Nuclear reaction measurements using solenoid

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http://nuastro.skku.edu
Chart of Nuclide

Stable nuclei

Known nuclei

Terra incognita

z = 26 for Iron!
The question driving the nuclear astrophysics

11 greatest unanswered questions of Physics
(National Academy of Science Report, 2002)

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?
Stellar Nuclear Reactions

- $(p,\gamma)$ reaction
- $(\alpha,\gamma)$ reaction
- $(p,\alpha)$ reaction
- $(\alpha,p)$ reaction
- $(n,\gamma)$ reaction
- $\beta^-$ decay
- $\beta^+$ decay

- light particle induced
- use of radioactive isotopes as the beam
- Radioactive Ion Beam Facility is needed!
Needs in experimental nuclear astrophysics & structure

- Radiative capture reactions, \((p,\gamma)\) & \((\alpha,\gamma)\), require high beam intensities:
  \(< 10^8\) particles per second or so
- Transfer reaction measurements can give spectroscopic information:
  \((d,p)\), \((^3\text{He},d)\), etc.

\[ ^{17}\text{F}(p,\gamma)^{18}\text{Ne} \]

Chipps et al., PRL (2009)

\[ ^{132}\text{Sn}(d,p)^{133}\text{Sn} \]

Jones et al., Nature (2010)
Gamow window

- eg. the $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$ reaction
- reaction rate $\propto \exp(-E/kT)\cdot\exp(-b/E^{1/2})$ → strongly localized in energy
- Nova temperature: 0.3-0.6 GK → $^{18}\text{F}$ beam energies of ~ 4-8 MeV are required.

$^{18}\text{F} + p, T = 0.1$ GK
Transfer reactions

• Transfer reaction involving single nucleon transfer
  - The state shows a structure that can be expressed as the core + transferred nucleon orbiting around it (“single particle” states)
  - The energies of shell model orbitals can be well probed

• \((d,p)\) deuteron ‘stripping’ reaction by Butler et al. (1967)
  - angular dist. of \(p\) → unique determination of \(l\)-value for the transferred neutron

https://www.phy.ornl.gov/groups/astro/measurements/transfer.html
(d,p) reactions

- To study single-neutron states (energies, angular momentum, spectroscopic information)
- Traditionally, deuteron beams on a target (normal kinematics)

\[
\text{Deuteron (d)} \rightarrow \text{Target nucleus} \rightarrow \text{Recoil nucleus} \rightarrow \text{Proton (p)} \\
A \rightarrow A+1
\]

- A neutron is transferred from the deuteron to the target nucleus, forming a recoil nucleus.
- The proton is ejected from the system, in a **forward direction**. Its energy and angle carries information on the nuclear state populated.

  e.g. \( ^{12}\text{C}(d,p)^{13}\text{C} \), \( ^{16}\text{O}(d,p)^{17}\text{O} \), \( ^{124}\text{Sn}(d,p)^{125}\text{Sn} \), \( ^{208}\text{Pb}(d,p)^{209}\text{Pb} \)
(d,p) measurements in inverse kinematics

$^{132}\text{Sn}(d,p)^{133}\text{Sn}$ in inverse kinematics

$^{132}\text{Sn}$ beam + CD$_2$ solid target, $E_x = 0, 1, \text{ and } 1$ MeV in $^{133}\text{Sn}$

- forward $\theta_{\text{C.M.}} = \theta_{\text{lab}}$
- at backward angle, cross section and $E_p$ become very small
- at forward angle, $E_p$ rises quickly with angle ($dE/d\theta$ is large)
- High solid angle coverage
- good resolutions (angle & energy)
- large dynamic range
- barrel-type silicon detector array: ORRUBA
previous works

