Experimental study of the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction for understanding type I X-ray bursts

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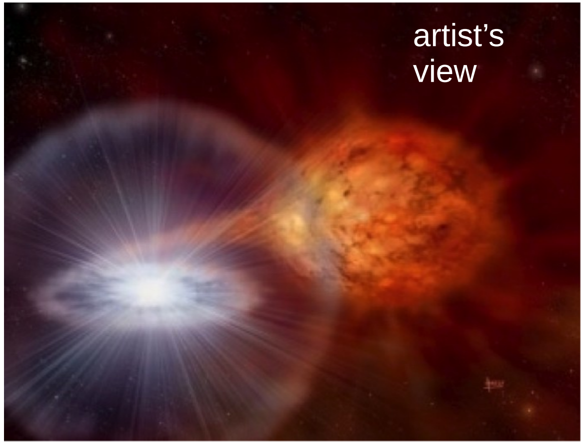
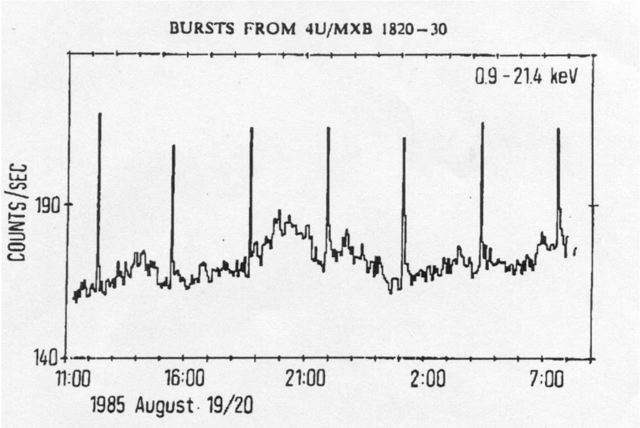
Type I X-ray bursts in a nutshell

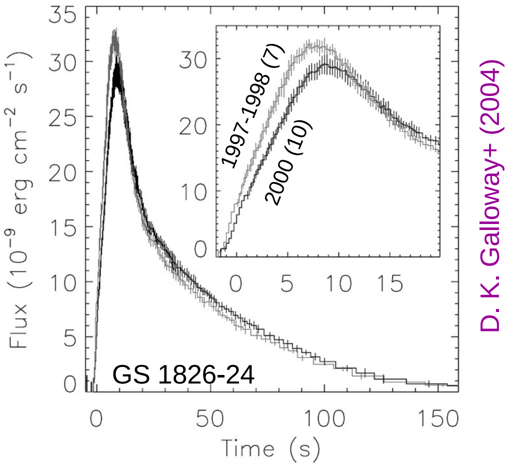
Thermonuclear runaway at the surface of an accreting neutron star (NS) in a close binary system



Recurrent flashes [e.g. 4U/MXB 1820-30]



Precision era for X-ray observations



Type I X-ray outbursts

- Very fast rise times: 2 – 10 s
- L_{peak} ~ 10^{38} erg s^{-1}
  (ccSN L_{peak} ~ 10^{51} erg.s^{-1})
- Short duration: 10 – 100 s
- Recurence time: ~ hours – days
- Mass ejected: maybe (?)

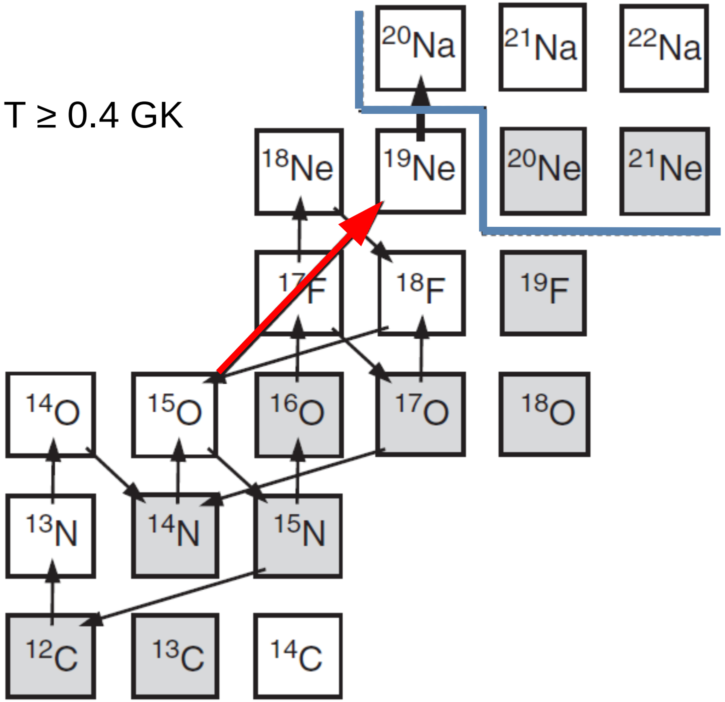
Y. Herrera+ (2023)

