Nuclear Astrophysics at TRIUMF-ISAC

@ DRAGON, TUDA, DSL, EMMA, ...

Chris Ruiz | Research Scientist | TRIUMF
“TRIUMF” Nuclear Astrophysics Group People

TRIUMF

Experiment: Barry Davids, Iris Dillmann, Reiner Krücken, Chris Ruiz
Theory: Petr Navratil

McMaster University

Prof. Alan Chen (Experiment)

University of Victoria

Prof. Falk Herwig and Dr. Pavel Denissenkov (Theory)
(+ JINA & NuGrid connection)
(+ Astronomy Research Centre)
Origin of the Elements
Origin of the Elements

- BBN & H Burning
- He Burning
- C Burning
- O Burning
- Cosmic Ray Spallation
- Classical Novae
- Supernovae

- s-process in AGB and massive stars
- r-process in supernovae, neutron star mergers?

Relative Abundance vs. Mass Number
Nucleosynthesis
What are the origins of the various groups of isotopes in the nuclear landscape?
What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
Can we use radioactivity as a diagnostic probe of stellar explosions?
Nucleosynthesis

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**Nucleosynthesis**

- **s-process** ("cold", slow neutron fusion)
- **rp-process** (hot hydrogen fusion in equilibrium with photodissociation)

- Hydrostatic H, He, C, O, Ne, & Si burning in massive stars

- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
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Nucleosynthesis

- **γ-process (photodissociation of r- & s- isotopes)**
- **s-process (“cold”, slow neutron fusion)**
- **rp-process (hot hydrogen fusion in equilibrium with photodissociation)**

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Nucleosynthesis

- **γ-process (photodissociation of r- & s- isotopes)**
- **s-process (“cold”, slow neutron fusion)**
- **rp-process (hot hydrogen fusion in equilibrium with photodissociation)**
- **r-process (hot, fast neutron fusion)**

- What are the origins of the various groups of isotopes in the nuclear landscape?
- What are the roles of nuclear reactions in stellar evolution and the energetics of stellar explosions?
- Can we use radioactivity as a diagnostic probe of stellar explosions?
Data Needs:

- Nuclear Masses
- Reaction Q-values
- $\beta$-decay lifetimes/branches
- $\gamma$-decay branches
- $\beta$-delayed n strengths
- Level energies and spin-parities
- ANC s / Spec. Factors
- Elastic scattering phaseshifts
- Level lifetimes
- Partial widths
- Cross section direct measurement

Particle Separation Energies

Effective nuclear lifetimes

Reaction Flow in Stellar Environment

Reaction cross sections
Through the lives of stars...

Research throughout the life cycles of stars

Nova
X-ray burst

Image credit: Scientific American/Malcolm Godwin

Astrophysical reactions studied at ISAC (DRAGON, TUDA, DSL)

He(α,γ)7Be
14N(p,γ)15O
40Ca(α,γ)44Ti
26mAl(p,γ)27Si
17O(α,γ)21Ne
16O(α,γ)20Ne
12C(α,γ)16O
17O(p,γ)18F
33S(p,γ)34Cl
26gAl(p,γ)27Si
18F(p,γ)19Ne
18F(p,α)15O
38K(p,γ)39Ca
18Ne(α,p)21Na
58Ni(p,γ)59Cr
23Na(α,p)26Mg

Chris Ruiz (TRIUMF)
Through the lives of stars...

Astrophysical reactions studied at ISAC (DRAGON, TUDA, DSL)

- $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$
- $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$
- $^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
- $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$
- $^{16}\text{O}(\alpha,\gamma)^{20}\text{Ne}$
- $^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$
- $^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$
- $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$
- $^{18}\text{F}(p,\alpha)^{15}\text{O}$
- $^{58}\text{Ni}(p,\gamma)^{59}\text{Cr}$
- $^{23}\text{Na}(\alpha,p)^{26}\text{Mg}$
- $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$
- $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$
- $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$
- $^{26m}\text{Al}(p,\gamma)^{27}\text{Si}$
- $^{26}\text{Mg}(p,\gamma)^{27}\text{Si}$
Observables - γ rays and grains

