X-ray bursts and the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate

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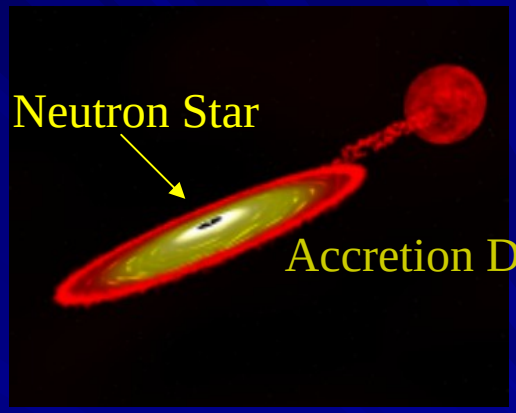
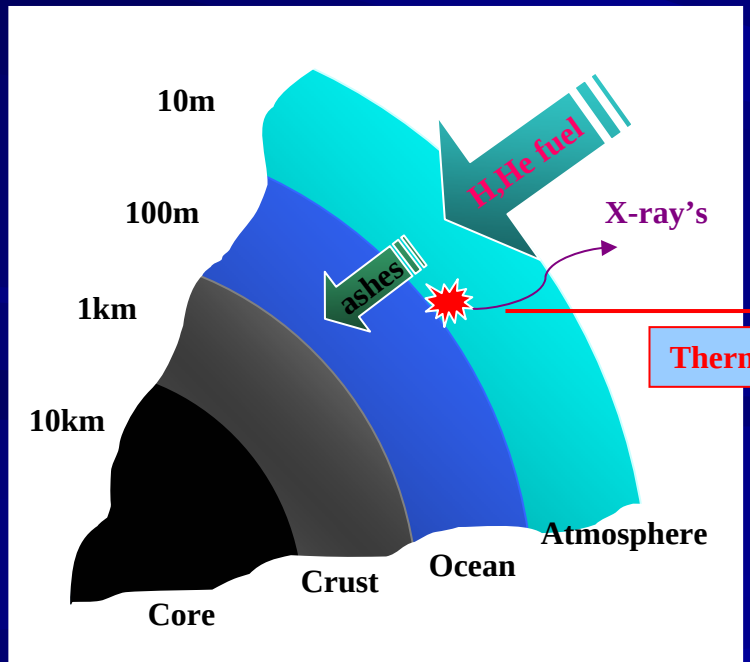
- $^{15}O(\alpha,\gamma)$ as the nuclear trigger for X-ray bursts
- Current progress in the $^{15}O(\alpha,\gamma)$ reaction rate
- Our new measurements at Notre Dame
- Astrophysical implications and conclusion

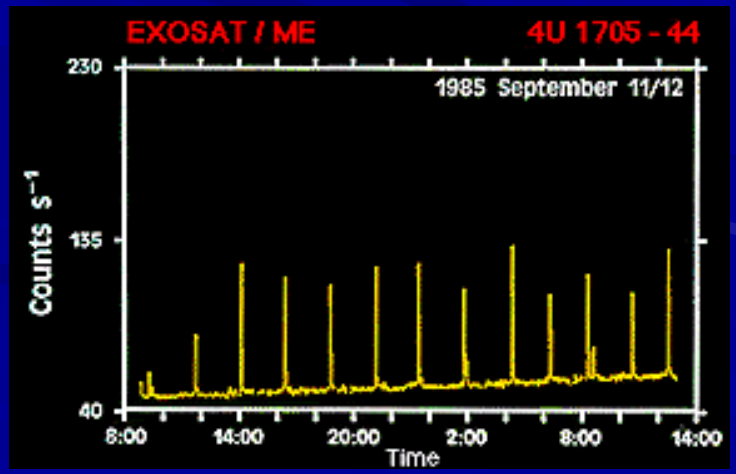
HRIBF Workshop -- Nuclear Measurements for Astrophysics, 2006

Accreting Neutron Stars and X-ray Bursts

- Thermonuclear runaways from the surface of accreting neutron stars are observed as X-ray bursts
- First **X-ray burst**: 3U 1820-30 by Grindlay et al, 1976
- Type I X-ray bursts: 10-100 s, 10^{39-40} ergs

