Nuclear astrophysics with DRAGON

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TRIUMF

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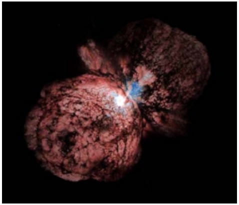
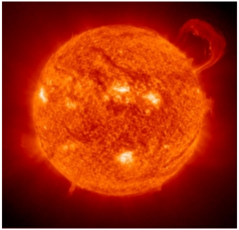
Motivation

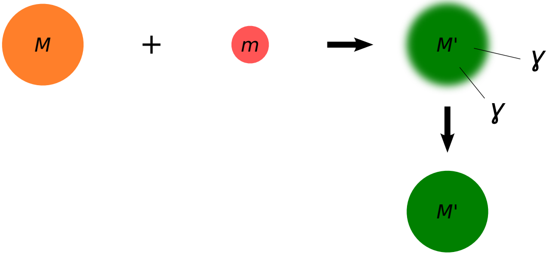




Heavy element synthesis

- Hydrogen, helium, and a small amount of lithium were formed in the Big Bang.
- Everything else formed in stellar environments, primarily explosive stellar events (novae, supernovae, X-ray bursts).
- Laboratory measurements of radiative capture rates [(p, γ), (α, γ)] are crucial inputs to models of stellar explosions.

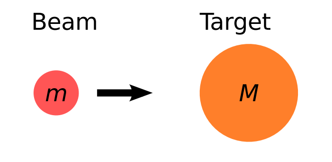
Radiative capture

- Heavy nucleus (mass M) captures a “light” nucleus (mass m).
- Product nucleus (mass M') de-excites by emitting γ rays.

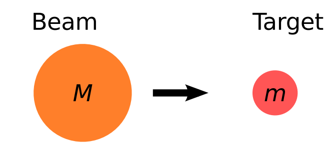


Inverse kinematics

Normal kinematics (light beam, heavy target)

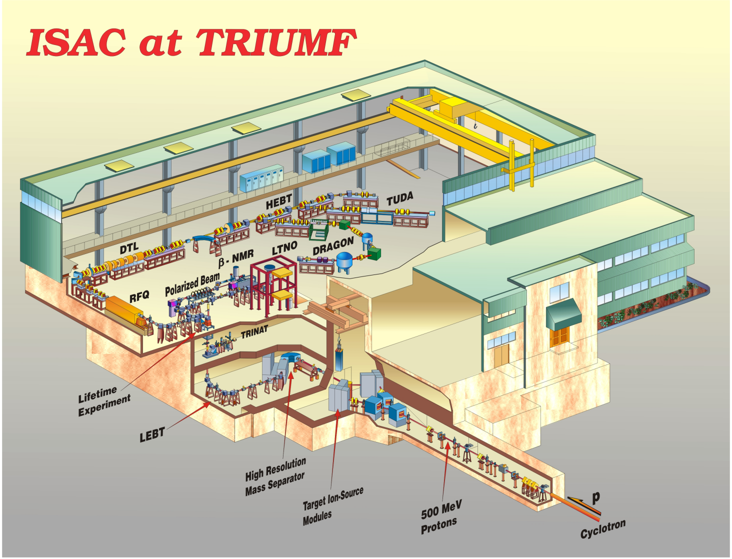


Inverse kinematics (heavy beam, light target)



Benefits

- Pure gas targets (H_2, He) - often results in simpler experiments (vs. using a solid target).
- Combined with recoil separators, one gets very high background suppression: measurements of very weak reactions possible in terrestrial labs.
- Experiments involving short-lived radioactive nuclei possible.


ISAC at TRIUMF
HEBT
TUDA
DTL
β - NMR
LTNO
DRAGON
RFQ
Polarized Beam
TRINAT
Lifetime
Experiment
LEBT
High Resolution
Mass Separator
Target Ion-Source
Modules
500 MeV
Protons
p
Cyclotron

