Nuclear Astrophysics at the ISAC Radioactive Beams Facility:
Prelude for RIA

John D’Auria for the DRAGON Collaboration
RIA is intended to be next generation RB facility producing with much higher intensites and perhaps purities. A key factor in designing it properly is to know what you wish to do with it and to learn from what has been developed in the past. It is important that it be appreciated that RIA is NOT starting from scratch. The purpose of this talk is to inform you about what we are doing with ISAC, the premier RB facility today generally in various areas of science and specifically in the area of nuclear astrophysics. I will use the first successful experiment performed with DRAGON using RB as an example to illustrate what we have learned working with RB at ISAC.
Outline

- Radioactive Beams and ISAC
- Experimental Facilities at ISAC
- TUDA and DRAGON
- The $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ Reaction
  - Motivation, Experiment, Results
- Future Plans (DRAGON and ISAC)
- Concluding Remarks and Suggestions
Triumf

Canada's National Laboratory
for Particle and Nuclear Physics

Operated as a Joint Venture
Members:
The University of Alberta
The University of British Columbia
Carleton University
Simon Fraser University
The University of Victoria

Associate Members:
The University of Manitoba
McMaster University
L'Université de Montréal
Queen's University
The University of Regina
The University of Toronto

Under the Contribution from the
National Research Council of Canada
Production of Radioactive Beams

Projectile Fragmentation

ISAC

RIA

Postaccelerator

Radioactive ion beam

Experiment
The TRIUMF-ISAC Radioactive Beams Facility

- ISAC Project proposed in 1985
- ISAC Project funded in 1995
- RB Production by the ISOL Method
- RB Accelerated using LINACS (0.15 – 1.5 MeV/u)
- Two Experimental Areas (LEBT and HEBT)
- Major Milestones
  - 1998 – First RB beam ($^{38m}$K) to TRINAT
  - 2000 – First physics ($^{74}$Rb lifetime with high precision)
  - 2001 – TUDA and DRAGON perform RB experiments
  - 2002 - $8\pi$ and $\beta$-NMR perform physics
  - 2003 - TITAN and TIGRESS FUNDED
TRIUMF BEAMLINES AND EXPERIMENTAL FACILITIES
ISAC - II UNDER CONSTRUCTION
Radioactive Beams at TRIUMF
The ISOL Method

M. Dombsky TRIUMF
www.triumf.ca/people/marik/

- 500 MeV protons onto thick target
- Have used Nb, Ta, SiC, TiC, CaO, CaZrO$_3$, (ZrC)
- Intensities up to 100 $\mu$A possible (now 40 $\mu$A)
- Products diffuse out at high temperatures
- Species ionized in surface ion source;
  ECR (2003); Laser(2004)

Some Beam Intensities at Yield Station

$^{8}\text{Li}$ (Ta) $8 \times 10^8$ pps
$^{11}\text{Li}$ (Ta) $2 \times 10^4$ pps
$^{21}\text{Na}$ (SiC) $9.9 \times 10^9$ pps
$^{74}\text{Rb}$ (Nb) $1.3 \times 10^4$ pps
$^{79}\text{Rb}$ (Nb) $4.6 \times 10^9$ pps
$^{160}\text{Yb}$ (Ta) $8.4 \times 10^9$ pps
ISAC I Science Program

ISAC 1 Facilities

- DRAGON
- TUDA
- TRINAT
- GPS
- LTNO
- Beta NMR
- $8\pi$ Gamma array
- RT Collection Station
- OSAKA Systems

- Nuclear Astrophysics
- Fundamental Symmetries
- Condensed Matter Physics
- Nuclear Structure
ISAC LINACS

Energy: 0.15 – 1.5 MeV/u
Pulse Iteration: 86 ns
Masses: A < 30 amu
Highly-Segmented $4\pi$ Si Array (TUDA-II)

- Transfer Reactions in inverse kinematics with accelerated radioactive beams from ISAC-II.
Aims of Nuclear Astrophysics