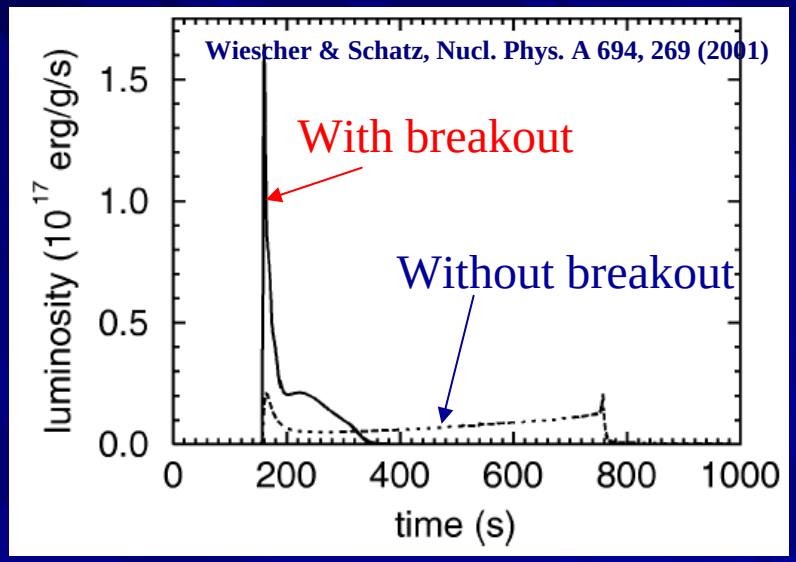




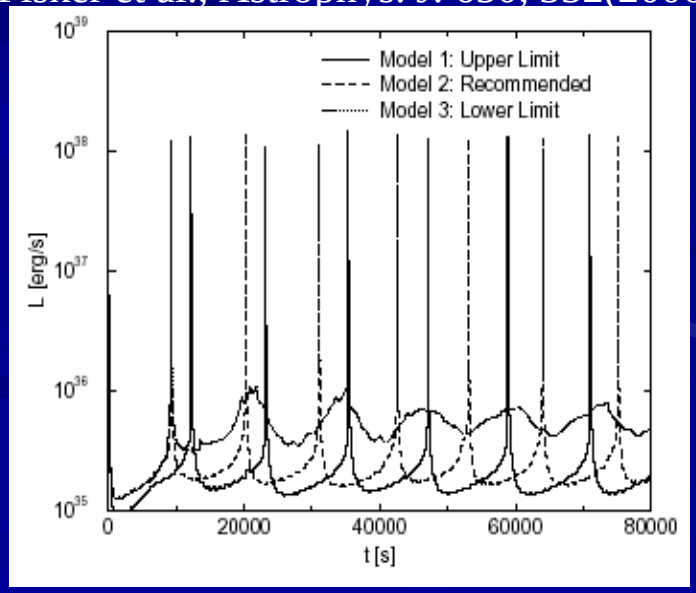


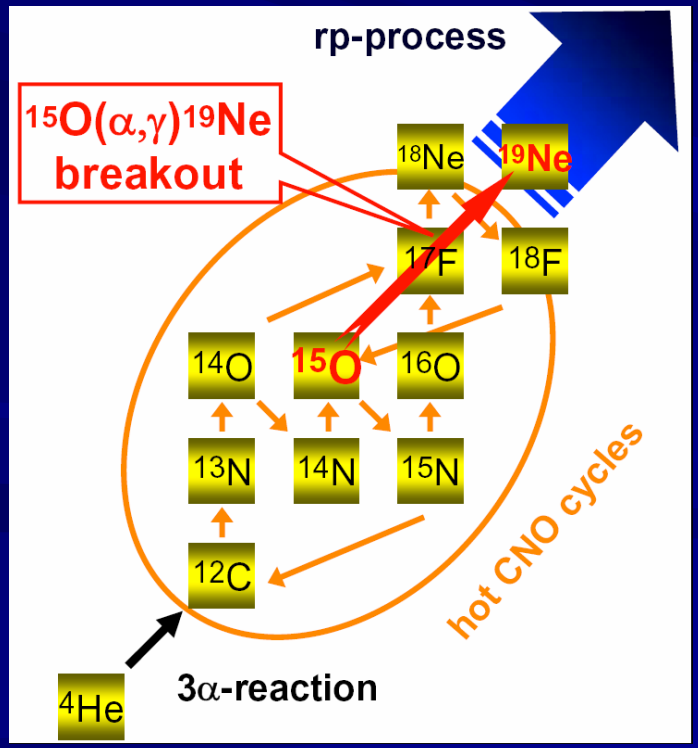
$^{15}O(\alpha,\gamma)$: the trigger

- $^{15}O(\alpha,\gamma)^{19}Ne$ is critical to break out CNO cycles and trigger rp-process
  - Energy production
  - Nucleosynthesis
- It is critical for the burst behavior of XRB's



Fisker et al., Astrophys. J. 650, 332(2006)



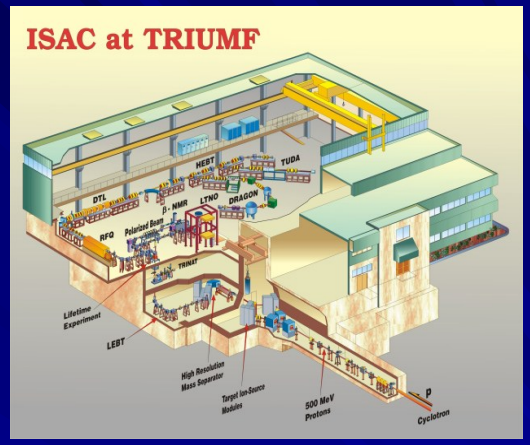


Experimental endeavor for $^{15}O(\alpha,\gamma)^{19}Ne$

- Direct measurement?

  Not likely now:

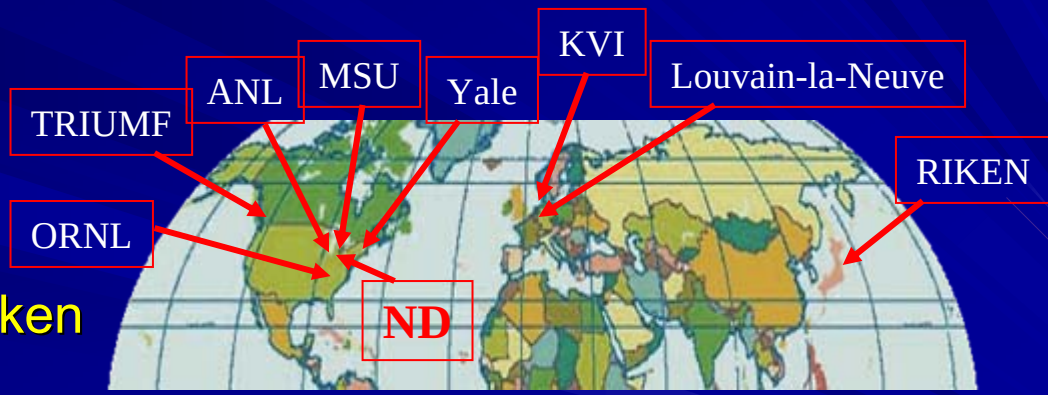
  – An intense (10^{11} /s) radioactive ^{15}O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)



- Indirect method?

  Yes,

  many attempts have been taken



  – Populate α-unbound states in ^{19}Ne
  – Measure lifetimes or gamma widths
  – Measure α-decay branching ratios B_α

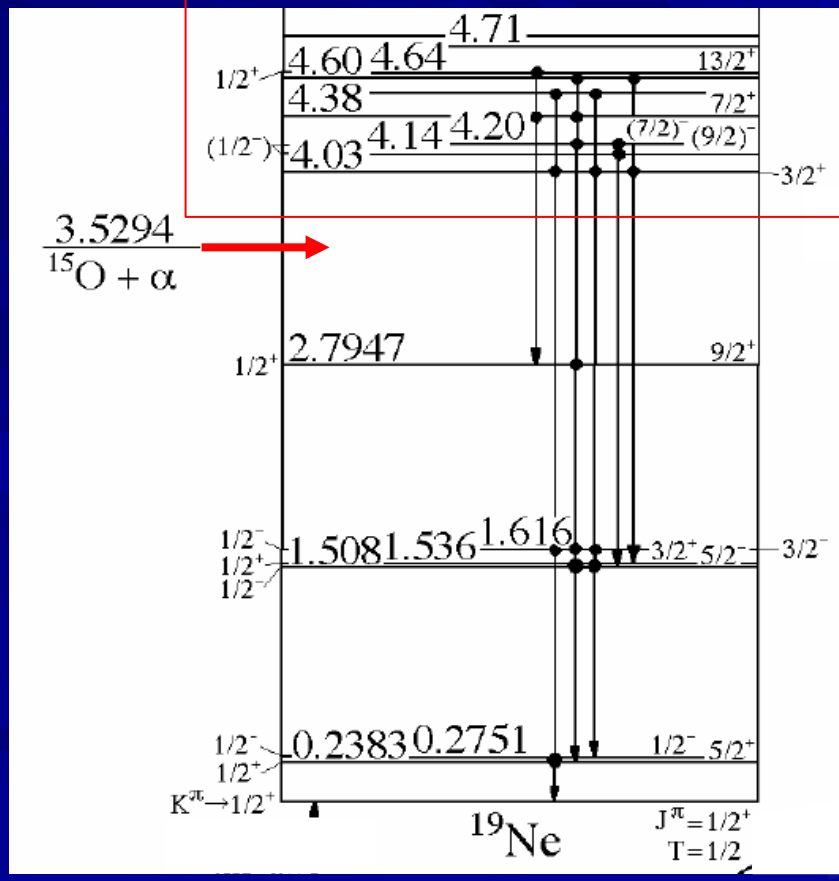
$^{17}O(^{3}He,n\text{-}\gamma)^{19}Ne$

$^{19}F(^{3}He,t\text{-}\alpha)^{19}Ne$

What we knew about $^{15}O(\alpha,\gamma)^{19}Ne$

- Direct capture contribution is negligible at $T_9>0.1$
- 4.03 MeV level dominates the rate at temperatures $T_9 < 0.6$
  - Right within Gamow window
  - Very small B_α ~ 10^{-4}
  - Only upper/lower limits on lifetime/gamma width
- Γ_γ of α-unbound states of ^{19}Ne are unmeasured

