THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

TUNL

Thermonuclear Reaction Rate of ^{17}O(p,γ)^{18}F

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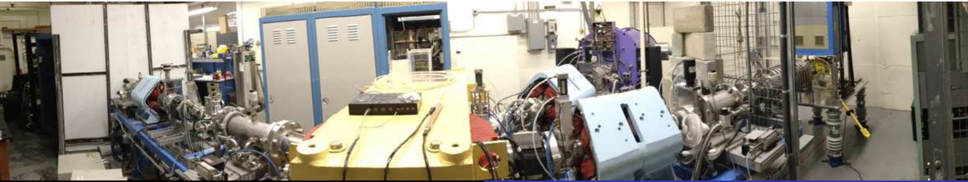
25 June 2013

DOE SSGF Annual Program Review 2013

Inn and Spa at Loretto, Santa Fe, NM



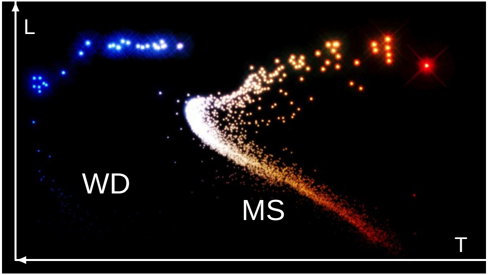
Summary

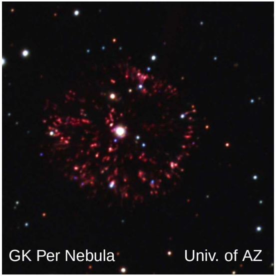
- Motivation
  - Classical novae
  - $^{17}O(p,\gamma)^{18}F$
  - Direct capture
- Experiment
  - Previous measurements
  - Preliminary calculations
  - Experimental projections
  - Progress
- Conclusion

Artist's interpretation of nova...

Classical Novae

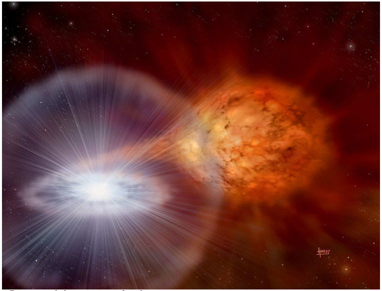
- WD accretes H-rich matter from binary companion
  - Often CO white dwarf (progenitor $\leq$ 9$-$10 $M_\odot$)
- Thermonuclear explosion of H-rich matter
- Only SN and γ-ray bursts exceed in energy
- Overlap of chemistry, physics, computer science





Classical Novae

- Mass transfer by Roche Lobe overflow
- Accretion disk (if weak magnetic field)
- Accreted layer electron degenerate
  - Heated by compression & reactions
  - P does not depend on T
  - thermonuclear runaway (TNR)
- 35 ± 11 per year in Galaxy
- Binary system *not* disrupted
  - Periodic: $10^4 - 10^5$ years



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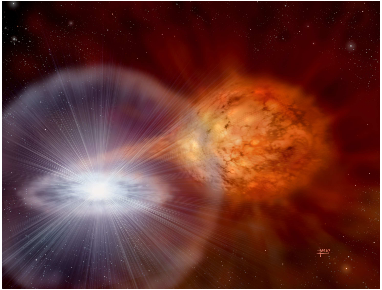
Classical Novae

- Ejecta reveals underlying WD properties
  - TNR evolution, peak temperature, expansion time
  - Constrain explosion burning models
  - Constrain evolutionary models
  - Mixing outer core to envelope $\rightarrow$ abundances
    - Shear mixing
    - Elemental diffusion



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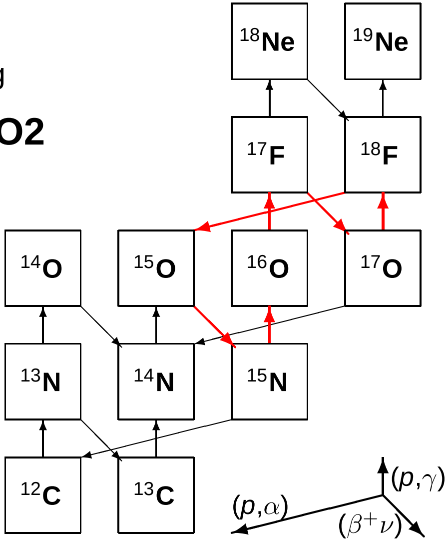
CNO Cycle

- Explosive hydrogen burning
  - During nova: **Hot CNO2**
- CNO not at equilibrium
- β^+-unstable nuclei
  - Convection to surface
  - (p,γ), (p,α) preserve
  - Catalyze outburst



Major Nova Products

- $\approx$1/3000th Galactic dust and gas
- Most significant source of:

17 O	13 C	15 N
O	**C**	**N**
Oxygen	**Carbon**	**Nitrogen**
16.999	13.003	15.000
8 9	6 7	7 8

  - Rarest oxygen isotope
    - $^{17}\mathrm{O}/^{16}\mathrm{O}$ = 0.038% [16]
    - $\mathrm{H_2}^{17}\mathrm{O}$ = $2535 per gram
  - CN are primary source

β^+-Unstable Nuclei

- 511 keV detection constrain models
- Detect before optical frequencies visible
- Temperature insensitive
- Slower than CNO

14 **O** **Oxygen** 14.009 8 6

15 **O** **Oxygen** 15.003 8 7

17 **F** **Fluorine** 17.002 9 8

18 **F** **Fluorine** 18.001 9 9

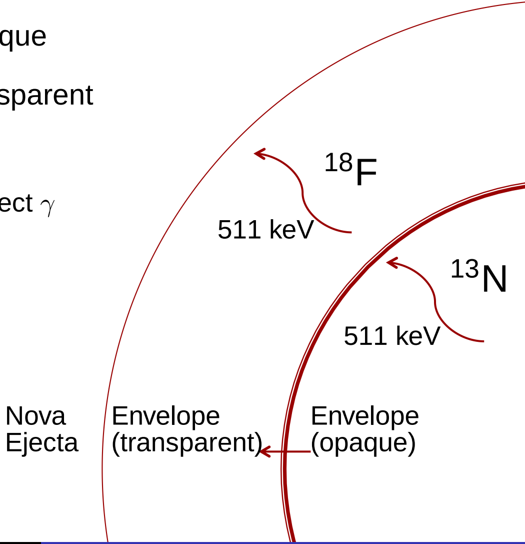
$t_{1/2}$ = 110 min

13 **N** **Nitrogen** 13.006 7 6

$t_{1/2}$ = 598 sec

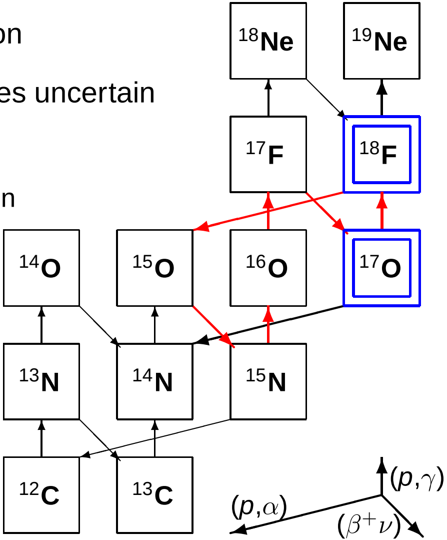
^{18}F Importance

- ^{13}N β^+ decay while opaque
- ^{18}F β^+ decay while transparent
  - Drives nova ejecta
  - INTEGRAL could detect γ



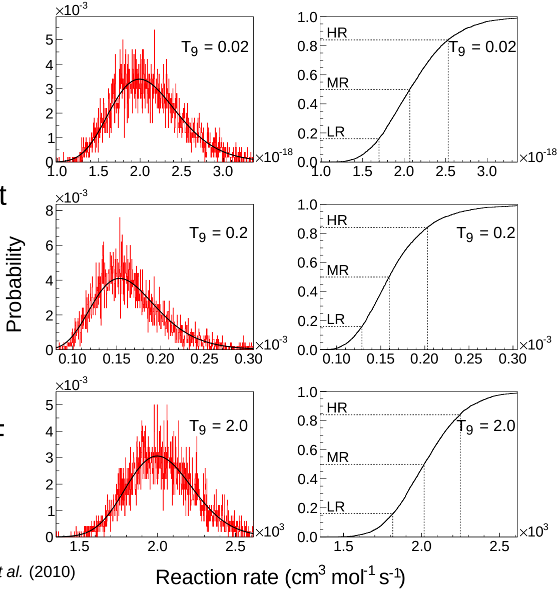
^{18}F Importance

- ^{18}F key to nova phenomenon
- Thermonuclear reaction rates uncertain
  - $^{17}O(p,\gamma)^{18}F$ creates ^{18}F
  - Measure DC cross section
    - Improve uncertainty
  - Affects ^{17}O and ^{18}F
  - Explosive H-burning



Reaction Rates

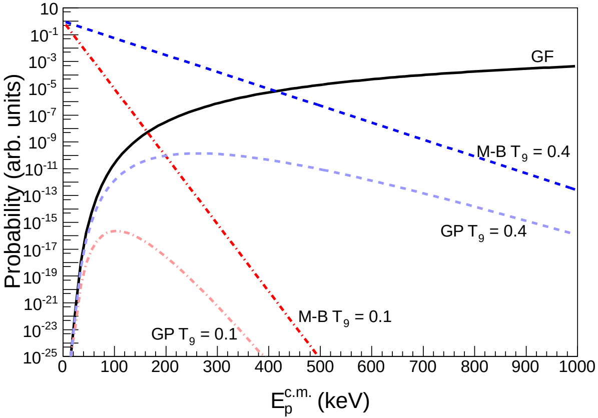
- Statistically meaningful
- Physically motivated
- PDFs assigned to MC input
- Input: exp. strengths
- Input: partial widths
- Output consistent with PDF