Understand the light curves: one of the most important challenge

- Sensitive to NS spin frequency (oscillations in rise part of light curve) S. Bhattacharyya+ (2007)
- Sensitive to NS mass-radius relation (tail of light curve) J. Nattila+ (2017)
- **Very sensitive to nuclear inputs**

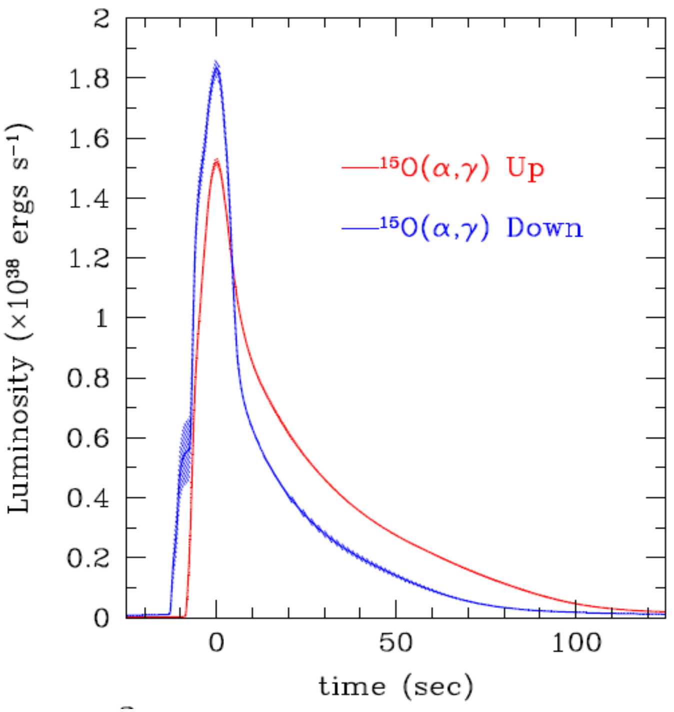
Hot CNO cycle break-out and the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction

$^{15}O(\alpha,\gamma)^{19}Ne$ provides a way to break out from hot CNO cycle



$^{15}O(\alpha,\gamma)^{19}Ne$ affects the onset and shape of the burst light curve

Parikh+ ApJ (2013), Cyburt+ ApJ (2016)

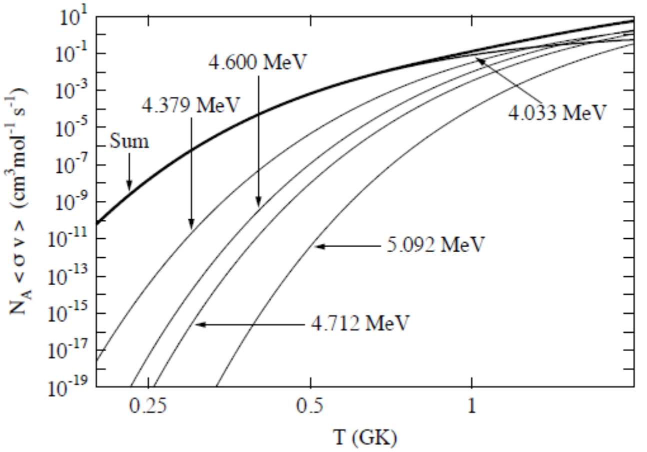


Cyburt+ 2016

- **$^{15}O(\alpha,\gamma)^{19}Ne$** much slower than $^{19}Ne(p,\gamma)^{20}Na$

State of the art for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction

Thermonuclear reaction rate



B. Davids+ (2003)

- Dominant state at E_x = 4.033 MeV
  (E_R = 505 keV; $J^\pi = 3/2^+$; $\ell_\alpha = 1$)
- Resonance strength

$$\omega\gamma \approx 0.5 \times (2J_R + 1)\,\Gamma_\alpha$$

Key experimental target for more than 3 decades

Previous works

$$\Gamma_\alpha = \frac{\Gamma_\alpha}{\Gamma} \times \Gamma = B_\alpha \times \Gamma$$