- Experiments intimately linked to observations via models:
  - Nuclear reactions → observations

  - Cas A Galactic 26Al: Massive stars, novae, AGB
    - 44Ti from core-collapse supernovae (e.g. Cas A, SN 1987a)
    - 26Al galaxy-wide, contributions from Type II SN, Asymptotic Giant Branch stars, O-Ne novae
    - 22Na from O-Ne novae, 511-keV flux from CO and O-Ne novae
    - Isotopic ratios from meteoric grains of pre-solar origin
Observables - γ rays and grains

- Experiments intimately linked to observations via models:
  - Nuclear reactions → observations

Cas A

Galactic $^{26}$Al: Massive stars, novae, AGB

- $^{44}$Ti from core-collapse supernovae (e.g. Cas A, SN 1987a)
- $^{26}$Al galaxy-wide, contributions from Type II SN, Asymptotic Giant Branch stars, O-Ne novae
- $^{22}$Na from O-Ne novae, 511-keV flux from CO and O-Ne novae
- Isotopic ratios from meteoric grains of pre-solar origin

INTEGRAL (& COMPTEL), NuStar etc
DRAGON: recoil separator

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Detector photons and reaction products in coincidence

Determine strength of particular nuclear reaction

DRAGON gas target

Fusion product (recoil nucleus)

Photon (gamma ray)

Beam of exotic nuclei

Hydrogen gas

DRAGON: recoil separator

Gas Target

Gamma Array

Magnetic Quads

Magnetic Dipole

Charge Slit Box

IC/PGAC Stop

MCP Start

Recoil Detectors

\[
\sqrt{\frac{\lambda_2}{M + m}} = \omega_\gamma
\]
$Y(\infty) = \frac{\lambda^2}{2} \frac{M+m}{m} \epsilon^{-1} \omega \gamma$

- Detect photons and reaction products in coincidence
- Determine strength of particular nuclear reaction
TUDA: charged particle reactions & scattering

- Direct cross-section measurements of charged particle reactions e.g. $^{18}\text{F}(p, \alpha)^{15}\text{O}$, $^{21}\text{Na}(p, \alpha)^{18}\text{Ne}$, $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$

- Elastic Scattering e.g. $^{20,21}\text{Na}(p, p)$, $^{18}\text{F}(p, p)$, $^{7}\text{Li}(^{8}\text{Li}, ^{7}\text{Li})^{8}\text{Li}$

- Indirect e.g. transfer $\rightarrow$ ANC, spectroscopy
TUDA: charged particle reactions & scattering

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DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer

Chris Ruiz (TRIUMF)

Nuclear Astrophysics

June 13, 2015 9 / 20
DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer

Doppler Shift Lifetime Facility: femtosecond nuclear lifetimes, e.g. \( ^3\text{He}(^{20}\text{Ne},^{4}\text{He})^{19}\text{Ne}^* \), \( ^3\text{He}(^{24}\text{Mg},^{4}\text{He})^{23}\text{Mg}^* \)
DSL and SHARC-TIGRESS: nuclear lifetimes, Coulex, transfer

**Doppler Shift Lifetime Facility:**
Femtosecond nuclear lifetimes, e.g. $^3\text{He}(^{20}\text{Ne},^4\text{He})^{19}\text{Ne}^*$, $^3\text{He}(^{24}\text{Mg},^4\text{He})^{23}\text{Mg}^*$

**SHARC+TIGRESS:** transfer, e.g. $^6\text{Li}(^{15}\text{O},d)^{19}\text{Ne}^*$, $^6\text{Li}(^{17}\text{O},d)^{21}\text{Ne}^*$

Diagram: 24Mg @ 75 MeV, Au 25 μm, 3He ≈ 0.1 μm, 500 μm, GRIFFIN Ge detector, 2908 → g.s.
ElectroMagnetic Mass Analyzer for structure & astrophysical reactions

