Nucleosynthesis History

What the Big Bang made...

What we observe in early stars

What we find today

(The primordial abundance pattern)
Brian Fields (2002)

(The abundance pattern in the oldest observed stars He1017 & HH1327)
Anna Frebel (2006)

(The solar abundance pattern)
From big bang to De Vinci

Each heavy atom in our body was built and processed through ~100-1000 star generations since the initial Big Bang event!

We are made of star stuff
Carl Sagan
The ultimate goal of nuclear astrophysics is to understand how nuclear processes generate the energy of stars over their lifetimes and, in doing so, synthesize heavier elements from the primordial hydrogen and helium in the big bang which led to the expanding universe.

W. Fowler
The Frontiers of Nuclear Science
A LONG RANGE PLAN

2007 Long range plan
Nuclei and Nuclear Astrophysics

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the nature of neutron stars and dense nuclear matter?
- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?
Voltage Range: 50–400 kV  
Output Current: 1 mA (@ 400 kV)  
Absolute Energy error: ±300 eV  
Beam energy spread: <100 eV  
Long term stability (1 h): 5 eV  
Terminal Voltage ripple: 5 Vpp Ge det
Institute for Structure and Nuclear Astrophysics
National Superconducting Cyclotron Laboratory at Michigan State University
New Coupled Cyclotron Facility – experiments since mid 2001

Ion Source: $^{86}$Kr beam

$^{86}$Kr beam 140 MeV/u

$^{86}$Kr hits Be target and fragments

Tracking (=Momentum)

Separated beam of r-process nuclei

TOF start

TOF stop dE detector

Implant beam in detector and observe decay

Fast beam fragmentation facility – allows event by event particle identification
Bright future for experiments and observations

- Experimental test of r-process models is within reach
- Vision: r-process as precision probe

NSCL reach

Reach of future facility

Mass, half life, decay mode, ...
The future of radioactive beam physics

High Intensity Radioactive Beam Accelerator Facility to be build in 2012 (postponed) and completed in 2021. The ND group has key position in science planning and R&D.
n-TOF facility at CERN / DANCE at LANL

Experimental Area
- Sample
- Neutron-Beam
- Detector

Neutron source
- Lead Spallation Target
- Proton Beam 20 GeV/c
- 7 x 10^{12} ppp
- Neutron-Beam 10° production angle

20 GeV/c Proton beam

TOF tube
185 meters

ISR
TT2A
TT2

PS
LINAC
BOOSTER

NSF
UNIVERSITY OF NOTRE DAME
High Intensity Gamma-Ray Source (HIGS) DUKE

16O(γ,α)12C
26Mg(γ,n)

HIGS2 Concept

Electron Bunches

E–beam

IR Laser

γ–rays

FEL Wiggler Switchyard

2012/06/01
Studying Nuclear Astrophysics at National Ignition Facility
Novel detectors
Hans Bethe
The Nobel Prize in Physics 1967

William A. Fowler
The Nobel Prize in Physics 1983

Raymond Davis Jr.
The Nobel Prize in Physics 2002
Solar Neutrino “Problem”

- Solar model
- Important cross sections: $^3\text{He}(^3\text{He,2p})^4\text{He}$, $^3\text{He}(^4\text{He,γ})^7\text{Be}$, $^7\text{Be}(p,γ)^8\text{B}$
- Unknown neutrino physics-neutrino oscillation???

"Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of $^8\text{B}$ neutrinos to within a factor of 2 or 3..."

Nuclear Physics, the Core of Matter, the Fuel of Stars

http://www.nap.edu/catalog.php?record_id=6288#toc
How does carbon burn in stellar environment?

X. Tang
University of Notre Dame
Carbon burning in the universe

The extrapolation to low energy is uncertain ... and more experimental and theoretical studies are urgently needed.

Fowler, Nobel Lecture (1983)

burning phase. The fusion of three alpha particles to $^{12}$C followed by the $^{12}$C$(\alpha,\gamma)$ reaction characterizes the red giant phase of stars and sets the stage for subsequent burning phases, such as carbon burning through $^{12}$C + $^{12}$C fusion and oxygen burning characterized by $^{16}$O + $^{16}$O fusion. These key reactions of late stellar burning are the main energy sources of the star and determine the duration of the respective burning phases. The extremely small cross sections of the stellar reaction rates result in the long lifetimes of stars but represent the main challenge to a direct experimental study of these reactions. While great progress has been made in
• Carbon burning processes in the Universe
• Carbon burning in the laboratory
  • Upper Limit for $^{12}\text{C}+^{12}\text{C}$ fusion cross sections
  • Neutron Branching
  • Measurements towards deep sub-barrier energies
  • Search of potential resonances using $^{24}\text{Mg}(a,a')$
Institute for Structure and Nuclear Astrophysics
Nuclear Science Laboratory

