Experimental Efforts to Determine the $^{15}O(\alpha,\gamma)^{19}Ne$ Reaction Rate

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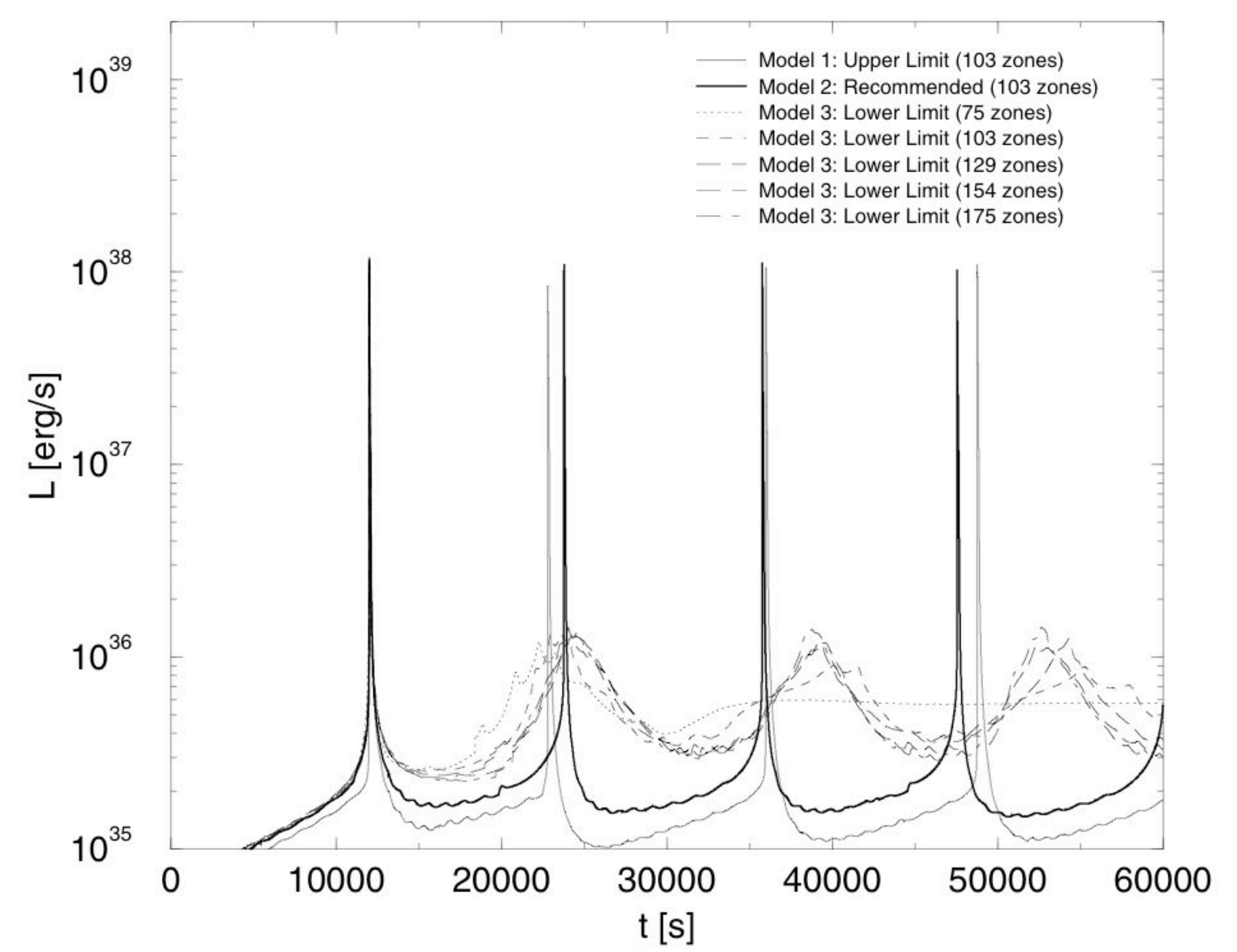
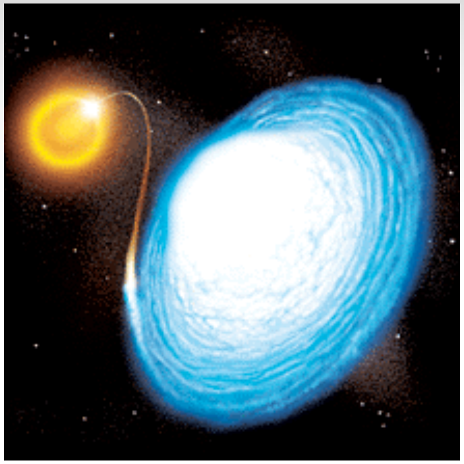
Type I X-Ray Bursts: Dependence on $^{15}O(\alpha,\gamma)^{19}Ne$



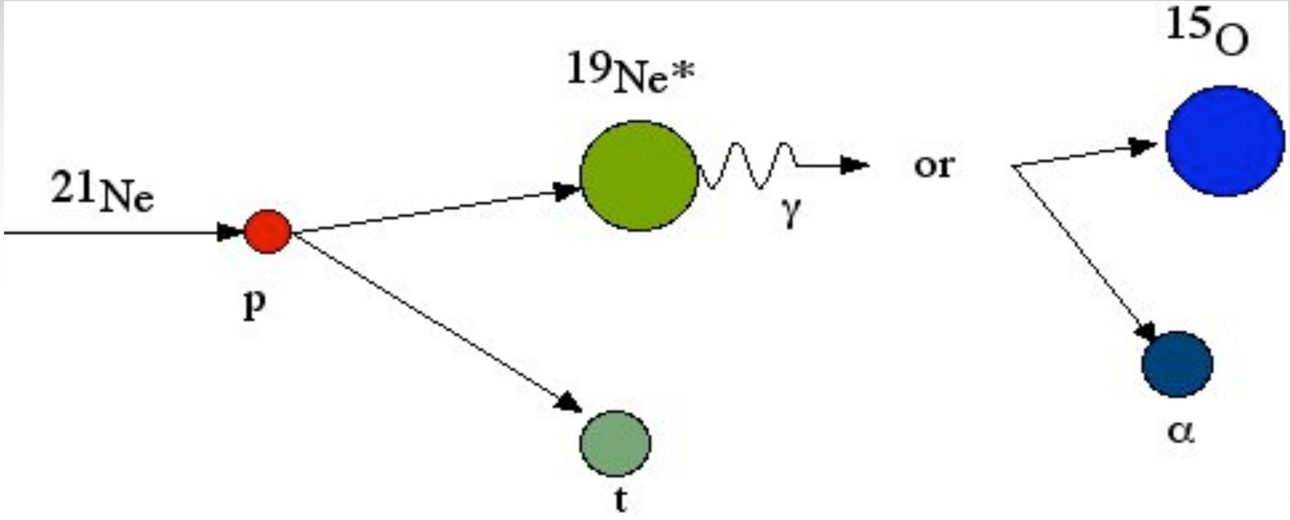
Fisker et al., ApJ 650, 332 (2006): reaction rate must be above certain value or accreted matter burns stably without bursting

