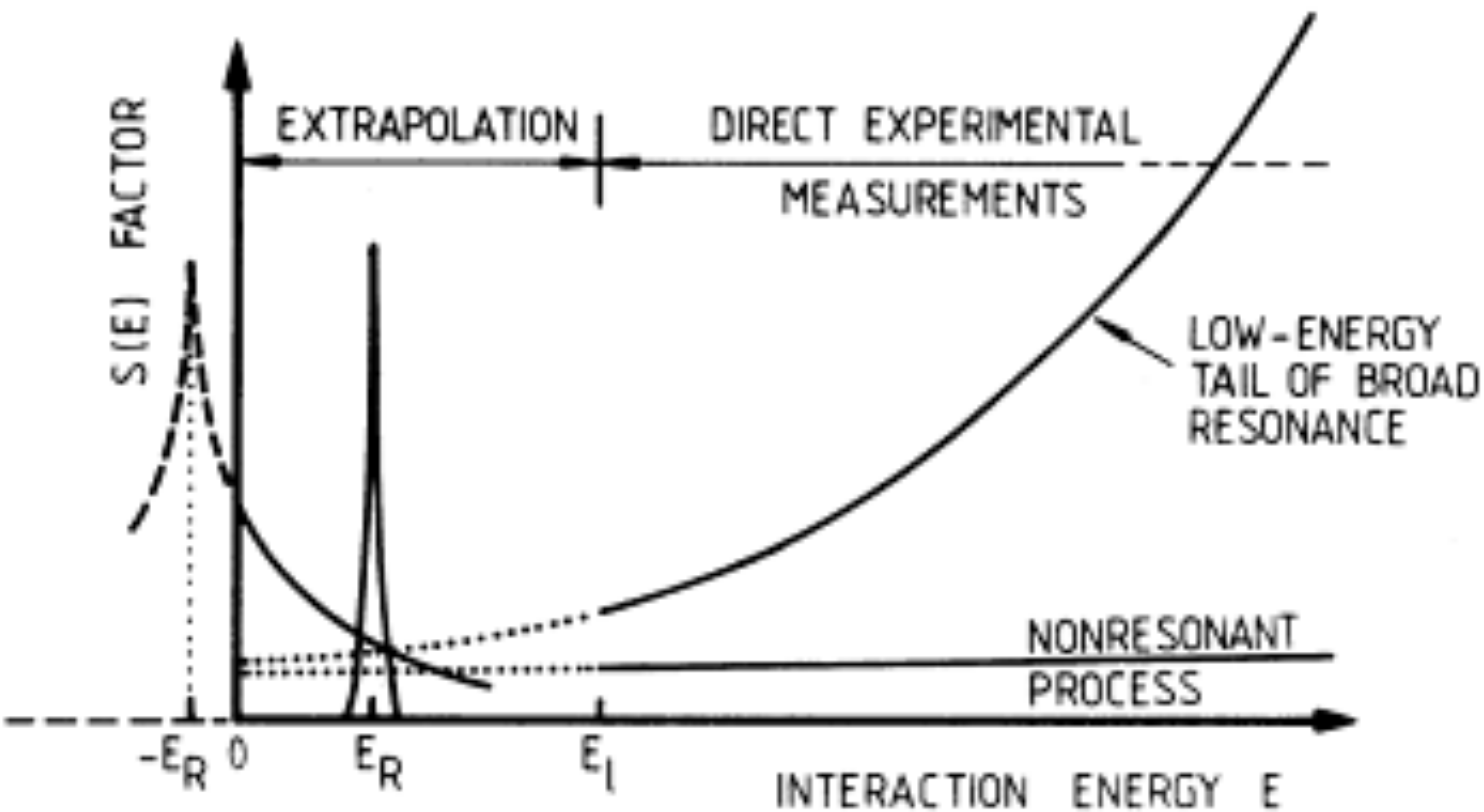
$$(\omega\gamma)_i = \frac{(2J_i+1)}{(2J_0+1)(2J_1+1)}(1+\delta_{01}) \frac{\Gamma_a \Gamma_b}{\Gamma_{tot}}$$

E_r = resonance energy
J = spins of states
Γ = particle widths

Resonant Reaction Rates



- Resonances can be narrow or broad
- Na
  –
- Re
  al
  –



$<< E_R$

ergy E

odney 1988

$.605 E_i / T_9$

- Br
  fo

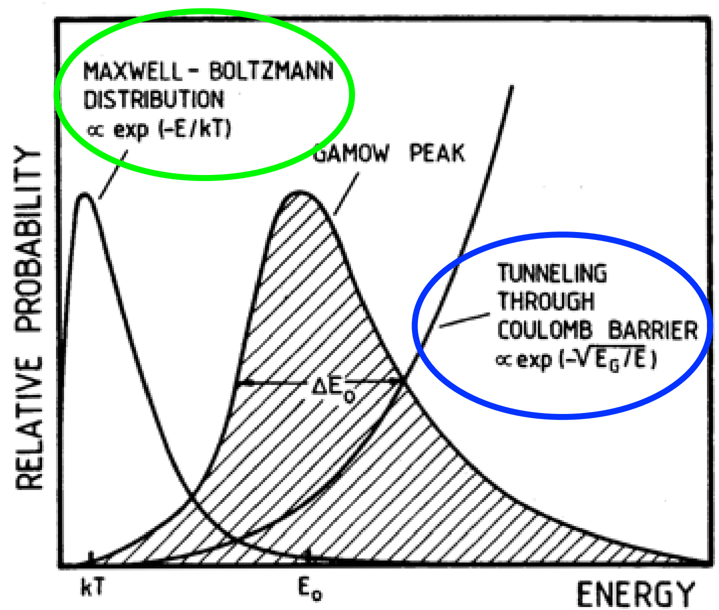
σ_{BW} $(2J_A+1)(2J_a+1)$ $(E-E_R)^2+(\Gamma/2)^2$ $\frac{\Gamma_a \Gamma_b}{\Gamma_{tot}}$

statistical factor

Γ = particle widths

Resonant Reaction Rates

- Two types of measurements:
  - **direct:** measure the reaction of interest directly
    - Pros: measuring what happens in nature
    - Cons: loooowwww cross sections, low intensity RIBs, challenging kinematics (inverse kinematics)
  - **indirect**: measure nuclear structure components which go into the reaction rate
    - Pros: you pick reaction (stable and/or high intensity beams, well-known experimental techniques, etc.)
    - Cons: not measuring reaction of interest
- **Both types of measurements are needed:**
  - nuclear structure information needed to know which resonances are important and where to find them!



Rolfs & Rodney 1988

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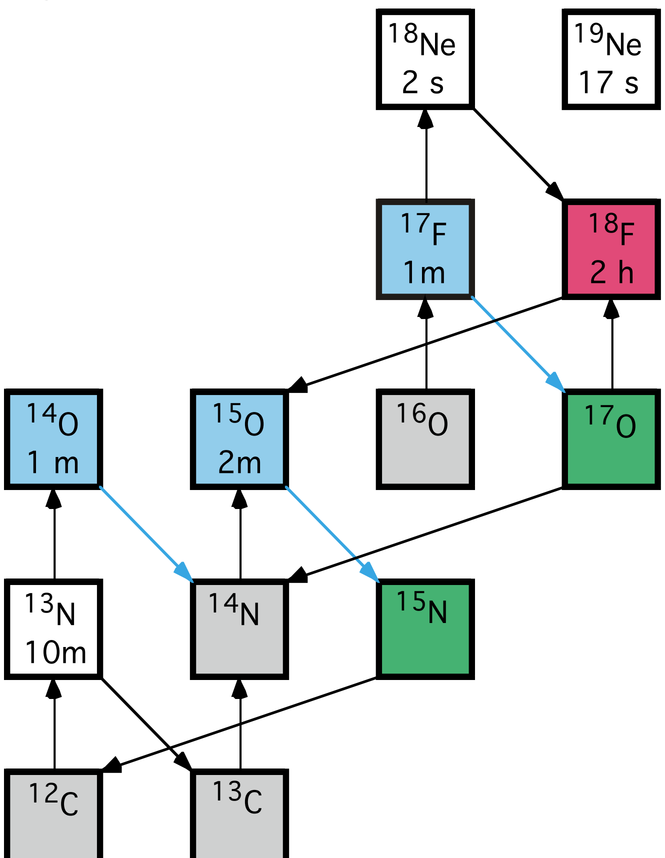
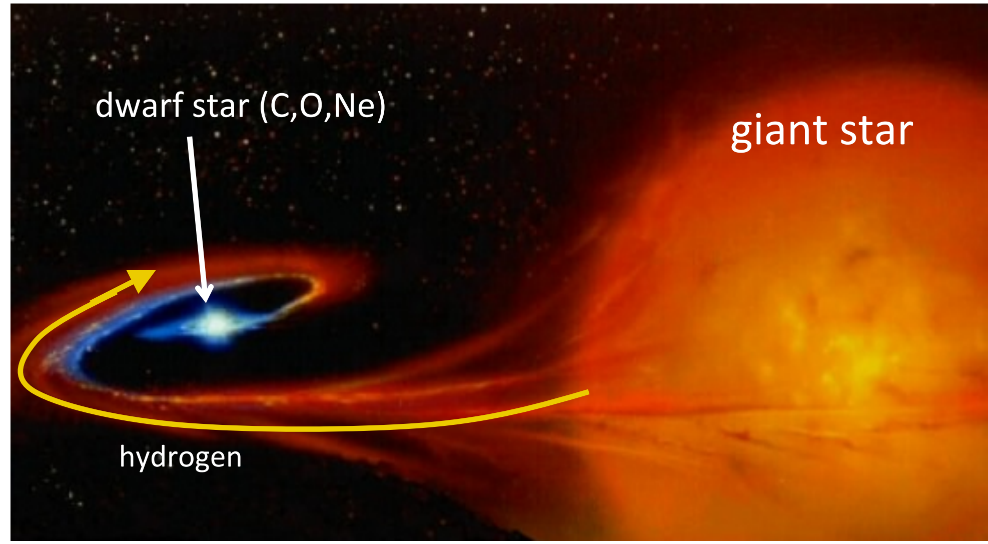
$$(\omega\gamma)_i = \frac{(2J_i + 1)}{(2J_0 + 1)(2J_1 + 1)} (1 + \delta_{01}) \frac{\Gamma_a \Gamma_b}{\Gamma_{tot}}$$

E_r = resonance energy
J = spins of states
Γ = particle widths

Reaction Rate Measurements: Classical Novae

- Classical nova rate = 35/year
- Peak temperatures: 0.1 – 0.4 GK
- Luminosity increase by a factor of 10^4