- Will measure $(d, p)$, $(p, \gamma)$, $(d, n)$ and $(p, n)$ reactions
- $^{88}\text{Rb}(d, p)^{89}\text{Rb}$ for $r$-process $^{88}\text{Rb}(n, \gamma)^{89}\text{Rb}$
- $^{83}\text{Rb}(p, \gamma)^{84}\text{Sr}$ for $p$-process in core-collapse supernovae
- $^{135}\text{l}(d, p)^{136}\text{l}$ for “$i$-process”
ElectroMagnetic Mass Analyzer for structure & astrophysical reactions

- Will measure \((d, p)\), \((p, \gamma)\), \((d, n)\) and \((p, n)\) reactions
- \(^{88}\text{Rb}(d, p)^{89}\text{Rb}\) for \(r\)-process \(^{88}\text{Rb}(n, \gamma)^{89}\text{Rb}\)
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\(^{135}\text{l}(d, p)^{136}\text{l}\) for “i-process”
<table>
<thead>
<tr>
<th>Reaction</th>
<th>Motivation</th>
<th>Intensity (s(^{-1}))</th>
<th>Purity (desired:contaminant)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{21})Na((p, \gamma))(^{22})Mg</td>
<td>1.275 MeV line emission in ONe novae</td>
<td>(5 \times 10^{9})</td>
<td>100%</td>
</tr>
<tr>
<td>(^{12})C((\alpha, \gamma))(^{16})O</td>
<td>Helium burning in red giants</td>
<td>(3 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td>(^{26})Al((p, \gamma))(^{27})Si</td>
<td>Nova contribution to galactic (^{26})Al</td>
<td>(3 \times 10^{9})</td>
<td>30,000:1</td>
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<tr>
<td>(^{12})C((^{12})C, (\gamma))(^{24})Mg</td>
<td>Nuclear cluster models</td>
<td>(3 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td>(^{40})Ca((\alpha, \gamma))(^{44})Ti</td>
<td>Production of (^{44})Ti in SNII</td>
<td>(3 \times 10^{11})</td>
<td>10,000:1 - 200:1</td>
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<tr>
<td>(^{12})C((^{16})O, (\gamma))(^{28})Si</td>
<td>Nuclear cluster models</td>
<td>(3 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td>(^{23})Mg((p, \gamma))(^{24})Al</td>
<td>1.275 MeV line emission in ONe novae</td>
<td>(5 \times 10^{7})</td>
<td>1:20 - 1:1,000</td>
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<tr>
<td>(^{17})O((\alpha, \gamma))(^{21})Ne</td>
<td>Neutron poison in massive stars</td>
<td>(1 \times 10^{12})</td>
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<tr>
<td>(^{18})F((p, \gamma))(^{19})Ne</td>
<td>511 keV line emission in ONe novae</td>
<td>(2 \times 10^{6})</td>
<td>100:1</td>
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<tr>
<td>(^{33})S((p, \gamma))(^{34})Cl</td>
<td>S isotopic ratios in nova grains</td>
<td>(1 \times 10^{10})</td>
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</tr>
<tr>
<td>(^{16})O((\alpha, \gamma))(^{20})Ne</td>
<td>Stellar helium burning</td>
<td>(1 \times 10^{12})</td>
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<tr>
<td>(^{17})O((p, \gamma))(^{18})F</td>
<td>Explosive H burning in novae</td>
<td>(1 \times 10^{12})</td>
<td></td>
</tr>
<tr>
<td>(^{3})He((\alpha, \gamma))(^{7})Be</td>
<td>Solar neutrino spectrum</td>
<td>(5 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td>(^{58})Ni((p, \gamma))(^{59})Cu</td>
<td>High mass tests (p-process, XRB)</td>
<td>(6 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td>(^{26})mAl((p, \gamma))(^{27})Si</td>
<td>SNII contribution to galactic (^{26})Al</td>
<td>(2 \times 10^{5})</td>
<td>1:10,000</td>
</tr>
<tr>
<td>(^{38})K((p, \gamma))(^{39})Ca</td>
<td>Ca/K/Ar production in novae</td>
<td>(2 \times 10^{7})</td>
<td>1:1</td>
</tr>
<tr>
<td>Reaction</td>
<td>Year</td>
<td>Location</td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
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<tr>
<td>$^{13}\text{N}(p,\gamma)^{14}\text{C}$</td>
<td>1991</td>
<td>CRC (Louvain-la-Neuve)</td>
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<tr>
<td>$^{7}\text{Be}(p,\gamma)^{8}\text{B}$</td>
<td>2000,2009</td>
<td>Nabona (Naples), DRS (HRIBF)</td>
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<tr>
<td>$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$</td>
<td>2001-2003</td>
<td>DRAGON (TRIUMF)</td>
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<tr>
<td>$^{26\text{g}}\text{Al}(p,\gamma)^{27}\text{Si}$</td>
<td>2004-2005</td>
<td>DRAGON (TRIUMF)</td>
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<tr>
<td>$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$</td>
<td>2008</td>
<td>DRS (HRIBF)</td>
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<tr>
<td>$^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$</td>
<td>2009</td>
<td>DRAGON (TRIUMF)</td>
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<tr>
<td>$^{18}\text{F}(p,\gamma)^{19}\text{Ne}$</td>
<td>2011</td>
<td>DRAGON (TRIUMF)</td>
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<td>$^{26\text{m}}\text{Al}(p,\gamma)^{27}\text{Si}$</td>
<td>2012</td>
<td>DRAGON (TRIUMF)</td>
<td></td>
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<tr>
<td>$^{38}\text{K}(p,\gamma)^{39}\text{Ca}$</td>
<td>2014</td>
<td>DRAGON (TRIUMF)</td>
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</table>