$^{15}\mathrm{O} + \alpha \rightarrow {}^{19}\mathrm{Ne} + \gamma$



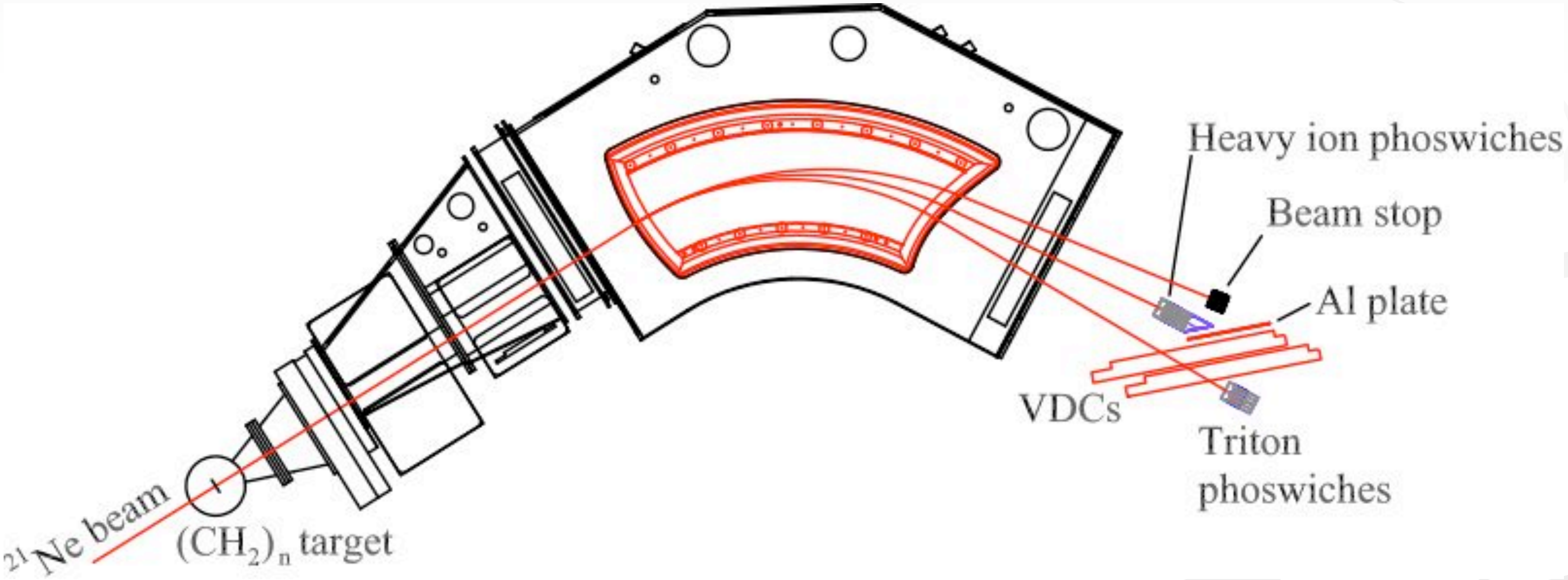
- No direct measurement is presently feasible (^{15}O is radioactive)
- Reaction proceeds resonantly at temperatures characteristic of x-ray bursts
- For narrow, isolated resonances, contributions add incoherently
- Contribution of each resonance to reaction rate proportional to its strength $\omega\gamma$
- Resonance strength $\omega\gamma \propto \Gamma_\alpha \Gamma_\gamma / \Gamma$
- $\Gamma_\alpha \Gamma_\gamma / \Gamma = B_\alpha (1- B_\alpha) \hbar/\tau$, where B_α is the alpha-decay branching ratio and τ the mean lifetime of the state

Experimental Technique: B_α



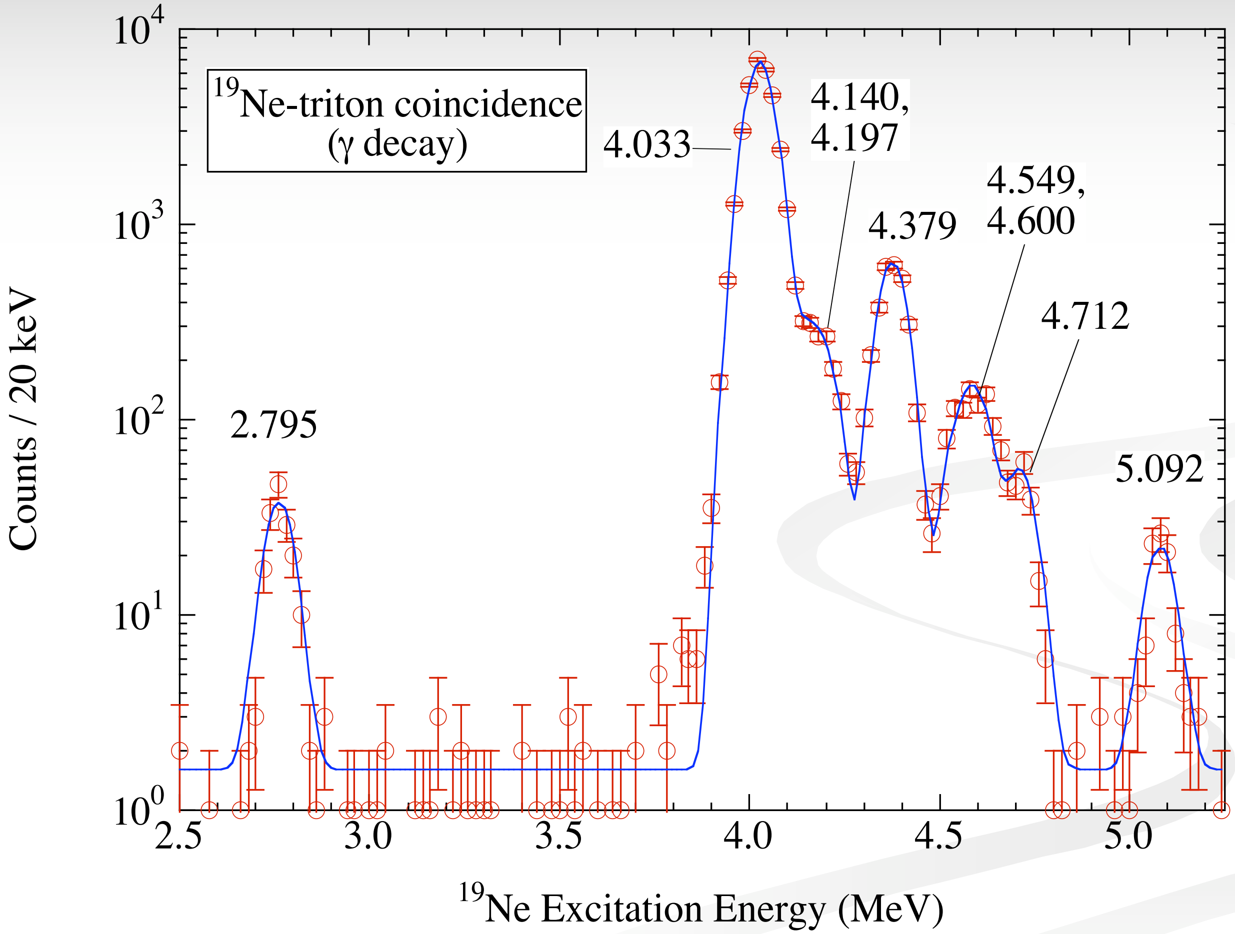
- Decay properties of excited states in ^{19}Ne determine reaction rate
- Populate states via transfer reaction, study decays
- States of interest decay exclusively by α or γ emission
- Populate states, count relative numbers of α & γ decays to obtain B_α
- Used $^{21}\text{Ne} + p \rightarrow {}^{19}\text{Ne} + t$ reaction at KVI, Groningen, Netherlands

