∂TRIUMF



Direct Measurements of (α,n) Reactions Using the DEMAND Array with DRAGON

Ben Reed

TRIUMF & Saint Mary's University

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Discovery, accelerated



Land Acknowledgement

MUSQUEAM

A LIVING CULTURE

TRIUMF is located on the traditional, ancestral, and unceded territory of the x^wməθk^wəy'əm (Musqueam) people, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.



RIUMF







Η			Big Bang				Cosmic Ray Spallation									He	
1			Low Mass Stars				Exploding Massive Stars				P	C	M	0	E	2	
3	4	Ex	Exploding White Dwarfs				Exploding Neutron Stars?				5	6	7	8	9	10	
Na 11	Mg 12		Nuclear Decay			Not Naturally Occuring				Al 13	Si 14	P 15	S 16	Cl 17	Ar 18		
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	 53	Xe 54
Cs 55	Ba 56	7	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	TI 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
Fr 87	Ra 88		Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	Rg 111	Cn 112	Nh 113	FI 114	Mc 115	Lv 116	Ts 117	Og 118
			La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
		L	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103













Hydrodynamic Simulations

Simulations of stellar environments depend on:

- Nuclear reaction rates and decay times
- Stellar masses
- Initial compositions
- Fluid dynamics and mixing

Able to predict properties such as:

- Composition
- Light curves
- Reoccurrence times
- Ejected & accreted mass
- Peak temperature

Results of simulations are highly dependent on the input reaction rates

Therefore, **better experimental knowledge of reaction rates is required**!



Reaction network in the Si-Ca region for classical novae (J. José, Nucl. Phys. A, 2006)

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Change factor in final isotopic abundance of an ONe classical nova (C. Iliadis, Astrophys. J. Sup. Series, 2002)

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X-ray burst light curve (R. H. Cybert, Astrophys. J., 2016)

The r-Process

The **r-process** is expected to produce **~50%** of all elements in the galaxy

Occurs in neutron star mergers

There is evidence that there **must be other sites:**

1. Stars older than neutron stars contain r-process nuclei

2. Some stars have an enhanced abundance of light r-process nuclei



The Weak r-Process

Core-collapse supernovae have been proposed as a potential site for the **weak r-process**

Nuclei up to Ag are produced via a series of (α,*n*) **reactions**

A sensitivity study by Bliss *et al*. identified **45 (α,***n***) reactions** that are **important for the weak r-process** (J. Bliss, Phys. Rev. C, 2020)



Resonant (a,n) Reactions

Fusion of a heavy nucleus and an α particle followed by the emission of a neutron

$$X + \alpha \rightarrow C^* \rightarrow Y + n$$

Reaction proceeds through an **excited state** in a **compound nucleus**

If the energy of the nuclei is equal to the resonance energy, there is a **massive increase in the cross section**



Direct Measurements

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_i (\omega \gamma)_i \exp\left(-\frac{E_{r,i}}{kT}\right)$$

To determine the reaction rate, we need to know:

- 1. Resonance Energy (E_r)
- 2. Resonance strength ($\omega\gamma$)

The **resonance strength** can be calculated using: $2 m \dots dE$

$$\omega \gamma = \frac{2}{\lambda^2} \frac{m}{M+m} Y \frac{dL}{dx}$$

Reaction yield is determined from number of detected coincidences:

$$Y = \frac{N_{coinc}^{det}}{N_b \eta}$$

The energy which gives the maximum yield gives the resonance energy



The DEMAND Array

DEMAND = Direct Experimental Measurements of Astrophysical reactions using Neutron Detectors

Organic glass scintillator (OGS) detectors produced by BlueShift Optics

OGS detectors have excellent **pulse shape discrimination**, light **output** and **timing** properties







$^{22}Ne(\alpha,n)^{25}Mg$ - a proof of principle

Strong resonances have already been **identified** in a measurement performed in **normal kinematics** (Jaeger, 2001)