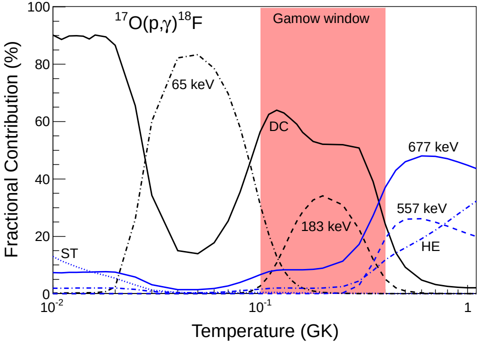
† Computed with $^{17}O(p,\gamma)^{18}F$ input from C. Iliadis *et al.* (2010)

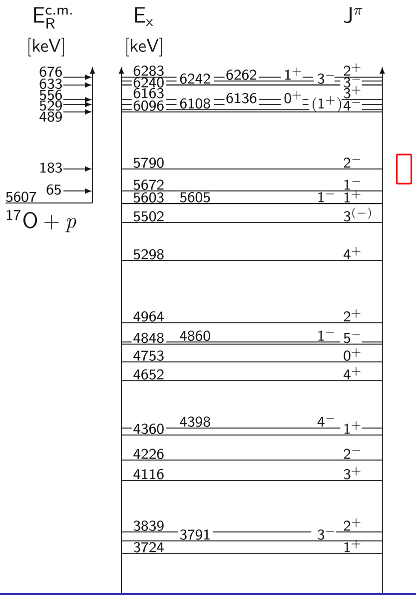
$^{17}O(p,\gamma)^{18}F$ Gamow Window

- Temperature region reactions contribute to rate
- T_{CN} = 100–400 MK $\rightarrow$ E_0 = 103–261 keV



Rate Contributions





- DC dominates rate
- $Q_{p\gamma}$ = 5607.1$\pm$ 0.5 keV

Direct Capture

- Proton *directly* captured from scattering to bound state
- Nuclear *exterior* more important than *interior*
- No compound nucleus formed
- γ-ray emission

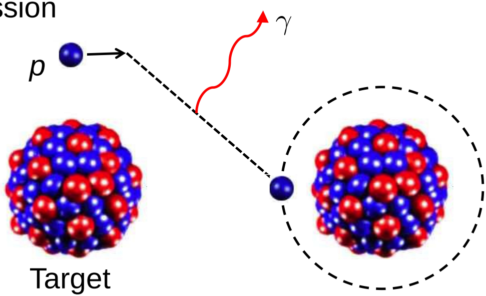


Figure based on C. E. Rolfs and W. S. Rodney, "Cauldrons in the Cosmos" (Univ. Chicago Press, 1988).

Previous ^{17}O(p,γ)^{18}F DC Measurements

^{17}O(p,γ)^{18}F Direct Capture Measurements

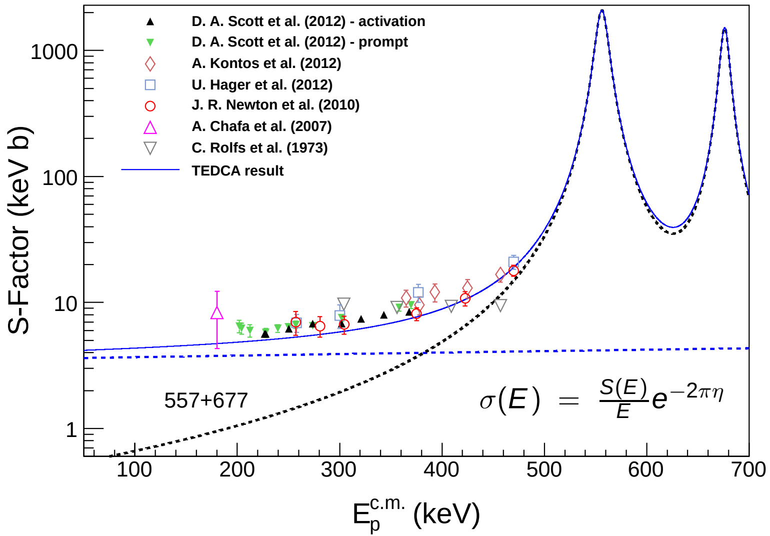
Group	Facility	Accelerator	E_p^{lab} (keV)	I (μA)
C. Rolfs (1973)†	University Toronto	1MV JN Van de Graaff	270 – 440	120
	McMaster University	3MV JN Van de Graaff	880 – 1780	150 – 200
C. Fox *et al.* (2005)†	LENA – TUNL	1MV JN Van de Graaff	180 – 540	100
A. Chafa *et al.* (2005)‡	CSNSM Orsay	Electrostatic PAPAP	< 250	≈ 70
J. R. Newton *et al.* (2010)†	LENA – TUNL	1MV JN Van de Graaff	275 – 500	75
U. Hager *et al.* (2012)∗	TRIUMF	DRAGON	260 – 505	—
A. Kontos *et al.* (2012)†	NSL – Univ. Notre Dame	1MV JN Van de Graaff	365 – 700	20 – 40
		4MV JN Van de Graaff	600 – 1800	20 – 40
D. A. Scott *et al.* (2012)†‡	LUNA – Gran Sasso	400 kV LUNA II	212 – 392	200