Experimental Setup at KVI's Big-Bite Spectrometer

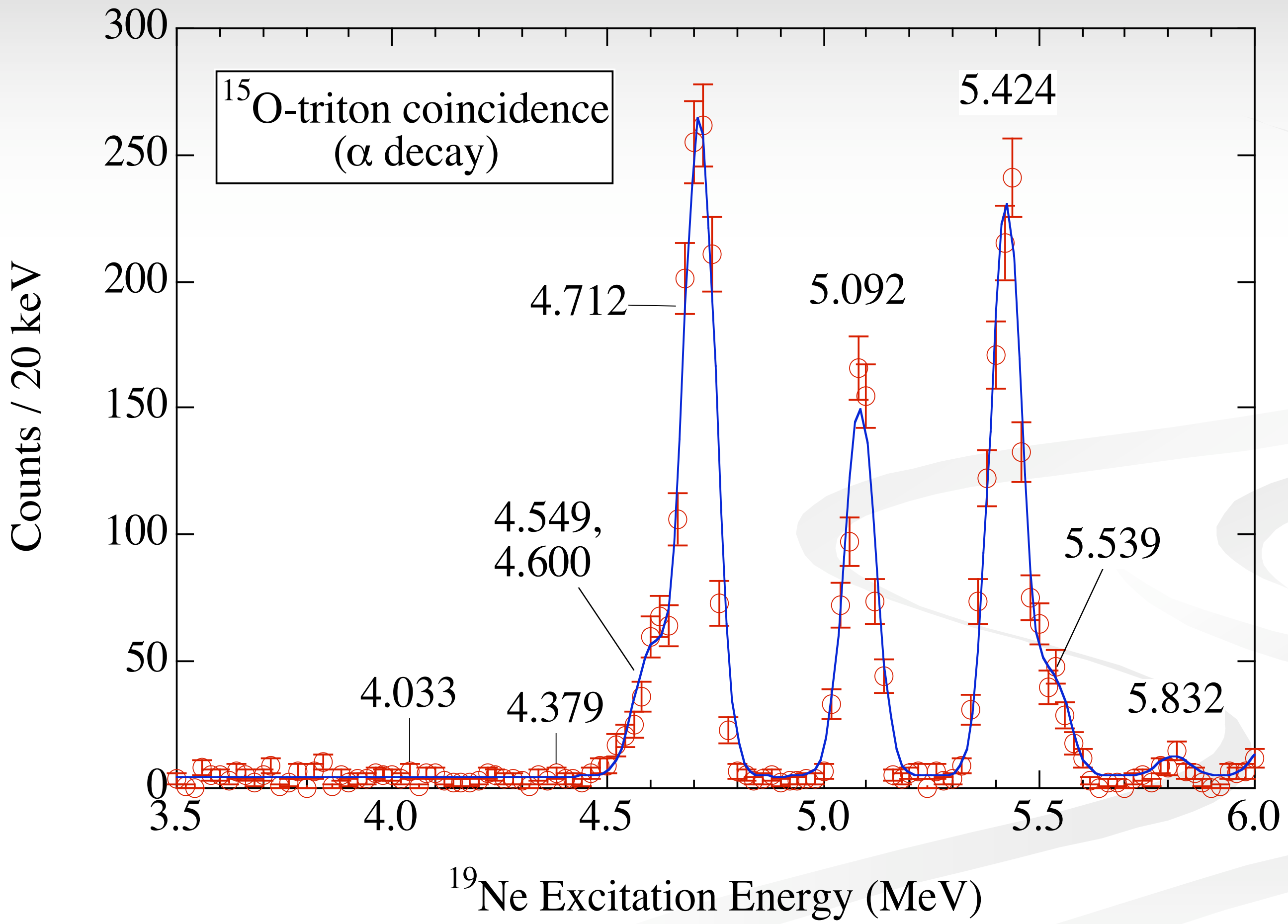


Triton determines ^{19}Ne excitation energy
Heavy ion in coincidence reveals decay mode