Understand the origin and evolution of the chemical elements

Understand the nuclear processes responsible for energy generation

light curve of X-ray burst MXB 1728-34
The Big Picture

Astrophysical Theory
- energy balance
- mass conservation
- hydrodynamics
- radiative transport

Astrophysical Observations

Nuclear Theory
- nuclear properties
- nuclei in a plasma
- reaction rate formalism

Nuclear Experiments
- accelerator

Thermonuclear Reaction Rates

Astrophysical Model
\[ \frac{dY_i}{dt} = \sum_{j} \text{create} (Rate)_{jm} Y_j Y_m - \sum_{k} \text{destroy} (Rate)_{ik} Y_i Y_k \]

Surface, Ejected Abundances

Astrophysical Observations
Explosive Astrophysical Sites

- Novae, X-ray bursters, supernovae type 1a
- Binary system – compact object and main sequence or red giant star
- Accretion of hydrogen rich material
- Thermonuclear runaway – lots of energy
- High temperatures and short timescales
  - **Radioactive nuclei important**
Explosive Nucleosynthesis in ONeMg-Novae

Present Understanding
H rich material accumulates on surface of white Dwarf that underwent C-burning in prior life

\[ T < 0.4 \text{ GK} \]
\[ \rho \sim 10^{-1} \text{ g/cm}^3 \]

\( \{ \) too low for rp breakout

source of thermonuclear runaway: NeNa cycle

Nova Cygni
Erupted 2/92
Left 5/93  Right 6/94
Astrophysical Interest in $^{21}\text{Na}(\text{p},\gamma)^{22}\text{Mg}$

$^{21}\text{Na}(\text{p},\gamma)^{22}\text{Mg}$ Reaction plays an important role in the abundance of $^{22}\text{Na}$ in expelled material.

Presence of $^{22}\text{Na}$ can be measured through observation of 1.28 MeV decay gamma. (COMPTEL, INTEGRAL)

For Novae Her1991 and Cyg1992 only upper limits on $^{22}\text{Na}$ abundance were detected, well below expected value at this time.

Observation of 1.28 MeV gamma will constrain models of Novae

INTEGRAL
If total yield of $^{22}\text{Na}$ is understood, the carbonaceous meteoritic grains enriched in $^{22}\text{Ne}$ could be linked to nova sites.

The isotopic abundance determined from such grains would provide further constraints on nova models.

But, rate of $^{21}\text{Na}(p, \gamma)^{22}\text{Mg}$ reaction unknown; Goal of E824
Levels of $^{22}\text{Mg}$

Proton capture on $^{21}\text{Na}$ dominated by isolated narrow resonances at $T \sim 0.4$ GK.

Knowledge so far based on
* transfer reactions, e.g. (p,t)
* isospin mirror nucleus $^{22}\text{Ne}$
Basic Experimental Approach

$^{21}\text{Na} + p \rightarrow ^{22}\text{Mg} + \gamma$

Inverse kinematics

$^{21}\text{Na}$

$\gamma$

$\theta$

$^2\text{H}$

Target

Recoil Detector

$^{22}\text{Mg}$

Advantage: $\theta < \sim 1 \text{ deg}$, could accept all recoils

Challenges: Beam and recoil have $\sim$same momentum.
Rate of beam $>>>$ rate of recoils ($10^{11}$/1).
Beam is radioactive leading to background.