† prompt γ

‡ activation

∗ inverse kinematics

Previous $^{17}O(p,\gamma)^{18}F$ S-factor

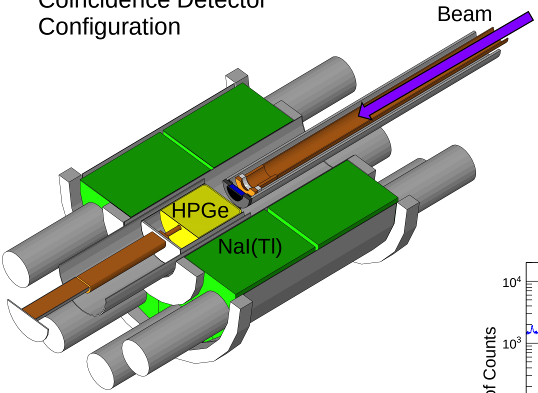


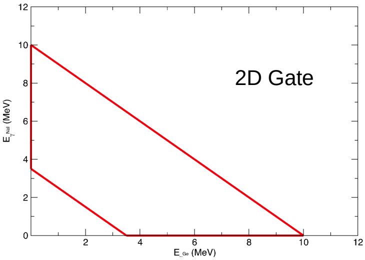
Direct Capture Calculations

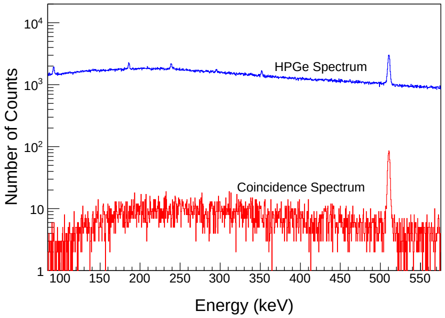
- TEDCA
  - Nuclear cross section calculator (Krauss *et al.*, 1992)
  - Potentials used to calculate DC contribution
- Zero scattering potential used
- Spectroscopic factors (C^2S) from literature
  - Polsky *et al.* (1969), Landre *et al.* (1989), Kontos *et al.* (2012)
- TEDCA cross sections $\rightarrow$ DC branching ratios
- GEANT4 simulations of DC γ-cascade