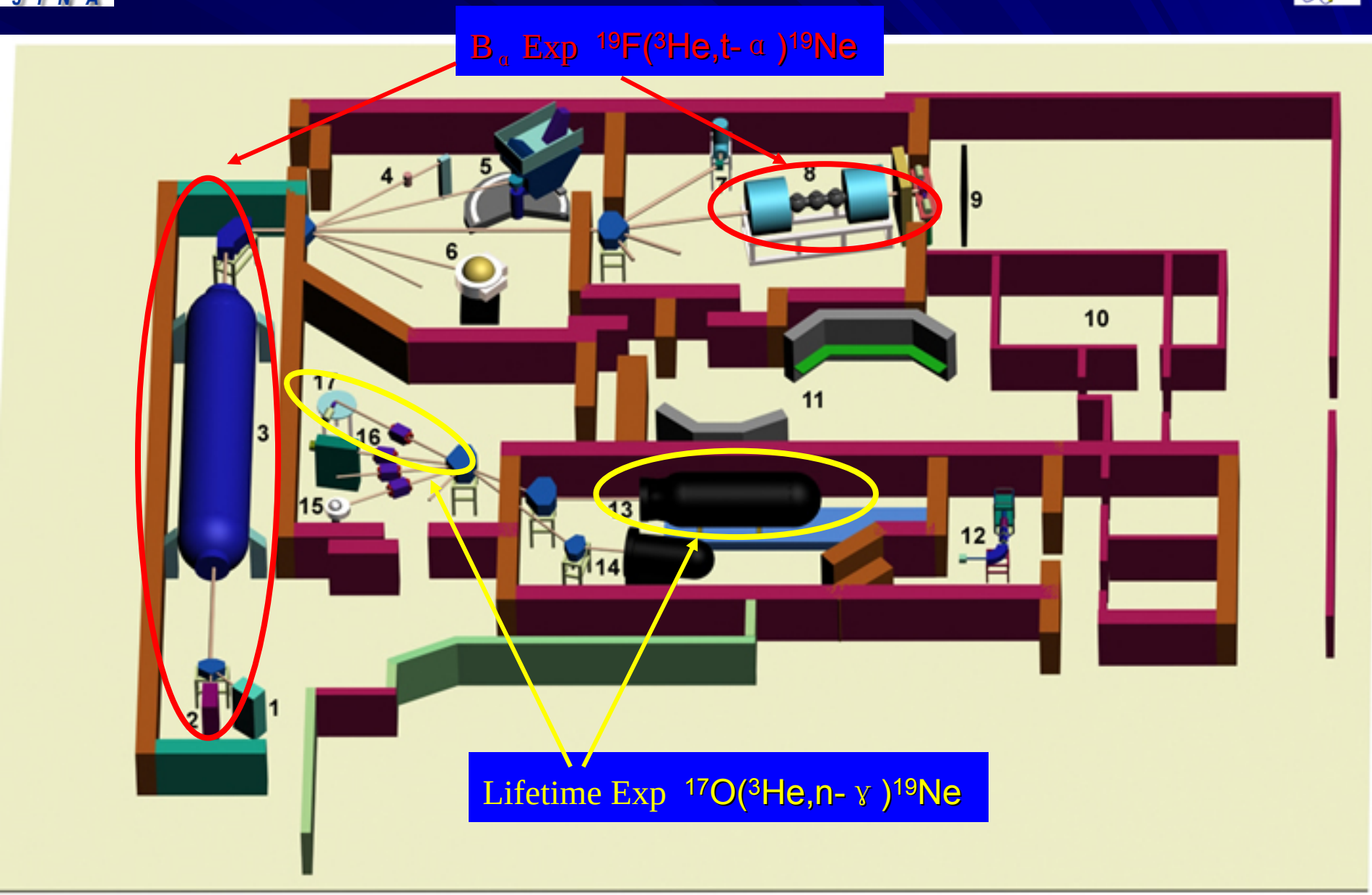
α-unbound states



Short answer: **not much !**

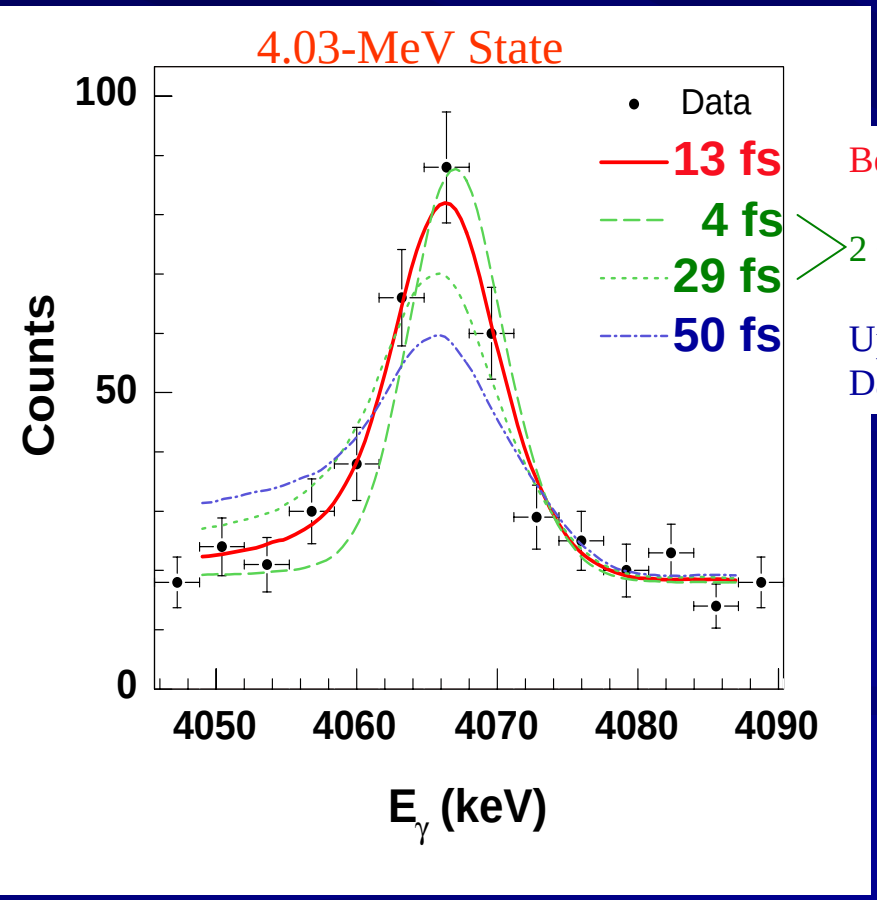
The rate is based on the information from analog states in ^{19}F and theoretical calculations