- Measurement of α branching ratio B_α
- Measurement of state lifetime $\tau \propto 1/\Gamma$

Lifetime measurement (DSAM)

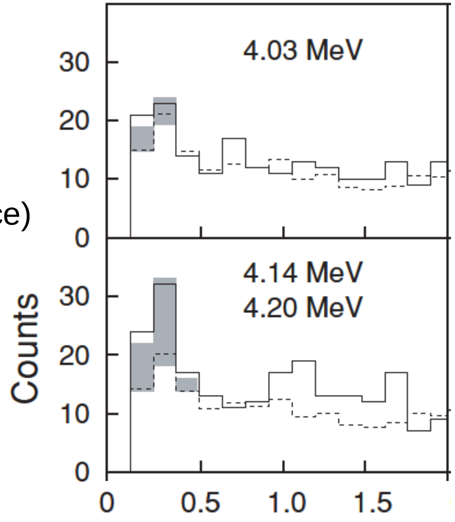
- Tan+ (2005) 13^{+9}_{-6} fs
- Kanungo+ (2006) 11^{+4}_{-3} fs
- Mythili+ (2008) $6.5 \pm 1.6 \pm 0.7$ fs

Agreement within 1σ

α-particle branching ratio

- Davids+ (2003) $\leq 4.3 \times 10^{-4}$
- Tan+ (2007,2009) $2.9 \pm 2.1 \times 10^{-4}$

  (**consistent with 0** at 90% confidence)



Tan+ (2009)

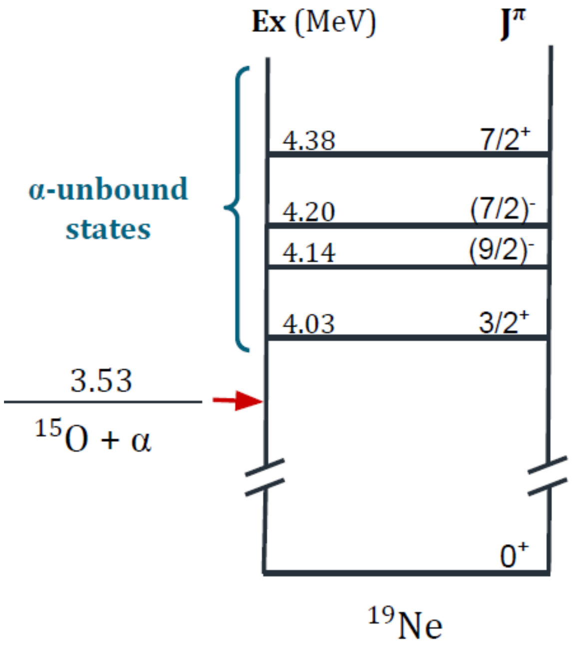
α-particle width

- $\Gamma_\alpha = 17 \pm 13\,\mu eV$ Tan+ (2009)
- $\Gamma_\alpha = 24 \pm 18\,\mu eV$ Fortune+ (2010)

  (combining lifetime measurements)

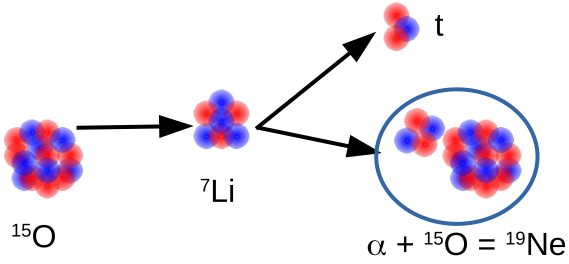
The ^{7}Li(^{15}O,t)^{19}Ne α-particle transfer reaction

Transfer reactions are a privileged tool to determine partial widths



- α-particle transfer reactions commonly use **(^{7}Li,t) reactions [^{7}Li = α + t]**
- **Inverse kinematics** since ^{15}O is radioactive ($T_{1/2}$ = 122 s)

  [not possible to produce targets]



- Comparison between experimental and theoretical differential cross-section

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S_\alpha \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

- α-particle partial width: $\Gamma_\alpha = C^2 S_\alpha \times \Gamma_\alpha^{s.p.}$ → Theoretical calculation