$\gamma\gamma$-Coincidence

Coincidence Detector Configuration

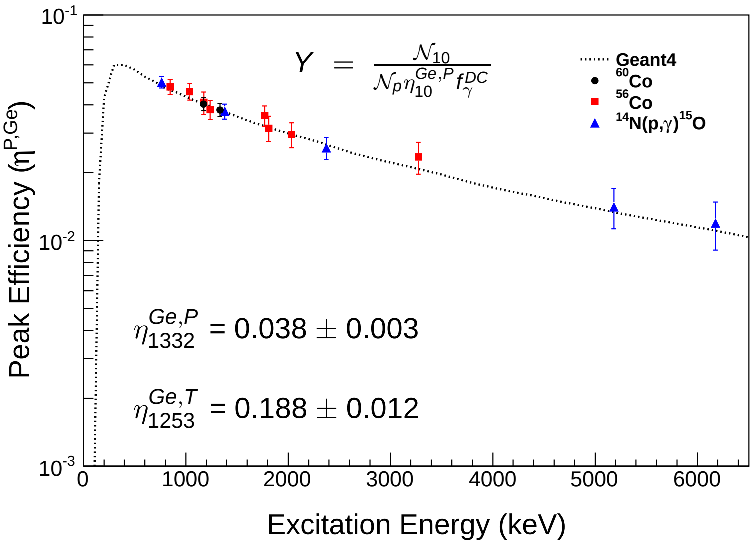




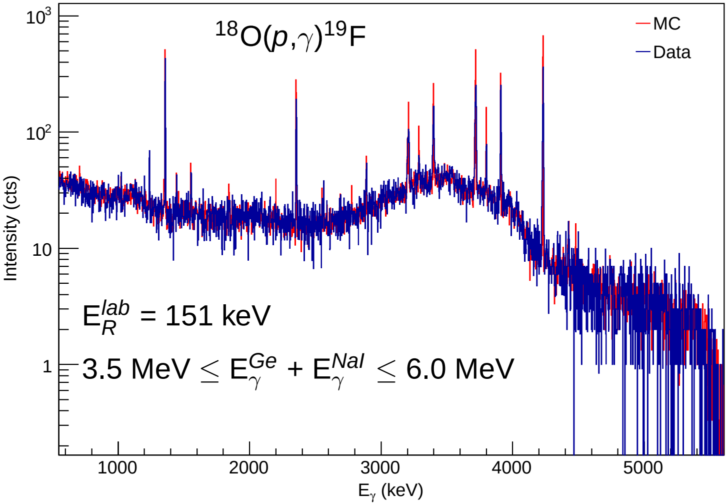


† Detector drawing courtesy of C. Howard

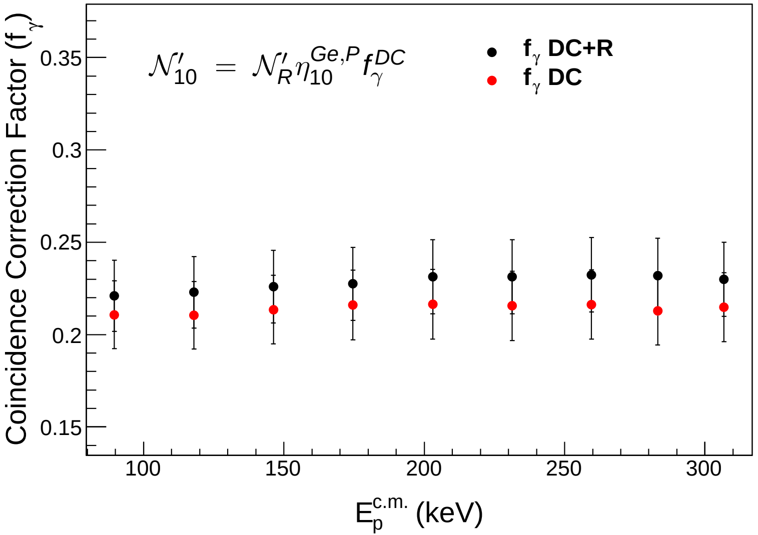
HPGe Peak Efficiency



Coincidence: MC vs. Data



Coincidence Correction Factor



Monte Carlo Experimental Estimates

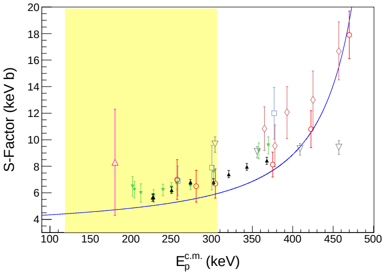
- Monte Carlo code written to estimate Q, t_{exp}
- Code solves:

$$Y = \frac{\mathcal{N}_{10}}{\mathcal{N}_p \eta_{10}^{Ge,P} f_\gamma^{DC}} = \int_{E_p^{c.m.}-\Delta E}^{E_p^{c.m.}} \frac{\sigma^{DC}(E)}{\epsilon_{eff}} dE$$

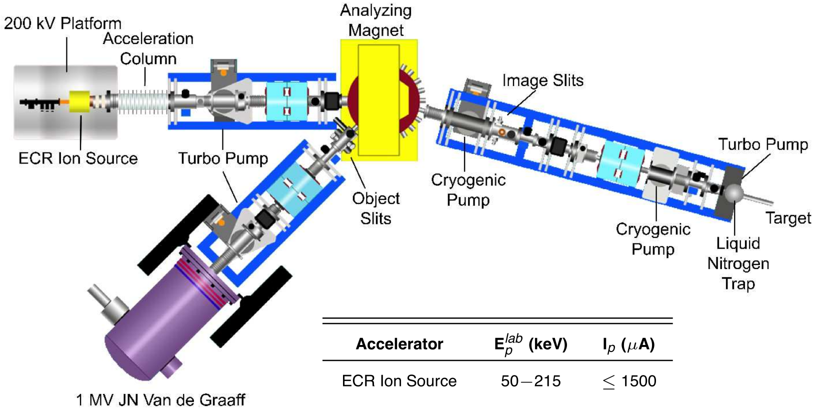
- Split experiment into two phases
  - High energy phase:

    E_p^{lab} = 215, 245, 275, 300, 325 keV
  - Low energy phase:

