Experimental Methods and Techniques in Nuclear Astrophysics

Probing CNO reactions: $^{14}\text{N} (p, \gamma) ^{15}\text{O}$, $^{15}\text{N} (p, \gamma) ^{16}\text{O}$.

Radioactive Beam reactions break-out from hot CNO.

Stellar neutron sources: $^{22}\text{Ne} (\alpha n) ^{25}\text{Mg}$, $^{22}\text{Ne} (\alpha, n) ^{25}\text{Mg}$.

Galactic radioactivity: $^{60}\text{Fe} (n, \gamma) ^{61}\text{Fe}$.

Ignition of carbon burning: $^{12}\text{C} + ^{12}\text{C}$.

Future Facilities & Opportunities.
Stars are cold!!!

\[ E_G = 1.22 \left( Z_1^2 Z_2^2 \mu T_6^2 \right)^{1/3} \]
But some like it hot!!!

\[ E_G = 1.22 \left( Z_1 Z_2 \mu T_6 \right)^{1/3} \]

Increase in Gamow Energy

Supernovae

X-Ray Bursts

Hydrogen Shell of AGB-Stars

Novae

Main Sequence Stars

Gamow Range

\[ \sigma \approx \exp \left( - \frac{b}{\sqrt{E}} \right) \]

[\text{Density [g/ccm]}]

[\text{Energy [MeV]}]
REACTION-RATE & S-FACTOR

\[ N_A \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{-3/2} \cdot \int_0^\infty E \cdot \sigma(E) \cdot \exp\left(-\frac{E}{kT}\right) dE \]

Factorization of cross section into Coulomb part & “nuclear” component

\[ \sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta) \]

Classical Problem:
how reliable are the present low energy extrapolations?
The problem with extrapolation

Introduction of large uncertainties, depending on method and reliability of extrapolation into the sub-sub-sub-sub Coulomb barrier range!

We need to account for all reaction contributions to extrapolate reliably:
- direct component,
- resonance components
- interference structures
- all orbital momentum contributions
- all coupled channel contributions

Main handicap for low energy studies:
- low reaction yield
- high background (natural, cosmic ray induced, beam induced)
Sub Coulomb barrier studies in low background conditions

- Active shielding through coincidence requirements. background reduction by: $10^{-3} - 10^{-4}$

- Passive shielding by rock in deep underground environments (Gran Sasso). background reduction by: $10^{-4} - 10^{-6}$

- Inverse kinematics with recoil separators such as: ERNA, DRAGON, and St. GEORGE, DIOCLETIAN
New low energy studies of the CNO cycles

LUNA experiments successfully pushed experimental data range down to ~70keV. The extrapolation is based on an two independent R-matrix fits of all data over the entire energy range and all reaction channels and shows excellent agreement.
CNO cycles and R-matrix

Systematic re-measurement of CNO capture reactions over a wide energy range for better S-factor extrapolation into stellar energy range.

\( ^{15}\text{N}(p,\alpha)^{12}\text{C} \)

\( ^{15}\text{N}(p,\gamma)^{16}\text{O} \)
Measurements of $^{15}\text{N}(p,\gamma)^{16}\text{O}$

4MV KN

1MV JN

0.4MV CW

Ge-clover detector in close geometry

Ge-large volume detector in close geometry with virgin lead shielding
Low energy excitation curve

![Graph showing low energy excitation curve with different data points and labels for LUNA, KN ND, JN ND, Rolfs'74, KN #2, KN #7, JN #2, LUNA #1, and LUNA #18.](image-url)
Analysis with multi-level, multi-channel R-matrix simulation

\[ ^{15}\text{N}(p,\gamma_0)^{16}\text{O} \]

\[ ^{15}\text{N}(p,p_0)^{15}\text{N} \]

\[ ^{15}\text{N}(p,\alpha_0)^{12}\text{C} \]

Old Data

New Data

\[ C_{1}\text{p}_{1/2} = 20.8 \text{ fm}^{1/2} \]
New Results since 2006

through new experimental data and re-analysis

\[ ^{12}\text{C}(p,\gamma)^{13}\text{N} \quad S_0=1.8 \text{ keV-barn} \quad (S_0=1.5 \text{ keV-barn}) \]
\[ ^{14}\text{N}(p,\gamma)^{15}\text{O} \quad S_0=1.7 \text{ keV-barn} \quad (S_0=3.2 \text{ keV-barn}) \]
\[ ^{15}\text{N}(p,\gamma)^{16}\text{O} \quad S_0=34 \text{ keV-barn} \quad (S_0=64 \text{ keV-barn}) \]
\[ ^{16}\text{O}(p,\gamma)^{17}\text{F} \quad S_0=10.6 \text{ keV-barn} \quad (S_0=9.3 \text{ keV-barn}) \]

