alpha induced reactions in stellar burning

Joachim Görres, University of Notre Dame & JINA

http://www.nd.edu/~nsl

http://www.jinaweb.org
But is it possible to admit that such a transmutation is occurring? It is difficult to assert, but perhaps more difficult to deny, that this is going on. Sir Ernest Rutherford has recently been breaking down the atoms of oxygen and nitrogen, driving out an isotope of helium from them; and what is possible in the Cavendish laboratory may not be too difficult in the Sun. I think that the suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms which abound...
Core Helium Burning

Ash of the CNO-cycles

Weak Component Of s-Process
A<100

\[ T \approx 0.2 - 0.4 \text{ GK} \]
\[ E = 0.4 - 0.8 \text{ MeV} \]

See talks/posters by:
C. Digest, earlier today
C. Tur, Thursday
D. Schürmann, this session
C. Matei, this session
H. Makii

Hubble Space Telescope
Betelgeuse
**TP-AGB Stars**

s-Process
(Main Component A>100)

\[ ^{22}\text{Ne}(\alpha,n)^{25}\text{Mg} \]

\[ ^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta^+)^{13}\text{C} \]

\[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \]

Convective Envelope  
protons mixed downward  
by semiconvection

flash driven  
convective pocket  
infection

**Fluorine Lines Observed On Surface of AGB Star**

\[ T \approx 0.1 - 0.4 \text{ GK} \]
\[ \downarrow \]
\[ E = 0.2 - 0.8 \text{ MeV} \]

Jorissen et al.

See talks/posters by:
M. Busso, earlier today  
F. Herwig, Friday  
R. Gallino  
M. Pellegriti  
G. Rogachev
Later Burning Stages

**Carbon/Neon Burning**

protons and alphas produced by reactions during burning:
e.g. $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}(p,\alpha)$
$^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$

$T \approx 0.5 \text{ – 1.5 GK}$
$E = 0.85 \text{ – 1.8 MeV}$

**Supernova**

$\alpha$-rich freeze-out during explosion

Adiabatic expansion
Starting at $T \approx 5 \text{ GK}$
$E < 5 \text{ MeV}$

Shock wave passing through outer layers

$T \approx 1 \text{ – 2 GK}$
$E = 1.0 \text{ – 2.0 MeV}$

See talks/posters by:
M. Paul, this session
C. Vockenhuber, this session
H.Y. Lee
Breakout From The Hot CNO Cycle & αp-Process

Important for the energy production in explosive hydrogen burning, e.g., Nova, X-Ray Burst

\[ T \approx 0.4 \text{ – } 1.5 \text{ GK} \]
\[ E = 0.30 \text{ – } 0.8 \text{ MeV} \]

\[ {}^{15}\text{O}(\alpha,\gamma){}^{19}\text{Ne} \]

See talks/posters by:
W. Tan, earlier today
C. Angulo

\[ {}^{18}\text{Ne}(\alpha,p){}^{21}\text{Na} \]
P-Process

Study of $(\gamma,\alpha)$ using the inverse $(\alpha,\gamma)$ reactions

SN II shock front passing through O/Ne layer

$E = 5 - 15\text{ MeV}$

See talks/posters by:
S. Harrisopoulos, Thu.
T. Hayakawa
N. Özkan
G. Kiss
M. Avrigeanu
Yield Of Narrow Resonances
(Number of Reactions Per Incoming Projectile)

\[ Y = \int_{E-\xi}^{E} (\sigma/\epsilon) dE \]

\[ Y = \frac{\sigma_R \Gamma}{2\epsilon} \left[ \tan^{-1} \frac{E-E_R}{\Gamma/2} - \tan^{-1} \frac{E-E_R-\xi}{\Gamma/2} \right] = \sigma_R \Gamma \left[ \frac{\pi}{2} + \tan^{-1} \frac{E-E_R}{\Gamma/2} \right]. \]

\[ \Gamma < < \xi \]

\[ Y_{max}(\infty) = \frac{\pi \sigma_R \Gamma}{2 \epsilon} = \frac{\lambda^2}{2 \epsilon} \omega \gamma \]

\[ \lambda^2 \sim 1/\mu \]

\[ \epsilon(\alpha,E) \approx (2-4) \epsilon(p,E/4) \]

\[ Y(\alpha)/Y(p) \approx 1/10 \] for same \( \omega \gamma \) and \( E \)
**Targets** ($\alpha$-beam)