- $^{132}\text{Sn}(d,p)^{133}\text{Sn}$ – double magicity (K.L. Jones, *Nature*)
- $^{10}\text{Be}(d,p)^{11}\text{Be}$ – systematic study (K.T. Schmitt, *Phys. Rev. Lett.*)
- $^{130}\text{Sn}(d,p)^{131}\text{Sn}$ – single particle levels (R.L. Kozub, *Phys. Rev. Lett.*)
- $^{26}\text{Al}(d,p)^{27}\text{Al}$ – mirror states for astrophysics (S.D. Pain, *Phys. Rev. Lett.*)
- $^{126,128}\text{Sn}(d,p)^{127,129}\text{Sn}$ – tracking the single-neutron levels (B. Manning, *Phys. Rev. C*)
- $^{80}\text{Ge}(d,p)^{81}\text{Ge}$ – light fission fragment (S. Ahn)
- $^{134}\text{Te}(d,p)^{135}\text{Te}$ – away from double shell closures (S.D. Pain)
- ...

Wonderful jobs! But, we think we can do better.
Solenoid-based charged particle detector system

Helical Orbit Spectrometer, HELIOS

- designed for transfer reaction measurements in inverse kinematics with RIBs
- large-bore, uniform-field magnetic solenoid with $B \sim 3$ Tesla
  → better Q-value resolution, large solid angle, easy particle ID
- used with RIBs from ATLAS $^{17}$O($d,p$), $^{19}$O($d,p$), $^{86}$Kr($d,p$), ...

Figures taken from Wuosmaa et al., NIMA 580, 1290 (2007)
Solenoid Spectrometer for Nuclear Astrophysics (SSNAP)

- TwinSol: a pair of superconducting solenoids for RIB production (\(^7\)Be, \(^{17}\)F, \(^{25}\)Al,... light particles)
- SSNAP: Solenoid Spectrometer for Nuclear Astrophysics, similar to HELIOS
- used to detect light charged ejectiles from reactions important for astrophysics
- path: determined by charge-to-mass ratio, energy, ejected angle
- time-of-flight, energy, position of ejectile can be measured

\( \rightarrow E_{\text{c.m.}} \) and \( \theta_{\text{c.m.}} \) can be reproduced!
New SSNAP with Super X3

- Super X3 detectors
  - 4 resistive front strips, 4 back segments
  - energy resolution: ~ 55 keV (back), ~ 75 keV (front)
  - position resolution: ~ 1.2 mm
  - 7.5 cm long active area
- updated frame for better data
- versatile array: \((d,p), (p,t), (^3\text{He},t)\)…
- \(^{12}\text{C}(d,p)^{13}\text{C}\) measurement for commissioning
- astrophysical \(^{24}\text{Mg}(\alpha,p)^{21}\text{Na}\) reaction?
Nucleosynthesis in X-ray bursts: \textit{rp}-process

- Series of proton captures and $\beta$-decays
- Main energy production mechanism
- Heavy elements production
- Conditions
  - High temperature
  - Hydrogen rich environment
  - Seed nuclei

$\alpha p$-process: alternating $(\alpha,p)$ & $(p,\gamma)$ reactions

H burning via CNO & Hot CNO

triple $\alpha$ reaction

SnSbTe cycle (Schatz et al. 2001)
Sensitivity study

  “The effects of variations in nuclear processes on type I x-ray burst nucleosynthesis”

- Koike et al. 2004 (K04) model:
  - a spherically symmetric, multizone model of accretion onto a 1.3 $M_\odot$ neutron star
  - peak temperature of 1.36 GK
  - densities ranging from 0.54-1.44 g/cm$^3$
  - burst duration of ~100 seconds

- investigates the effect of reaction rate variations in final abundance ratios by a factor of 10 (up and down)

$^{24}$Mg($\alpha$,p)$^{27}$Al reaction affects on the final abundances of $^{34}$S and $^{30}$Si, and the total nuclear energy of burst