- Textbook radiative capture measurement in inverse kinematics: $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$
- Weakest resonance strength ever measured using most intense RIB ever: $^{26\text{g}}\text{Al}(p,\gamma)^{27}\text{Si}$
- First measurement of radiative capture using isomeric beam: $^{26\text{m}}\text{Al}(p,\gamma)^{27}\text{Si}$
- Highest mass RIB for radiative capture: $^{38}\text{K}(p,\gamma)^{39}\text{Ca}$
Program successes: TUDA, DSL, ...

- Lowest energy measurement of $^{18}\text{F}(p, \alpha)^{19}\text{Ne}$
- Best quality RIB resonant elastic scattering data: $^{21,20}\text{Na}(p, p)^{21,20}\text{Na}$, $^{18}\text{F}(p, p)^{18}\text{F}$
- Spectroscopic quality RIB transfer data: $^{26g}\text{Al}(d, p)^{27}\text{Al}$

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- Spectroscopic quality RIB transfer data: $^{26g}\text{Al}(d, p)^{27}\text{Al}$
TUDA direct measurement of $^{23}\text{Na}(\alpha, p)^{26}\text{Mg}$ accepted for publication in Phys. Rev. Lett.†

Best founded $^{15}\text{O}^*_{6.79}\text{MeV}$ lifetime limit at DSL via $^3\text{He}(^{16}\text{O}, ^4\text{He})^{15}\text{O}^*$ for $^{14}\text{N}(p, \gamma)^{15}\text{O}$ in oldest stars*

Only absolute strength measurements of important $^{22}\text{Na}(p, \gamma)^{23}\text{Mg}$ resonances: implanted $^{22}\text{Na}$ at ISAC Implantation Station‡

Implanted $^{26}\text{Al}$ targets for $^{26}\text{Al}(^3\text{He}, t/d)$ spectroscopic studies at Orsay, Munich, Florida State§

† J.R. Tomlinson et al., Accepted for publication in Phys. Rev. Lett, June 2015


§ TRIUMF Experiments S1071/S1171
Program successes: TUDA, DSL, ...