*Better Than Protons:*

- Use of lower Z target material is possible: e.g. TiN, Cu backing
- Larger Coulomb Barrier
- Less beam induced background than protons at same energy

*Worse Than Protons*

- Blistering (in many metals)
- Blisters after $\alpha$-bombardment
- $Y \sim \lambda^2/\varepsilon$ (factor $\approx 10$)
- Sputtering
- $^{21}\text{Ne}$ implanted in Cu

Surface Damage $\rightarrow$ Thicker Target
Activation Method: $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}$

\[ E_{\text{f(lab)}} = 1136 \]

\[ \beta^+ , t_{1/2} = 110 \text{ min.} \]

Online Spectroscopy

present result: \( 577.5 \pm 4.5 \text{ keV} \)

Couch et al.: 559 keV from literature

normalized to 1042 keV transition

$^{14}\text{N+}\alpha$

\( \beta^+ , t_{1/2} = 110 \text{ min.} \)
511keV coincidences

Advantage: high efficiency = 3.46% (large detector volume) low background = 0.6/h (high energy resolution) (granularity: directional correlation!)
Reduction Of Reaction Rate Mainly Because Of Change In Resonance Energy Of 14 keV !!
Coincidence Method: $^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si}$
\( \Omega(\text{Ge}) \approx 30\% \quad \Omega(\text{NaI}) \approx 40\% \)

**Background Run:**

- **Ungated Ge**
- **NaI and TAC Gated**

Suppression Factor > 30000

**Gammasphere:** 10\% at 1.33 MeV
1180keV Resonance:

Ungated Ge Sum

Gated Ge Sum

$E(\text{NaI}) > 3\text{MeV}$

$1^{\text{st}}$ Excited State to Ground State

$\omega_{\gamma_{\text{part}}} \approx 35 \mu\text{eV}$

Compilation: $1^+, 100\% \rightarrow gs$
Reaction Rate

\[ ^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si} \text{ Reaction Rate} \]

low energy contributions from:
Underground Laboratory

*(see H. Costantini talk)*

background reduction by 3 orders of magnitude
Recoil Separator

(general concept)

Inverse Kinematics

Cooled Beam Stop

Q-1

Magnetic Dipole

Q, Q-1

Target

Beam

Q

Magnetic Dipole

Wien Filter

Velocity Filter

Focal Plane

Gamma Energy

10 MeV

Large Momentum Spread

Large Opening Angle
The Design Goal

Alpha and Proton Capture Reactions on sd-Shell Nuclei

Realistic Evaluation of Eight Reactions

Assumptions:
100 microA Beam Intensity
1/h Minimum Count Rate
33 % Efficiency

Stable Beam

Existing Recoil Separators
Erna
Dragon
Ares
DRS

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Yield Estimate (for $\alpha,\gamma$ reactions)

Not including background count rates

Assume:
- count rate of 1/hour
- efficiency 33%

Number of reactions 3/h

For 100 $\mu$A
\[ Y = 1.3 \times 10^{-18} \]

For nonresonant reactions:
- $N_t = 3 \times 10^{17}/cm^2$
- $\sigma \geq 10$ pb

For resonant reactions:
- $\omega \gamma \geq 5$ neV

Need $\gamma$-recoil coinc. to clean up

Place device underground to reduce count rate in $\gamma$-detector
Preliminary Layout Of Recoil Separator At Notre Dame
Acknowledgement

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Cautious Dædalus will apply his theories where he feels most confident they will safely go; but by his excess of caution their hidden weaknesses cannot be brought to light. Icarus will strain his theories to the breaking-point till the weak joints gape. For a spectacular stunt? Perhaps partly; he is often very human. But if he is not yet destined to reach the Sun and solve for all time the riddle of its constitution, yet he may hope to learn from his journey some hints to build a better machine.

Sir Arthur Eddington

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