Lab Layout at Notre Dame



Lifetime Measurement via $^{17}O(^{3}He,n\text{-}\gamma)^{19}Ne$

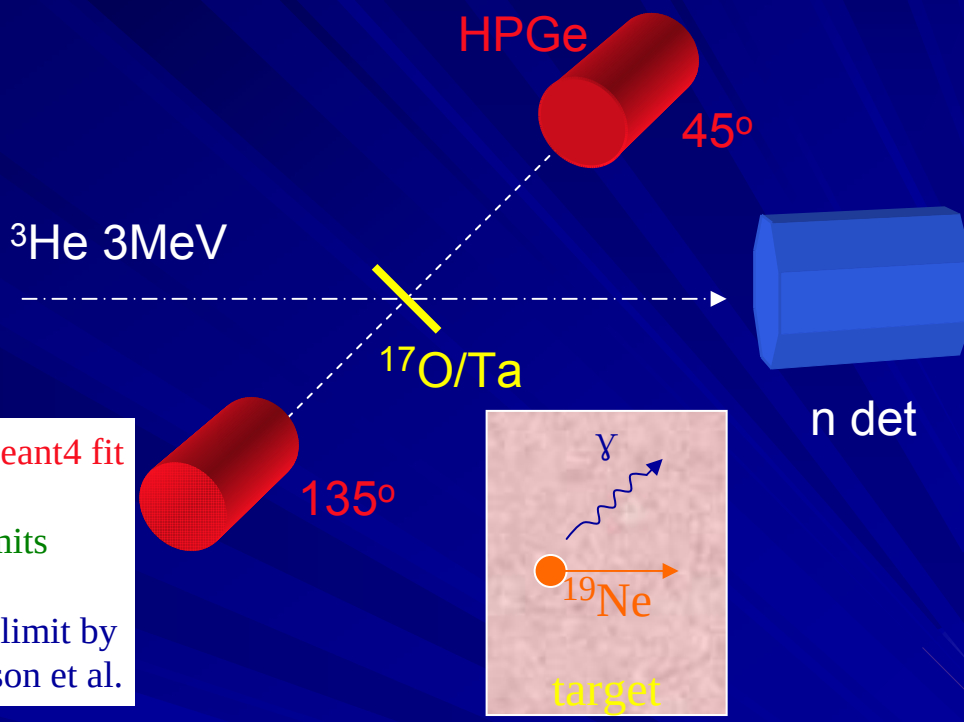
- Doppler-Shift Attenuation Method (DSAM)
- Full line shape analysis



Best Geant4 fit

2 σ limits

Upper limit by Davidson et al.



Measured lifetime $\tau = 13 \pm {}^{9}_{6}$ fs

or $\Gamma = 51 \pm {}^{43}_{21}$ meV

Tan et al., Phys. Rev. C72, 041302R (2005)

Recent result of $11 \pm {}^{4}_{3}$ fs via $^{20}Ne(^{3}He,\alpha)$ by Kanungo et al., Phys. Rev. C74, 045803(2006)

See also P. Woods's talk later.

Summary of Lifetime Results

Compilation (TUNL)			Present work	
E* [keV]	J^{π}	τ_m [fs]	E*[keV]	τ_m[fs]
4032.9±2.4	3/2+	<50	4034.5±0.8	13^{+9}_{-6}
4140±4	(9/2)-*	<300	4143.5±0.6	18^{+2}_{-3}
4197.1±2.4	(7/2)-*	<350	4200.3±1.1	43^{+12}_{-9}
4379.1±2.2	7/2+	<120	4377.8±0.6	5^{+3}_{-2}
4549±4	(1/2,3/2)-	<80	4547.7±1.0	15^{+11}_{-5}
4600±4	(5/2+)	<160	4601.8±0.8	7^{+5}_{-4}
4635±4	13/2+	>1x10^3	4634.0±0.9	>1x10^3

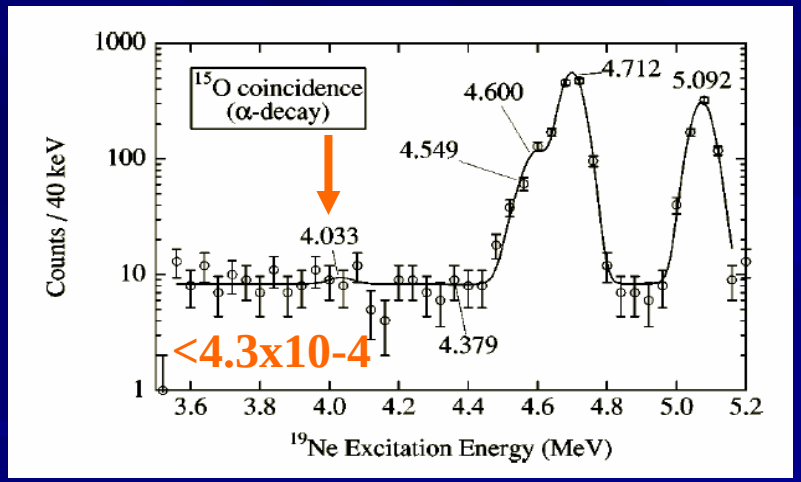
* Our study shows the spin assignments should be exchanged

W.P. Tan et al., Phys. Rev. C72, 041302R (2005)

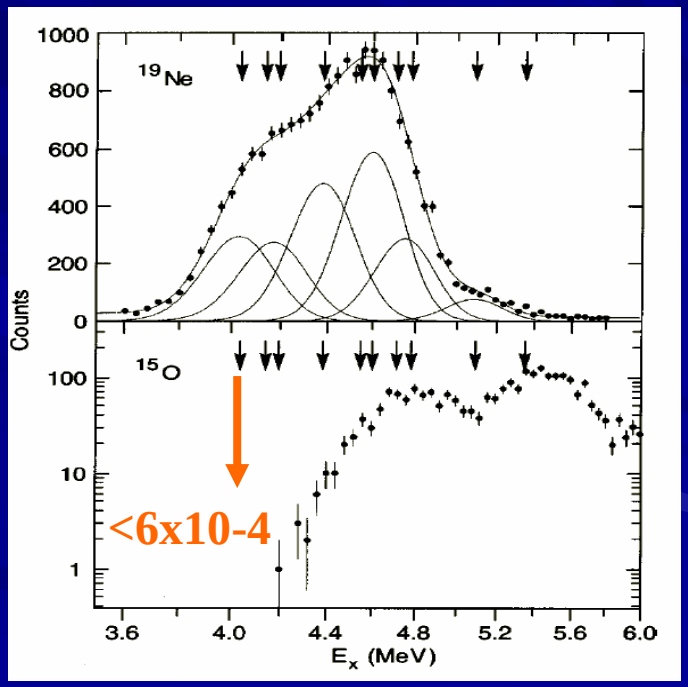
Alpha-decay branching ratios

- Pursued at many places such as Yale, ANL, ORNL, Louvain-la-Neuve, KVI, TRIUMF, and RIKEN
- Dominant resonance of 4.03 MeV state in 19Ne
  - **Its branching ratio $\Gamma_\alpha / \Gamma \sim 10^{-4}$**