Requires: Intense source of radioactive $^{21}\text{Na}$ - ISAC
Efficient detection of $^{22}\text{Mg}$
Very efficient rejection of $^{21}\text{Na}$
Windowless hydrogen gas target - DRAGON
21Na(p,γ)22Mg

**GOAL:** Measure astrophysical rate at explosive stellar temperatures (Nova)

**WHY:** Clarify mechanism of nova explosion

**HOW:** Inverse kinematics using 21Na beam

**PROBLEMS:**
- Reaction governed by weak resonances
- Requires intense 21Na radioactive beam
- Requires hydrogen gas target
- Requires high beam suppression
- Intense gamma background around
DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions

Gas Target
Gamma Array
Magnetic Quads
Magnetic Dipole
Charge Slit Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
Magnetic Dipole

Final Focus Box
Magnetic Quads
Electrostatic Dipole
Quads

IC/PGAC Stop
MCP Start
Recoil Detectors
The DRAGON Gas Target

windowless, recirculating, differentially pumped

inner cell: 11 cm, 4.5 Torr
thickness: \((3.65 \pm 0.12) \times 10^{18}\) at/cm\(^2\)
DRAGON Gamma Array

30 BGO scintillator units
GEANT simulations
Experimental verifications
Eye of the DRAGON
Gas Profile Measurement

**Theory**

- Replace inner collimator by 1.5 mm
- Reduces opening holes by factor 22
- Almost no gas outside

\[ L_{\text{eff}}(6/8) = \frac{B_{\Delta}}{B} \times L_{\text{geo}}(1.5) \]

**Practice**

- \[ L_{\text{eff}} = 12.4 \pm 0.2 \text{ mm} \]
Measurement of Beam Energy

Approach:  
- Calibrate NMR probe for MD1  
- Use known narrow resonances

\[ ^{21}\text{Ne}(p,\gamma) \text{ at } E_{\text{cm}} = 258.6 \text{ keV} \]
\[ ^{20}\text{Ne}(p,\gamma) \text{ at } E_{\text{cm}} = 1112.6 \text{ keV} \]
\[ ^{24}\text{Mg} (p, \gamma) \text{ at } E_{\text{cm}} = 214.0 \text{ keV} \]
## Calibration Reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>E [keV]</th>
<th>$\omega_\gamma$ [eV] lit.</th>
<th>$\Phi$ [mrad]</th>
<th>$\omega_\gamma$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Ne}(p,\gamma)$</td>
<td>1112.6</td>
<td>1.13 +/- 0.07</td>
<td>3.8</td>
<td>0.92 +/- 0.17</td>
</tr>
<tr>
<td>$^{21}\text{Ne}(p,\gamma)$</td>
<td>258.6</td>
<td>0.0825 +/- 0.0125</td>
<td>14.9</td>
<td>0.21 +/- 0.03</td>
</tr>
<tr>
<td>$^{21}\text{Ne}(p,\gamma)$</td>
<td>731.5</td>
<td>3.95 +/- 0.79</td>
<td>9.4</td>
<td>3.85 +/- 0.49</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(p,\gamma)$</td>
<td>214.0</td>
<td>0.0127 +/- 0.009</td>
<td>5.2</td>
<td>0.0117 +/- 0.016</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(p,\gamma)$</td>
<td>420.2</td>
<td>0.0416 +/- 0.0026</td>
<td>4.0</td>
<td>0.0574 +/- 0.0087</td>
</tr>
<tr>
<td>$^{24}\text{Mg}(p,\gamma)$</td>
<td>790.4</td>
<td>0.532 +/- 0.41</td>
<td>3.3</td>
<td>0.576 +/- 0.040</td>
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</tbody>
</table>
Beam Suppression with DRAGON

![Graph showing beam suppression as a function of beam energy. The x-axis represents beam energy in keV/u, and the y-axis represents beam suppression. The graph includes data points for singles mode and coincidence mode.]
Initial Results

\( E_{\text{cm}} = 821 \text{ keV} \)

Coincidence not needed
Initial Results

$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ at $E_{\text{cm}} = 821$ keV

$\omega_\gamma = 556 \pm 77$ meV

$E = 821.3 \pm 1.9$ keV

$\Gamma = 16.1 \pm 2.8$ keV
Run #4587

215keV/u $^{21}\text{Na(p,\gamma)^{22}Mg}$ Recoils

Counts

$y$-projection

$y$-Time (\mu s)

HI-Time (\mu s)

HI-TOF (\mu s)


$^{21}\text{Na}(\rho,\gamma)^{22}\text{Mg}$

E$_{\text{beam}}$ = 220 keV/u  
E$_{\text{c.m.}}$ = 212 keV  
I($^{21}\text{Na}$) $\leq$ 2 x 10$^9$ s$^{-1}$

**BGO-DSSD coincidence**

- Prompt $\gamma$ – recoil coin.