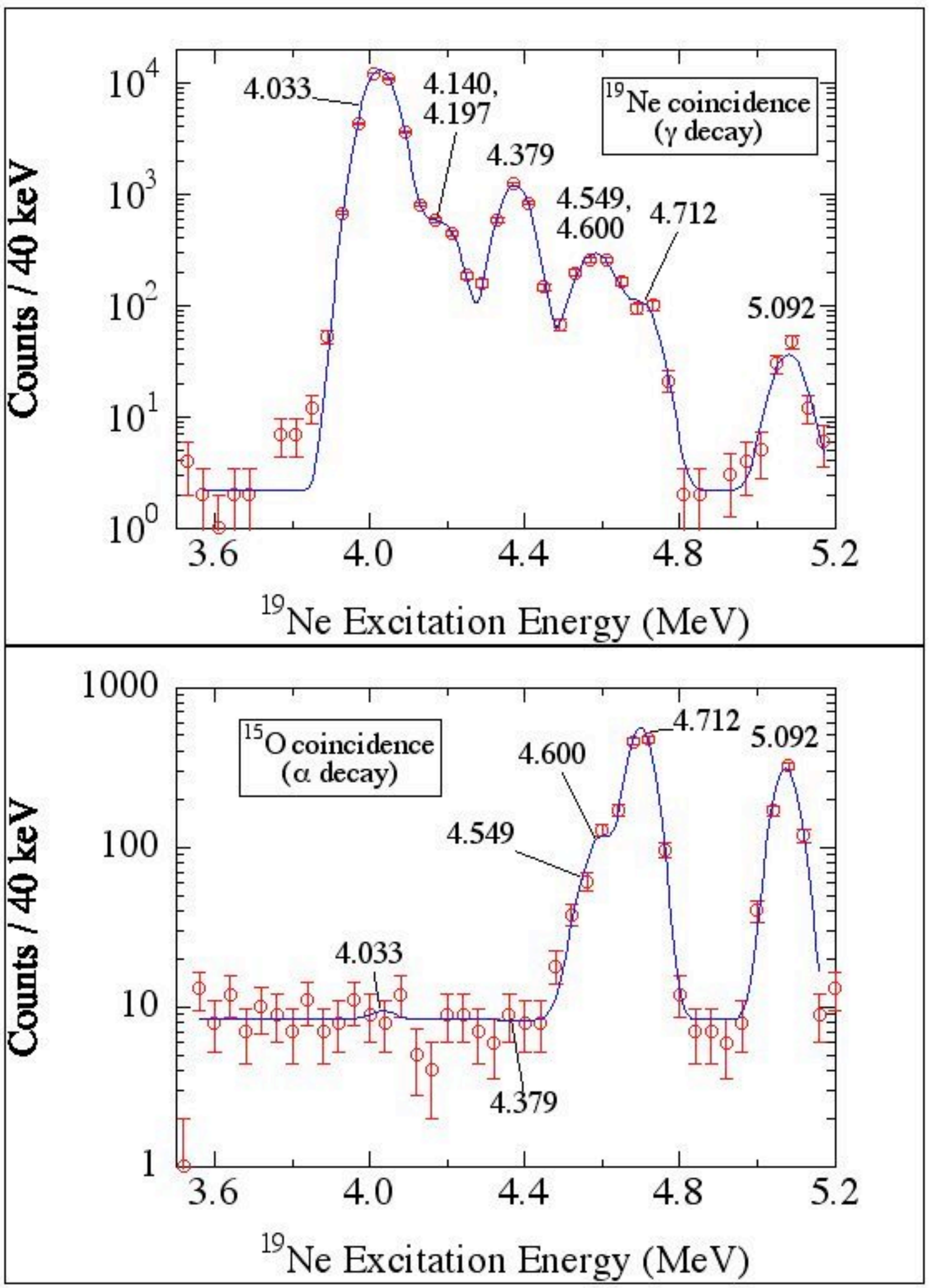
Gamma Decay


^{19}Ne-triton coincidence
(γ decay)
2.795
4.033
4.140,
4.197
4.379
4.549,
4.600
4.712
5.092
10^4
10^3
10^2
10^1
10^0
Counts / 20 keV
2.5
3.0
3.5
4.0
4.5
5.0
^{19}Ne Excitation Energy (MeV)

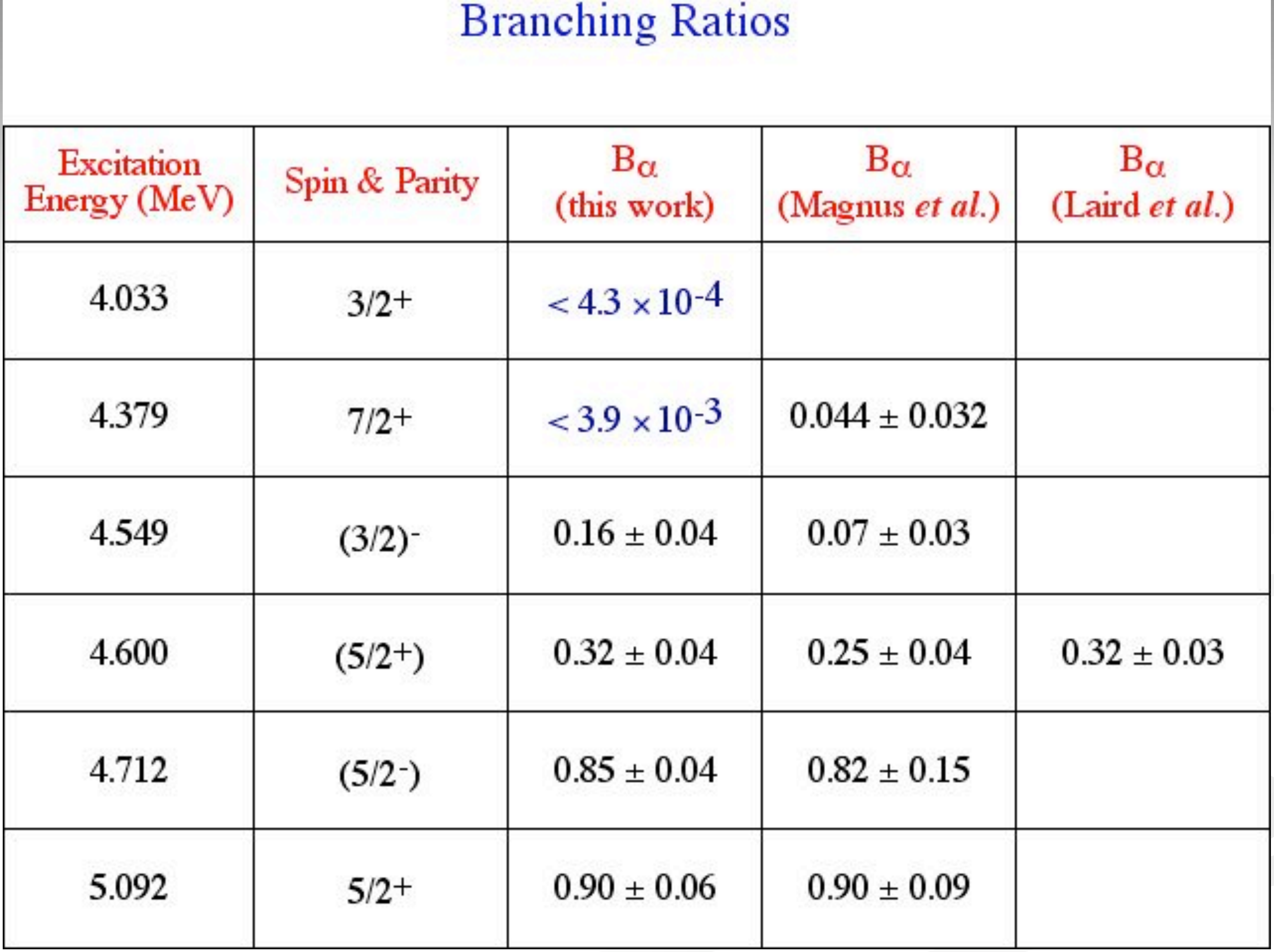
Alpha Decay



^{15}O-triton coincidence
(α decay)
300
250
200
150
100
50
0
3.5
4.0
4.5
5.0
5.5
6.0
Counts / 20 keV
^{19}Ne Excitation Energy (MeV)
4.033
4.379
4.549,
4.600
4.712
5.092
5.424
5.539
5.832