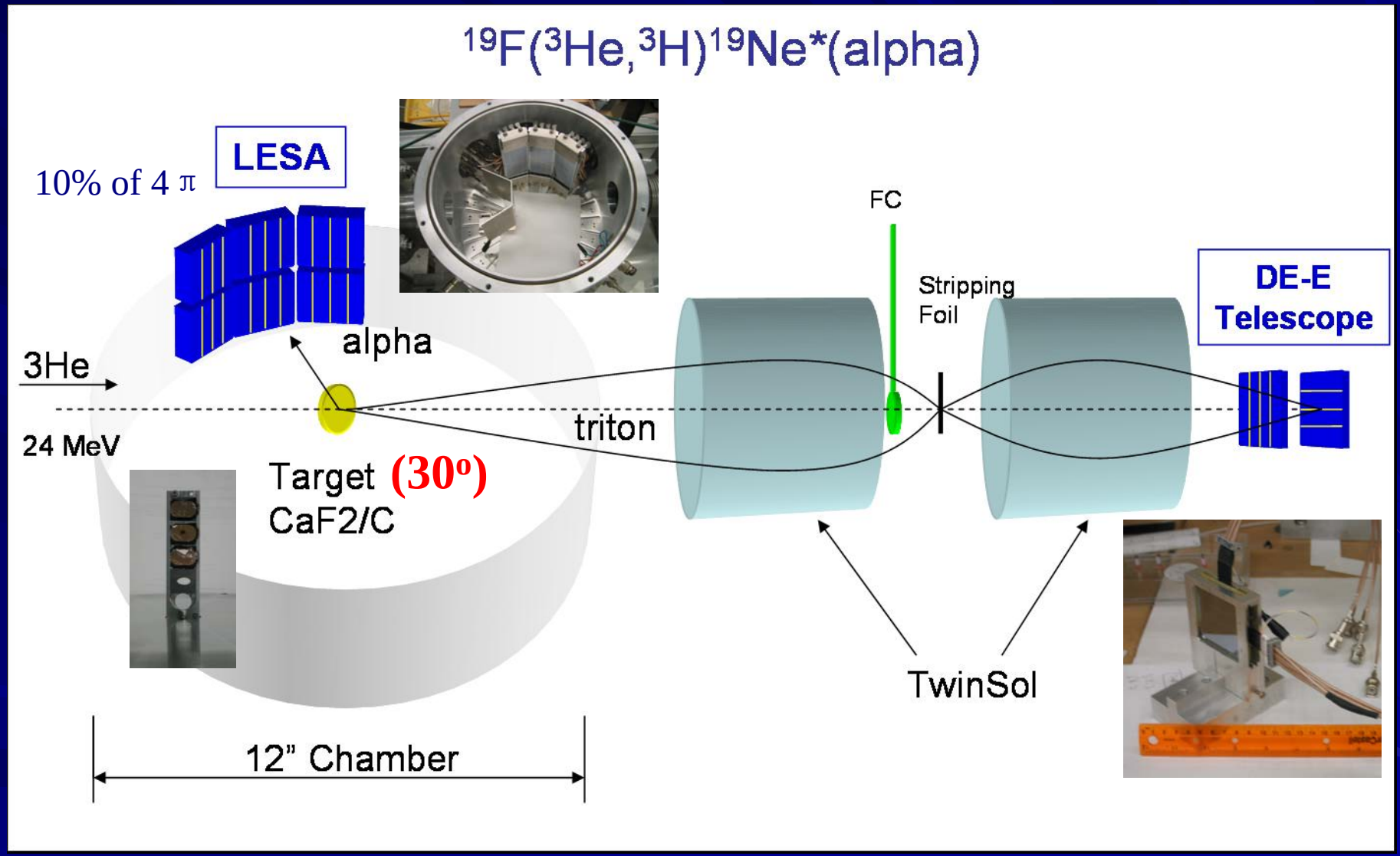
Davids et al, 2003 at KVI, p(^{21}Ne,t)



Rehm et al, 2003 at ANL, ^{3}He(^{20}Ne,^{4}He)

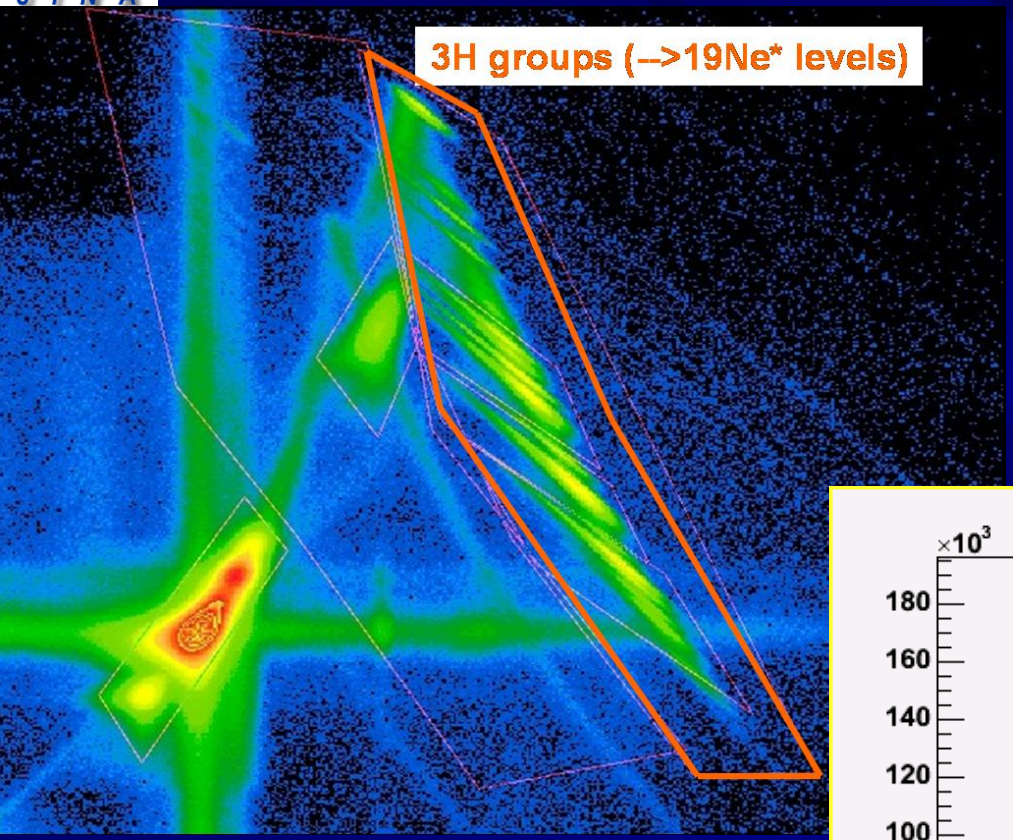


Experimental Setup



- Populate excited states in ^{19}Ne
- 3H-alpha coincidences → alpha-decay branching ratios