The MUGAST + VAMOS + AGATA experimental set-up

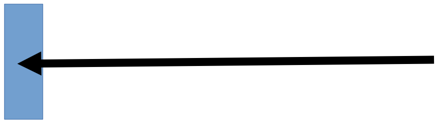
J. Sanchez Rojo (2022 PhD)

$^{7}Li(^{15}O,t)^{19}Ne^{*} \rightarrow \gamma + {}^{19}Ne_{g.s.}$

laboratoire commun CEA/DRF CNRS/IN2P3

^{15}O @ 4.7 MeV/u

- ~ 10^{7} pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %



^{7}LiF target
1.25 mg/cm^{2}
+ ^{nat}C 20 μg/cm^{2}

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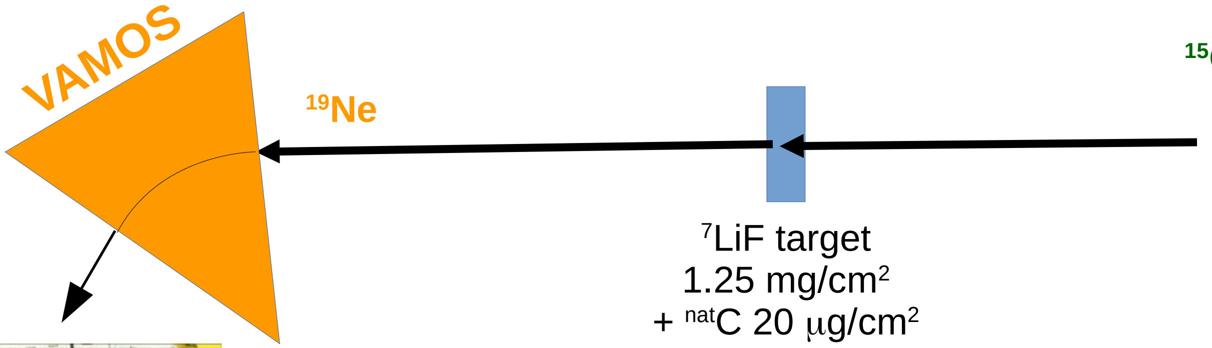

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VAMOS @ 0°

- $\Delta\Theta \pm 7°$
- $\Delta B\rho \pm 5\%$

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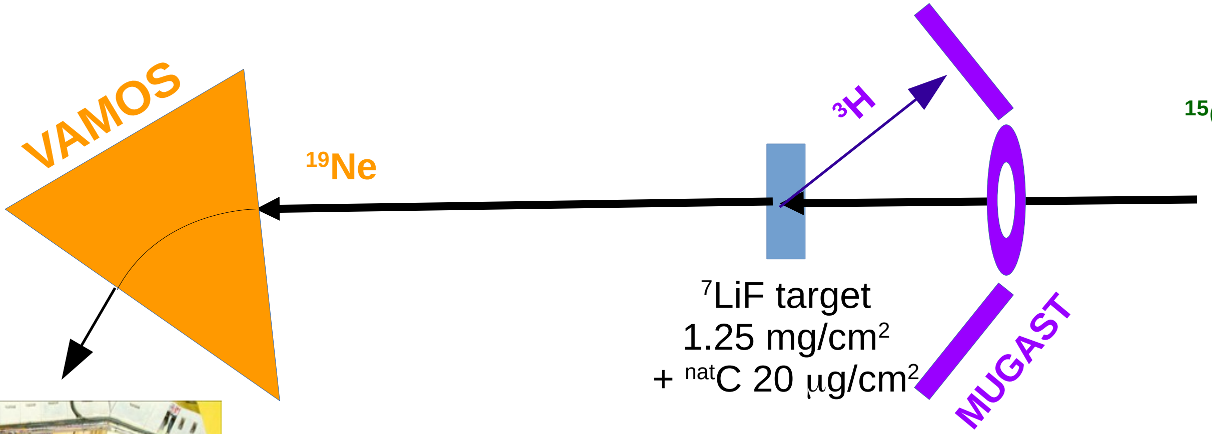

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VAMOS @ 0°

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MUGAST

- DSSSD 500 μm
- Trapezoid (x5), annular (x1), square (x2)
- 128+128 strips

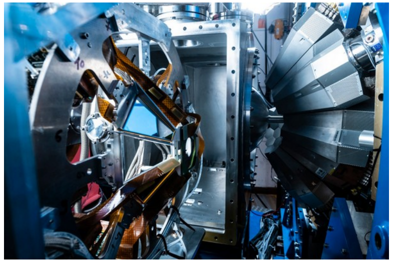
The MUGAST + VAMOS + AGATA experimental set-up