Resonance at $E_r = 1.43$ MeV has a measured resonance strength of 1.067 eV, making it an ideal test case

Main source of neutrons for the s-process







TRIUMF & DRAGON





Detector of Recoils And Gammas Of Nuclear Reactions



DRAGON – Gas Target

Wrapped OGS Gas Targe BCM_ MD1 DEMAND Beam Detector Focal Plane Q Charge Slits FCCH Array BGO Array Q1 Q2 SI SX1 Q3 ⁴He Gas Target Q4 DRAGON ED1 = quadrupole Focal Plane M Mass Slits Q MD = magnetic dipole = electric dipole ED FCM SX = sextupole **S**2 FC = Faraday cup BCM = beam monitor 22Ne Beam = horizontal & vertical steerer S SX3 BCM MD2 Q8 SX4 Focal Plane F Final Slits Q10Q9 \$4 FCF BGO PMT Array BCN ED2 End Detector lm

DRAGON – DEMAND Array

DRAGON – Optics





Electric and magnetic dipoles behave like prisms

Electric dipoles provide E/Q separation

Magnetic dipoles provide p/Q separation

Can select recoils based on their mass, charge and energy

DRAGON – Optics





Quadrupole and sextuple magnets focus the recoils back into a beam

DRAGON – Microchannel Plates (MCPs)





Primarily provide **timing** information but can also give position and number of recoils





<u>Key</u>

 $\Delta E \propto mZ^2/E$

Results: Recoil ID



Results: Recoil ID



Results: Pulse Shape Discrimination



$$Y = \frac{N_{coinc}^{det}}{N_b \eta}$$





	Efficiency	Source	Value
$\begin{array}{c} 1.00 \\ 0.05 \\ \hline \\ \hline \\ \hline \\ \hline \\ \hline \\ \hline \\ \\ \\ \hline \\ \hline \\ \\ \hline \\ \hline \\ \\ \\ \hline \hline \\ \hline \hline \\ \hline \\ \hline \hline \\ \hline \\ \hline \\ \hline \hline \\ \hline \\ \hline \hline \hline \\ \hline \hline \hline \\ \hline \hline \hline \\ \hline \hline \hline \\ \hline \hline \\ \hline \hline \hline \hline \\ \hline \hline \hline \\ \hline \hline \hline \hline \\ \hline \hline \hline \hline \\ \hline \hline \hline \hline \hline \\ \hline \hline \hline \hline \hline \hline \hline \\ \hline \hline$	Neutron Detection	Simulation	0.2%*
$\begin{array}{c} \hline 0 & 0.25 \\ 0 & 0.00 \\ 0 & 0 & 0.25 \\ 0 & 0.00 \\ \hline 0 & 0 & 0.25 \\ \hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0.25 \\ \hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0.25 \\ \hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0.25 \\ \hline 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 \\ \hline 0 \\ \hline 0 & 0 \\ \hline 0$	Charge State Fraction	Experimentally measured	40%*
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Separator Transmission	Simulation	4%*
$\sum_{\substack{0.00\\0.25\\0.50\\0.25\\0.50\\0.25\\0.50\\0.75\\1.00}$	MCP Transmission	Source measurement	76.5%
Energy [MeVee] Energy [MeVee] $Y = \frac{N_b n_b}{N_b n_b}$	MCP Detection	Attenuated beam	93.7%
	IC Detection	Attenuated beam	67.7%
H ₂ /He gas cell Collimator	Live time	Recorded during experiment	97.3%
Elastic monitor detectors Fill tube from recycling Feedthru connectors	*Preliminary values – cal	culations to be finalized	