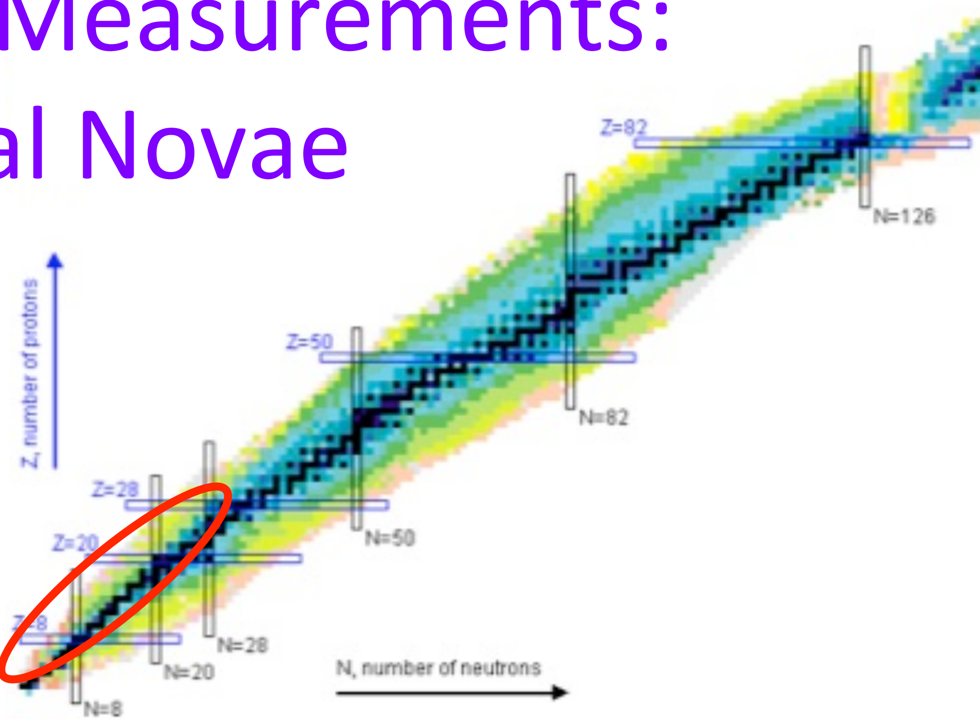


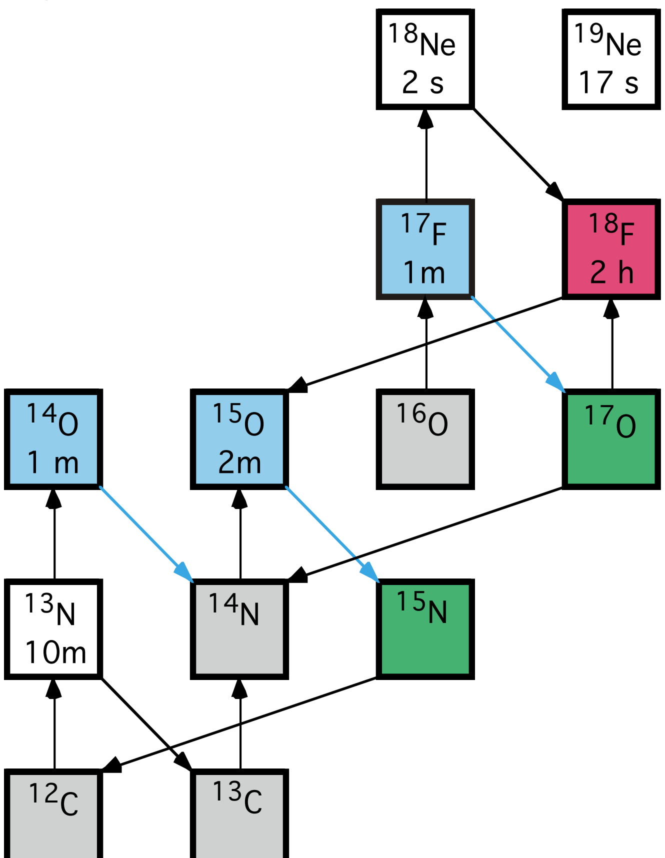


- Hydrogen converted to He via hot CNO cycle
- electron degeneracy → pressure
- Temperature builds → thermonuclear runaway
- Breakout from CNO cycle from ^{18}F:
  - $^{18}F(p,\alpha)^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$
  - $^{18}F(p,\gamma)^{19}Ne(p,\gamma)^{20}Na$
  - $^{18}F(\beta)^{18}Ne(\alpha,p)^{21}Na$

Reaction Rate Measurements: Classical Novae

- Classical nova rate = 35/year
- Peak temperatures: 0.1 – 0.4 GK
- Luminosity increase by a factor of 10^4





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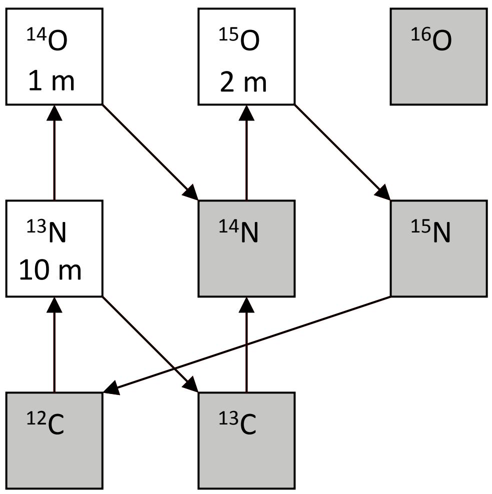
  - $^{18}F(\beta)^{18}Ne(\alpha,p)^{21}Na$

Solving a reaction rate network

The CN cycle: hydrogen burning

Identify important reactions



Nuclear physics → reaction rates

Astrophysical model to define the equations of state: ρ, T

Network of many coupled equations

$$\frac{dN_{12C}}{dt} = N_{15N}N_p\langle\sigma v\rangle_{15Np} - N_{12C}N_p\langle\sigma v\rangle_{12Cp}$$

$$\frac{dN_{13N}}{dt} = N_{12C}N_p\langle\sigma v\rangle_{12Cp} - N_{13N}N_p\langle\sigma v\rangle_{13Np} - \lambda_{13N}N_{13N}$$

$$\frac{dN_{13C}}{dt} = \lambda_{13N}N_{13N} - N_{13C}N_p\langle\sigma v\rangle_{13Cp}$$

$$\frac{dN_{14O}}{dt} = N_{13N}N_p\langle\sigma v\rangle_{13Np} - \lambda_{14O}N_{14O}$$

$$\frac{dN_{14N}}{dt} = N_{13C}N_p\langle\sigma v\rangle_{13Cp} + \lambda_{14O}N_{14O} - N_{14N}N_p\langle\sigma v\rangle_{14Np}$$

$$\frac{dN_{15O}}{dt} = N_{14N}N_p\langle\sigma v\rangle_{14Np} - \lambda_{15O}N_{15O}$$

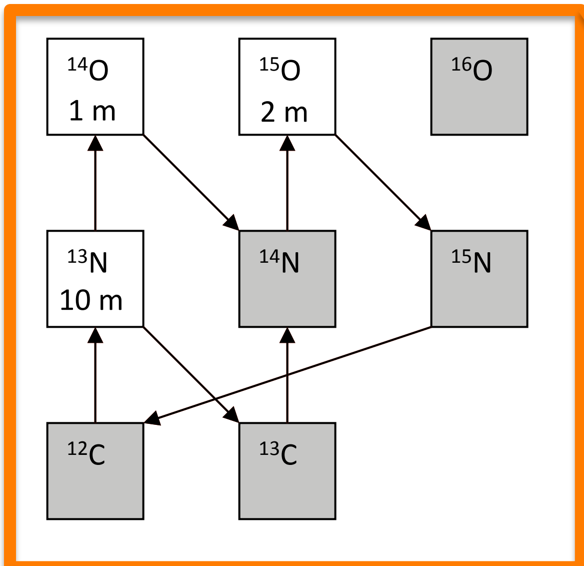
$$\frac{dN_{15N}}{dt} = \lambda_{15O}N_{15O} - N_{15N}N_p\langle\sigma v\rangle_{15Np}$$

➡ Numerically solve for $N_x(t)$

Solving a reaction rate network

The CN cycle: hydrogen burning

Identify important reactions



Nuclear physics → reaction

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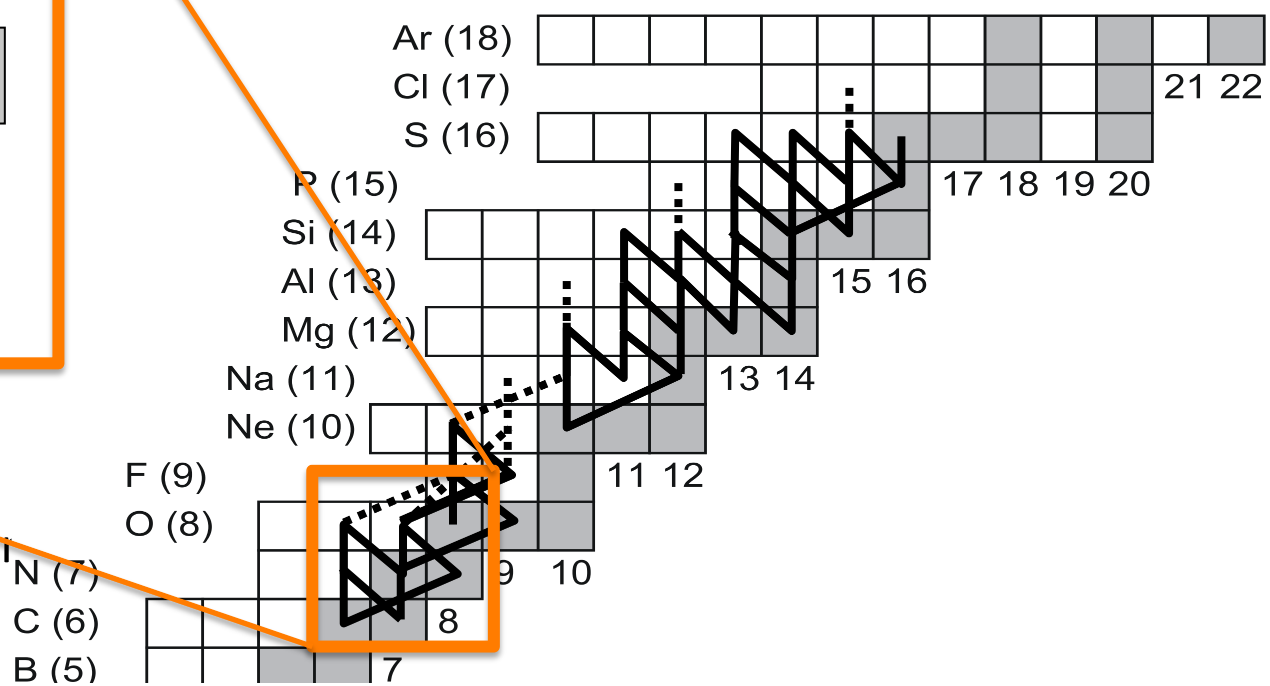
$$\frac{dN_{12C}}{dt} = N_{15N} N_p \langle \sigma v \rangle_{15Np} - N_{12C} N_p \langle \sigma v \rangle_{12Cp}$$



Numerically solve for $N_x(t)$

Reactions in Classical Novae

Sensitivity studies vary the reaction rates to show which ones affect the final elemental abundances produce by novae

C. Iliadis *et al*, ApJ SS **142**, 105 (2002)

- Most important reaction rates known, except a few such as
  $^{18}F(p,\alpha)^{15}O$
  $^{30}P(p,\gamma)^{31}S$
  $^{25}Al(p,\gamma)^{26}Si$