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Models Affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}$O($\alpha$, $\gamma$)$^{19}$Ne$^a$</td>
<td>K04, K04-B1, K04-B6</td>
</tr>
<tr>
<td>$^{18}$Ne($\alpha$, p)$^{21}$Na$^a$</td>
<td>K04-B1, K04-B6</td>
</tr>
<tr>
<td>$^{22}$Mg($\alpha$, p)$^{25}$Al</td>
<td>F08</td>
</tr>
<tr>
<td>$^{23}$Al(p, $\gamma$)$^{24}$Si</td>
<td>K04-B1</td>
</tr>
<tr>
<td>$^{24}$Mg($\alpha$, p)$^{27}$Al$^a$</td>
<td>K04-B2</td>
</tr>
<tr>
<td>$^{26}$Al(p, $\gamma$)$^{27}$Si$^a$</td>
<td>F08</td>
</tr>
<tr>
<td>$^{28}$Si($\alpha$, p)$^{31}$P$^a$</td>
<td>K04-B4</td>
</tr>
<tr>
<td>$^{30}$S($\alpha$, p)$^{33}$Cl</td>
<td>K04-B4, K04-B5</td>
</tr>
<tr>
<td>$^{31}$Cl(p, $\gamma$)$^{32}$Ar</td>
<td>K04-B3</td>
</tr>
<tr>
<td>$^{32}$S($\alpha$, p)$^{35}$Cl</td>
<td>K04-B2</td>
</tr>
<tr>
<td>$^{35}$Cl(p, $\gamma$)$^{36}$Ar$^a$</td>
<td>K04-B2</td>
</tr>
<tr>
<td>$^{56}$Ni($\alpha$, p)$^{59}$Cu</td>
<td>S01</td>
</tr>
<tr>
<td>$^{59}$Cu(p, $\gamma$)$^{60}$Zn</td>
<td>S01</td>
</tr>
<tr>
<td>$^{65}$As(p, $\gamma$)$^{66}$Se</td>
<td>K04, K04-B2, K04-B3</td>
</tr>
<tr>
<td>$^{69}$Br(p, $\gamma$)$^{70}$Kr</td>
<td>S01</td>
</tr>
<tr>
<td>$^{71}$Br(p, $\gamma$)$^{72}$Kr</td>
<td>K04-B7</td>
</tr>
<tr>
<td>$^{103}$Sn($\alpha$, p)$^{106}$Sb</td>
<td>S01</td>
</tr>
</tbody>
</table>
The $^{24}\text{Mg}(\alpha,p)^{27}\text{Al}$ reaction

Gamow window for the reaction x-ray bursts ($T \leq 2$ GK)

$E_{\text{c.m.}} = 1.5 - 3.3$ MeV

$E_p \leq \sim 2$ MeV (Lab.)

The lowest energy in direct measurement stops at $\sim 2.8$ MeV
$^{24}\text{Mg}(\alpha,p)^{27}\text{Al}$ measurement at U. of Notre Dame

- $\alpha$ beams ($I \sim 2$ nA) from 10 MV FN tandem accelerator
- $E_{\text{beam}} = 3 - 5$ MeV ($E_{\text{c.m.}} = 2.6 - 4.3$ MeV)
- evaporated $^{24}\text{Mg}$ solid targets ($\sim 50$ µg/cm$^2$ thick) on thin $^{12}\text{C}$ backing material ($\sim 5$ µg/cm$^2$ thick)
- $\Delta E_{\text{beam}} \sim 30-40 \text{ keV}$, about 40 beam energies
- $\sim$ few hours per beam energy
Preliminary results

Protons from $^{24}\text{Mg}(\alpha,p)^{27}\text{Al}$

Distance from target

Blank frame

$^{24}\text{Mg}$ target
**Future Plan**

- develop simulation code for SSNAP
- extract differential cross section values at $E_{\text{c.m.}} = 2.6 - 4.3$ MeV
- identify populated resonances in $^{24}\text{Mg} + \alpha$ ($^{26}\text{Si}$) system
- $R$-matrix fitting for resonance parameters
- $^{24}\text{Mg}(\alpha,\alpha)^{27}\text{Al}$ reaction rate calculation
- nucleosynthesis calculation

