The first campaign of direct-reaction measurements using GODDESS

Steven D. Pain
Oak Ridge National Laboratory

- Particle-gamma measurements
- $^{26}$Al(d,p)$^{27}$Al measurement – a “good” example
- GODDESS design
- The first GODDESS campaign

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GODDESS Acknowledgements

Andrew Ratkiewicz
(LLNL, formerly Rutgers)

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Gammasphere
- Array of ~110 HPGe detectors
- Compton-suppressed
- Hevimet collimators (optional)
- Large (18cm radius) internal geometry

Gammasphere-ORRUBA: Dual Detectors for Experimental Structure Studies
- Light-ion stripping/pickup
- Heavy-ion transfer
- Inelastic scattering
- Coulex
- Charge exchange…

ORRUBA
- Center-built device
- Barrel array of 24 silicon telescopes
- Resistive-strip detectors (~1 mm position resolution at 6 MeV)
- 288+ channels
- 45-135 deg coverage
$^{26}\text{Al}(d,p)^{27}\text{Al}$ to constrain $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ reaction rate

- 117 MeV $^{26}\text{Al}$
- $5 \times 10^6$ pps
- 150 $\mu$g/cm$^2$ CD$_2$
- MCP normalization (200 kHz)

Constrain $C^2S$ via mirror symmetry
Constraint of the Astrophysical $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ Destruction Rate at Stellar Temperatures


7805(12) keV (127-keV mirror)

Nearest ell=0 states

FWHM 72 keV (CoM)

<table>
<thead>
<tr>
<th>$^{27}\text{Al}$</th>
<th>$^{27}\text{Al}$</th>
<th>$^{27}\text{Al}^a$</th>
<th>$^{27}\text{Si}^a$</th>
<th>$^{27}\text{Si}$</th>
<th>$\Gamma_{sp}$</th>
<th>$\Gamma_p$</th>
<th>$\omega_{\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J^\pi$</td>
<td>$E_x$ (keV)</td>
<td>$C^2S_{v}^{\text{exp}}$</td>
<td>$C^2S_{v}^{\text{th}}$</td>
<td>$C^2S_{\pi}^{\text{th}}$</td>
<td>$C^2S_{\pi}$</td>
<td>(meV)</td>
<td>(meV)</td>
</tr>
<tr>
<td>$9/2^+$</td>
<td>7807</td>
<td>0.0102 ± 0.0021</td>
<td>0.0112$^{-0.0002}_{+0.0007}$</td>
<td>0.0094$^{+0.0016}_{-0.0024}$</td>
<td>0.0085$^{+0.0024}_{-0.0031}$</td>
<td>6.70 $\times 10^{-3}$</td>
<td>5.7$^{+1.6}_{-2.1}$$\times 10^{-5}$</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>7790</td>
<td>$\leq 0.061$</td>
<td>0.0100$^{+0.0006}_{-0.0002}$</td>
<td>0.0088$^{+0.0010}_{-0.0022}$</td>
<td>$\leq 0.054$</td>
<td>2.06 $\times 10^{-10}$</td>
<td>$\leq 1.1 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

$^a$From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of $-650$ MeV fm$^3$. 
Experimental information:

- Al(\(d,p\)) experiment at ORNL
- 7805(12 keV) - 127 keV mirror
  - FWHM 72 keV
  - CoM

Graphical information:

- Plot of \(N_A \sigma_v\) vs. Temperature (GK) for ORNL rate (127 keV) and previous upper limit (127 keV), ORNL upper limit (68 keV), and previous upper limit (68 keV), and 189 keV rate.