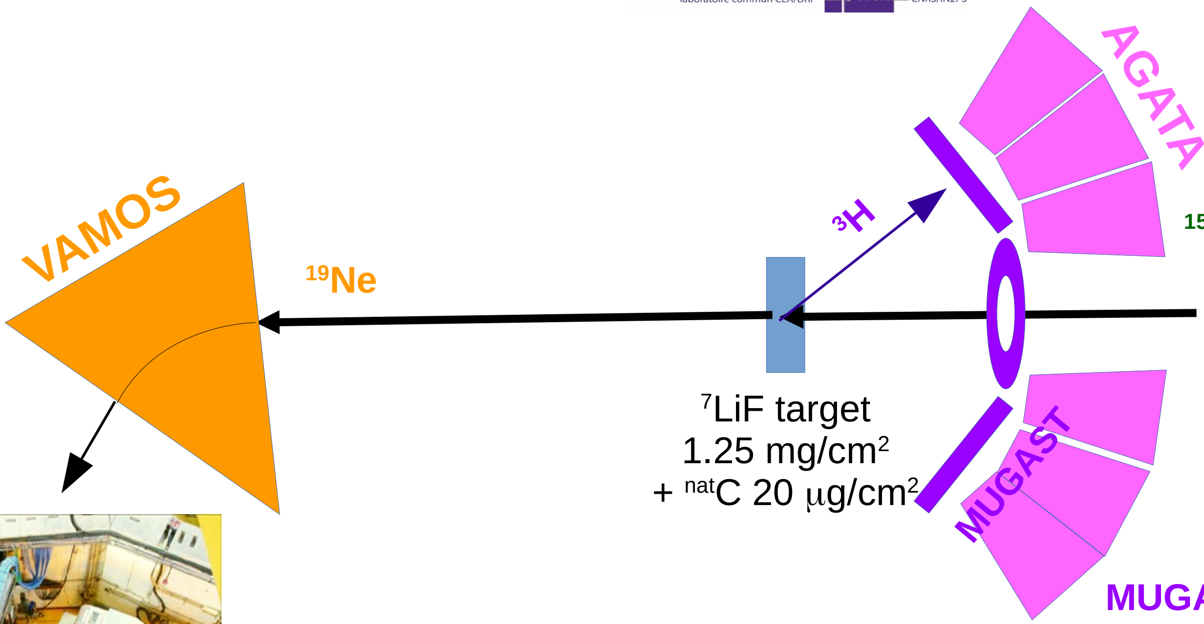
$^{7}\mathrm{Li}(^{15}\mathrm{O},t)^{19}\mathrm{Ne}^{*} \rightarrow \gamma + {}^{19}\mathrm{Ne}_{g.s.}$