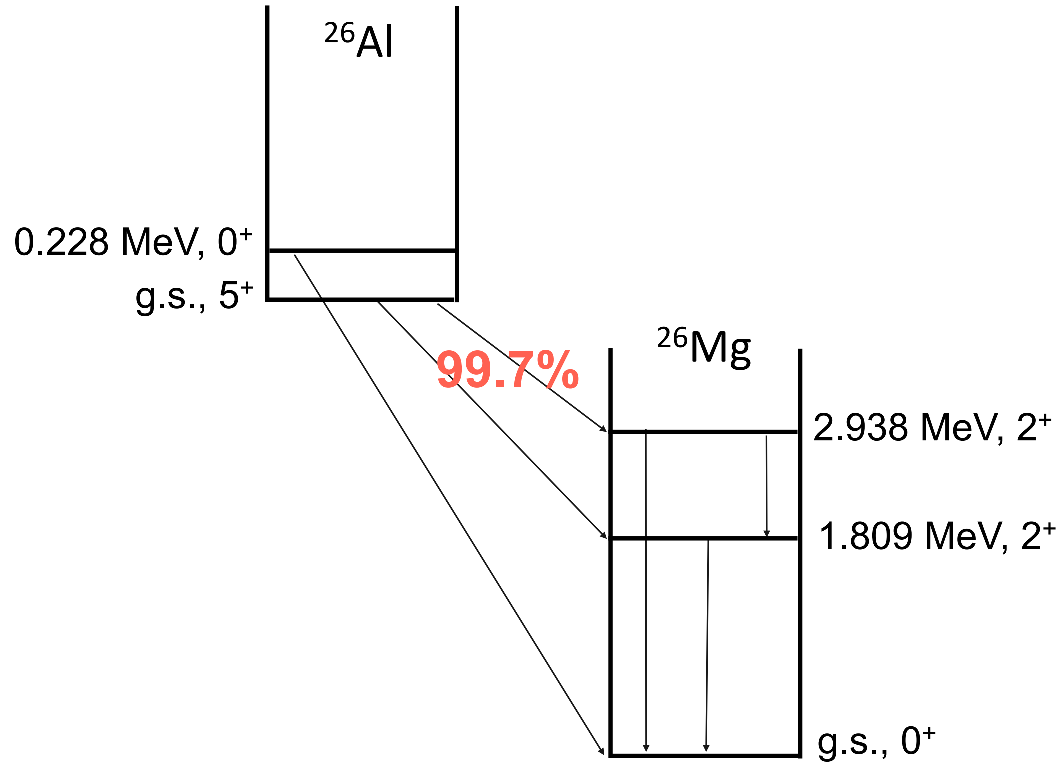
TABLE 12

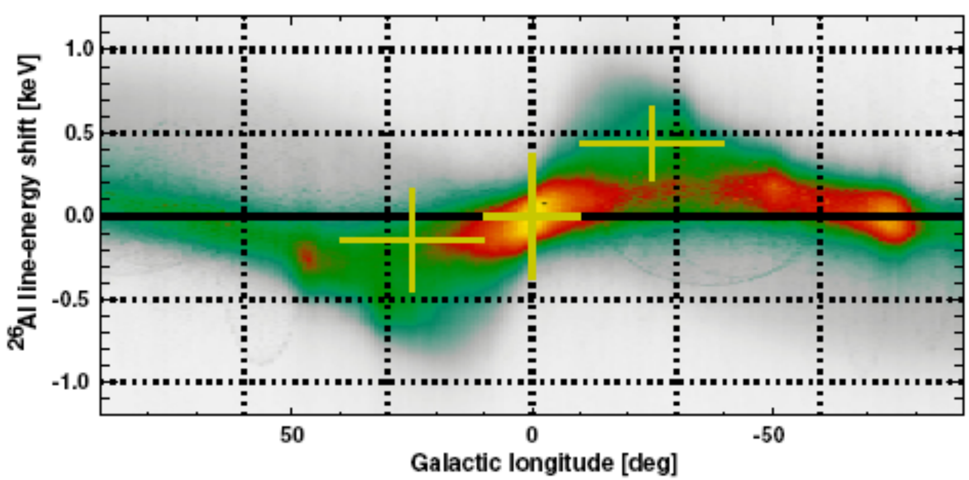
INFLUENCE OF REACTION-RATE VARIATIONS ON ISOTOPIC ABUNDANCES IN NOVA NUCLEOSYNTHESIS[a]

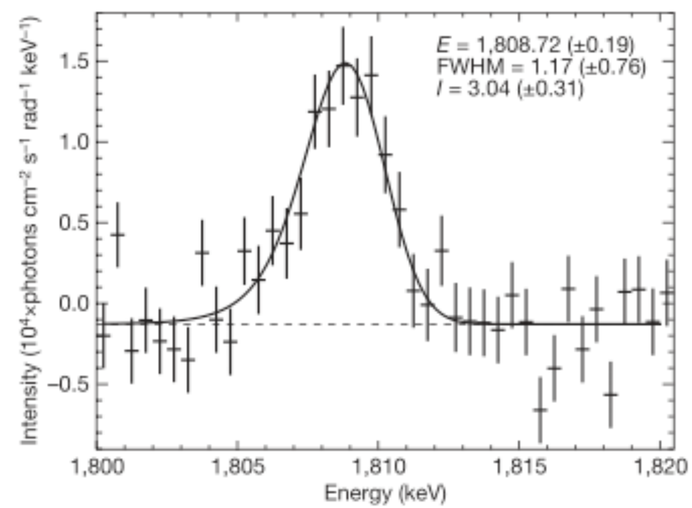
Reaction-Rate Variation[b]	Isotopic Abundance Change[c]
	CO Nova Models
$^{17}O(p,\gamma)^{18}F$	^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{18}F
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Al
$^{23}Na(p,\gamma)^{24}Mg$	^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
	ONe Nova Models
$^{17}O(p,\gamma)^{18}F$	^{17}O, ^{18}F
$^{17}O(p,\alpha)^{14}N$	^{17}O, ^{18}F
$^{17}F(p,\gamma)^{18}Ne$	^{17}O, ^{18}F
$^{18}F(p,\alpha)^{15}O$	^{16}O, ^{17}O, ^{18}F
$^{21}Na(p,\gamma)^{22}Mg$	^{21}Ne, ^{22}Na, ^{22}Ne
$^{22}Ne(p,\gamma)^{23}Na$	^{22}Ne
$^{23}Na(p,\gamma)^{24}Mg$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
$^{23}Mg(p,\gamma)^{24}Al$	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$	^{26}Al
$^{26}Al^{m}(p,\gamma)^{27}Si$	^{26}Mg
$^{29}Si(p,\gamma)^{30}P$	^{29}Si
$^{30}P(p,\gamma)^{31}S$	^{30}Si, ^{32}S, ^{33}S, ^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
$^{33}S(p,\gamma)^{34}Cl$	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
$^{33}Cl(p,\gamma)^{34}Ar$	^{33}S
$^{34}S(p,\gamma)^{35}Cl$	^{34}S, ^{35}Cl, ^{36}Ar
$^{34}Cl(p,\gamma)^{35}Ar$	^{34}S
$^{37}Ar(p,\gamma)^{38}K$	^{37}Cl, ^{37}Ar, ^{38}Ar
$^{38}K(p,\gamma)^{39}Ca$	^{38}Ar

Why ^{26}Al?

- Radioisotope!
  - $^{26}Al^{g}$ has a long half-life (7.2×10^5 yrs), that is *short* on Galactic time scales
  - 1.809-MeV γ ray emitted from excited ^{26}Mg level populated via $^{26}Al^{g}$ β decay can be detected
  - despite all-sky map of $^{26}Al^{g}$ production site(s) remain in question





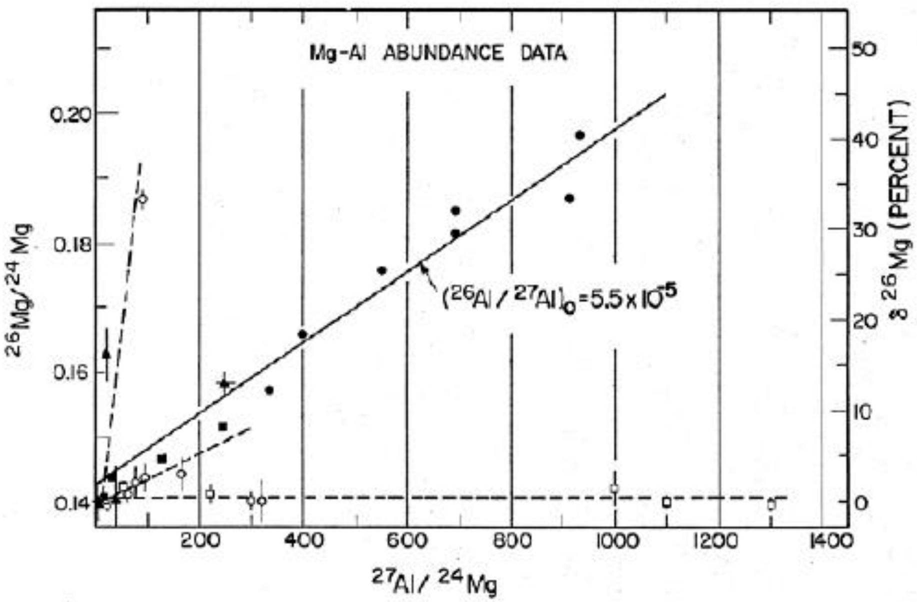


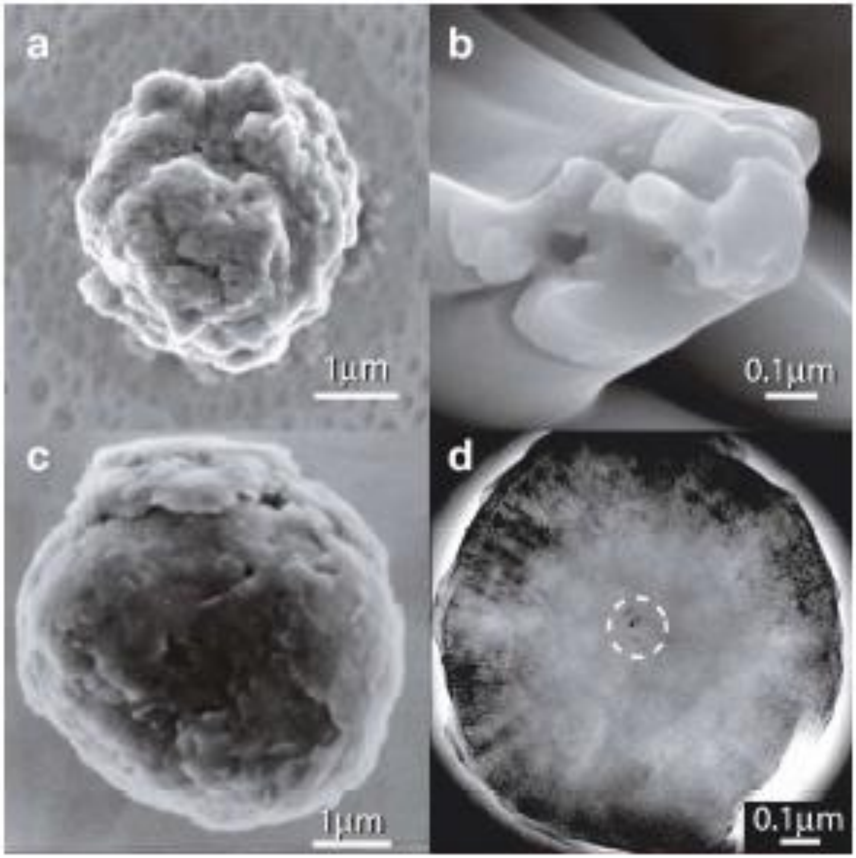
R. Diehl *et al.*, New Astr. Rev. **50**, 534 (2006).

^{26}Al in Pre-Solar Grains

- Snap shots of stars brought to Earth via meteorites

- Allende meteorite:
  - $^{26}Al/^{27}Al \sim 5.5 \times 10^{-5}$ at time of formation
  - first indication of ^{26}Al being produced in our Galaxy!