10^4
10^3
10^2
10^1
10^0
Counts / 40 keV
4.033
4.140,
4.197
4.379
4.549,
4.600
4.712
5.092
^{19}Ne coincidence
(γ decay)
3.6
4.0
4.4
4.8
5.2
^{19}Ne Excitation Energy (MeV)
1000
100
10
1
Counts / 40 keV
^{15}O coincidence
(α decay)
4.600
4.712
5.092
4.549
4.033
4.379
3.6
4.0
4.4
4.8
5.2
^{19}Ne Excitation Energy (MeV)



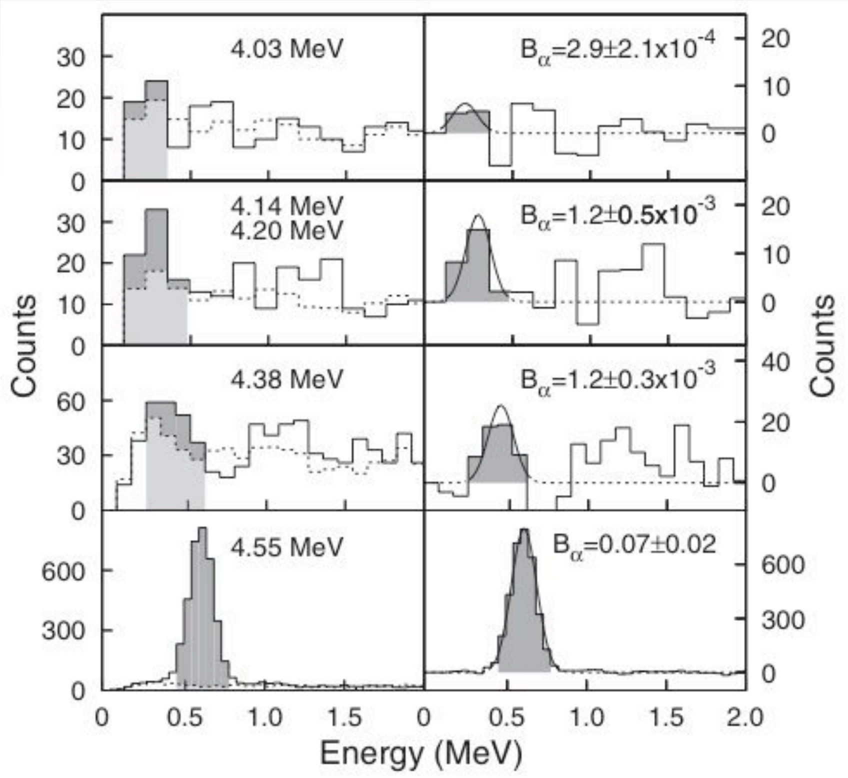
Branching Ratios

Excitation Energy (MeV)	Spin & Parity	B_α (this work)	B_α (Magnus *et al.*)	B_α (Laird *et al.*)
4.033	$3/2^+$	$< 4.3 \times 10^{-4}$		
4.379	$7/2^+$	$< 3.9 \times 10^{-3}$	0.044 ± 0.032	
4.549	$(3/2)^-$	0.16 ± 0.04	0.07 ± 0.03	
4.600	$(5/2^+)$	0.32 ± 0.04	0.25 ± 0.04	0.32 ± 0.03
4.712	$(5/2^-)$	0.85 ± 0.04	0.82 ± 0.15	
5.092	$5/2^+$	0.90 ± 0.06	0.90 ± 0.09	

Davids et al., Phys Rev C 67, 065808 (2003)

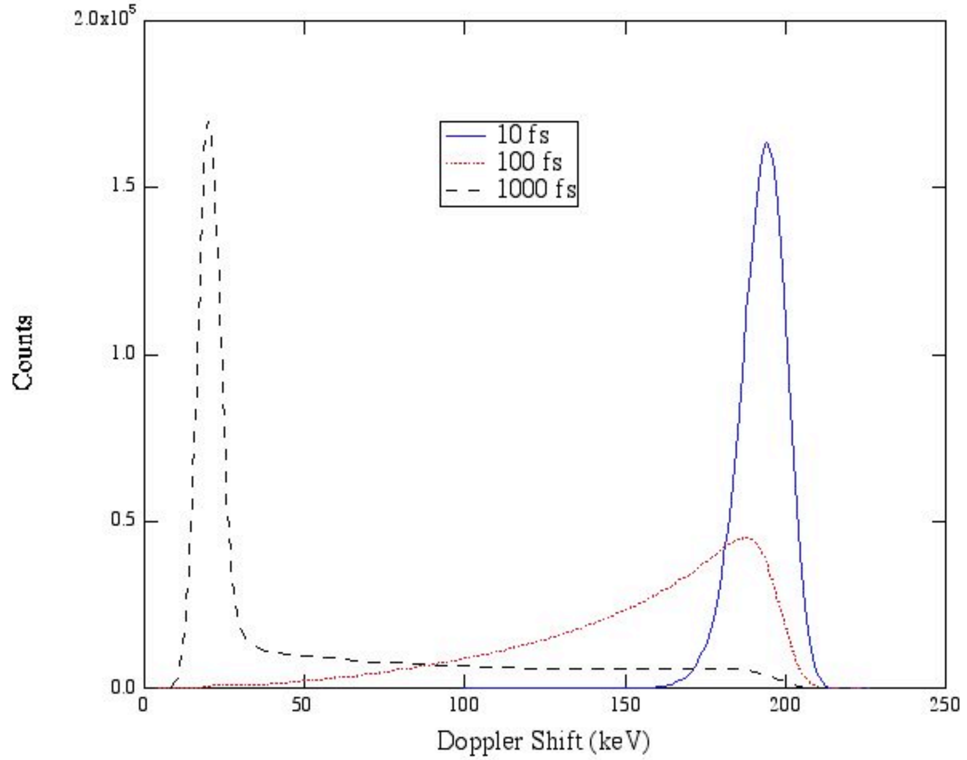
Notre Dame B_α Measurement?