    E_p^{lab} = 125, 155, 185 keV

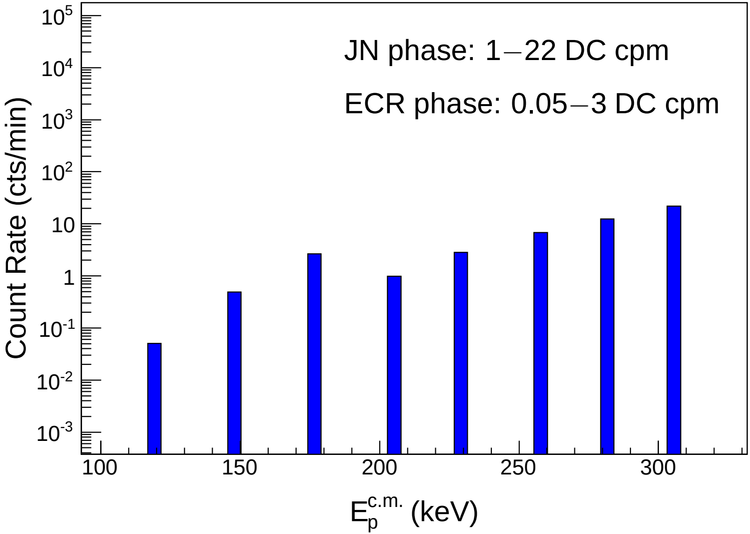


Laboratory for Experimental Nuclear Astrophysics

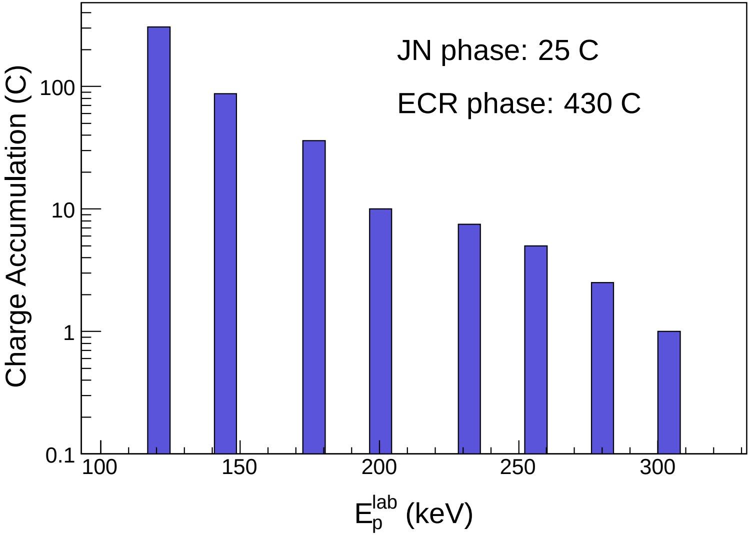


Accelerator	**E_p^{lab} (keV)**	**I_p (μA)**
ECR Ion Source	50 − 215	$\leq$ 1500
JN Van de Graaff	200 − 1000	$\leq$ 250