L. Nittler, EPS Lett. **209** (2003) 259.

^{26}Al in Pre-Solar Grains

- Snap shots of stars brought to Earth via meteorites

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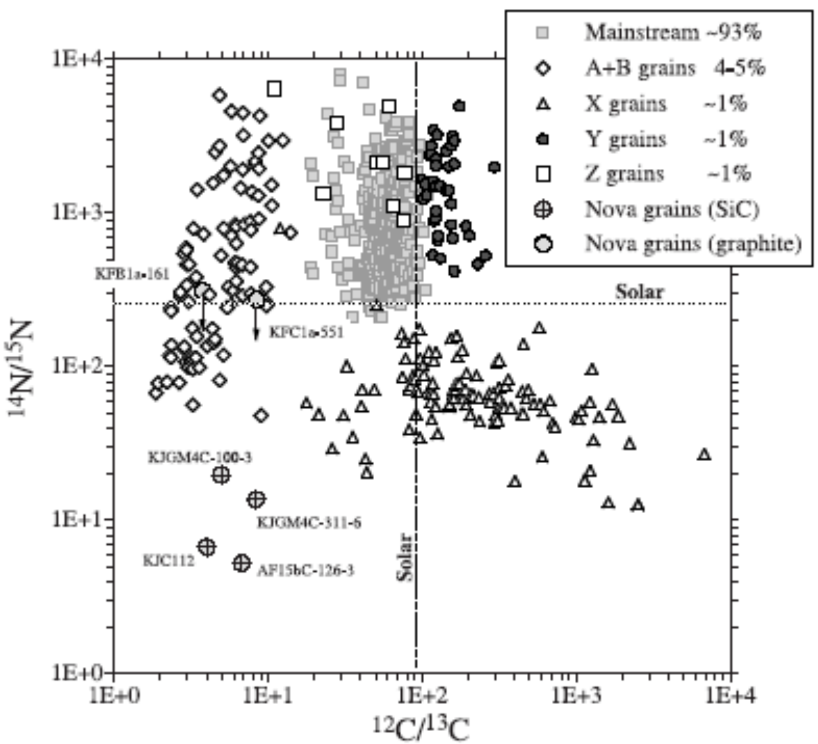
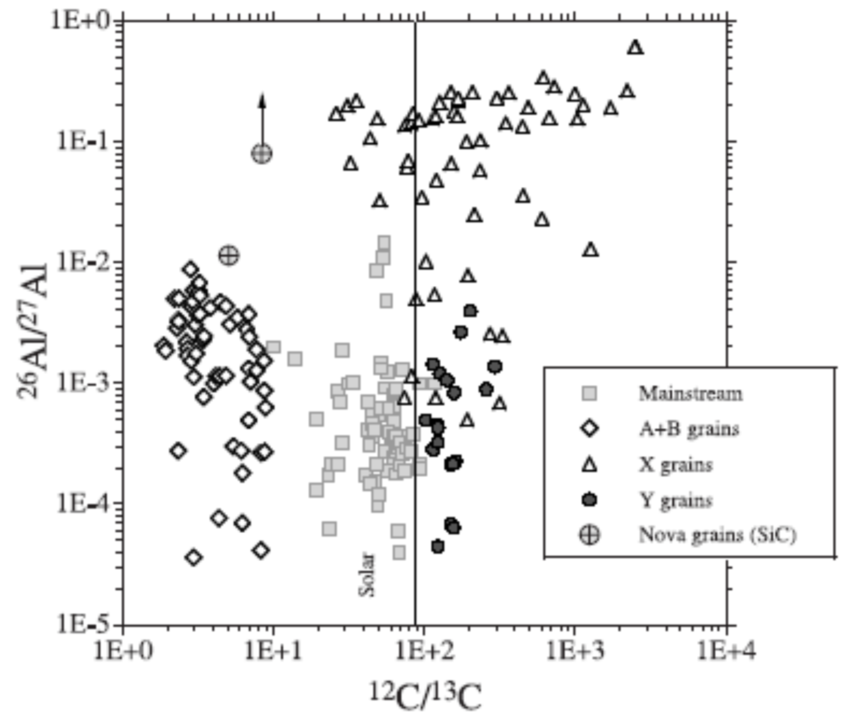
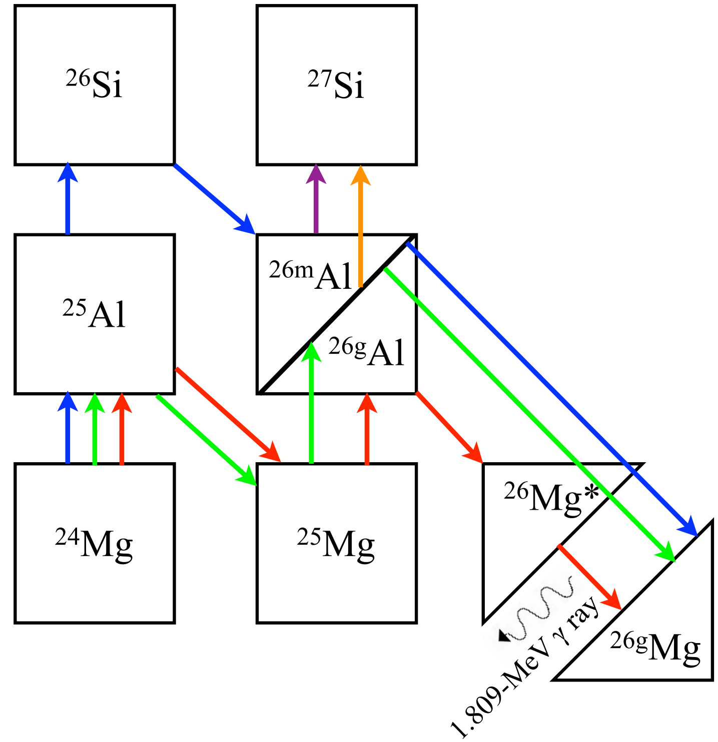
J. Jose *et al.*, ApJ, **612** (2004) 414.





^{26}Al(p,γ)^{27}Si and ^{25}Al(p,γ)^{26}Si

- ^{26}Al^{g} is formed:
  - decays to ^{26}Mg*
  - proton capture to ^{27}Si
- ^{25}Al(p,γ)^{26}Si
  - competes with β decay
  - bypasses production of ^{26}Al^{g}
- Indirect and direct measurements both needed
- Where are the ^{27}Si resonances?
  - ➢ transfer reaction data e.g. ^{26}Al(^{3}He,d)^{27}Si



$^{26}Al(p,\gamma)^{27}Si$ and $^{25}Al(p,\gamma)^{26}Si$

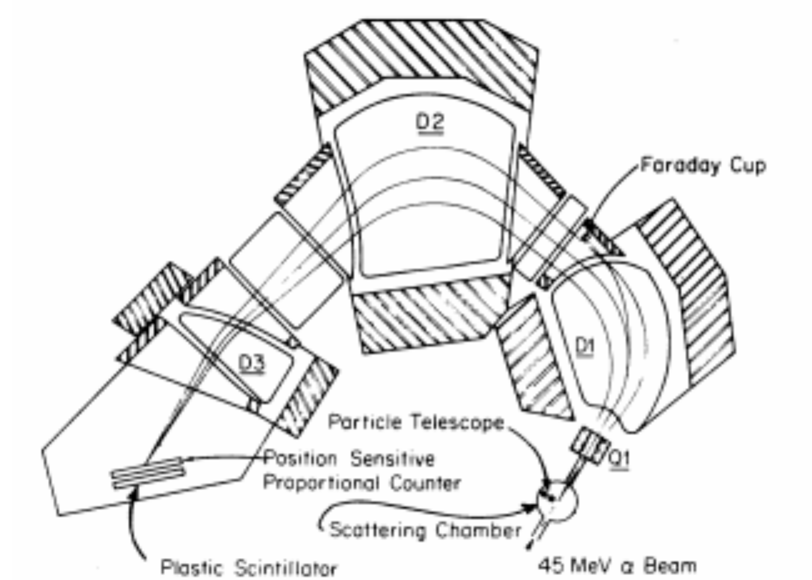
- $^{26}Al^g$ is formed:
  - decays to $^{26}Mg^*$
  - proton capture to ^{27}Si

- $^{25}Al(p,\gamma)^{26}Si$
  - competes with β decay
  - bypasses production of $^{26}Al^g$

- Indirect and direct measurements both needed

- Where are the ^{27}Si resonances?
  - ➢ transfer reaction data
    e.g. $^{26}Al(^3He,d)^{27}Si$

- Performed with the Princeton cyclotron and QDDD spectrometer
  - ^3He beam incident on ^{26}Al target



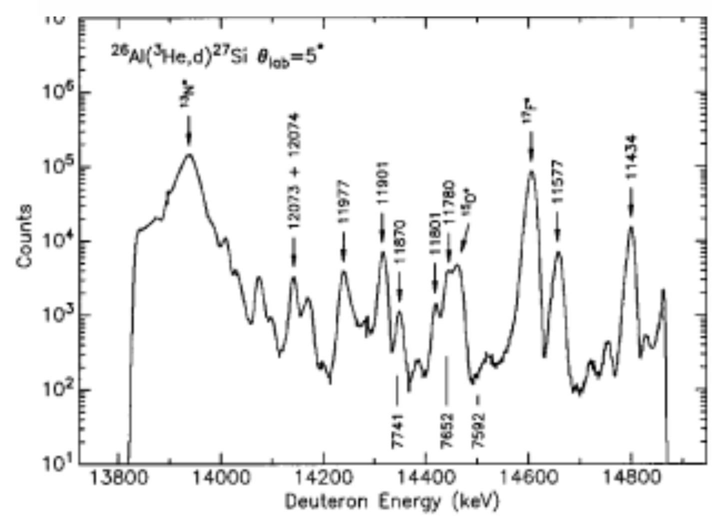


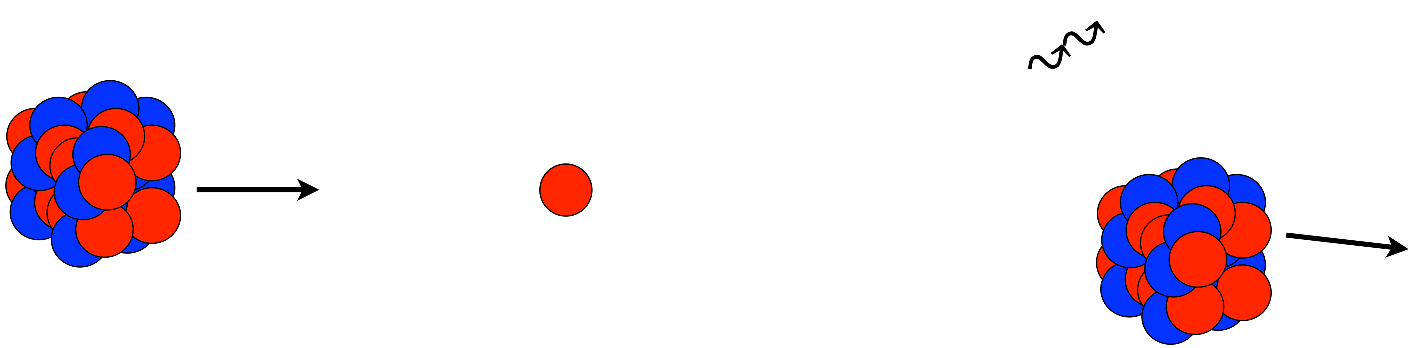
FIG. 3. Deuteron groups identified by the excited state of the residual nucleus. Those from ^{28}Si are labeled above the curve, while those from ^{27}Si states are labeled below.