- Translates into reduction of CNO neutrino production,
- Resets CNO abundance predictions
- Impacts timescale of hydrogen burning in massive stars
The nuclear trigger of X-ray Bursts

break-out from HCNO cycles: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$, $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$
Reaction Rate of $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

- Reaction Rate

$$N_A < \sigma v > \propto T^{-3/2} \omega \gamma e^{-E_R/kT}$$

determined by resonance energy $E_R$ and strength $\omega \gamma$

where $$\omega \gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

- Three measurable quantities characterize the resonance strength: $J, \Gamma_\gamma, \text{and } B_\alpha$

![Graph showing energy levels and transitions for $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$]
What experimentalists need to do for $^{15}$O(α,γ)$^{19}$Ne

- Direct measurement is difficult!
  - An intense ($10^{11}$/s) radioactive $^{15}$O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)

$$\omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} \cdot \frac{\Gamma_\alpha \cdot \Gamma_\gamma}{\Gamma}$$

$$\sim B_\alpha \Gamma_\gamma$$

$$\sim Y(^{19}Ne)$$

- Indirect method has been approached many times!
  - Populate α-unbound states in $^{19}$Ne
  - Measure lifetimes or gamma widths
  - Measure α-decay branching ratios $B_\alpha$

$^{17}$O(³He,n-γ)$^{19}$Ne

$^{19}$F(³He,t-α)$^{19}$Ne
Probing the Structure

\[ E_\gamma = E_{\gamma_0} (1 + F(\tau) \beta \cos \theta) \]

Measured lifetime \( \tau = 13^{+9}_{-6} \text{ fs} \)

or \( \Gamma = 51^{+43}_{-21} \text{ meV} \)

TRIUMF 2006 \( \tau = 11^{+8}_{-7} \text{ fs} \)

or \( \Gamma = 60^{+40}_{-25} \text{ meV} \)

LWFG86: \( \Gamma = 73 \text{ meV} \)

\( E_x = 4034.5 \pm 0.8 \text{ keV} \)
\[ \omega \gamma = \frac{2J_R + 1}{(2J_p + 1)(2J_T + 1)} B_\alpha \Gamma \gamma \]

\[ N_A < \sigma v \propto T^{-3/2} \omega \gamma e^{-E_R/kT} \]
Stellar Neutron Source

\[ {^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+\nu)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}(\alpha,n)} \]

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

low energy resonances?

Direct Method
U. Stuttgart
U. Notre Dame
Uncertainties in neutron production

- Extrapolation to lower energies
- Impact of the $^{22}$Ne($\alpha$,γ) branch

The biggest uncertainty is the 628 keV resonance in the 1$^-$ state at 11.15 MeV. Jaeger et al. reported this in PRL 2001.
Uncertainties and Consequences

Weak s-process nucleosynthesis?

$^{22}\text{Ne}(\alpha,n)$ reaction rate determines s-process seed abundance for p-, and r-process analysis!

Arnould & Goriely, PR, 2003
First measurement at HIγS

\( ^{26}\text{Mg}(\gamma,\text{n})^{25}\text{Mg} \) with 13.3 MeV Bremsstrahlung \( \gamma \)-radiation suggests possible 1\(^{-}\) state at 11.153 MeV

*Berman et al PRL 1969*

New experiment with polarized mono-energetic \( \gamma \) radiation to probe the level structure and spin assignments in \( ^{26}\text{Mg} \) through a measurement of the analyzing power.
Revised spin assignment

$^{26}\text{Mg}(\gamma,\gamma')^{26}\text{Mg}$ with 11.3 MeV $\gamma$-radiation to probe $\gamma$-decay of critical 11.153 state near neutron threshold. Analyzing power measurement indicates 1$^+$ assignment for the level. The level cannot contribute to the $^{22}\text{Ne}+\alpha$ reaction channel!
Reduction in $^{22}\text{Ne}(\alpha,n)$ rate, with possible increase in $^{22}\text{Ne}(\alpha,\gamma)$ rate because of two 1- alpha unbound and neutron bound states in $^{26}\text{Mg}$. 
Origin of $^{60}$Fe

Observed: $^{26}$Al/$^{60}$Fe = 0.08-0.22

Detection of $^{60}$Fe with INTEGRAL

$^{60}$Fe enrichment in deep sea iron manganese sediments

t$_{1/2}$ = 1.5 Myr

Exposure, distance, time ... depends on $^{59}$Fe(n,$\gamma$)$^{60}$Fe(n,$\gamma$) rates

Observational evidence for nearby Supernova 2.8 Myr ago at a distance of ~10pc!
60Fe measurements

The production of 60Fe by neutron capture prior to core collapse depends strongly on the uncertain cross sections of 59Fe(n,γ)60Fe and 60Fe(n,γ)61Fe.