A million of ^{3}H detected for 4.03 MeV State



dE

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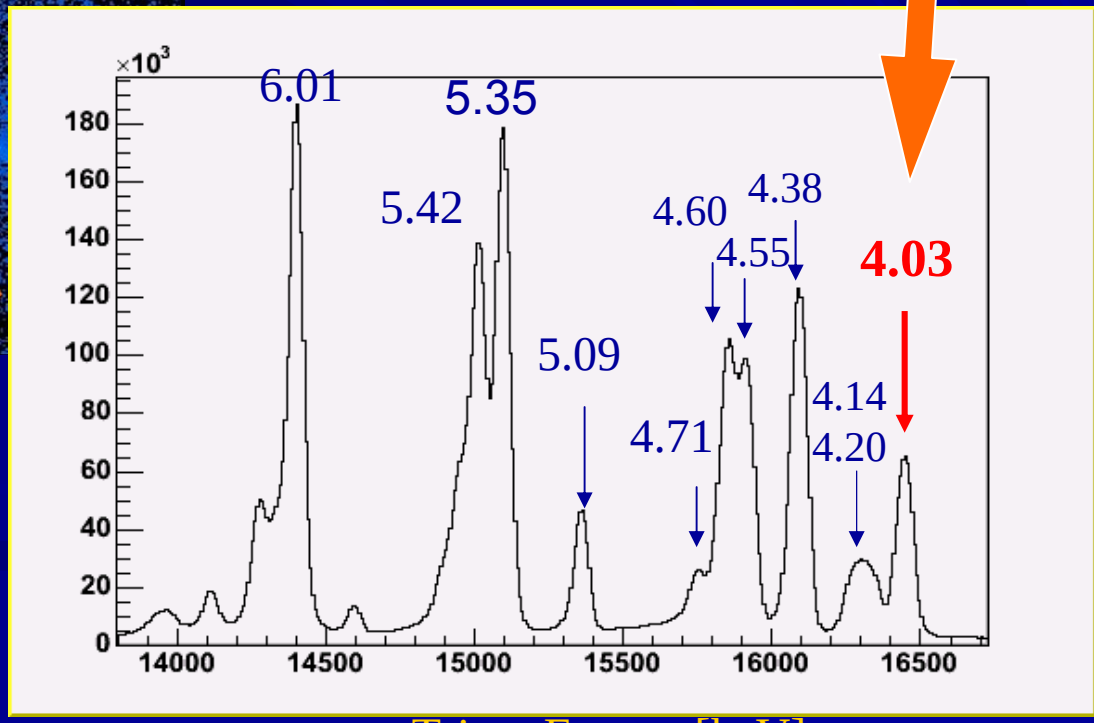
… to reach the sensitivity of 10^{-4} in B_α

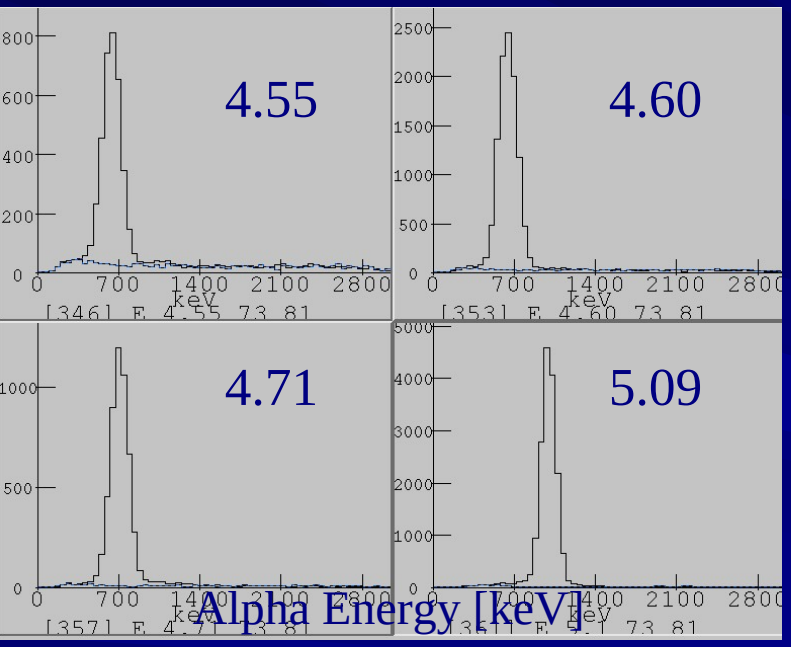
… after two weeks



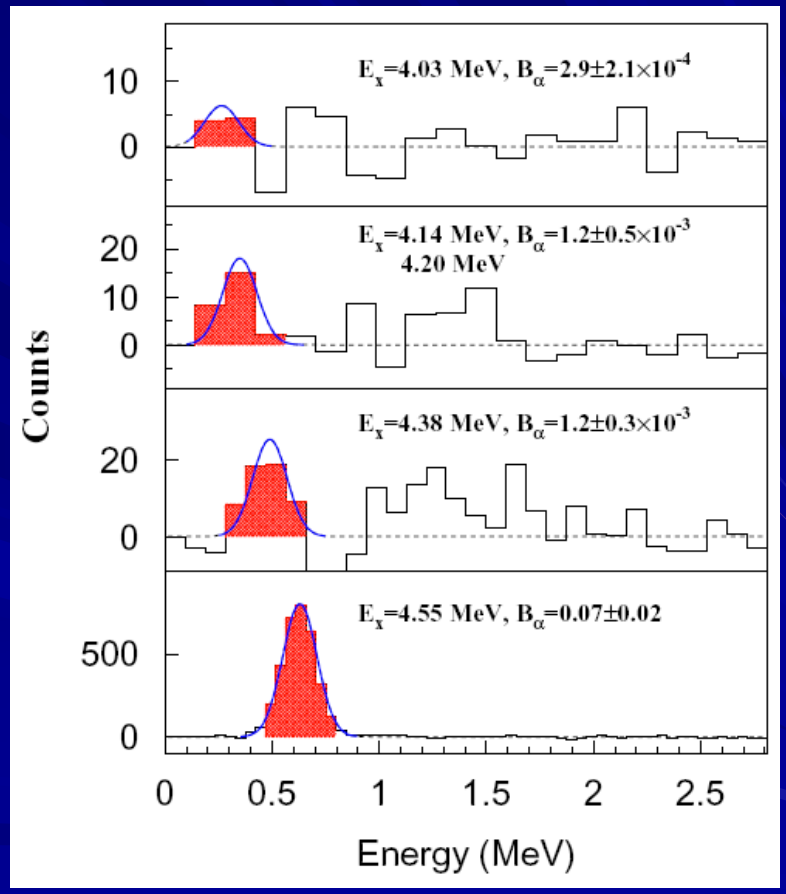
Triton Energy [keV]