Vogelaar *et al*, PRC **53**, 1945 (1996)

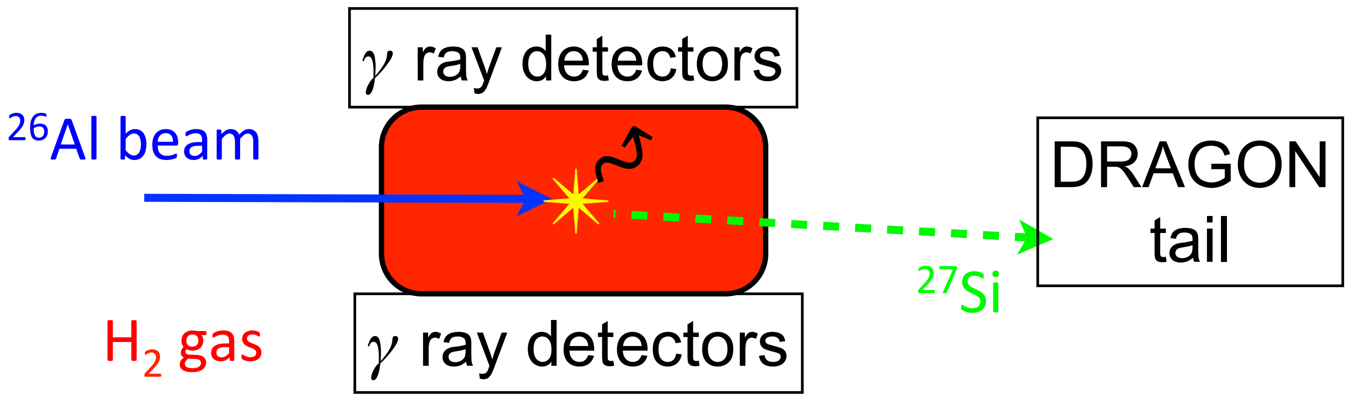
Direct Study of $^{26}Al^{g}(p,\gamma)^{27}Si$

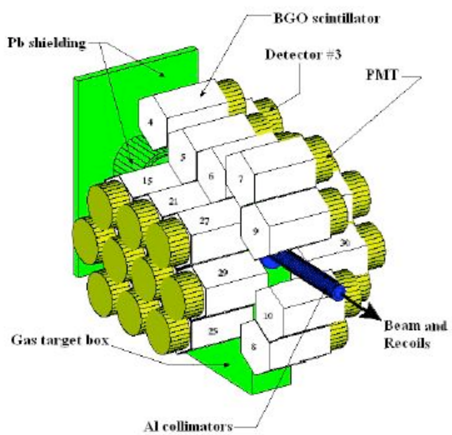
- Recoil separators do what the name says → **separate** recoiling reaction products!
- Multiple recoil separators in the world:
  - DRAGON (TRIUMF)
  - St. George (Notre Dame)
  - Daresbury Recoil Separator (ORNL)
  - ARES (Louvain-le-Neuve)
  - Future: SECAR at ReA3 and FRIB

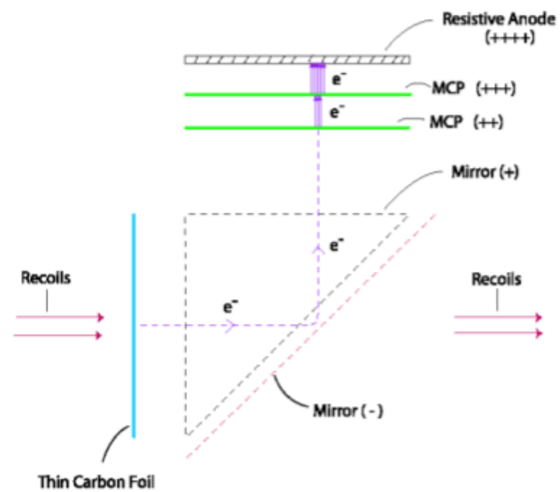
^{26}**Al** + **p** ⟶ γ + ^{27}**Si**



Direct Study of $^{26}Al(p,\gamma)^{27}Si$





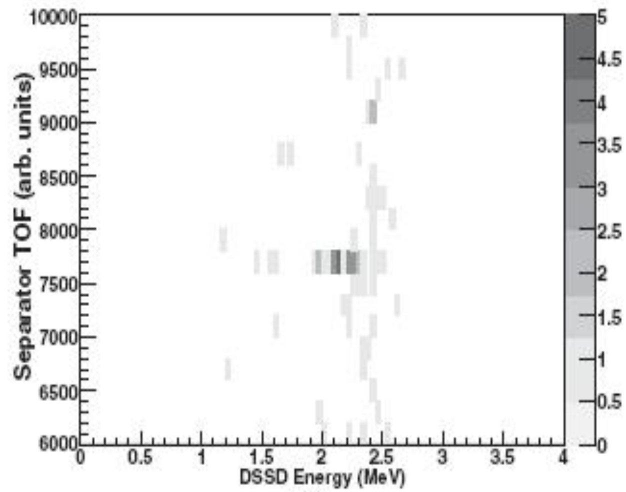


γ rays detected in DRAGON head by an array of BGO detectors

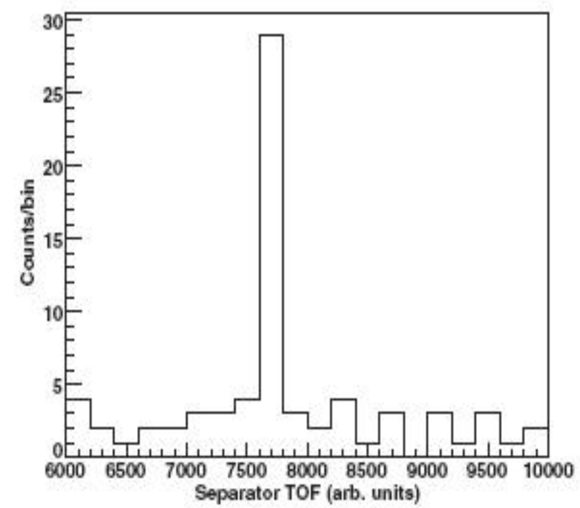
^{27}Si detected in DRAGON tail by MCP detector

Direct Study of $^{26}Al(p,\gamma)^{27}Si$

- New results [Ruiz *et al.* PRL **96** 252501 (2006)]
  - $E_{c.m.}$ = 184 ± 1 keV
  - $\omega\gamma$ = 35 ± 7 μeV
- Old values [Vogelaar, PhD Thesis (1989)]
  - $E_{c.m.}$ = 188 keV
  - $\omega\gamma$ = 55 ± 9 μeV
- Lower resonance strength favors production of ^{26}Al in novae
- New data results in 20% increase in ^{26}Al ejected in ONe novae using current models (compared with Vogelaar data)



(a)



(b)

Reactions in Classical Novae

Sensitivity
reaction ra
ones affect
abundance

C. Iliadis *et al*,

- Most impor
  except a few such a
  $^{18}F(p,\alpha)^{15}O$
  $^{30}P(p,\gamma)^{31}S$
  $^{25}Al(p,\gamma)^{26}Si$

Unfortunately, current radioactive ion beams of ^{25}Al and $^{26}Al^{m}$, do not yet have sufficient intensity to directly measure $^{25}Al(p,\gamma)^{26}Si$ and $^{26}Al^{m}(p,\gamma)^{27}Si$

We must use *indirect techniques!*

TABLE 12

INFLUENCE OF REACTION-RATE VARIATIONS ON ISOTOPIC ABUNDANCES IN NOVA NUCLEOSYNTHESIS[a]

	...ance Change[c]
	^{18}F
	...g, ^{25}Mg, ^{26}Al
	...g
	...g
	...l
	^{18}F
	^{18}F
	^{18}F
	..., ^{18}F
	...a, ^{22}Ne
	...e
	...g, ^{25}Mg, ^{26}Mg, ^{26}Al, ^{27}Al
$^{23}Mg(p,\gamma)^{24}Al$........	^{20}Ne, ^{21}Ne, ^{22}Na, ^{23}Na, ^{24}Mg
$^{26}Mg(p,\gamma)^{27}Al$........	^{26}Mg
$^{26}Al^{g}(p,\gamma)^{27}Si$........	^{26}Al
	^{26}Mg
	^{29}Si
	^{34}S, ^{35}Cl, ^{37}Cl, ^{36}Ar, ^{37}Ar, ^{38}Ar
	^{33}S, ^{34}S, ^{35}Cl, ^{36}Ar
	^{33}S
	^{34}S, ^{35}Cl, ^{36}Ar
	^{34}S
	^{37}Cl, ^{37}Ar, ^{38}Ar
	^{38}Ar

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

$$(\omega\gamma)_i = \frac{(2J_i+1)}{(2J_0+1)(2J_1+1)}(1+\delta_{01})\frac{\Gamma_a\Gamma_b}{\Gamma_{tot}}$$

Studying levels in ^{26}Si

- Indirect techniques used to study:
  - energies of excited states (resonance energies)
  - spins
  - particle partial widths

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

$$(\omega\gamma)_i = \frac{(2J_i+1)}{(2J_0+1)(2J_1+1)}(1+\delta_{01})\frac{\Gamma_a\Gamma_b}{\Gamma_{tot}}$$

- Transfer reactions:
  - **regular kinematics** with stable beams
  - **inverse kinematics** with stable or radioactive ion beams
  - different transfer reactions probe different states in compound nucleus

Transfer studies for ^{26}Si:

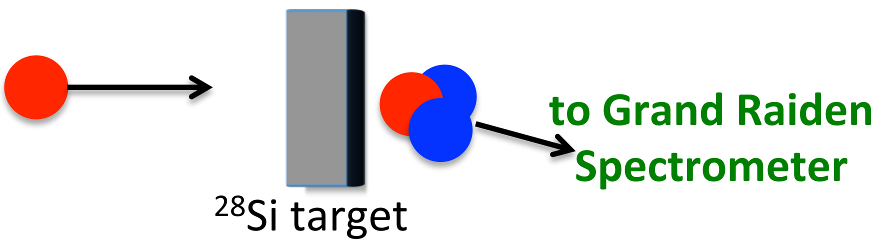
- ^{28}Si(p,t)^{26}Si
- ^{29}Si(^{3}He,^{6}He) ^{26}Si
- ^{24}Mg(^{3}He,n)^{26}Si
- ^{25}Al(d,n)^{26}Si

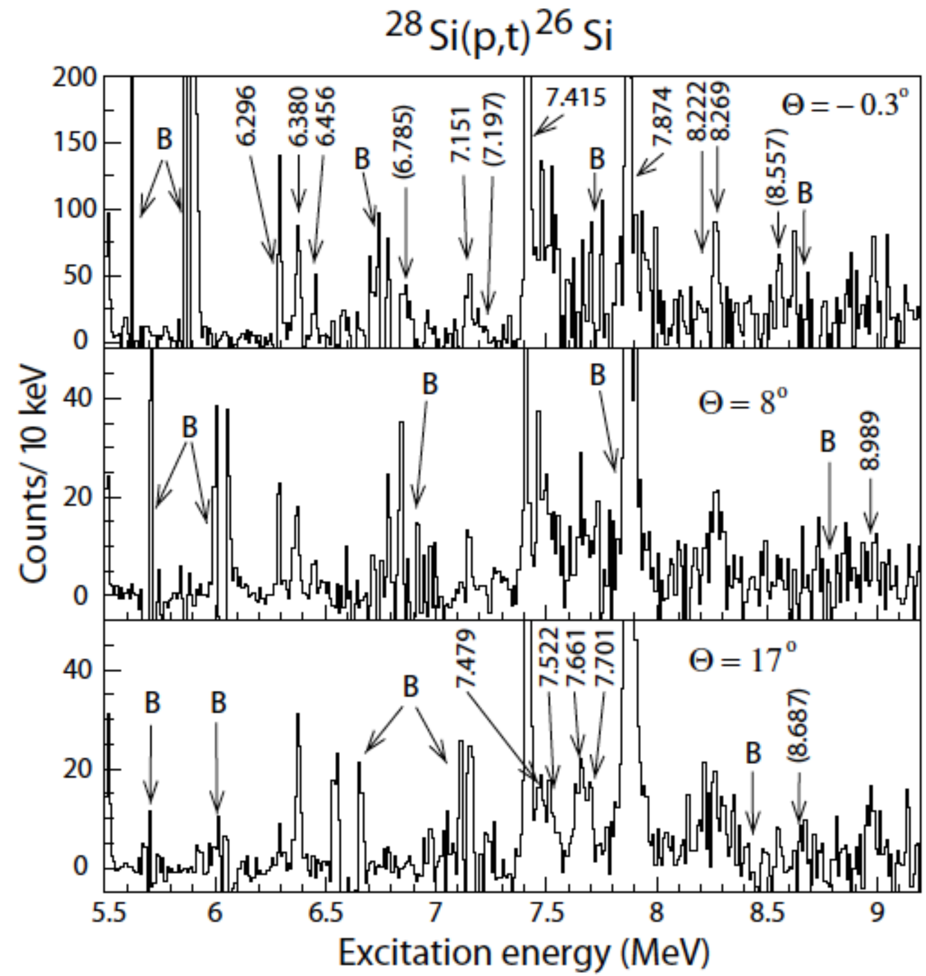
- Other studies:
  - delayed proton decays
  - coincidence measurements with particle decays