J. Sanchez Rojo (2022 PhD)

AGATA @ 18 cm

- 37 crystals
- ε(1 MeV) ~ 8% w/ add-back





^{15}O @ 4.7 MeV/u

- ~ 10^{7} pps
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VAMOS @ 0°

- ΔΘ ± 7°
- ΔBρ ± 5%

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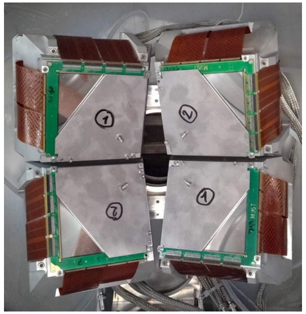
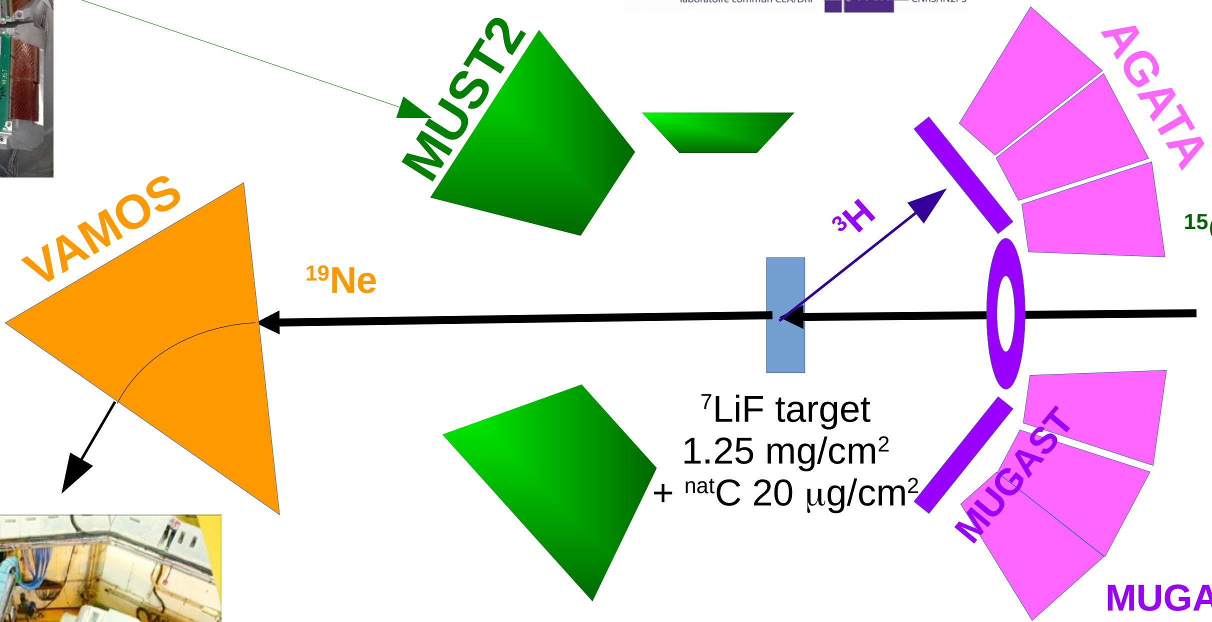


MUST2

- DSSSD 300 μm + CsI
- 128+128 strips (10x10 cm²)



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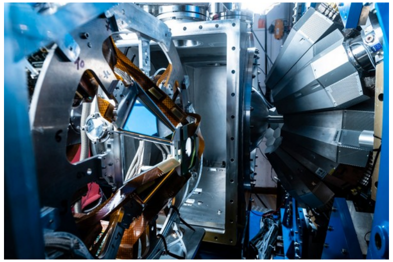

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- ~ 10^{7} pps
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VAMOS @ 0°

- ΔΘ ± 7°
- ΔBρ ± 5%

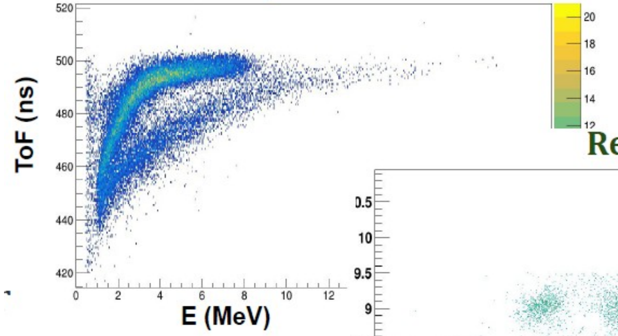
MUGAST

- DSSSD 500 μm
- Trapezoid (x5), annular (x1), square (x2)
- 128+128 strips

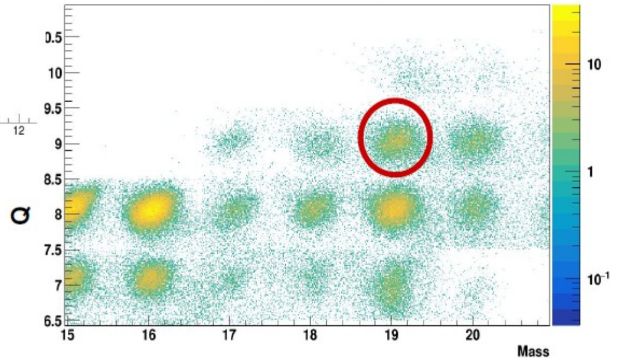
Particle identification

- VAMOS spectrometer (recoils)
  - Good selectivity of recoils: A, Z, Q
  - ^{19}Ne well identified
  - Crucial for background rejection
- MUGAST (light ejectiles)
  - Identification of tritons
  - Crucial for angular distribution
- AGATA (γ-rays)
  - Very good selectivity
  - High energy resolution (after Doppler correction)
  - → FWHM 10 keV (@ 1 MeV); 40 keV (@ 4 MeV)