DRAGON

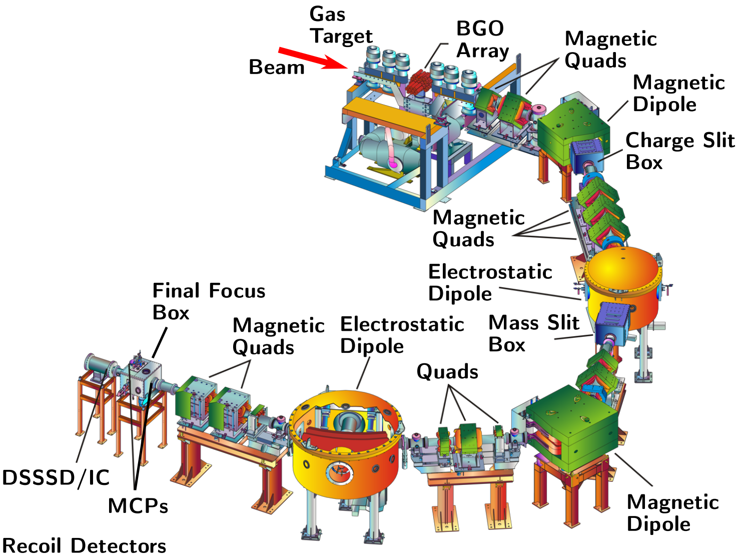
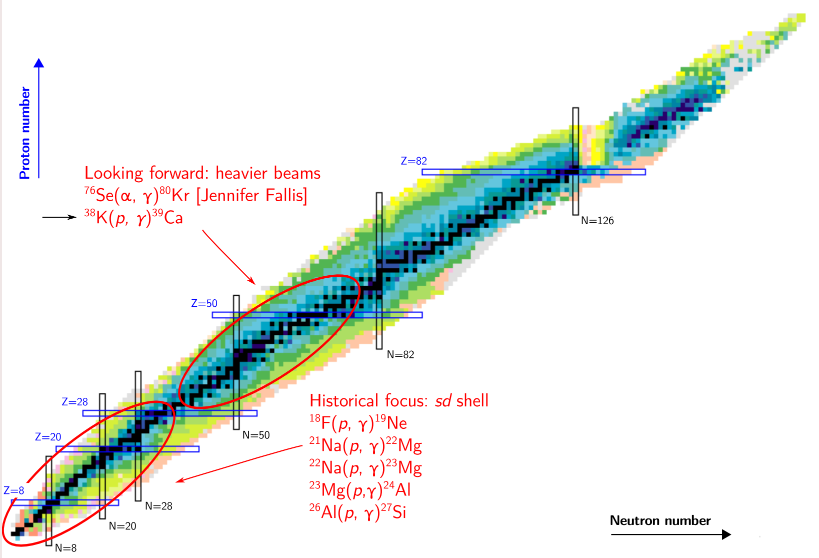

Gas Target
Beam
BGO Array
Magnetic Quads
Magnetic Dipole
Charge Slit Box
Magnetic Quads
Electrostatic Dipole
Final Focus Box
Magnetic Quads
Electrostatic Dipole
Mass Slit Box
Quads
DSSSD/IC
MCPs
Magnetic Dipole
Recoil Detectors

Chart of the nuclides



Today's talk

Present (Two weeks old)

- First direct measurement of $^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$.

Future (Next year or so)

- Approved proposal to measure $^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$ via $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$.

Present

- First direct measurement of $^{38}K(p,\gamma)^{39}Ca$

Motivation

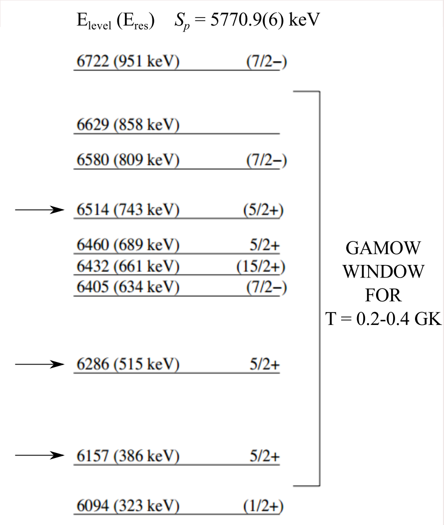
ONe Novae

- ^{38}K$(p,\gamma)^{39}$Ca one of a handful of "significant" reactions[1].
- Currently no experimental information on this reaction: "uncertainty" of 10^4.
- Varying the rate can change the respective abundances of ^{38}Ar ^{39}K, and ^{40}Ca in ejecta by factors of ~ 18, ~ 17, and ~ 24.

[1] C. Illiadis *et al.*, Astrophys. J Suppl. Ser. **142**, 105 (2002).