Transfer Studies in Regular Kinematics

- ^{28}Si(*p*,*t*)^{26}Si transfer reaction at RCNP, Osaka
- Measured:
  - excitation energies
  - angular distributions → transferred *L*
  - Calculated particle partial widths

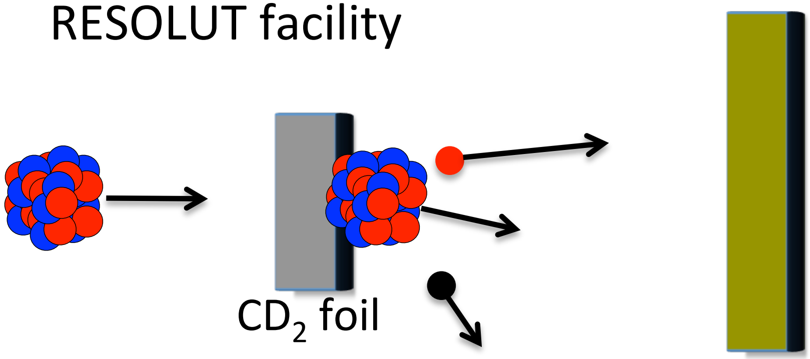
Matic *et al.*,
PRC **82**, 025807 (2010)





Transfer Studies in Inverse Kinematics

- ^{25}Al(*d,n*)^{26}Si*(*p*)^{25}Al proton-adding reaction
- Performed at Florida State University's RESOLUT facility



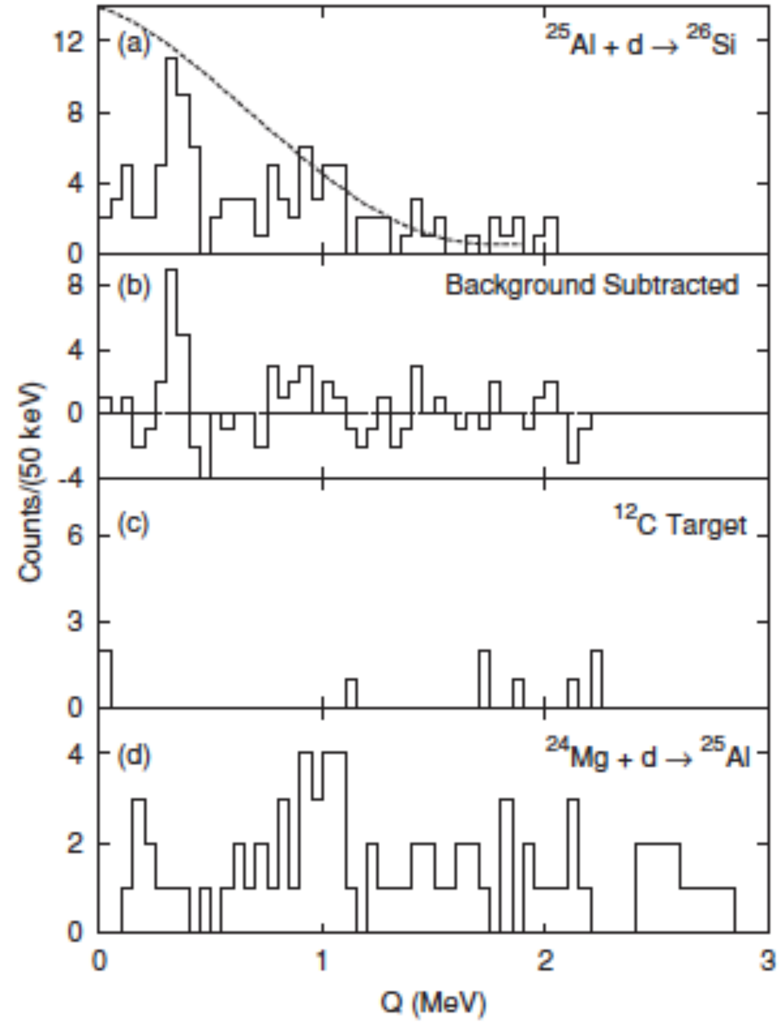


FIG. 1. (a) Proton decay Q-value spectrum, in the inverse-kinematics ^{25}Al$(d,n)^{26}$Si → $p + ^{25}$Al reaction, measured with a CD_2 target. The dashed line indicates the energy dependence of the particle detection efficiency in arbitrary units. (b) Beam-background-subtracted spectrum obtained by subtracting the ^{24}Mg $Q = 12+$ beam contamination from the spectrum A. (c) Spectrum measured using a ^{12}C target. (d) Proton decay Q-value spectrum, measured in the inverse-kinematics ^{24}Mg$(d,n)^{25}$Al → $p + ^{24}$Mg reaction while

P. N. Peplowski *et al.,* PRC **79,** 032801(R) (2009)

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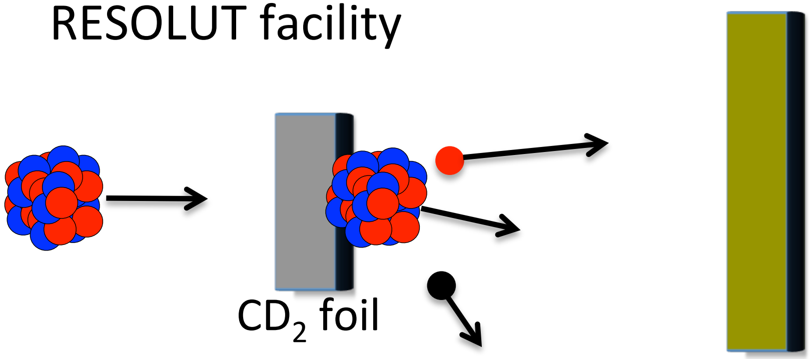
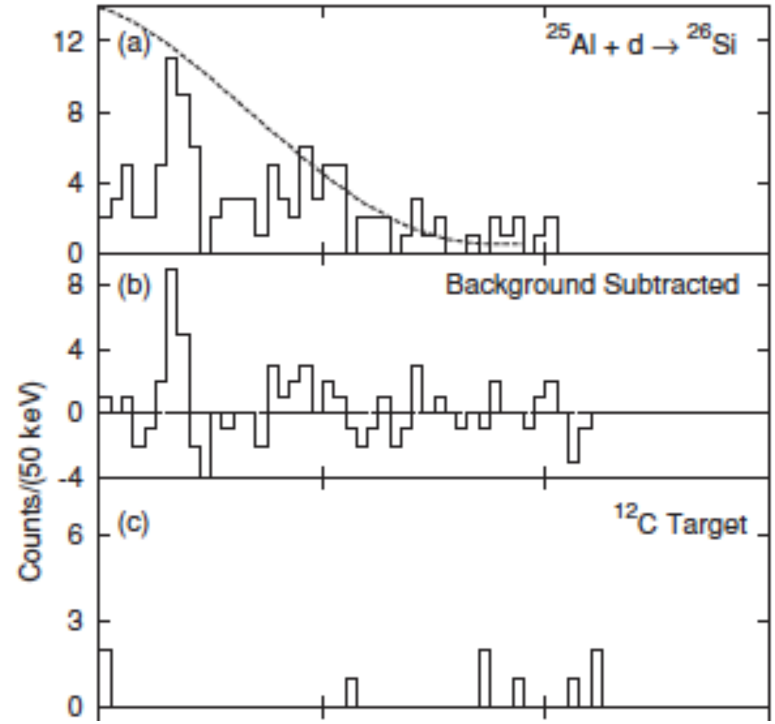




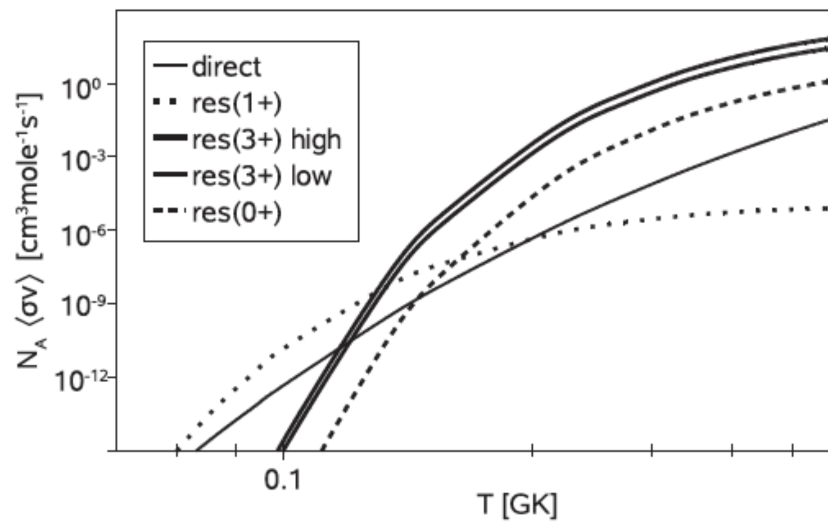
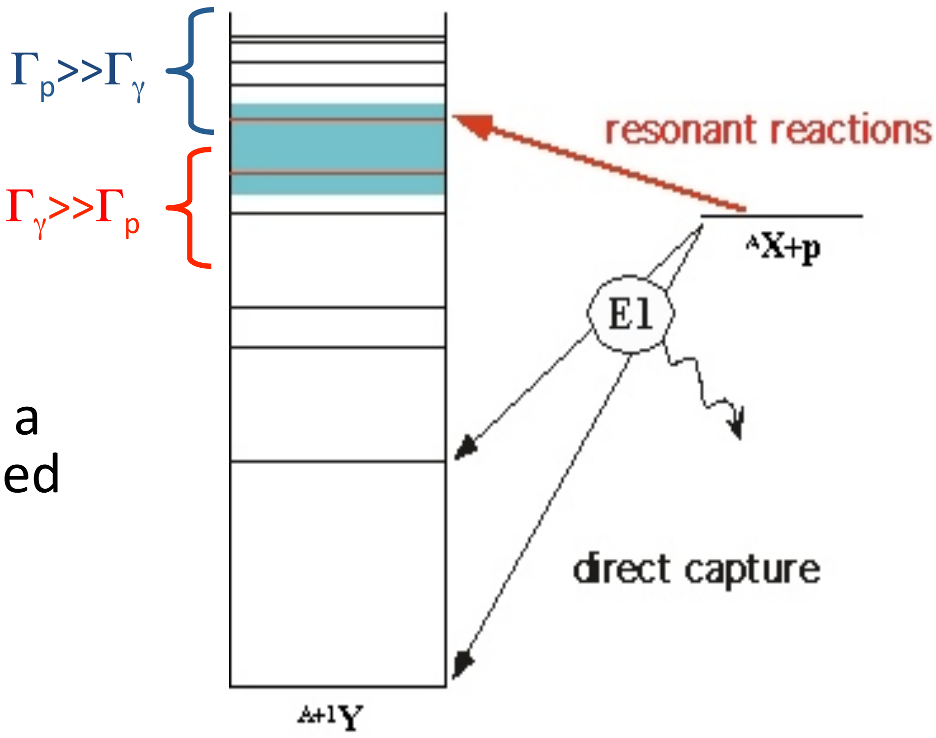


FIG. 2. Reaction rates based on direct capture and the three resonances displayed in Table I (see text).