Alpha spectra from $^{19}Ne^*$ decay

High-lying States



Low-lying States

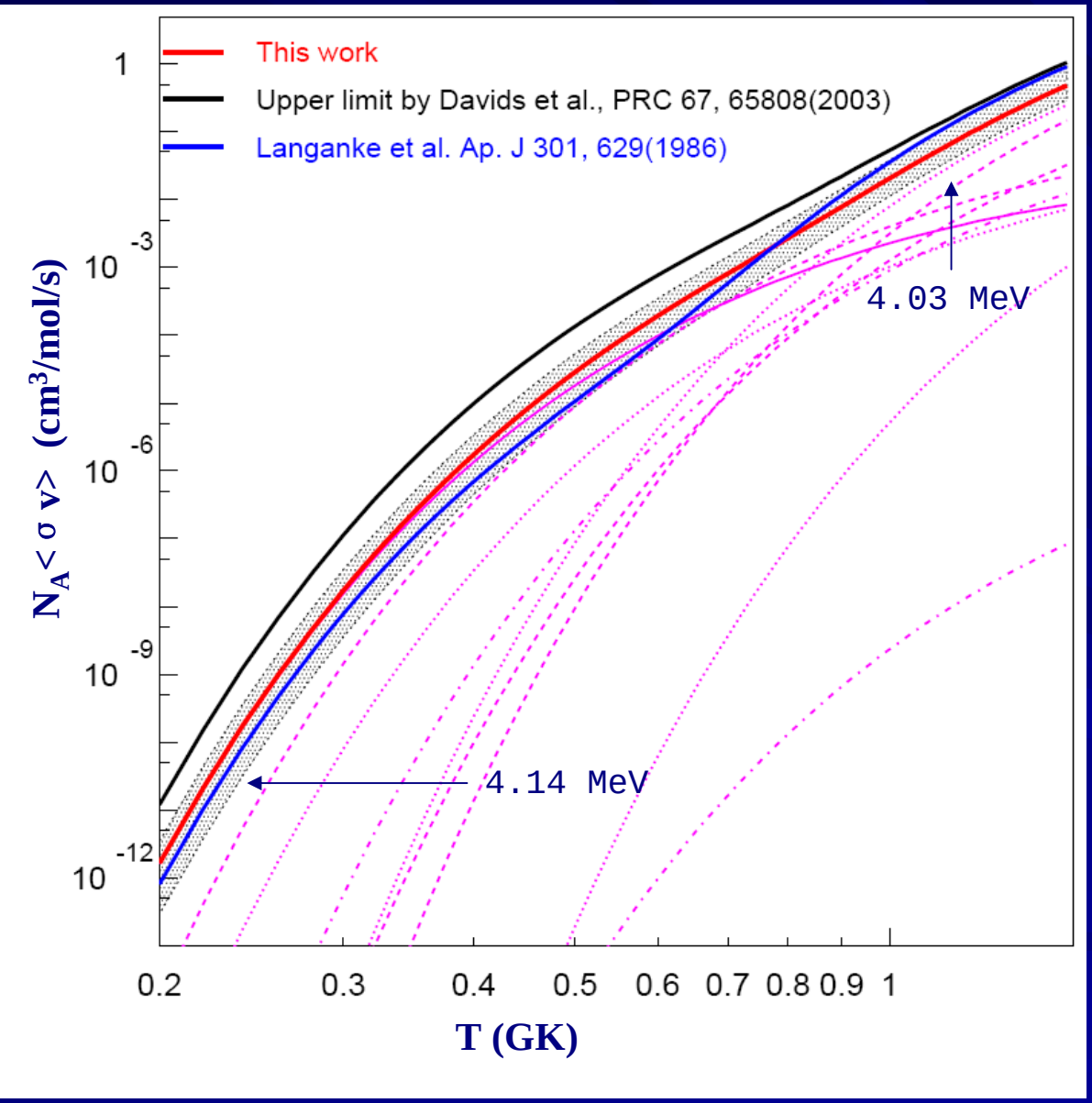


Results of α -decay Branching Ratios

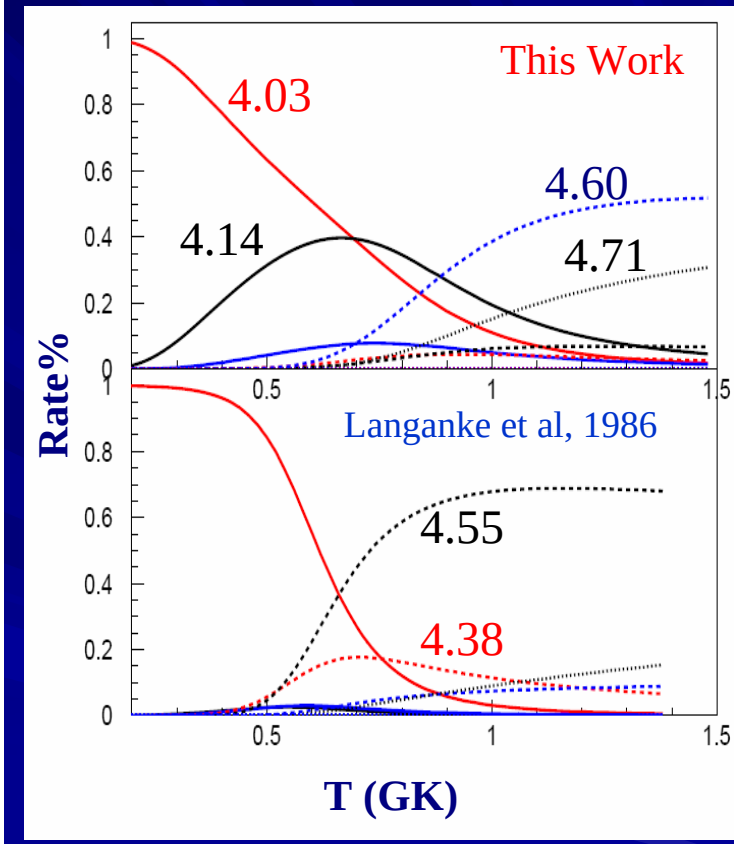
Ex [MeV]	Magnus90	RIKEN	Laird02	Rehm03	Davids03	Visser04	This work
4.03		<0.03	<0.01	$<6\times10^{-4}$	$<4.3\times10^{-4}$		$2.9\pm2.1\times10^{-4}$
4.14 4.20			<0.01				$1.2\pm0.5\times10^{-3}$
4.38	0.044 ± 0.032	<0.04		$16\pm5\times10^{-3}$	$<3.9\times10^{-3}$	(>0.0027)	$1.2\pm0.3\times10^{-3}$
4.55	0.07 ± 0.03	$0.09^{+0.04}_{-0.02}$			0.16 ± 0.04	0.06 ± 0.04	0.07 ± 0.02
4.60	0.25 ± 0.04	$0.29^{+0.06}_{-0.04}$	0.32 ± 0.03		0.32 ± 0.04	0.208 ± 0.026	0.26 ± 0.03
4.71	0.82 ± 0.15	$0.67^{+0.23}_{-0.14}$			0.85 ± 0.04	$0.69^{+0.11}_{-0.14}$	0.80 ± 0.15
5.09	0.90 ± 0.09	$1.11^{+0.17}_{-0.13}$	1.8 ± 0.9	0.8 ± 0.1	0.90 ± 0.06	$0.75^{+0.06}_{-0.07}$	0.87 ± 0.03

- Magnus90: Magnus et al, Nucl. Phys. A 506, 332 (1990)
- RIKEN: private communication from T. Motobayashi
- Laird02: Phys. Rev. C 66, 048801 (2002)
- Rehm03: Phys. Rev. C 67, 065809 (2003)
- Davids03: Phys. Rev. C 67, 012801R (2003)
- Visser04: Phys. Rev. C 69, 048801 (2004)