- Recent PRL from Tan et al. claims to detect α decay from states below $E_x = 4.5$ MeV
- Data do not warrant claim
- Background poorly understood and modeled
- Statistical analysis flawed
- Reported branching ratios of 4.03, 4.14/4.20, and 4.38 MeV states are unreliable
- KVI data have highest sensitivity

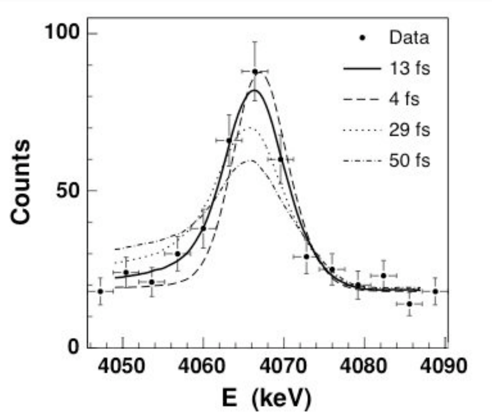


Lifetime Measurements

- Lifetimes measured via Doppler shift of emitted γ rays
- Fast decay ⇒ large Doppler shift, slow decay ⇒ small Doppler shift
- Shapes of detected γ ray lines yield lifetime; sensitive to fs lifetimes



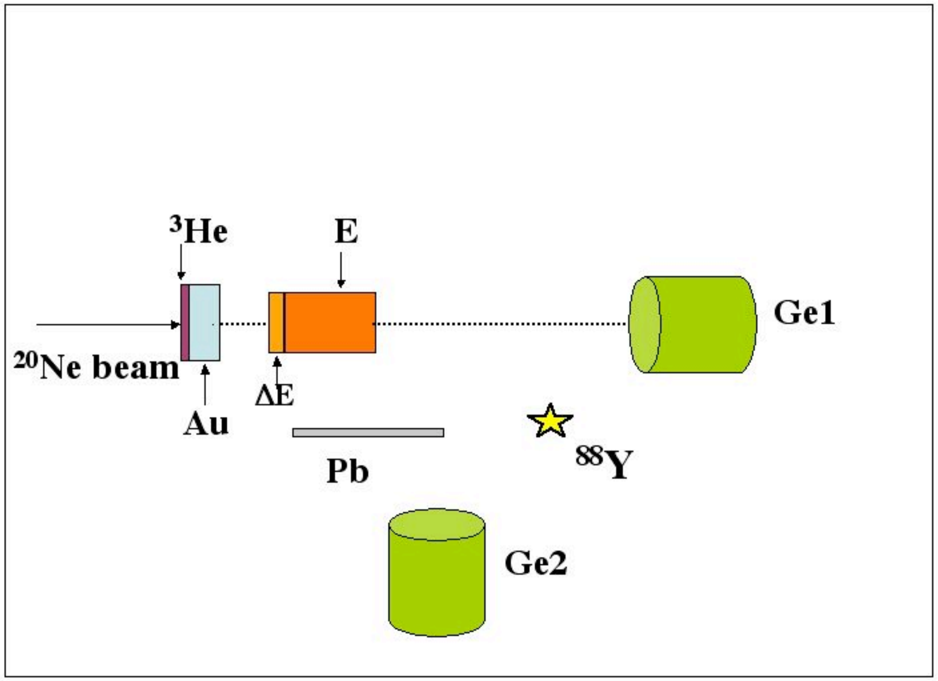
Notre Dame Data: $^{17}O + ^{3}He \rightarrow ^{19}Ne + n$



Measured ten lifetimes, precisely determined transition energies
Lifetime of 4.03 MeV state = 13 (+ 9, - 6) fs

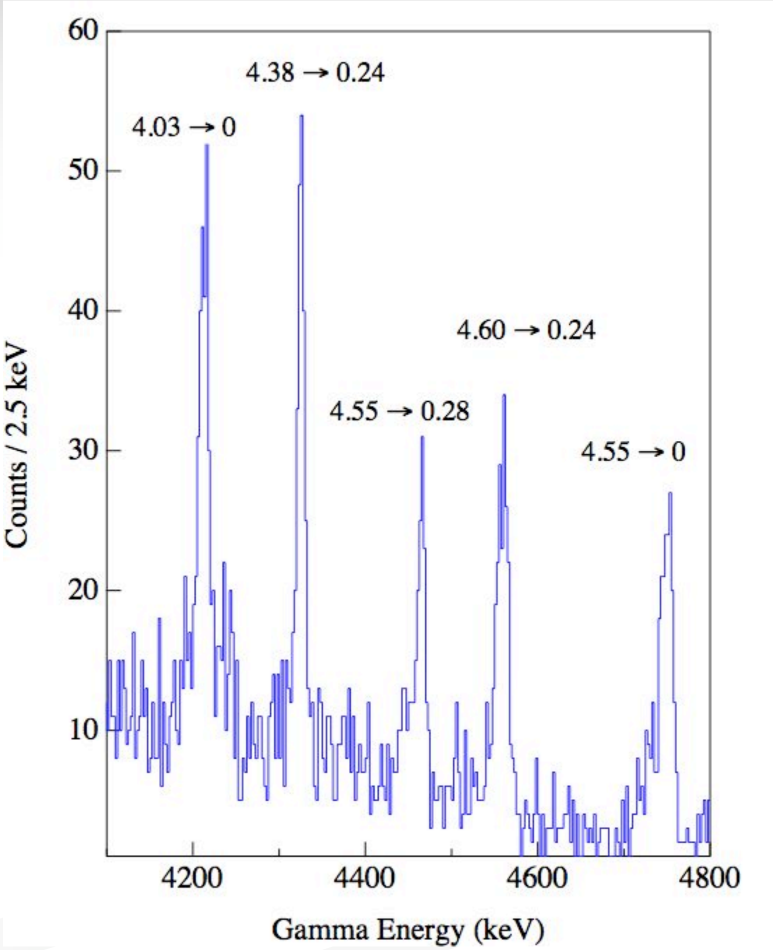
TRIUMF Measurement

- ^{3}He-implanted gold foil target
- ^{20}Ne + ^{3}He → ^{19}Ne + α
- α particles detected in Si Δ E-E telescope
- ^{19}Ne emits a γ ray after slowing down in gold foil
- Detect Doppler-shifted de-excitation γ rays from ^{19}Ne states