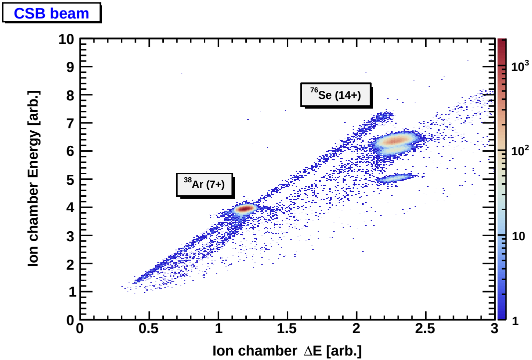
Where to measure?

^{39}Ca



- Astrophysical reaction expected to be dominated by low-ℓ capture to states within the Gamow Window.
- Focus on three resonances:
  - $E_r = 743$ keV (proof of principle).
  - $E_r = 515$ keV.
  - $E_r = 386$ keV.

The beam

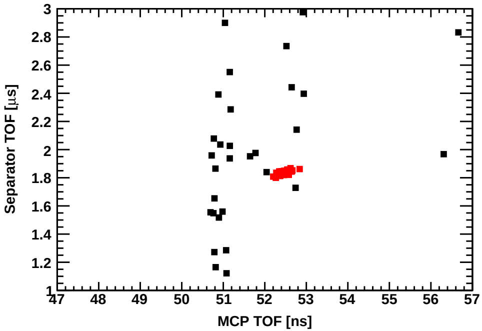


^{38}K

- Heaviest re-accelerated RIB ever sent to ISAC-I.
- Requires use of new TRIUMF charge state booster (first time in ICAC-I).
- CSB contaminants: ^{38}Ar, ^{76}Se

$E_r = 743$ keV: PID

$E_r = 743$ keV

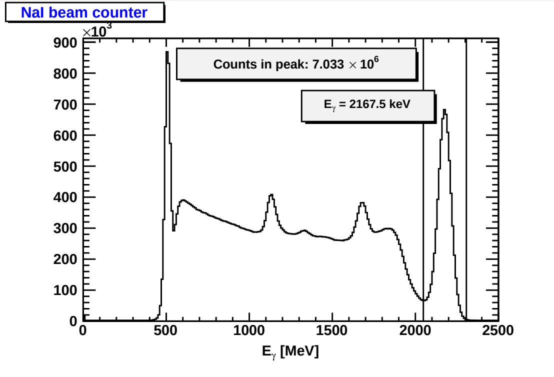


Recoils

- Clear recoil signal in separator vs. MCP TOF.
- 27 candidate recoils in preliminary analysis.

$E_r = 743$ keV: Beam normalization

$E_r = 743$ keV



Integrated beam current

- Detect γ rays from decay of implanted ^{38}K: photopeak efficiency $\simeq 4.94 \times 10^{-6}$, charge state fracion $\sim 30\%$.
- Total ^{38}K on target: 4.7×10^{12} $(4.1 \times 10^{7}$ pps).

$E_r = 743$ keV: Strength

Resonance strength

$$\omega\gamma = \frac{2Y\epsilon}{\lambda_{cm}^2}\frac{m}{m+M}$$

Yield Y

- 27 recoils, 50% BGO efficiency, 76% recoil detection efficiency, 30% CSF, 4.7×10^{12} beam on target.

$$5.0 \times 10^{-11}$$

Stopping power ϵ

- From target pressure vs. beam energy measurements.

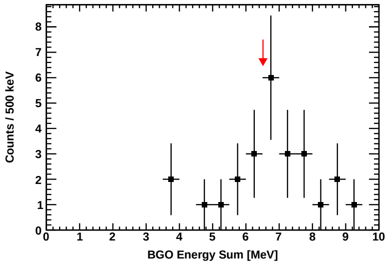
$$144 \text{ eV cm}^2 / \ 10^{15} \text{ atom}$$

Result [preliminary]