Light particle: p, n, α
Gamma: 440 keV (p channel)
1634 keV (α channel)
Fusion residue: 20Ne, 23Na ...
no success under barrier
23Mg: decay spectroscopy
$^{60}$Fe Production in supernovae

$^{60}$Fe ($t_{1/2}=2.6$ Ma) production

Non-smoker
Normal Enzyme Level

Smoker
Reduced Enzyme Level
Impact to nucleosynthesis

Gasques et al. PRC 76 (2007) 035802
Superburst: ignited by Carbon burning

- Rare, long duration bursts; By 2009, 15 bursts from 10 sources
- Recurrence times 1-2 years, energies $10^{42}$ ergs.
- Triggered by $^{12}\text{C}+^{12}\text{C}$ fusion in the ashes left over after the rp-process
  Cumming & Bildsten 2001; Strohmayer & Brown 2002; Cumming 2003; Brown 2004; Cooper & Narayan 2005; Cumming et al. 2006; Gupta et al. 2007
Superburst: ignited by Carbon burning

Ashes from rp process (He burning) deposit in the outer crust.

Key problem: With the standard rate (CF88), the crust temperature is too low to ignite the carbon fuel!

- Crust processes (EC, pycnonuclear fusion)
  - crust heating
  - crust conductivity
Carbon burning in the labs

Cross section within Gamow window (1 ~ 3MeV)

$10^{-22} b \sim 10^{-7} b$

Gasques et al. PRC 72 (2005) 025806
Jiang et al. PRC 75 (2007) 015803

Challenge for Laboratory nuclear-Astrophysics in Underground and Surface 2009: CLAUS2009
Strong resonances in the unexplored energy range


R. Cooper et al., APJ (2009) 702, 660
Strong resonances in the unexplored energy range

R. Cooper et al., APJ (2009) 702, 660
Institute for Structure and Nuclear Astrophysics
Nuclear Science Laboratory

- Direct measurement
  - The exact cross section
  - Search the possible Resonances at RCNP

- Provide potential to model the gross structure
  - $^{12}\text{C} + ^{13}\text{C}$
  - $^{13}\text{C} + ^{13}\text{C}$

- $^{24}\text{Mg}(a,a')$ inelastic

- $^{12}\text{C}^{(12}\text{C},a)^{20}\text{Ne}$
- $^{12}\text{C}^{(12}\text{C},p)^{23}\text{Na}$
- $^{12}\text{C}^{(12}\text{C},n)^{23}\text{Mg}$
- $^{12}\text{C}^{(12}\text{C},^8\text{Be})^{16}\text{O}$
Measurements towards deep sub-barrier energies

Part of X. Fang’s thesis, University of Notre Dame
Extension of $^{12}\text{C} + ^{12}\text{C}$ towards lower energies:

Particle-\(\gamma\) coincidences (e.g. \(p - \gamma\) or \(\alpha - \gamma\))

Particle-recoil coincidences (e.g. \(p - ^{23}\text{Na}\))

\(\gamma\)-recoil coincidences (e.g. \(\gamma - ^{23}\text{Na}\))

\(E_{cm} = 4\text{MeV}\)

100 pnA beam

\(\text{xsec} \sim 10\ \mu\text{b}\)
Branching ratio for ground state transitions

Calculation by Yunju Li
Institute for Structure and Nuclear Astrophysics
Nuclear Science Laboratory

Looking for the particles which do not emit photos?!
HELical Orbit Spectrometer (HELIOS)

Conceptual design

Recoil detector

Upstream Si array

Beam axis

Target

Downstream Si array

Solenoid

$T_{(cyc)} = \frac{2\pi m}{qB}$

TOF = 1 cyclotron period

Dispersion in parallel velocity

NIM A 580, 590 (2007)
Realistic Simulations: $d(^{132}\text{Sn},p)^{133}\text{Sn}$

$\Delta E = 50$ keV, $\Delta \theta = 1^\circ$

“kinematic compression”

Improved resolution for $(d,p)$ – similar for other reactions
HELIOS (ANL) under construction

$B_{\text{max}} = 3 \text{ T}$

90 cm
Disadvantage of Particle-gamma technique: not work for the channels without γ-ray (p0 and a0) which potentially have large decay branching ratios.
Institute for Structure and Nuclear Astrophysics
Nuclear Science Laboratory