Table of data:

<table>
<thead>
<tr>
<th>(J^\pi)</th>
<th>(E_x) (keV)</th>
<th>(\omega\gamma) (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/2(^+)</td>
<td>7807</td>
<td>(2.6^{+0.7}_{-0.9} \times 10^{-5})</td>
</tr>
<tr>
<td>5/2(^+)</td>
<td>7790</td>
<td>(\leq 3.0 \times 10^{-12})</td>
</tr>
</tbody>
</table>

Footnote:

\(^8\)From SMEC calculations using the USD-b effective interaction, using a continuum coupling constant of \(-650\) MeV fm\(^3\).
Define Kinematic Compression Factor (KCF)

The separation in $E_{lab}$ at $\theta_{lab}=180$ deg (0 deg CoM), between two states that are separated by $E_{CoM} = 1$ MeV (Does change with angle)

Multiplicative factor telling how your detector resolution will appear in the CoM

- Larger than 1 😞
- Less than 1 😊

For (d,p) reactions in inverse kinematics, typically ~3
Transfer on r-process nuclei - level densities

Level spacings as low as 20 keV

\[ \begin{array}{c}
\text{Excitation Energy (MeV)} \\
0 & 1 & 2 & 3 & 4 & 5
\end{array} \]

\[ \begin{array}{c}
\text{Counts} \\
0 & 50 & 100 & 150
\end{array} \]

\[ \begin{array}{c}
\text{132Sn(d,p)} \\
\text{135Te} \\
\text{134Te(d,p)} \\
\text{134Te(9Be,8Be)135Te}
\end{array} \]
GODDESS performance for light-ion transfer reactions

10 A MeV
Recoil direction
Recoil energy (targ)
Recoil energy (reaction)
Intrinsic resolution
Opening angle of GS

$^{138}\text{Xe}(d,p)$

~0.5 deg (0.05 deg)

~3% (500 $\mu$g CD$_2$)

0.01%

2 keV

5.5 deg

$^{138}\text{Xe}(d,t)$

~1 deg (~0.1 deg)

~3% (500 $\mu$g CD$_2$)

0.01%

2 keV

5.5 deg

Gammasphere ~13 keV

Gammasphere efficiency

No heavy-mets, gsima30

With heavy-mets, gs101

delta/E (MeV)
GODDESS design

- Flowerpot spun to match the BGO profile
- Preamps mounted in space between flowerpot and FMA quad

- Remove no GS detectors
- Mount ORRUBA detectors inside Gammasphere
- Thin-walled (1/16”, 1.6mm Al) chamber (minimize absorption/scattering of gammas)
- Minimize detector-preamplifier distance (<2 feet)
- Maintain possibility of coupling with the FMA
- Fit ~700 preamplifiers within space occupied by 17-deg ring of GS
- Maintain space for 0-degree detector (IC)
**GODDESS**

*Polar angle coverage*

15 to 165 degree coverage (>75%)

- Elastically scattered deuterons
- Elastically scattered protons
- Tritons from (d,t)
- $^3$He from (d,$^3$He)
- Protons from (d,p)

**Energy (MeV)**

**Lab Angle (deg)**

Forward endcap  |  Barrel  |  Backward endcap
GODDESS ionization chamber

- Re-entrant
- Tilted-grid wire electrodes (1 km 18 um wire) [K.Y. Chae et al., *NIM A 715C*, 6 (2014)]
- >2 x 10^5 pps rate (previous ORNL IC)
- Acceptance of 4.5 deg +
- 2-part design to enable assembly in place (FMA quad interference)
GODDESS Campaign Summer 2015

- **July**: Set up
- **August**: $^{134}\text{Xe}$, Analysis/Refine
- **September**: $^{95}\text{Mo}$
- **October**: $^{19}\text{F}$

GODDESS campaign

Beam development campaign

Map showing the route from Argonne National Laboratory to Louisville, KY.

A yellow Penske truck is parked near the GODDESS equipment.
Beam time approved by the ATLAS PAC

1383x - Coupling the ORRUBA and Gammasphere arrays: a request for equipment development time
S.D. Pain et al.

1454 - Developing the \((d,p\gamma)\) reaction as a surrogate for \((n,\gamma)\) in inverse kinematics:
\(^{95}\text{Mo}(d,p\gamma)\) with Gammasphere
J.A. Cizewski et al.

1488 - Study of the Near-Threshold Levels in \(^{19}\text{Ne}\) and the \(^{18}\text{F}(p,\alpha)^{15}\text{O}\) Rate in Novae
D.W. Bardayan et al.