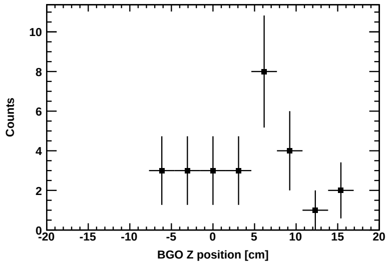
$$\omega\gamma = 30 \text{ meV}$$

$E_r = 743$ keV: γ Rays

γ-Ray energies



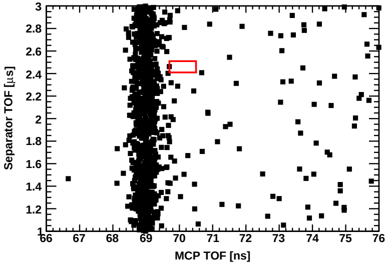
γ-Ray z positions



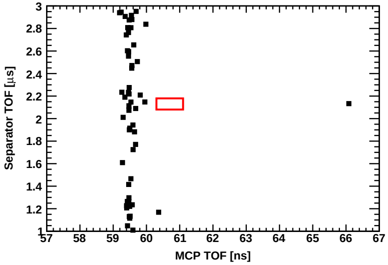
- Sum of γ-ray energies matches the Q value of the reaction (6.514 MeV).
- BGO z position indicates resonance is downstream in the target: determination of resonance energy should be possible.

Lower resonances

$E_r = 386$ keV



$E_r = 515$ keV



- No indication of recoils in $E_r = 386$ keV, 515 keV measurements.

Lower resonances: Upper limits

Resonance strength

$$\omega\gamma = \frac{2Y\epsilon}{\lambda_{cm}^2}\frac{m}{m+M}$$

Number of recoils (both cases)

- Feldman-Cousins upper limit: 1.29 counts (zero signal, zero b.g.).
- Efficiency: 50% BGO, 76% separator, 30% CSF.
- $N_r \leq 11.3$ recoils.

$E_r = 386$ keV

- 6.0×10^{12} ^{38}K on target:
  $Y \leq 1.9 \times 10^{-12}$
- $\epsilon = 135$ eV cm^2/ 10^{15} atom.
- $\omega\gamma \leq 640$ μeV.

$E_r = 515$ keV

- 1.4×10^{12} ^{38}K on target:
  $Y \leq 7.8 \times 10^{-12}$
- $\epsilon = 139$ eV cm^2/ 10^{15} atom.
- $\omega\gamma \leq 3.4$ meV.

$^{38}K(p,\gamma)^{39}Ca$

- Weak strengths of lower-lying resonances suggests lower astrophysical reaction rate.
- Is $^{38}K(p,\gamma)^{39}Ca$ a possible endpoint for nucleosynthesis in ONe novae?
- Collaboration with modelers will be necessary to discern the real consequence of the measurement.

Future

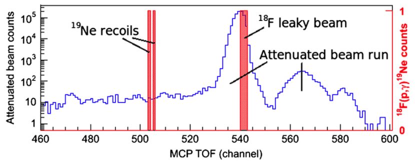
- ^{18}F(p,γ)^{19}Ne via ^{15}O(α,γ)^{19}Ne

^{18}F

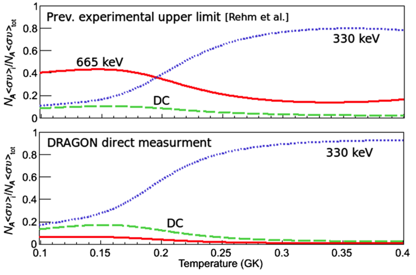
- Important in classical novae.
- Half life of 1.8 hours, source of 511 keV γ rays observed in satellite telescopes.
- Production (and destruction) of ^{18}F must be well understood: need experimental constraints on $^{18}F(p,\gamma)^{19}Ne$.

Previous DRAGON measurement

Recoil ID



Consequences

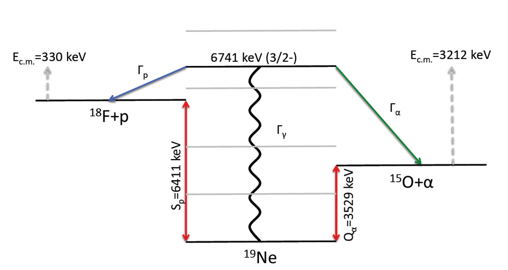


- DRAGON previously measured the strength of the 665 keV resonance.[1]
- Two recoils observed in around one week of beam time $\Rightarrow \omega\gamma = 19^{+45}_{-16}$ meV.
- 330 keV resonance completely dominates the rate at nova temperatures.
- Would measure $E_r = 330$ keV directly, except ^{18}F beam intensities are too low.

