Reaction rates in the Laboratory

Example I: $^{14}\text{N}(p,\gamma)^{15}\text{O}$

- slowest reaction in the CNO cycle
  - Controls duration of hydrogen burning
  - Determines main sequence turnoff – glob. cluster ages

- stable target $\rightarrow$ can be measured directly:

  $\text{Accelerator}$

  $\text{Proton beam}$

  $\text{gamma-ray detectors}$

  $\text{N-target}$

  $\text{Faraday cup to collect charge}$

- but cross sections are extremely low:
  $\rightarrow$ Measure as low an energy as possible
  - then extrapolate to Gamow window
Calculating experimental event rates and yields

beam of particles hits target at rest

\[ j, \nu \]

\[ \text{area } A \]

\[ \text{thickness } d \]

assume thin target (unattenuated beam intensity throughout target)

Reaction rate (per target nucleus):

\[ \lambda = \sigma j \]

Total reaction rate (reactions per second)

\[ R = \lambda A d n_T = \sigma I d n_T \]

with \( n_T \): number density of target nuclei

\( I = j A \): beam number current (number of particles per second hitting the target)

note: \( dn_T \) is number of target nuclei per cm\(^2\). Often the target thickness is specified in these terms.
Events detected in experiment per second $R_{\text{det}}$

$$R_{\text{det}} = R \varepsilon$$

$\varepsilon$ is the detection efficiency and can accounts for:

- detector efficiency
  (fraction of particles hitting a detector that produce a signal that is registered)
- solid angle limitations
- absorption losses in materials
- energy losses that cause particles energies to slide below a detection threshold
- …
$^{14}\text{N}(p,\gamma)$ level scheme

$\gamma_0$ signature of resonance

Direct gs capture

$\sim 7297 \text{ keV} + E_p$

Gamow window

0.1 GK:

91-97 keV

$\gamma$-signature of resonance

6791 keV
LUNA
Laboratory Underground for Nuclear Astrophysics
(Transparencies: F. Strieder http://www.jinaweb.org/events/tucson/Talk_Strieder.pdf)

1:1 Mio cosmic ray suppression
HP Ge-Detector
earth surface
detector without any shielding

3 MeV < $E_\gamma$ < 8 MeV
$\Rightarrow$ 0.5 counts/s

HP Ge-Detector
LNGS underground
detector with Pb shielding

3 MeV < $E_\gamma$ < 8 MeV
$\Rightarrow$ 0.0002 counts/s
400 kV LUNA accelerator

Inline-Crockcroft-Walton power supply inside tank mixture $\text{N}_2/\text{CO}_2$ @ 20 bar

$U_{\text{max}} = 50 - 400$ kV

$H\text{V-ripple} = 20$ Vpp

$\Delta E_{\text{max}} = 0.07$ keV (meas.)

ion beams: protons, alphas

$I_{\text{max}} = 700$ $\mu$A
Experiment – additional shielding
low energy γ background

$^{14}\text{N}(p,\gamma)^{15}\text{O}$

beam induced background

$^{11}\text{B}(p,\gamma)^{12}\text{C}$ (also $^{18}\text{O}(p,\gamma)^{19}\text{F}$)

TiN (deposited) on Copper thickness 50 keV

$E_p = 145$ keV
\( \gamma \) spectrum (HP-Ge) for \( ^{14}\text{N}(p,\gamma)^{15}\text{O} \)

\[ \gamma_6793 \]

\( ^{14}\text{N}(p,\gamma)^{15}\text{O} \)

\( E_p = 140 \text{ keV} \)

Counts

\( E_{\gamma} [\text{keV}] \)

6700 6800 6900 7000 7100 7200 7300 7400 7500
Results:

New $S(0)=1.7 \pm 0.2$ keVb  (NACRE: $3.2 \pm 0.8$)
New Resonance?