$E_{\text{cm}}=5.0 \text{ MeV}, \text{ Al-foil 5.8um, } B=3.96 \text{ T}$

$x\text{sec}(p0): 1 \text{ mb}$
Beam: $\sim80$ pnA
Duration: 6 hr
After energy loss correction

$E_{cm} = 5.0$ MeV

<table>
<thead>
<tr>
<th>$h2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries: 142909</td>
</tr>
<tr>
<td>Mean $x$: 0.231</td>
</tr>
<tr>
<td>Mean $y$: 2.805</td>
</tr>
<tr>
<td>RMS $x$: 0.07439</td>
</tr>
<tr>
<td>RMS $y$: 0.7729</td>
</tr>
</tbody>
</table>

$q_{val\_p}$ vs. pos

<table>
<thead>
<tr>
<th>$h2_qval_p_pcs$</th>
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</thead>
<tbody>
<tr>
<td>Entries: 159866</td>
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<tr>
<td>Mean $x$: 0.2171</td>
</tr>
<tr>
<td>Mean $y$: -2.804</td>
</tr>
<tr>
<td>RMS $x$: 0.07865</td>
</tr>
<tr>
<td>RMS $y$: 1.427</td>
</tr>
</tbody>
</table>
$E_{cm} = 4.0$ MeV, Al-foil 5.8um, $B = 3.96$ T

- $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$
- $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$

**Xsec(p0): 0.01 mb**
- Beam: $\sim 30$ pnA
- Duration: 8 hr
Simulation: $E_{cm} = 2.0$ MeV, Al-foil 5.8um

Xsec(p0): 1 pb
Estimation of event rate

Table 1 Comparisons among different experiments studying the $^{12}$C+$^{12}$C fusion

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Beam intensity ($p\mu$A)</th>
<th>Detector efficiency</th>
<th>Event Rate (evt/day) $E_{cm}=2.1$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naples (world record)$^1$</td>
<td>10</td>
<td>1.5%</td>
<td>0.5 (proton only)</td>
</tr>
<tr>
<td>ND SAND</td>
<td>40</td>
<td>45%</td>
<td>120 = $120 \times 2 \times 0.5$</td>
</tr>
<tr>
<td>ND SAND + Gamma$^2$</td>
<td>40</td>
<td>45%($\text{SAND}) \times 8%$ (Gamma)</td>
<td>10 = $10 \times 2 \times 0.5$</td>
</tr>
<tr>
<td>ND SAND + Gamma$^3$</td>
<td>40</td>
<td>45%($\text{SAND}) \times 32%$ (Gamma)</td>
<td>38 = $38 \times 2 \times 0.5$</td>
</tr>
<tr>
<td>ND SSNAP</td>
<td>40</td>
<td>30%</td>
<td>80 = $80 \times 2 \times 0.5$</td>
</tr>
</tbody>
</table>

2. Only took the photopeak efficiency (440 keV and 1630 keV)
3. Used all the gamma energy > 0.1 MeV

2.1 MeV: $\sim 10^{-11}$ b
1.7 MeV: $\sim 10^{-13}$ b
Prediction for the new low energy limit

Naples: 10 puA beam; 1.5% eff.; proton channel only; 0.5 evt/days;
ND-ANL-IU: >40 puA beam; 45% eff.; both proton and alpha; 4*30*2 evt/days;

If add particle + gamma coincidence: 240*8% evt/days
Long Range Plan: DIANA or CJPL
Summary

- The $^{12}$C+$^{12}$C reaction rate is highly uncertain.

- Measurement at deep sub-barrier energies
  Particle-Gamma coincidence method:
  - to obtain reliable experimental data at lower energies ($1.7\text{MeV} - 3\text{MeV}$)
  - Disadvantage: not be able to detect $p_0$ and $\alpha_0$

Solenoid spectrometer:
- to obtain data of $p_0$ and $\alpha_0$ channels
Collaborators

Correlation between the $^{12}$C+$^{12}$C, $^{12}$C+$^{13}$C, and $^{13}$C+$^{13}$C fusion cross sections

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K. E. Rehm,$^{2}$ W. P. Tan,$^{1}$ S. Thomas,$^{1}$ X. D. Tang,$^{1,4}$ and E. Brown$^{5}$

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$^{24}$Mg($\alpha$, $\alpha'$) measurement at RCNP


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Osaka University: A. Tamii, H. Fujita, Y. Fujita, K. Hatanaka, B. Liu, K. Miki

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Texas A&M University: Y.-W. Lui

University of Birmingham: M. Freer

ND-IU-ANL-CIAE carbon fusion project (SAND, SSNAP)


China Institute of Atomic Energy: Y.J. Li

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