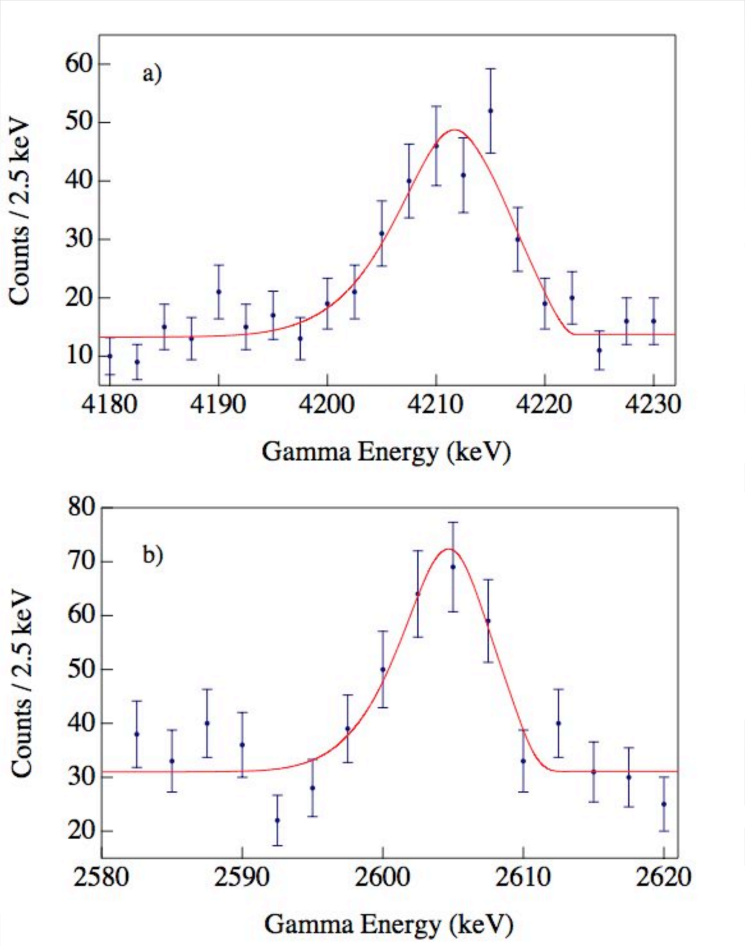
TRIUMF Data

- Measured lifetimes of 6 states above α threshold
- Two states observed via two transitions, other states only seen in one transition
- In general, lifetimes are consistent with and more precise than Notre Dame measurements

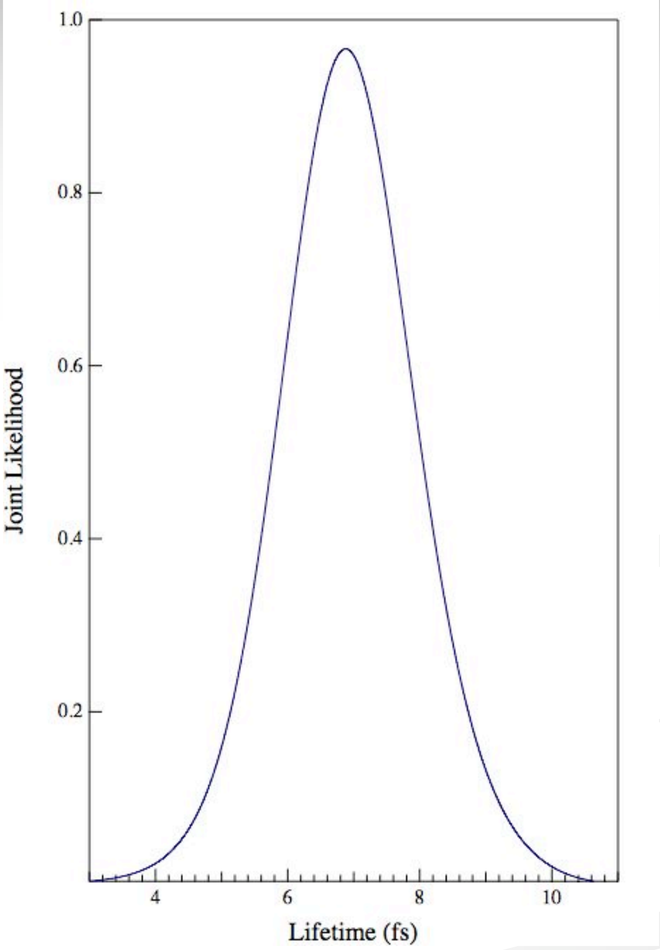


Transitions of 4.03 MeV State

- Two transitions observed, direct to ground state and also to 1536 keV state
- Two inferred lifetimes are mutually consistent