Infinite thick target measurement  TUNL 2001

No confirming evidence in UNC data 2002
Effect that speculative resonance would have had
Example II: $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$

problem: $^{21}\text{Na}$ is unstable (half-life 22.5 s)

difficulty: beam intensity typically $10^{7-11}$ 1/s

(solution: radioactive beam experiment in inverse kinematics: $^{21}\text{Na} + p \rightarrow ^{22}\text{Mg} + \gamma$

$\rightarrow$ so far only succeeded in 2 cases: $^{13}\text{N}(p,\gamma)$ at Louvain la Neuve and $^{21}\text{Na}(p,\gamma)$ in TRIUMF (for capture reaction)
DRAGON
Detector of Recoils And Gammas Of Nuclear reactions

Recoil Detectors
Final Focus Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
IC/PGAC Stop
MCP Start
Magnetic Dipole
Magnetic Quads
Gas Target
Gamma Array
Magnetic Quads
Charge Slit Box
Magnetic Dipole
Electrostatic Dipole
Mass Slit Box
Quads
Results

Example III: $^{32}\text{Cl}(p,\gamma)^{33}\text{Ar}$

TABLE V. Nonresonant direct capture transitions and the astrophysical $S$ factors; resonance energies, $\gamma$ widths, proton widths, and resonance strengths for $^{32}\text{Cl}(p,\gamma)^{33}\text{Ar}$.  

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$J^\pi$</th>
<th>$\ell_i$</th>
<th>$n f_f$</th>
<th>$C^2 S_f$</th>
<th>$S(E_0)$ (MeV b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>$\frac{1}{2}^+$</td>
<td>$p$</td>
<td>$2s_{1/2}$</td>
<td>0.080</td>
<td>$7.00 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$p$</td>
<td>$1d_{3/2}$</td>
<td>0.672</td>
<td>$6.14 \times 10^{-3}$</td>
<td></td>
</tr>
<tr>
<td>1.34</td>
<td>$\frac{3}{2}^+$</td>
<td>$p$</td>
<td>$1d_{3/2}$</td>
<td>0.185</td>
<td>$2.62 \times 10^{-3}$</td>
</tr>
<tr>
<td>1.79</td>
<td>$\frac{5}{2}^+$</td>
<td>$p$</td>
<td>$1d_{3/2}$</td>
<td>0.145</td>
<td>$2.74 \times 10^{-3}$</td>
</tr>
<tr>
<td>2.47</td>
<td>$\frac{3}{2}^+$</td>
<td>$p$</td>
<td>$2s_{1/2}$</td>
<td>0.031</td>
<td>$6.16 \times 10^{-3}$</td>
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<tr>
<td></td>
<td>$p$</td>
<td>$1d_{3/2}$</td>
<td>0.167</td>
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<td></td>
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<tr>
<td>3.15</td>
<td>$\frac{3}{2}^+$</td>
<td>$p$</td>
<td>$2s_{1/2}$</td>
<td>0.068</td>
<td>$1.46 \times 10^{-2}$</td>
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<tr>
<td></td>
<td>$p$</td>
<td>$1d_{3/2}$</td>
<td>0.516</td>
<td>$3.01 \times 10^{-3}$</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$E_x$</th>
<th>$E_p$</th>
<th>$J^\pi$</th>
<th>$\Gamma_\gamma$ (eV)</th>
<th>$\Gamma_p$ (eV)</th>
<th>$\omega_\gamma$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.43</td>
<td>0.09</td>
<td>$\frac{5}{2}^+$</td>
<td>$1.77 \times 10^{-2}$</td>
<td>$8.7 \times 10^{-18}$</td>
<td>$8.7 \times 10^{-18}$</td>
</tr>
<tr>
<td>3.56</td>
<td>0.22</td>
<td>$\frac{7}{2}^+$</td>
<td>$1.94 \times 10^{-3}$</td>
<td>$1.13 \times 10^{-9}$</td>
<td>$1.51 \times 10^{-9}$</td>
</tr>
<tr>
<td>3.97</td>
<td>0.63</td>
<td>$\frac{5}{2}^+$</td>
<td>$1.54 \times 10^{-2}$</td>
<td>$2.22 \times 10^{-2}$</td>
<td>$9.09 \times 10^{-3}$</td>
</tr>
<tr>
<td>4.19</td>
<td>0.85</td>
<td>$\frac{1}{2}^+$</td>
<td>$1.54 \times 10^{-1}$</td>
<td>46.74</td>
<td>5.12 \times 10^{-2}$</td>
</tr>
<tr>
<td>4.73</td>
<td>1.39</td>
<td>$\frac{3}{2}^+$</td>
<td>$8.48 \times 10^{-2}$</td>
<td>100.3</td>
<td>5.65 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Shell model calculations