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$^§$TRIUMF Experiments S1071/S1171
What we need

- Continued support for DRAGON program
- Redoubled support for direct & indirect reactions program (TUDA, DSL, ...)
- Continued support for EMMA, starting of experimental program
- DRAGON High Mass Upgrade (see next slides)
- LaBr$_3$ Array for $\gamma$-tagging and fast timing at DRAGON & EMMA (see next slides)
- BEAMS! → alternate production methods for most difficult astrophysics RIB of high priority, e.g. $^{15}$O, $^{18,19}$Ne, $^{30}$P, $^{44}$Ti,... → V.A.S.T evaporating liquid spallation ISOL targets e.g. salts, sulphur + advanced transport techniques
DRAGON High Mass Upgrade

- Successful experiments $^{58}\text{Ni}(p, \gamma)^{59}\text{Cu}$ and $^{76}\text{Se}(\alpha, \gamma)^{80}\text{Kr}$ show DRAGON capability far above $A<30$ design limit\footnote{A. Simon et al., Eur. Phys. J. A 49 (2013) 60; A. Simon et al., Proc. Sci. 028 (2014)}.
- Prospect of $p$-process measurement program with limited RIB and high intensity stable beam $\rightarrow$ expanding reach.
- Upgrades of electrostatics and magnet power supplies needed.

$$^{58}\text{Ni}(p, \gamma)^{59}\text{Cu}: \omega \gamma_{\exp} = 0.687(96) \text{ eV}, \omega \gamma_{\text{lit}} = 0.63(10) \text{ eV}$$
BGO $\rightarrow$ LaBr$_3$

- 30-element Bi$_4$Ge$_3$O$_{12}$ array
- $\sim$40% - 80% efficiency, multiplicity & energy dependent

---

BGO → LaBr$_3$

- 30-element Bi$_4$Ge$_3$O$_{12}$ array
- ∼40% - 80% efficiency, multiplicity & energy dependent

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BGO → LaBr$_3$

- 30-element Bi$_4$Ge$_3$O$_{12}$ array
- ~40% - 80% efficiency, multiplicity & energy dependent

$E_{\text{res}}$ to 0.5% via this method (in limit of high statistics)

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BGO $\rightarrow$ LaBr$_3$

<table>
<thead>
<tr>
<th></th>
<th>BGO</th>
<th>LaBr$_3$(Ce)</th>
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</thead>
<tbody>
<tr>
<td>Density [g·cm$^2$]</td>
<td>7.13</td>
<td>5.1</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Light Yield [photons/keV$\gamma$]</td>
<td>8-10</td>
<td>63</td>
</tr>
<tr>
<td>Decay Const [ns]</td>
<td>300</td>
<td>16</td>
</tr>
<tr>
<td>$\sigma_{662}$ [%]</td>
<td>10</td>
<td>2.9</td>
</tr>
<tr>
<td>$\sigma_{2615}$ [%]</td>
<td>$\sim$ 6.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- LaBr$_3$ $\rightarrow$ fast timing for high efficiency
- Buncher time focus at DRAGON + LaBr$_3$ $\rightarrow$ low-statistic resonance position measure
- Improved energy resolution $\rightarrow$ cascade transitions $\rightarrow$ much lower systematics
- $\gamma$-tagging at EMMA: same issues apply
Direct (DRAGON & TUDA) and Indirect (TUDA & DSL) Program (includes computational work): $380k/yr
DRAGON Upgrades: $200k one-time cost
LaBr$_3$ array for DRAGON & EMMA: $1M
Total ask $3.1M over 5 years (minimum $1.9M)
Increase Direct & Indirect program manpower (PDRA) by 2-3
V.A.S.T. Likely to cost $900k for full implementation by 2019. NSERC component (personnel $ equipment based) originally estimated at $\sim$500k

= Significant return on investment given likely program successes
The DRAGON & TUDA Collaborations:

- **TRIUMF**: Barry Davids, Iris Dillmann, Dave Hutcheon, Chris Ruiz
- **McMaster University**: Alan Chen
- **Simon Fraser University**: John D’Auria
- **University of Northern British Columbia**: Ahmed Hussein
- **Colorado School of Mines**: Uwe Greife
- **University of York**: Alison Laird, Brian Fulton
- **Michigan State University**: Ulrike Hager, Artemis Spyrou
- **Texas A&M**: Greg Christian
- **University of Edinburgh**: Tom Davinson, Alex Murphy, Marialuisa Aliotta, Phil Woods
- **University of Surrey**: G. Lotay
- **Polytechnic University of Catalunia**: Jordi José, Anuj Parikh
- **Notre Dame University**: James deBoer, Patrick O’Malley
- **Ohio University**: Carl Brune