[1] C. Akers *et al.*, Phys. Rev. Lett. **110**, 262502 (2013).

$E_r = 330$ keV: Technique

^{19}Ne



Relating resonance strengths

$$
\begin{aligned}
(\omega\gamma)_{^{18}\mathrm{F}+p} &= \frac{(2\ell_{^{15}\mathrm{O}}+1)(2\ell_{\alpha}+1)}{(2\ell_{^{18}\mathrm{F}}+1)(2\ell_{p}+1)} \times \frac{\Gamma_p}{\Gamma_\alpha} (\omega\gamma)_{^{15}\mathrm{O}+\alpha} \\
&= \frac{\Gamma_p}{3\Gamma_\alpha} (\omega\gamma)_{^{15}\mathrm{O}+\alpha}
\end{aligned}
$$

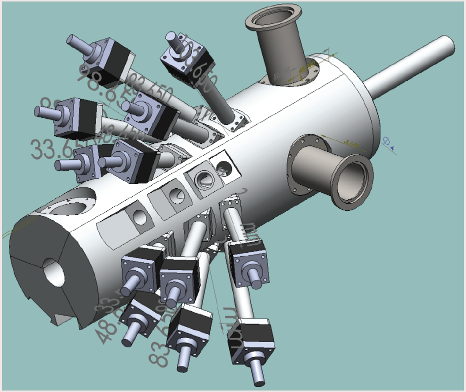
Proposed experiments

Plan

- Measure $(\omega\gamma)_{^{15}\mathrm{O}+\alpha}$ and Γ_α at DRAGON: deduce $(\omega\gamma)_{^{18}\mathrm{F}+p}$ (Γ_p already known).
- $(\omega\gamma)_{^{15}\mathrm{O}+\alpha}$: standard DRAGON measurement, possible with $\sim 1 \times 10^6$ pps ^{15}O.
- Measure Γ_α by $^{15}\mathrm{O}(\alpha,\alpha)^{15}\mathrm{O}$ elastic scattering.

Elastic scattering at DRAGON

SPIKE (SONIC?? PORCUPINE??)



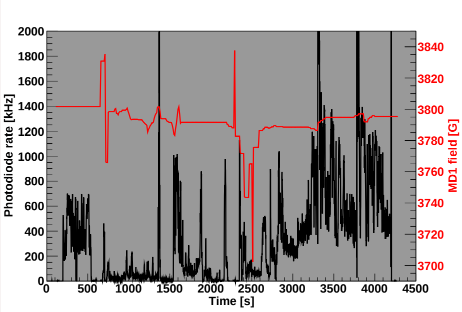
- SPIKE (Scattering of Protons in Inverse Kinematics) chamber designed for elastic scattering.
- Commissioning scheduled for August, 2014.

Photodiodes

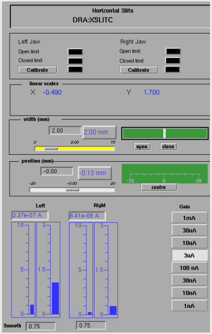
- ^{15}O current of 1×10^6 pps is too low to read on Faraday cups and slits.
- Send attenuated beam directly into 1×1 cm^2 photodiode detectors as an alternative:
- Three detectors in total:
  1. Upstream of gas target.
  2. Downstream of gas target.
  3. Downstream of first charge slit.
- Allows for gas target transmission optimization and beam energy measurement; scaling of full DRAGON tune past MD1.

Photodiode energy measurement

Centering on charge slits



Result



- With slits closed to 2 mm, maximize rate on the photodiode.
- Energy measurement 0.3% off compared with standard tuning.
- Tests measuring 3.212 MeV resonance in $^{15}N(\alpha,\gamma)^{19}F$ indicate $\sim$ 10% systematic error when tuning with PDs (mainly due to transmission).

Collaborators

TRIUMF

- **Chris Ruiz**, Jennifer Fallis, Dave Hutcheon, Alex Rojas, Barry Davids, Charlie Akers, Lothar Buchmann

University of Surrey

- **Gavin Lotay**

University of York

- Alison Laird, Charlie Akers, Brian Fulton

Colorado School of Mines

- Ulrike Hager, Devin Connol, Adam Mahl, Uwe Greife

McMaster University

- Alan Chen, Devin Burke

Michigan State University

- Artemis Spyrou, Steve Quinn, Anna Simon