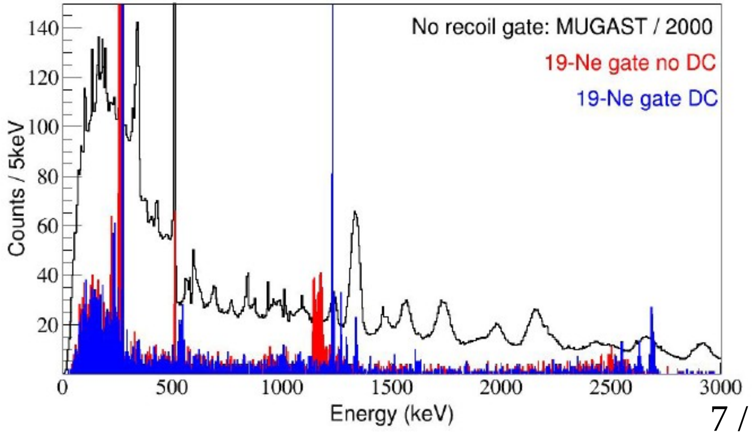
Light ejectiles (MUGAST)



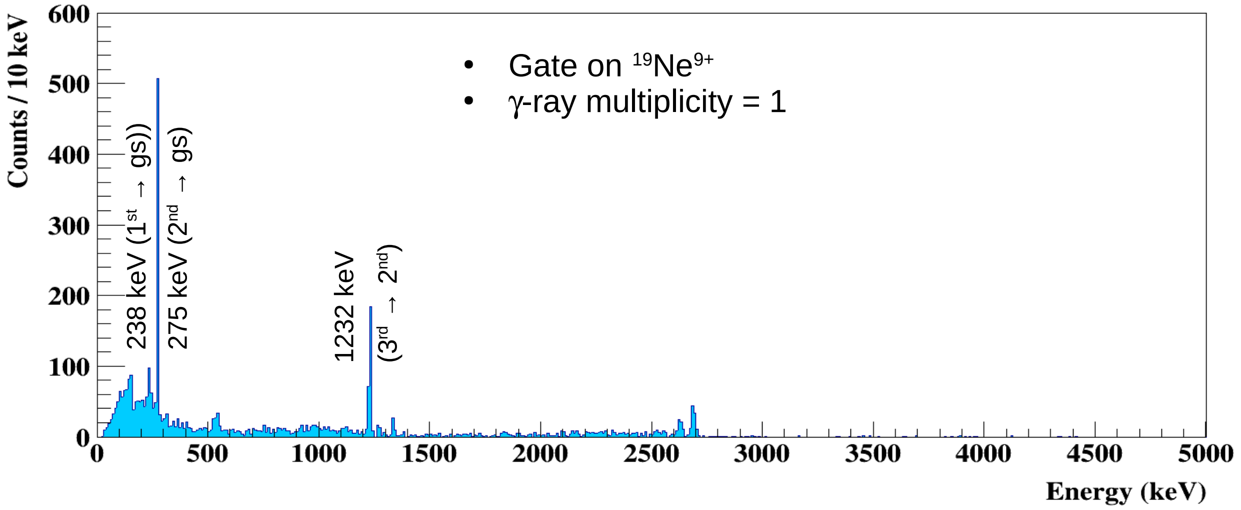
Recoils (VAMOS)



γ-rays (AGATA)