Reaction Rate of $^{15}O(\alpha,\gamma)^{19}Ne$



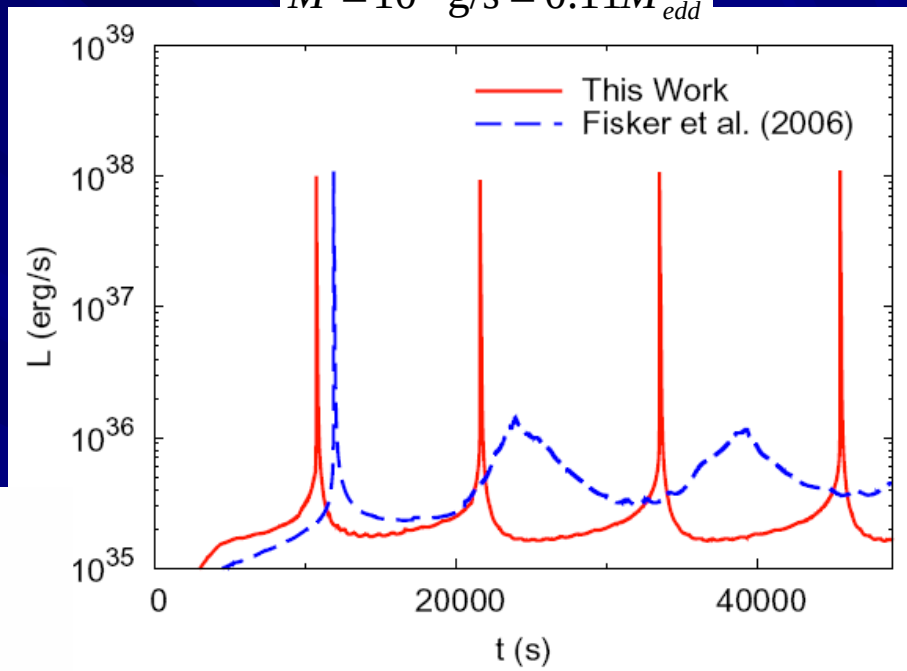
Differences in detail

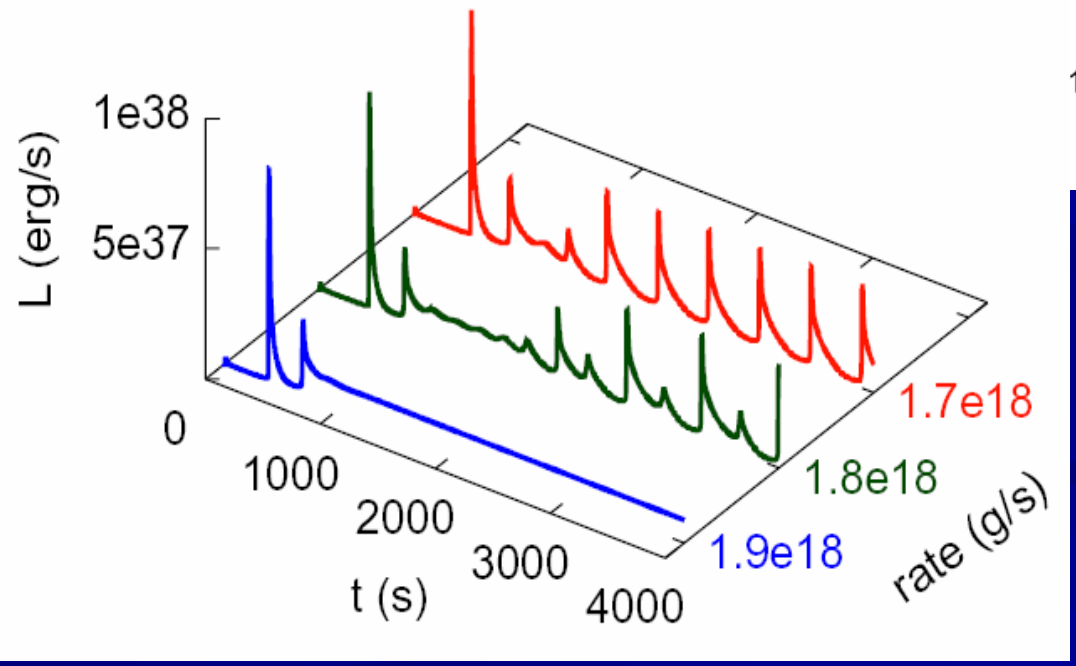


Astrophysical Implications

- Multi-zone self-consistent X-ray burst model is used (Fisker et al.)
- Low reaction rate quenches bursts
- New rate provides better understanding of the bursting dynamics and periodicity

$\dot{M} = 10^{17}\,\mathrm{g/s} = 0.11\dot{M}_{edd}$





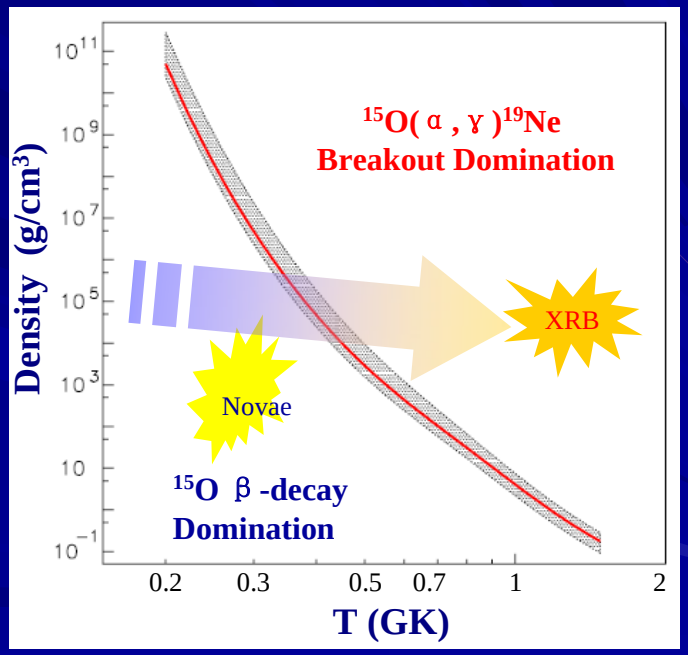
- Study the transition conditions
- The transition accretion rate between steady state burning and bursting phases is constrained as 1.9-2.1x10^{18} g/s

Conclusion

- Critical reaction rate of $^{15}O(\alpha,\gamma)^{19}Ne$ is determined experimentally via measurement of lifetimes and branching ratios of the α-unbound states in ^{19}Ne

- As a trigger of X-ray bursts, the measured $^{15}O(\alpha,\gamma)^{19}Ne$ rate provides stringent experimental constraint on the burst behavior of accreting neutron stars

- With this new rate we are able to study the parameters in X-ray model simulations like the transition accretion rate



- Future work
  - Precise measurement is needed for the near threshold states (4.03, 4.14, and 4.20)
  - Direct measurement requires development of intense radioacive beams in future facilities like RIA

Acknowledgements

- Collaborators:

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E. Stech, E. Strandberg, C. Ugalde

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