$^{27}\text{Al} + p$ [Nelson et al. PRC 29, 1656 (1984)] and $^{24}\text{Mg}(\alpha,\alpha)$ [Nucl. Phys. A 385, 43 (1982)]
**Korea Broad acceptance Recoil spectrometer and Apparatus**

- **RI beam production** at a few MeV/u or at about 20-40 MeV/u using stable beams
- **Recoil mass separator** (with the use of stage 2)
### Radioisotopes produced in novae

#### Isotope Lifetime Decay process

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Lifetime</th>
<th>Decay Mode</th>
<th>$\gamma$-ray produced</th>
<th>Nova type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}\text{N}$</td>
<td>0.24h</td>
<td>$\beta^+$-decay</td>
<td>511 keV + cont.</td>
<td>CO &amp; ONeMg</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>2h</td>
<td>$\beta^+$-decay</td>
<td>511 keV + cont.</td>
<td>CO &amp; ONeMg</td>
</tr>
<tr>
<td>$^{7}\text{Be}$</td>
<td>77d</td>
<td>$e^-$-capture</td>
<td>478 keV line</td>
<td>CO</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>3.75y</td>
<td>$\beta^+$-decay</td>
<td>1275 keV + 511 keV</td>
<td>ONeMg</td>
</tr>
<tr>
<td>$^{26}\text{Al}$</td>
<td>$10^6$y</td>
<td>$\beta^+$-decay</td>
<td>1809 keV + 511 keV</td>
<td>ONeMg</td>
</tr>
</tbody>
</table>

#### All sky map of 1.809 MeV $\gamma$-rays

*INTEGRAL (ESA, 2002)*
Radionuclide $^{18}$F

$^{17}$O($p, \gamma$) $^{18}$F
$^{17}$F($p, \gamma$) $^{18}$Ne($e^+, \nu_e$)

$^{18}$F
- $\tau \sim 2$ hrs, $\beta^+$-decay ($^{18}$O)
- large production rate
- important positron annihilation source!

$^{18}$F($p, \alpha$) $^{15}$O
- direct measurements:
- many indirect measurements

$^{18}$F($p, \gamma$) $^{19}$Ne: measured only one time by Akers (2013)
Previous $^{18}\text{F}(p,\alpha)^{15}\text{O}$ measurements

- precise measurement
- first measurement of 330 keV
- first study on the interference effect

Bardayan et al. (2002)

Chae et al. (2006)

Beer et al. (2011)

Bardayan et al. (2002)

Chae et al. (2006)

Beer et al. (2011)
18F Beams

- beam intensities:
  - For $^{18}$F($p,\alpha$)$^{15}$O: $\sim 10^6$ pps (for the 330 keV resonance)
  - For $^{18}$F($p,\gamma$)$^{19}$Ne: $\sim 10^7-8$ pps

- beam production:
  - high intensity $\alpha$ beam from the cyclotron and HfO$_2$ ISOL target
  - Radionuclide $^{18}$F will be produced through the $^{16}$O($\alpha,pn$)$^{18}$F reaction

- beam size: $\sim$ few mm$^2$ at the target position
- high beam purity
- beam time of $\sim$ 10 days
- very wide range of beam energy is required
Silicon detector system

YY-1 type
- 16 radial strips
- $\alpha$'s from the $(\rho,\alpha)$ reaction
- covers forward angles

QQQ type
- newly developed QQQ5
- 36 channels per wedge
- covers very forward angles
- $\alpha$'s from the $(\rho,\alpha)$ reaction,
  heavy recoils
Summary

- Solenoid-based detector system SSNAP was originally developed for transfer reaction studies

- SSNAP was used to measure astrophysical $^{24}\text{Mg}(\alpha,p)^{21}\text{Na}$ reaction

- Excitation function for the reaction was obtained at Ec.m. = 2.6-4.3 MeV by using a beams at various beam energies from FN tandem accelerator

- Data analysis is on going

Thank you very much!