Measurement of neutron capture reactions important since Hauser Feshbach simulations are not reliable in this mass range.
$^{60}\text{Fe}(n,\gamma)$ activation experiment

Summed $\gamma$-spectrum of $^{61}\text{Fe}$ decay, the background yields from $^{60}\text{Co}$ decay

Coincidence requirement between 229 keV and 1027 keV cascade transitions in $^{61}\text{Fe}$. ($t_{1/2} = 5.98$ min)

Sample contains $7 \cdot 10^{15}$ $^{60}\text{Fe}$ atoms
$^{60}$Fe($n,\gamma$) cross section at 25 keV

Hauser Feshbach model prediction: $\sim$5 mbarn

Significant deviation which suggests reduction in $^{60}$Fe production!

Result scales with half life value, confirmation of literature value necessary!

$$T_{1/2} = 1.5 \text{ Myr} \Rightarrow 2.6 \text{ Myr} ???$$

(PSI - TU Munich, FZK Karlsruhe – VERA, Vienna, NSCL/MSU – Notre Dame)
Uncertainties in the $^{12}\text{C}+^{12}\text{C}$ fusion rate?

Consequences for:
- Stellar Carbon burning
- Type Ia supernova ignition
- Superburst ignition conditions

Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

- standard potential model
- hindrance potential model

Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Yakovlev et al. PRC 2006
Jiang et al. PRC 2007
Resonance Structures in $^{12}$C+$^{12}$C

Recent data suggest strong but narrow resonance structures in the $^{12}$C+$^{12}$C reaction system. The data point towards a $^{12}$C configuration without a specific preference for the subsequent proton or alpha decay! The branching ratio is very uncertain.

Spillane et al. PRL 2007
Zickefoose et al. Capri 2009

Thick target technique indicates low energy resonance at 1.5 MeV in the $^{12}$C+$^{12}$C$\Rightarrow^{23}$Na+p channel.
Location of new 1.5 MeV resonance

Strong, molecular $^{12}$C+$^{12}$C resonance causes enormous enhancement of S-factor and reaction rate at stellar burning conditions.

- standard potential model
- low energy resonances

Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Spillane et al. PRL 2007
Zickefoose et al. Capri 2009
Impact of a 1.5 MeV resonance

\[ N_A \langle \sigma v \rangle = \sqrt{\frac{8}{\pi \cdot \mu}} \cdot (kT)^{-3/2} \cdot \int_0^\infty E \cdot \sigma(E) \cdot \exp\left(-\frac{E}{kT}\right) dE \]
Future Facilities in Nuclear Astrophysics
Towards low energies - underground

DIANA at DUSEL for measurements at stellar energies
International Situation
Away from Stability!

Understanding nuclear processes at the extreme density and temperature conditions of stellar environments!
Alternatives

RIKEN, Japan (2008)

GANIL, France (2013)

GSI/FAIR Germany (2015)
Neutron spallation sources for s-process neutron capture studies

Conversion of neutron time of flight spectrum into the neutron energy spectrum for $^{151}\text{Sm}(n,\gamma)$

180 m flight pass
Other Facilities LANSCE & FRANZ

Frankfurt Neutron Source FRANZ with the FZK Ba$_2$F detector array.

Neutron ToF facility at Los Alamos National Laboratory, with DANCE Ba$_2$F detector array
Towards Reality? Astrophysics at NIF
The laser approach NIF

- short period: $t = 20 - 200 \text{ ps}$
- high temperature: $T = 15 \text{ GK}$
- high density: $\rho = 1000 \text{ g/cm}^3$

1. Charge particle reactions
2. Neutron capture reactions

Fast electronics and data processing required
Conclusion

Nuclear astrophysics experiments are necessary for providing reliable understanding model predictions and interpreting observational results!

New experimental techniques have been developed to reach lower energies for stellar reactions studies and to probe the limits of stability in explosive nucleosynthesis events!

This promises a new era of experimental efforts in the field!

Coordinated effort and communication between experimentalists and theorist is necessary to extrapolate the data and to enhance the over-all efficiency of the experimental program!