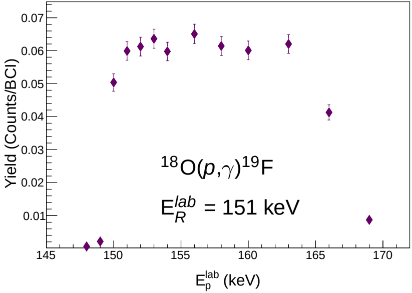
Projected DC Count Rate



Projected Charge Accumulation

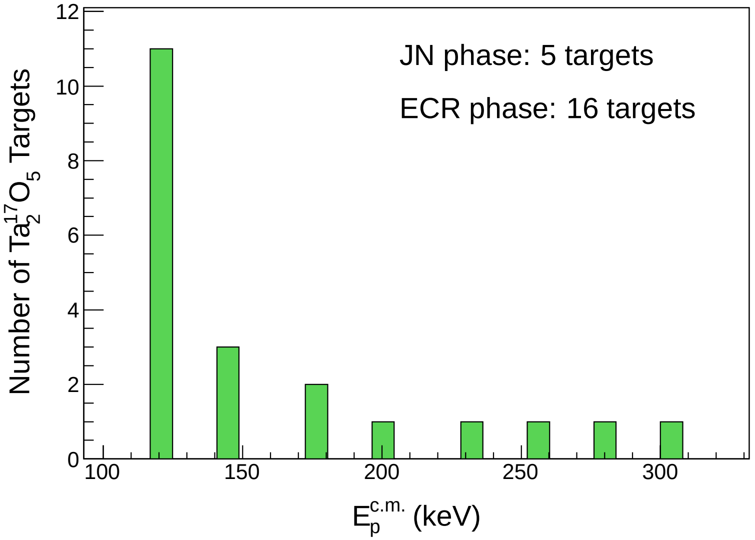


Target Testing and Longevity

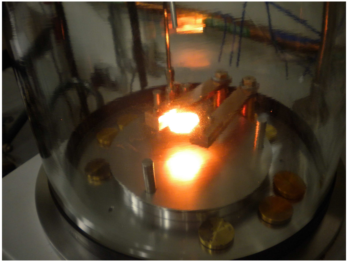


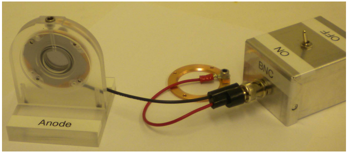
- Excitation functions with JN
- E_R^{lab} = 519 keV resonance
  - $\omega\gamma$ = 13.0 $\pm$ 1.5 meV - Kontos *et al.* (2012)
  - $\omega\gamma$ = 13.7 $\pm$ 2.2 meV - Fox *et al.* (2005)
- ^{18}O target tests $\rightarrow$ Q $>$ 45 C per target - Buckner *et al.* (2012)
- ^{17}O target $\rightarrow$ Q $\leq$ 30 C per target (conservative)

Projected Target Number

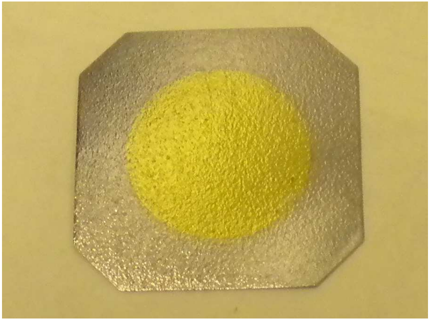


Target Fabrication

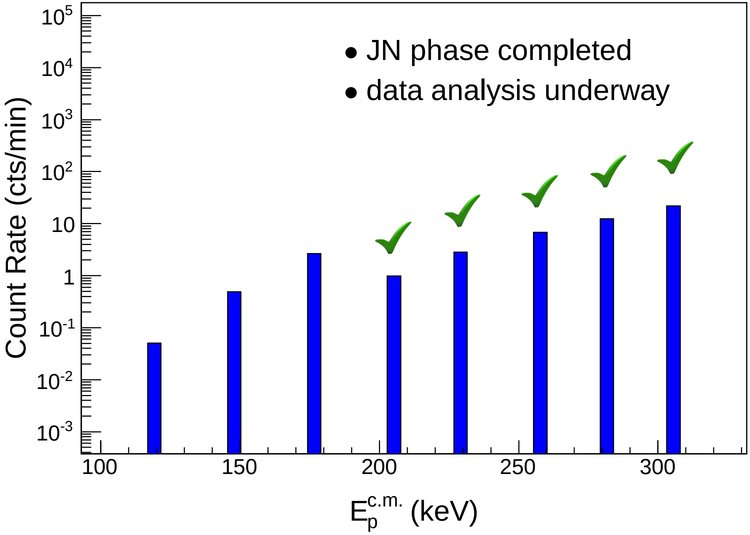




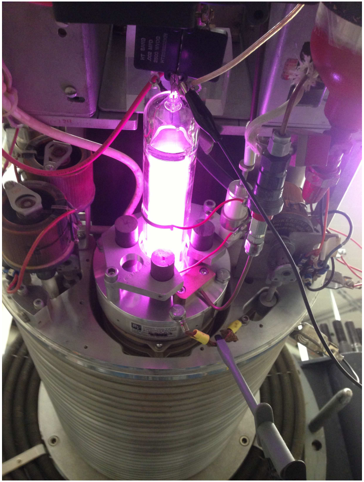
- Ultra-pure tantalum substrate
- Etched in acid bath
- Resistively heated in vacuum
- Anodized in ^{17}O-enriched water

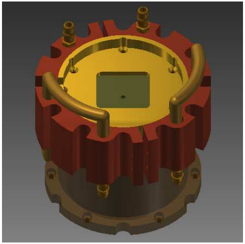


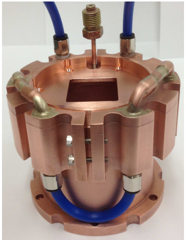
Experiment Progress

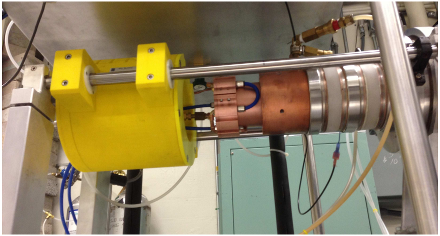


Experimental Hurdles







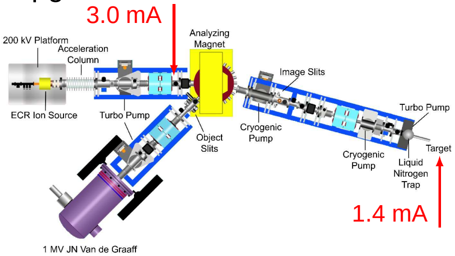


- JN overhaul/optimization

- ECR control upgrade
- Plasma chamber heat sink

Low Energy Phase (ECRIS)