**BGO Efficiency**
Results for ‘212’ Resonance

Thick target yield
- only mid point used

Resonance energy
\[ E_{cm} = 205.7 \pm 0.5 \text{ keV} \]

Not 212 keV

Why?

Mass of \(^{22}\text{Mg}\)
\[ = -403.2 \pm 1.3 \text{ keV} \]

Not –396.8 keV
Resonance Strength
for 5.714 MeV state

Thick target yield;

\[ Y = \frac{\lambda^2}{2} \frac{M + m}{m} \omega \gamma \left( \frac{dE}{dx} \right)^{-1} \]

\[ \omega \gamma = 1.03 \pm 0.16_{\text{stat}} \pm 0.14_{\text{sys}} \]

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<table>
<thead>
<tr>
<th>TABLE I: Summary of systematic errors.</th>
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<tbody>
<tr>
<td>Factors</td>
</tr>
<tr>
<td>---------------------------------------</td>
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<tr>
<td>BGO array efficiency (@211 keV)</td>
</tr>
<tr>
<td>Separator transmission</td>
</tr>
<tr>
<td>DSSSD efficiency</td>
</tr>
<tr>
<td>Charge state fraction</td>
</tr>
<tr>
<td>Integrated beam (@211 keV)</td>
</tr>
<tr>
<td>dE/dx (eV/(atom/cm^2))_{lab}</td>
</tr>
</tbody>
</table>
Stellar Rate for $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ Reaction

$$N_A\langle\sigma\nu\rangle = 1.54 \times 10^{11}(\mu T_9)^{-3/2} \omega \gamma \exp[-11.605 E_R/T_9]$$
Summary Report on E824

$^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$

- Received $^{21}\text{Na}$ beam ($\leq 2 \times 10^9; \sim 600$ epA)
- DRAGON operational
  - used DSSSD as focal plane detector
  - used beta activity, FC and elastics for flux
  - used BGO gamma despite high $\gamma$ bgd.
- Measured $\omega\gamma$, $\Gamma$ for resonance at $E_{\text{cm}} = 821$ keV
- Measured $\omega\gamma$ for resonance at $E_{\text{cm}} = '212'\text{ keV}$
- Measured new mass excess for $^{22}\text{Mg}$
- Preliminary results ($\omega\gamma$) from other levels
  - $E_{\text{cm}} = 336$ keV (no coincidences)
  - $E_{\text{cm}} = 461$ keV ($\omega\gamma < 0.2$ meV)
  - $E_{\text{cm}} = 545$ keV ($\omega\gamma \sim 8$ meV)
  - $E_{\text{cm}} = 747$ keV ($\omega\gamma \sim 171$ meV)
Scientific Collaborators - E824

**Simon Fraser University**
- Shawn Bishop
- John D’Auria
- Mike Lamey
- Wenjie Liu
- Chris Wrede

**TRIUMF**
- Lothar Buchmann
- Dave Hutcheon
- Alison Laird
- Art Olin
- Dave Ottewell
- Joel Rogers

**Colorado School of Mines**
- Uwe Greife
- Cybele Jewett

**McMaster University**
- Alan Chen

**University of Northern B.C.**
- Dario Gigliotti
- Ahmed Hussein

**Saha Institute of Nuclear Physics**
- Mohan Chatterjee

**Ruhr-Universitat Bochum**
- Sabine Engel
- Frank Strieder

**Yale University**
- Peter Parker
- Rachel Lewis

**University of Tokyo**
- Shigeru Kubono
- S. Mitimasa
Planned DRAGON Experiments

Radioactive Beams

\[ ^{19}\text{Ne}(p,\gamma)^{20}\text{Na} \]
hot CNO breakout; rp process

\[ ^{13}\text{N}(p,\gamma)^{14}\text{O} \]
dC hot CNO breakout

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

\[ ^{25}\text{Al}(p,\gamma)^{26}\text{Si} \]
rp process; \(^{26}\text{Al}\) production