1484 - Measurements of \((d,p\gamma)\) on neutron-rich Xe and Te with CARIBU beams
S.D. Pain et al.

1614 – Probing fragmentation of single-particle strength in reflection asymmetric Ba nuclei with GODDESS
J.A. Cizewski, A. Ratkiewicz, et al.

Stable \(^{134}\text{Xe and }^{82}\text{Kr}\) beam for equipment development August 10-16

\(^{95}\text{Mo beam for }(d,p\gamma)\) surrogate development
Aug 25 – Sept 30

\(^{3}\text{He beam for }^{19}\text{F}(^{3}\text{He},t\gamma)^{19}\text{Ne}\) measurement
Sept 3-4, 8-9

\(^{134}\text{Te CARIBU beam for }(d,p\gamma)\) measurement
Approved, awaiting CARIBU beam intensity

\(^{144}\text{Ba CARIBU beam for }(d,p\gamma)\) measurement
Approved (priority II)
• Six-day run to debug, optimize and demonstrate the capability of GODDESS

• Six days beam ($^{134}$Xe and $^{82}$Kr beam) (10 A MeV)

• Set up full Si array
  • Barrel of sX3+BB10 detectors
  • Endcaps of QQQ5-1000 and QQQ5-100 detectors

• Instrument 400 channels (digital) + 320 channels (analog) with MyRIAD

• Optimize digitizers

• Debug DAQ (ensure coincidences)

• Debug/optimize IC with beam

• Acquire physics data
Data Acquisition Scheme

ORNL DAQ (Master 2)

DFMA (Master 1)

~ 320 ch

Beam Left

Beam Right

DGS (slave)

Δ time
$^{134}$Xe(d,X)$\gamma$ experiment

165 deg 135 deg Lab Angle 90 deg 45 deg

$^{134}$Xe

10$^6$-10$^7$ pps
10 MeV/A

768 $\mu$g CD$_2$
$^{134}\text{Xe}(X, X\gamma)$ data

Inelastic scattering of the beam

Preliminary! Single run
$^{134}\text{Xe}(d,X\gamma)$ data

134 Xe

1731

847

0

1731

847

0

$\gamma$-ray energy x 3 (keV)

EhICln

hUp

<table>
<thead>
<tr>
<th>Entries</th>
<th>308503</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>761.4</td>
</tr>
<tr>
<td>RMS</td>
<td>452.9</td>
</tr>
</tbody>
</table>

134 Xe

Preliminary!

Single run

134 Xe

768 mg CD

ORRUBA angle

ORRUBA energy

$g$-ray energy (keV)

$g$-ray energy x 3 (keV)
$^{134}\text{Xe}(d,p\gamma)$ experiment

No low-spin $-ve$ $\pi$ states known

130Sn($d,p$)

2.5 MeV shell gap

Preliminary! Single run
Developing the \((d,p\gamma)\) reaction as a surrogate for \((n,\gamma)\) in inverse kinematics: \(^{95}\text{Mo}(d,p\gamma)\) with Gammasphere

- Five-day run to validate and benchmark \((d,p\gamma)\) in inverse kinematics with GODDESS as a surrogate for neutron capture
- Four days \(^{95}\text{Mo}\) (8 MeV/A, <10\(^7\) pps, 200 \(\mu\text{g/cm}^2\) CD\(_2\) target)
- Address experimental challenges of measuring in inverse kinematics
  - Fusion-evaporation bg from C in target
  - Quantify Doppler broadening limitations
  - Determine practical limit of kinematics
- Suppress fusion-evaporation with FMA
- Ascertain that equivalent results can be obtained in normal and inverse kinematics
- Measure \(\gamma\) multiplicity (no Hevimets)
- Looking for yields going through 2+ collecting transition
$^{95}\text{Mo}(d,p\gamma)$ experiment

Run 345: Gated on QQQ5 UA and UB, Multiplicity=1

- Entries: 12532
- Underflow: 3
- Overflow: 65
- Integral: $1.13e+04$

$\gamma$-ray energy (keV)