$\rightarrow$ proton width strongly energy dependent
$\rightarrow$ rate strongly resonance energy dependent
NSCL Coupled Cyclotron Facility
Installation of D4 steel, Jul/2000
Fast radioactive beams at the NSCL:

- low beam intensities
- Impure, mixed beams
- high energies (80-100 MeV per nucleon)
  (astrophysical rates at 1-2 MeV per nucleon)

→ great for indirect techniques

- Coulomb breakup
- Transfer reactions
- Decay studies
- ...
S800 Spectrometer at NSCL:

Radioactive $^{34}\text{Ar}$ beam $84$ MeV/u $T_{1/2}=844$ ms (from $150$ MeV/u $^{36}\text{Ar}$)

Plastic target

SEGA Ge array (18 Detectors)

Focal plane: identify $^{33}\text{Ar}$

Beam blocker

People:
- D. Bazin
- R. Clement
- A. Cole
- A. Gade
- T. Glasmacher
- B. Lynch
- W. Mueller
- H. Schatz
- B. Sherrill
- M. VanGoethem
- M. Wallace
SEGA Ge-array

S800 Spectrometer
Doppler corrected $\gamma$-rays in coincidence with 33Ar in S800 focal plane:

$\gamma$-rays from predicted 3.97 MeV state

$^{33}$Ar level energies measured:

3819(4) keV  (150 keV below SM)
3456(6) keV  (104 keV below SM)

New $^{32}$Cl($p,\gamma$)$^{33}$Ar rate – Clement et al. PRL 92 (2004) 2502

stellar reaction rate

with experimental data x 3 uncertainty

$^{33}$Ar level energies measured:

3819(4) keV  (150 keV below SM)
3456(6) keV  (104 keV below SM)
Science with CCF reaccelerated beams

Rates in pps

- $>10^8$
- $10^7$-8
- $10^6$-7
- $10^5$-6
- $10^4$-5
- $10^2$-4

**direct (p,γ)**

**direct (p,α) or (α,p) transfer**

**(p,p), some transfer**

Up to here:
For indirect measurements: many
For direct measurements: some important rates

and p-process …

**Capabilities:**
- sufficient beam intensities for many important measurements
- all beams available once system commissioned
- probably very good beam purity
- none of the measurements identified can be performed at another facility as of now
Overview of the FRIB Layout
ReA12 and Experimental Areas

- A full suite of experimental equipment will be available for fast, stopped and reaccelerated beams
- New equipment
  - Stopped beam area (LASERS)
  - ISLA Recoil Separator
  - Solenoid spectrometer
  - Active Target TPC
Science with reaccelerated beams at FRIB

Rates in pps

- $10^{>10}$
- $10^9-10$
- $10^8-9$
- $10^7-8$
- $10^6-7$
- $10^5-6$
- $10^4-5$
- $10^2-4$

Direct measurements for many ($\alpha,\gamma$) reactions in p-process

All reaction rates can be indirectly measured including $^{72}$Kr waiting point

Most reaction rates up to $\sim$Sr can be directly measured

All reaction rates up to $\sim$Ti can be directly measured

→ Very strong nuclear astrophysics science case