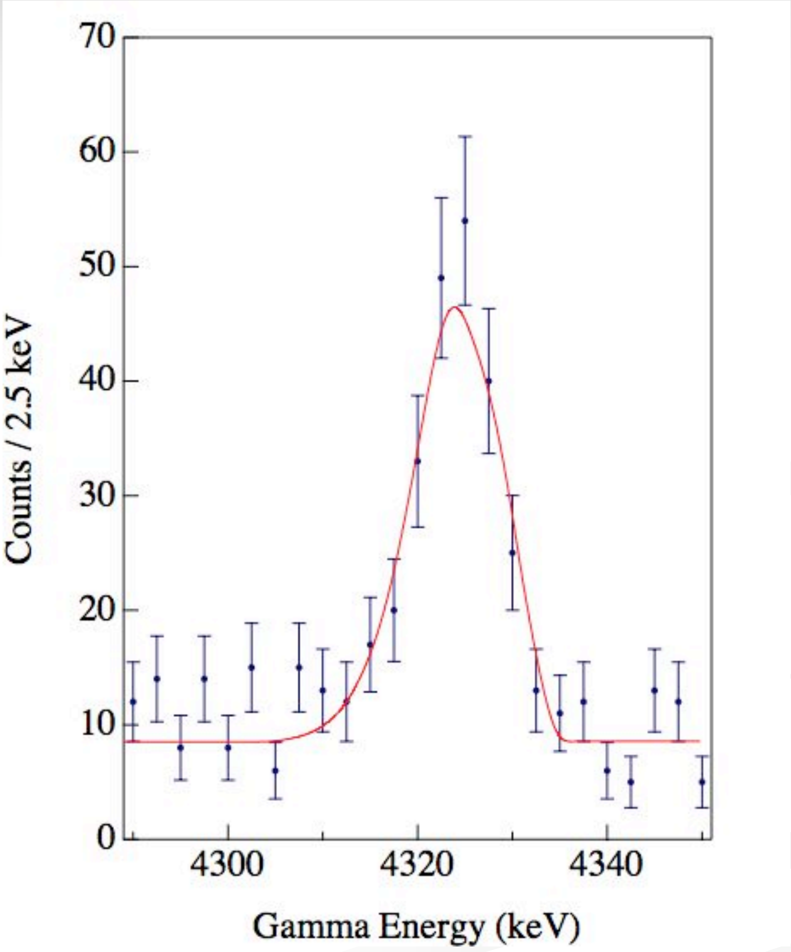


Lifetime of 4.03 MeV State



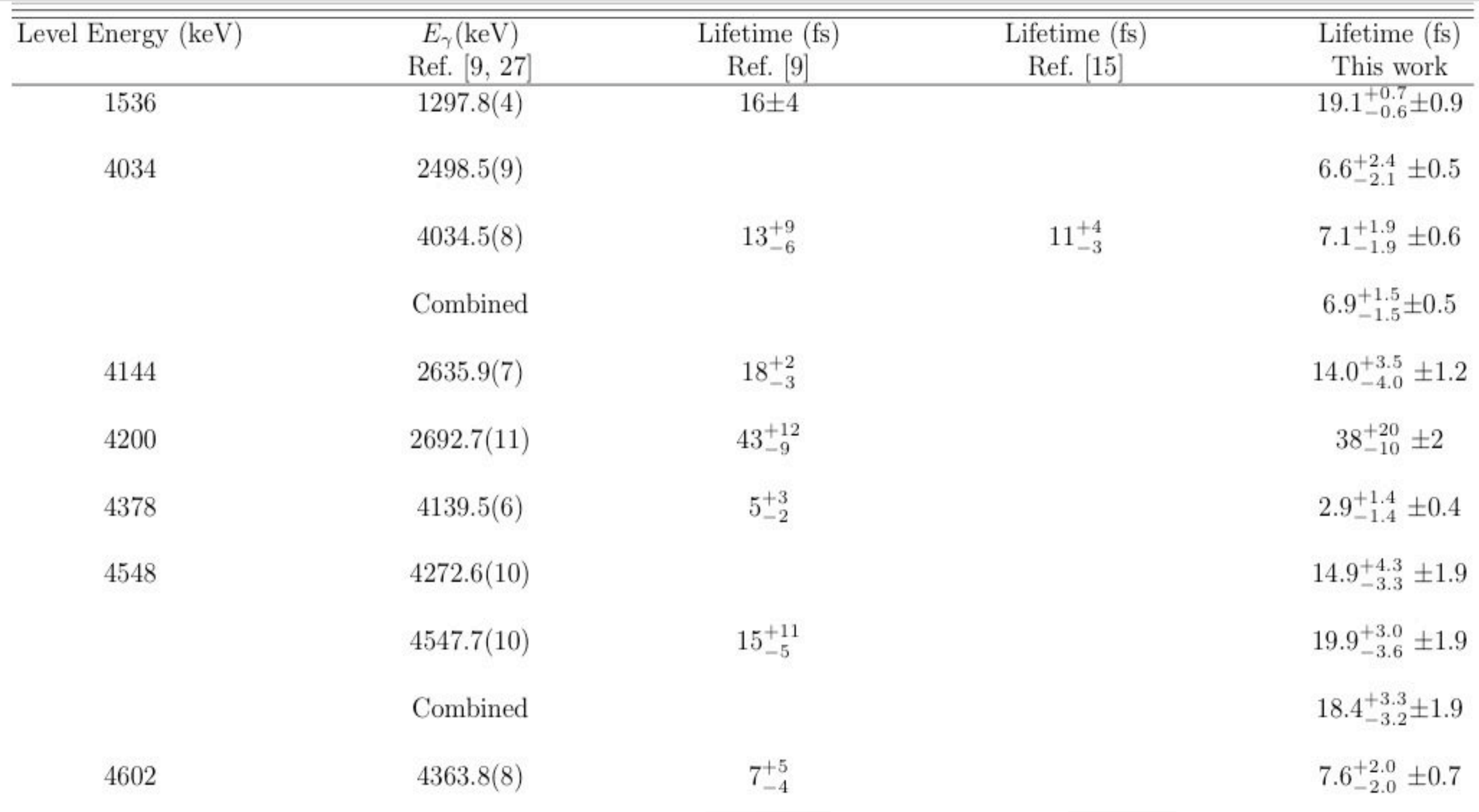
Joint likelihood analysis of two transitions yields
$\tau = 6.9 \pm 1.5$ (statistical) ± 0.5 (systematic) fs

Lifetime of 4.38 MeV State



τ = 2.9 ± 1.4 (statistical) ± 0.4 (systematic) fs

Comparison of Notre Dame and TRIUMF Lifetime Measurements



Level Energy (keV)	E_γ(keV) Ref. [9, 27]	Lifetime (fs) Ref. [9]	Lifetime (fs) Ref. [15]	Lifetime (fs) This work
1536	1297.8(4)	16±4		$19.1^{+0.7}_{-0.6}\pm0.9$
4034	2498.5(9)			$6.6^{+2.4}_{-2.1}\pm0.5$
	4034.5(8)	13^{+9}_{-6}	11^{+4}_{-3}	$7.1^{+1.9}_{-1.9}\pm0.6$
	Combined			$6.9^{+1.5}_{-1.5}\pm0.5$
4144	2635.9(7)	18^{+2}_{-3}		$14.0^{+3.5}_{-4.0}\pm1.2$
4200	2692.7(11)	43^{+12}_{-9}		$38^{+20}_{-10}\pm2$
4378	4139.5(6)	5^{+3}_{-2}		$2.9^{+1.4}_{-1.4}\pm0.4$
4548	4272.6(10)			$14.9^{+4.3}_{-3.3}\pm1.9$
	4547.7(10)	15^{+11}_{-5}		$19.9^{+3.0}_{-3.6}\pm1.9$
	Combined			$18.4^{+3.3}_{-3.2}\pm1.9$
4602	4363.8(8)	7^{+5}_{-4}		$7.6^{+2.0}_{-2.0}\pm0.7$

$^{15}O(\alpha,\gamma)^{19}Ne$: Status

- Lifetimes are now well measured
- B_α of important low-lying states @ 4.03 and 4.38 MeV still only constrained from above by upper limits
- Combining best experimental measurements, upper limit on reaction rate still much larger (~100 times) than theoretical lower limit
- New theoretical upper limit from Cooper and Narayan 2006: find that bursts would be observed from rapidly accreting neutron stars from which only stable burning is seen, if reaction rate were more than ~ 1/25 of experimental upper limit
- Theoretical bounds on rate are presently tightest (if they are to be believed)
- More sensitive B_α measurements required to make further progress

Credits

- Jacob Fisker, Lawrence Livermore National Lab (x-ray burst calculations)
- Wanpeng Tan, University of Notre Dame (lifetime measurements)
- Mythili Subramanian, TRIUMF and University of British Columbia (lifetime measurements)