Preliminary!
Single run
1488 - Study of the Near-Threshold Levels in $^{19}\text{Ne}$ and the $^{18}\text{F}(p,\alpha)^{15}\text{O}$ Rate in Novae (Bardayan/Hall)

- $^{18}\text{F}$ production in novae potentially prompt observable
- $^{18}\text{F}(p,\alpha)^{15}\text{O}$ rate uncertain due to properties of $^{19}\text{Ne}$ states close to the proton threshold at 6.411 MeV
- Interference with strong higher-lying resonances (6.290 MeV and 7.076 MeV) potentially critical
- Recent measurement of $(^{3}\text{He},t)$ suggested no $e\ell=0$ state to triplet

$^{3/2+}$ 665 keV

<table>
<thead>
<tr>
<th>$^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}$ [Ut98]</th>
<th>$^{18}\text{F}(d,n)^{19}\text{Ne}$ [Ad11]</th>
<th>$^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}$ [La13]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-121 keV – (1/2+, 3/2+)</td>
<td>-122 keV</td>
<td></td>
</tr>
<tr>
<td>8 keV – (3/2+)</td>
<td>8 keV – 3/2-</td>
<td>5 keV – (3/2-,5/2+)</td>
</tr>
<tr>
<td>38 keV – (3/2+)</td>
<td></td>
<td>29 keV – (11/2+)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48 keV – (5/2-)</td>
</tr>
</tbody>
</table>

$^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}$ experiment for $^{18}\text{F}(p,\alpha)$ in novae

Matt Hall  
University of Notre Dame (PhD)

- Search for $3/2^+$ state (implied by mirror system)
$^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}$ experiment for $^{18}\text{F}(p,\alpha)$ in novae

- $238\; ^{19}\text{Ne}$
- $275\; ^{19}\text{Ne}$
- $893\; \text{keV} (^{40}\text{Sc})$
- $1232\; 1297\; \text{Q value (au)}$
- $238\; ^{19}\text{Ne}$
- $3/2^+$
- $2556\; ^{19}\text{Ne}$
- $1297\; 1232\; \text{Q value (au)}$
- Preliminary!
- Astro states $3/2^+$?
**G(RETINA)ODDESS for transfer reactions**

Doppler correction largest remaining contribution to resolution

Fast beams at FRIB

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**Gammasphere ~13 keV**

**GRETINA ~3 keV**
Fits inside standard (DGS) GRETINA chamber

Marginally tighter squeeze inside GS

Room to bring out electronics?
Summary

• $^{26}\text{Al}(d,p)^{27}\text{Al}$ used to constrain $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$ reaction rate for massive stars
• Probably this is a best-case scenario for IK RIB measurements
• First GODDESS campaign completed 2015
• Successful operation of ORRUBA, Ionization Chamber, Gammasphere, FMA Focal Plane detectors
• Successful operation of all three data acquisition systems (ORNL, DFMA, DGS)
• $^{134}\text{Xe}$ data taken, demonstrating GODDESS capabilities and beginning study of Xe isotopic chain
• $^{95}\text{Mo}(d,p\gamma)^{96}\text{Mo}$ experiment successfully completed. Preliminary data look promising
• $^{19}\text{F}(^{3}\text{He},t)^{19}\text{Ne}$ experiment successfully run. Triton-gated $^{19}\text{Ne}$ gamma rays observed
• First in-flight beam developed that could be delivered to Gammasphere
• Two PAC-approved experiments to be run
Collaborators

K.A. Chipps, M. Febbraro, I. Marsh, M.S. Smith, R. Varner
Oak Ridge National Laboratory

Rutgers University

S. Burcher, K.L. Jones, W.A. Peters, K. Smith, P. Thompson, C. Thornsberry
University of Tennessee

A. Engelhardt, R.L. Kozub, S. Shadrick
Tennessee Tech. University

J.C. Blackmon, C. Rasco, D. Santiago-Gonzales
Louisiana State University

J. Anderson, M. Carpenter, D. Seweryniak, S. Zhu
Argonne National University

Argonne National University

G. Wilson
UMass Lowell

N. Scielzo, R. Hughes
LLNL

B. Manning
LANL

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