P. N. Peplowski *et al.*, PRC **79,** 032801(R) (2009)

Measuring Partial Widths

- Excitation energies and spins: straight forward transfer measurements
- Particle widths can be more challenging . . .
- ^{26}P (produced at NSCL via ^{36}Ar on a ^{9}Be target) implanted in segmented germanium detector (GeDSSD)
- Gammas from ^{26}P(β)^{26}Si*(p)^{25}Al detected by SeGA array in coincidence with β's detected in the GeDSSD



$$\frac{\Gamma_p \Gamma_\gamma}{\Gamma_{tot}}, \text{ where } \Gamma_{tot} = \Gamma_p + \Gamma_\gamma$$

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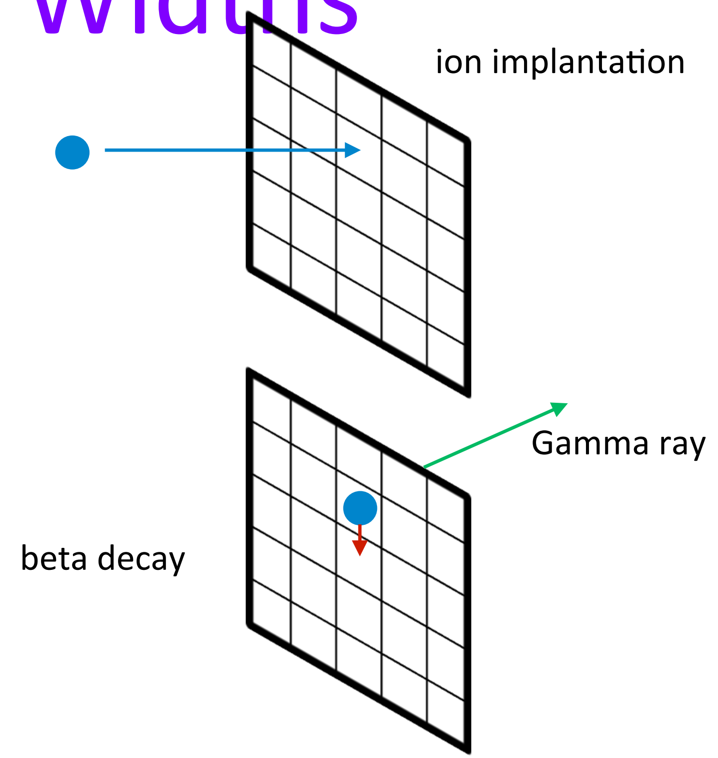

Courtesy Sean Liddick

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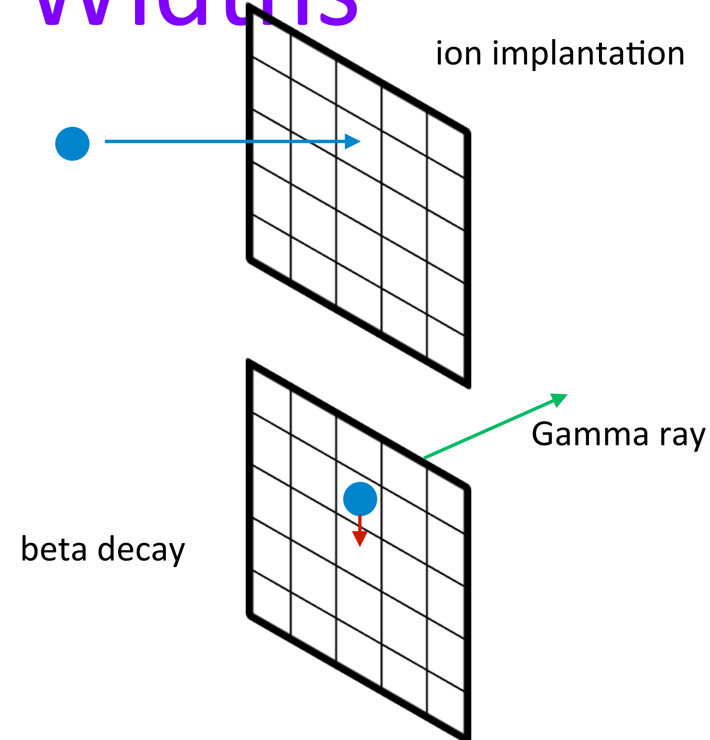
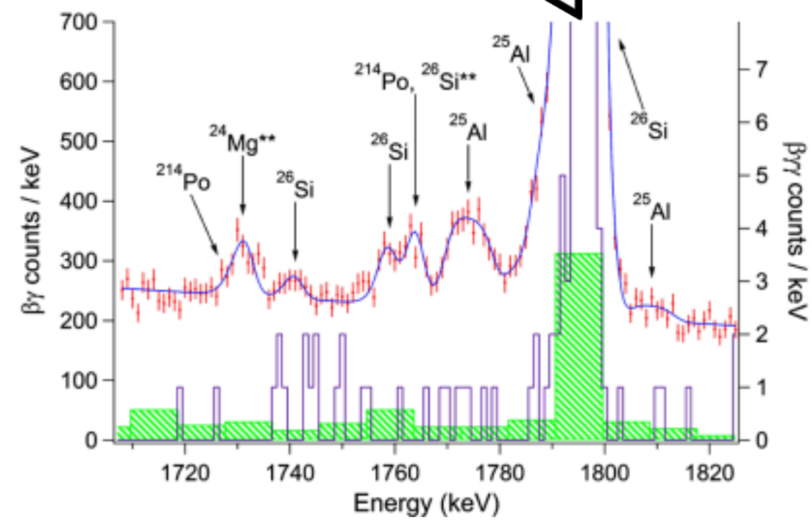
- Gammas from $^{26}P(\beta)^{26}Si^{*}(\gamma)^{26}Si$ detected by SeGA array in coincidence with β's detected in the GeDSSD

- New results of gamma width increase from 20% to 30% in ^{26}Al produced by novae!

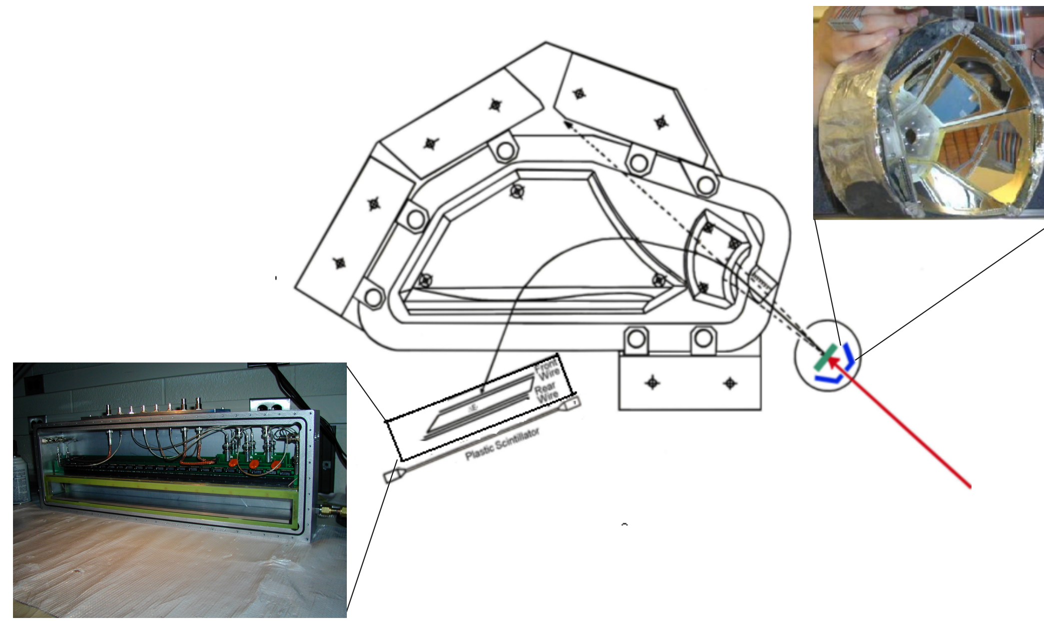




M. B. Bennett *et al.*, PRL **111**, 232503 (2013)

Coincidence Measurements

- Two transfer reactions performed at Yale's Wright Nuclear Structure Laboratory
  - ^{28}Si(^{3}He,α)^{27}Si*(p)^{26}Al
  - ^{27}Al(^{3}He,t)^{27}Si*(p)^{26}Al
- Enge spectrograph used to determine energy of excited states
- Proton decays from ^{27}Si resonances detected using Si array in coincidence