\[ ^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne} \]
hot CNO breakout; x-ray burst

\[ ^{30}\text{P}(p,\gamma)^{31}\text{S} \]
nova mechanisms; rp process

Approved Experiments

‘ISAC II’ Experiments

\[ ^{34}\text{Ar}(p,\gamma)^{35}\text{K} \]
rp process

\[ ^{56}\text{Ni}(p,\gamma)^{57}\text{Cu} \]
rp process

\[ ^{57}\text{Cu}(p,\gamma)^{58}\text{Zn} \]
rp process

Stable Beams

\[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]

\[ ^{12}\text{C}(^{12}\text{C},\gamma)^{24}\text{Mg} \]
Planned/Proposed Experimental Facilities at ISAC (II)

ISAC II EXPERIMENTAL HALL
From SE Entry Door

123’ x 90’ x 33’ h
11000 ft²

Planned Facilities
- TIGRESS (8M CD)
- TITAN (3M CD)
- HERACLES
- ‘BIG DRAGON’
- TUDA II

ISAC II
March 7, 2003
## ISAC-II: Stage 1 - 2005

<table>
<thead>
<tr>
<th>Device</th>
<th>$E_{in}$ (MeV/u)</th>
<th>$E_{out}$ (MeV/u)</th>
<th>A/q</th>
<th>$V_{eff}$ (MV)</th>
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<tbody>
<tr>
<td>CSB</td>
<td>0.002</td>
<td>0.002</td>
<td>$\leq 150 \rightarrow \leq 30$</td>
<td>-</td>
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<tr>
<td>RFQ</td>
<td>0.002</td>
<td>0.153</td>
<td>$\leq 30$</td>
<td>4.5</td>
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<tr>
<td>IH-DTL1</td>
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<td>1.53</td>
<td>$\leq 6$</td>
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<td>SCDTL</td>
<td>0.4</td>
<td>5.7</td>
<td>6</td>
<td>25</td>
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<tr>
<td></td>
<td>0.4</td>
<td>9.8</td>
<td>3</td>
<td>25</td>
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</tbody>
</table>
### ISAC-II: Stage 2 - 2007

![Diagram of ISAC-II Stage 2](image)

<table>
<thead>
<tr>
<th>Device</th>
<th>$E_{in}$ (MeV/u)</th>
<th>$E_{out}$ (MeV/u)</th>
<th>$A/q$</th>
<th>$V_{eff}$ (MV)</th>
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<tr>
<td>CSB</td>
<td>0.002</td>
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<tr>
<td>RFQ</td>
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<td>SCDTL</td>
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<td>6.5</td>
<td>7</td>
<td>42.7</td>
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<tr>
<td></td>
<td>0.4</td>
<td>14</td>
<td>3</td>
<td>42.7</td>
</tr>
</tbody>
</table>
Concluding Remarks

- ISAC (with ISAC II) is now a premier radioactive beams facility in the world
- Experimental program has started
- Many facilities now operational
- $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$ has been measured in inverse kinematics using DRAGON
Concluding suggestions (RIA Workshop-OakRidge)

Be clear about the objectives of the facility
Bring team together with common goal
Develop detailed specifications
Ensure good communications between builders and scientists
Maintain close contact with progress
Long term support for university labs to develop techniques before RIA

**RIA needs multiple beam lines**

- ISAC is a premier radioactive beams facility
- Available as site for tests and experiments