	Efficiency	Source	Value
$\begin{array}{c} 1.00 \\ 0.075 \\ \hline g \\ 0.50 \\ \hline 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 $	Neutron Detection	Simulation	0.2%*
$\begin{array}{c} \hline 0 & 0.25 \\ 0 & 0.00 \\ 0 & 0.00 \\ 0 & 0.25 \\ 0 & 0.00 \\ 0 & 0.00 \\ 0 & 0.25 \\ 0 & 0.00 \\ 0 & 0.00 \\ 0 & 0.25 \\ 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0.00 \\ 0 & 0 & 0 & 0.00 \\ 0 & 0 & 0 & 0.00 \\ 0 & 0 & 0 & 0.00 \\ 0 & 0 & 0 & 0.00 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 &$	Charge State Fraction	Experimentally measured	40%*
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	Separator Transmission	Simulation	4%*
$\begin{bmatrix} 0.25 \\ 0.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 10^{\circ} \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 1.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 0.00 \\ 0.75 \\ 0.00 \\ 0.00 \\ 0.25 \\ 0.50 \\ 0.75 \\ 0.00 \\ 0.0$	MCP Transmission	Source measurement	76.5%
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$\frac{dE}{dx} \rightarrow$	Preliminary resonance Close agree valu	r measuremer e strength of 1 ement with lite ue (1.067 eV)!	nt of the .1 eV erature
	Efficient Neutron Dete Charge St Fraction Separato Transmiss MCP Transm MCP Detect IC Detect Live time *Preliminary val	Efficiency Neutron Detection Charge State E Fraction Separator Transmission MCP Transmission MCP Detection MCP Detection MCP Detection MCP Detection MCP Detection Att Live time *Preliminary values – calculation Close agree Value	EfficiencySourceNeutron DetectionSimulationCharge StateExperimentally measuredFractionmeasuredSeparatorSimulationTransmissionSource measurementMCP TransmissionSource measurementMCP DetectionAttenuated beamIC DetectionAttenuated beamLive timeRecorded during experiment*Preliminary values – calculations to be finalized MEE dxClose agreement with lited value (1.067 eV)!

Conclusions

The **DEMAND** array has been developed to **directly study** (α,*n*) reactions which are important to both the weak r-process and s-process

Performed a proof-of-principal study of the **1.43 MeV resonance in** ²²**Ne(α,***n***)** and preliminary results show good agreement with the literature values

Need to **finalize charge state fraction**, **neutron detection efficiency** and **separator transmission**

Experiment to study the **astrophysical dominant resonance** in ${}^{22}Ne(\alpha,n)$ has been **approved** at TRIUMF and will hopefully be scheduled

Thank you! Merci!

RIUMF

Chris Ruiz Dave Hutcheon Alex Katrusiak Annika Lennarz Mallory Loria Louis Wagner



Greg Christian



Science and Technology Facilities Council



Gavin Lotay Gee Bartram Dan Doherty Jack Henderson Joey O'Neill Connor O'Shea Charlie Paxman Matt Williams





Pulse Shape Discrimination

v



Nuclear Reactions



Resonant Reaction Rates

$$r = \frac{1}{1 + \delta_{aX}} N_a N_X \langle \sigma v \rangle$$

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \sum_{i} (\omega \gamma)_i \exp\left(-\frac{E_{r,i}}{kT}\right)$$

Resonance strength $\omega\gamma$ is proportional to the cross-section at the resonance energy

Organic Glass Scintillator (OGS)

OGS is a scintillator material made by BlueShift Optics

The chemical composition is a 90:10 mixture of bis(9,9dimethyl-9H-flouren-2-yl)(dismethyl)silane: tris(9,9dimethyl-9H-flouren-2-yl)(methyl)silane along with 0.2 wt. % of 1,4-Bis(2-methlystyryl)benzane

OGS detectors have excellent **PSD**, light output and timing properties



An OGS cube scintillating under UV radiation



T. A. Laplace, J. Inst., 2020

What is Next?

The $E_x = 11.319$ keV resonance is predicted to **dominate** the reaction rate at astrophysical temperatures

There are **large discrepancies** in previous attempts to measure the **resonance strength**

An experiment to **directly measure the resonance strength** of this state **using DRAGON** has been approved



Contributions to the $^{22}Ne(\alpha,n)$ reaction rate (S. Ota, Phys. Lett. B, 2020)