- ECR ion source LabVIEW control
  - extended to MW, H_2, magnet
- Upgraded ion source benchmarked



- 24/7 acquisition scheduled for July

Conclusion

- ^{18}F critical to studying classical novae
- Improved ^{17}O(p,γ)^{18}F rates necessary
- Direct capture dominates reaction rate
- LENA facility ideal for low-energy measurement
- Poised to begin ECR phase of experiment
- Improved rates have broad ramifications
    - Classical nova models
    - Explosive hydrogen burning
    - Stellar evolution & Galactic chemical evolution

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  - Professors *Christian Iliadis, Tom Clegg, Art Champagne*
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  - Students *Stephen Daigle, Keegan Kelly*
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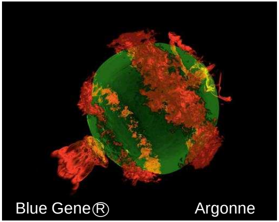
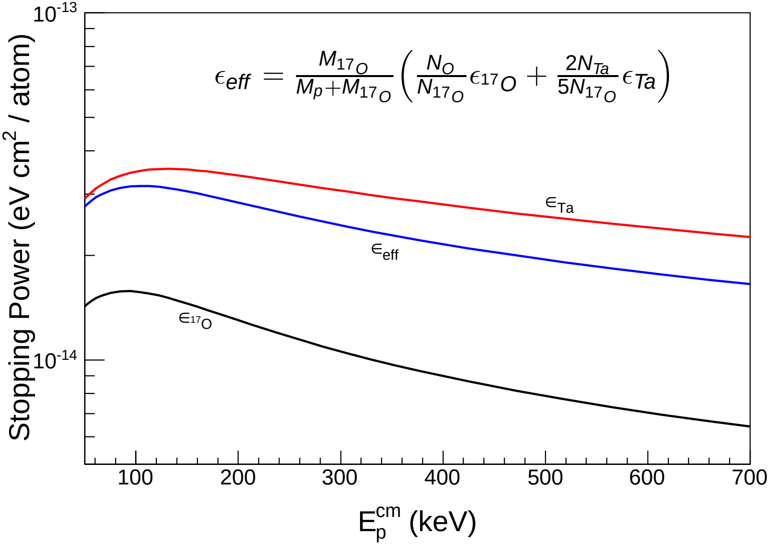
Supernova Type Ia

- WD exceeds Chandrasekhar mass limit
  - $M_{WD} \approx 1.44\ M_{\odot}$
- No H or He in outburst spectrum
- System disrupted
- Classical nova SN Ia scenario?
  - Usually more mass lost than accreted
  - Super soft X-ray source
    - WD does not cool after nova
    - Accretion balances burning
    - Mass exceeds limit

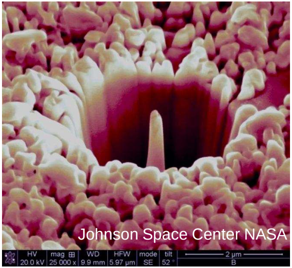


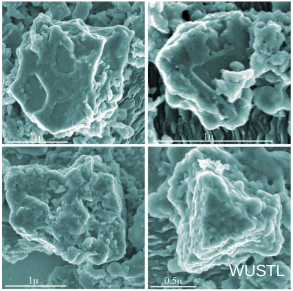
Effective Stopping Power



Classical Nova Grains

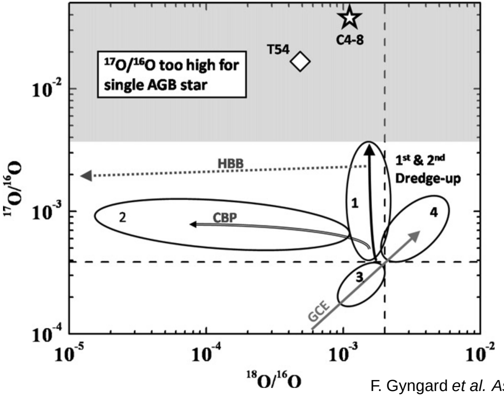
- IR frequencies indicate grain formation
- CO novae have dust forming phase
  - ONe novae not prolific dust creators
- O-rich grains constrain:
  - Nova type and WD mass
  - Stellar evolution models
  - Galactic chemical evolution
  - Mixing processes during TNR
- O-rich nova grains *rare*





Classical Nova Grains

- Nova grain candidates
  - ^{17}O-rich and ^{18}O-poor
- T54 and C4-8 consistent with nova source



F. Gyngard *et al.* *Astrophys. J.* **717** (2010) 107.