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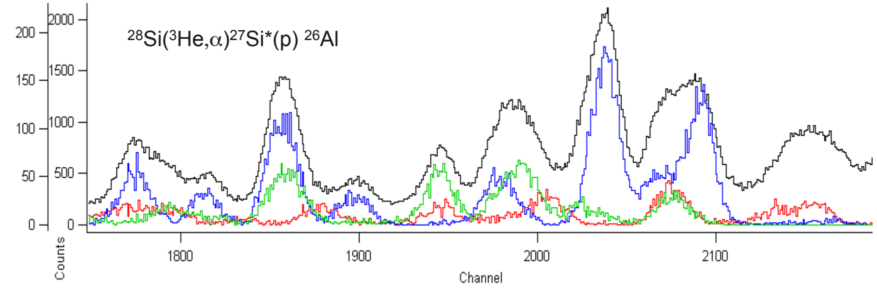
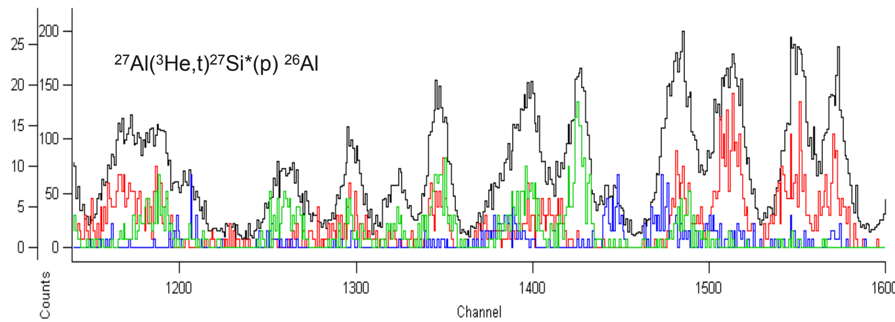
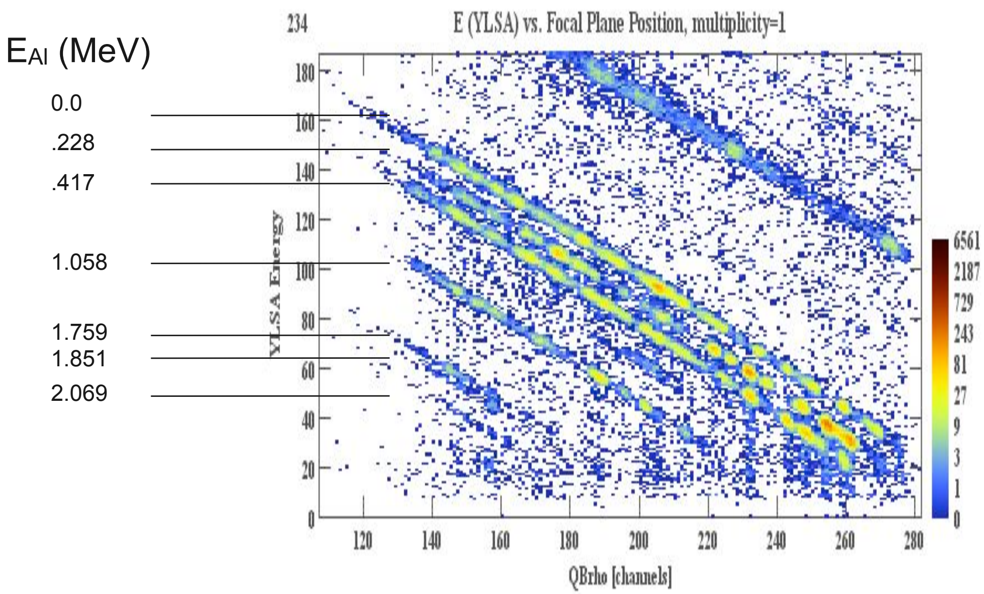
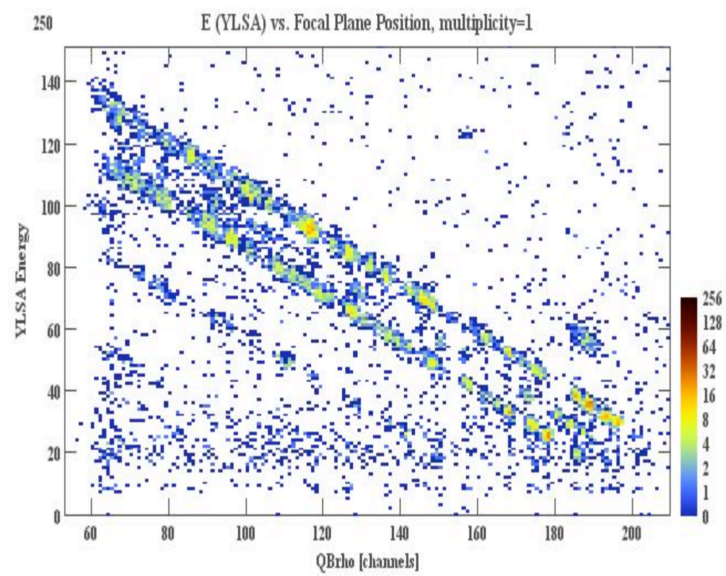


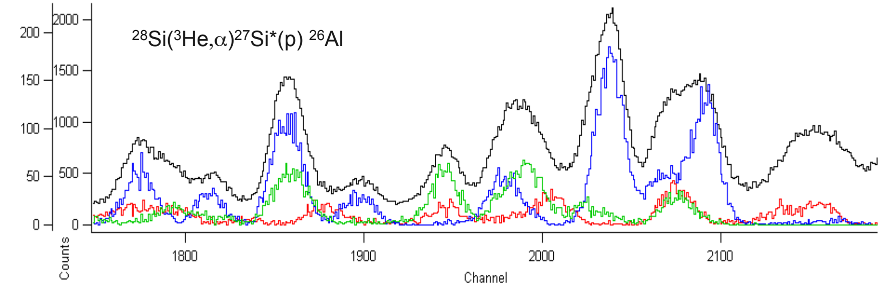


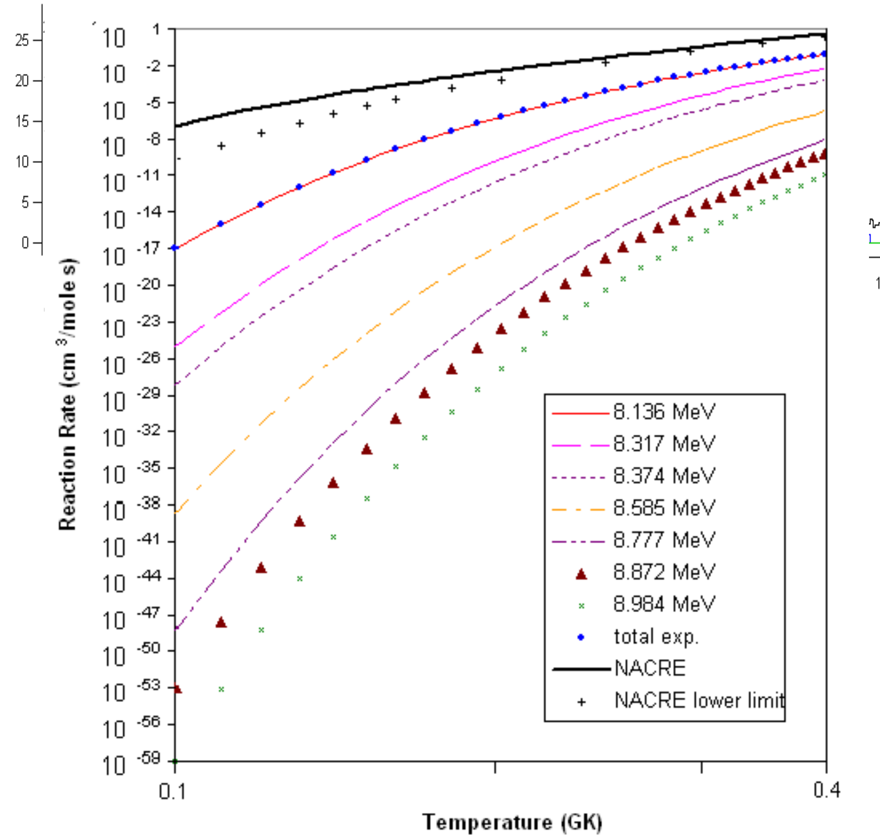




Coincidence Measurements

- Two transfer reactions performed at Yale's Wright Nuclear Structure Laboratory
  - $^{28}Si(^{3}He,\alpha)^{27}Si^{*}(p)^{26}Al$
  - $^{27}Al(^{3}He,t)^{27}Si^{*}(p)^{26}Al$
- Enge spectrograph used to determine energy of excited states
- Proton decays from ^{27}Si resonances detected using Si array in coincidence
- Measured
  - excitation energies (resonance energies)
  - angular momentum transfer (spin information)
  - proton branching ratios: Γ_p/Γ_{tot}
- Indirectly calculated $^{26}Al^{m}(p,\gamma)^{27}Si$ reaction rate

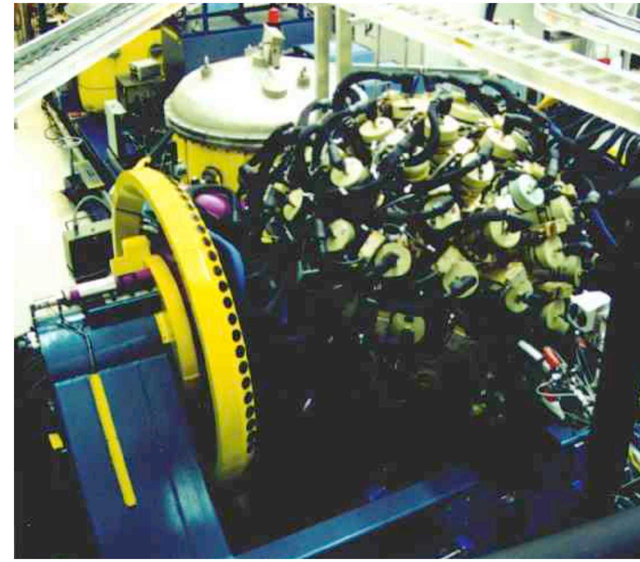


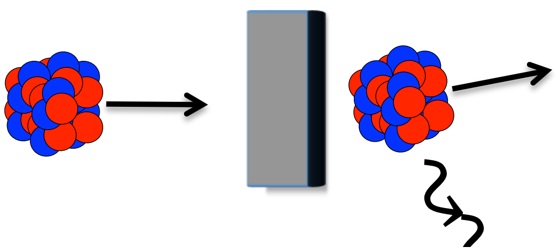


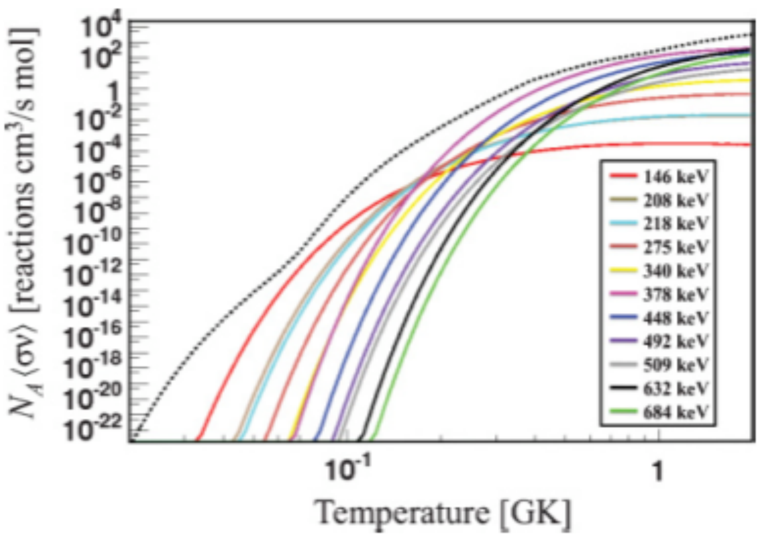
C. M. Deibel *et al.*, PRC **80** 035806 (2009)

Fusion Evaporation Studies with Gammasphere

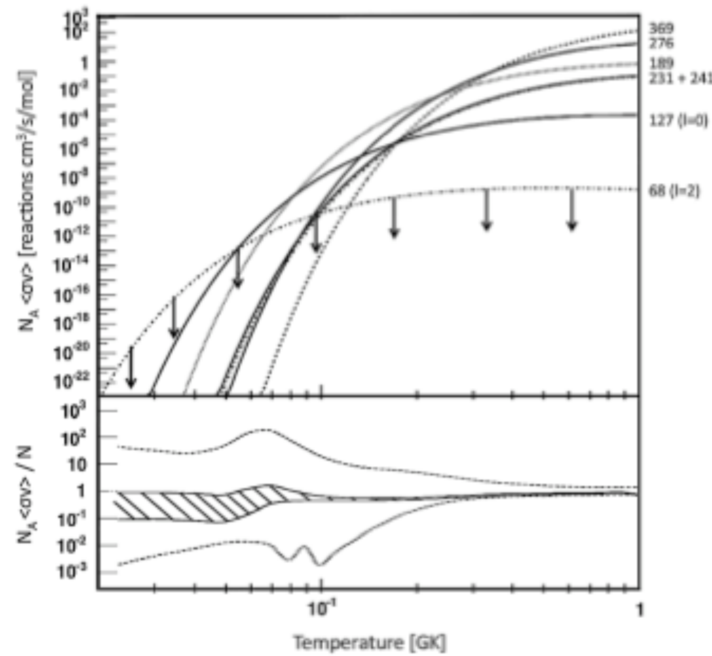
- 26-MeV ^{16}O beam on ^{12}C target
- Fusion evaporation used to populate ^{27}Si resonances
- Gamma-rays detected in Gammasphere to determine energies and spins







G. Lotay et *al.*, PRC **80**, 055802 (2009)



G. Lotay et *al.*, PRL **102**, 162502 (2009)