^{19}Ne – tritons – γ triple coincidences



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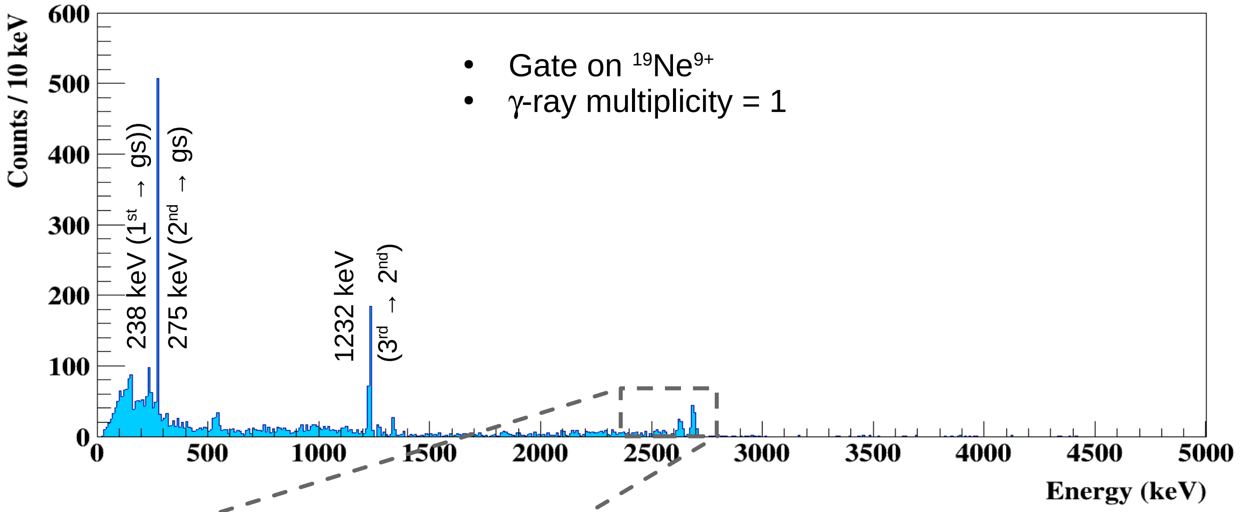
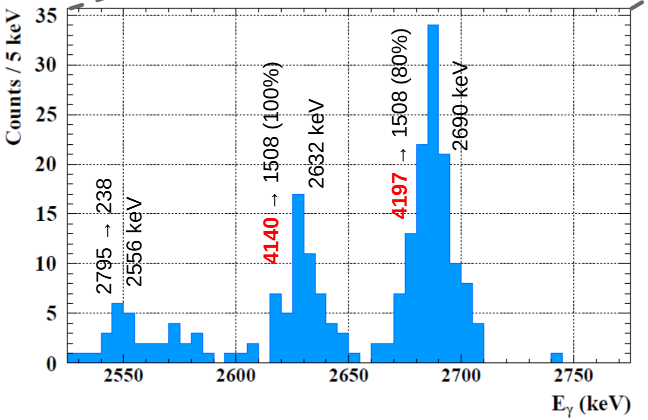


γ-ray transitions from the doublet at 4140 keV and 4197-keV



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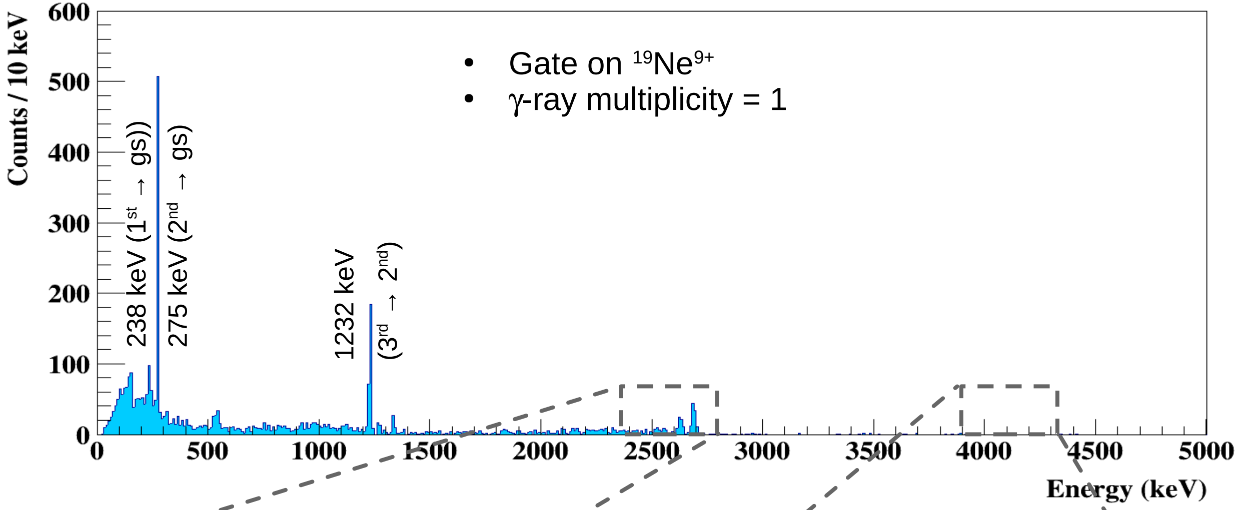

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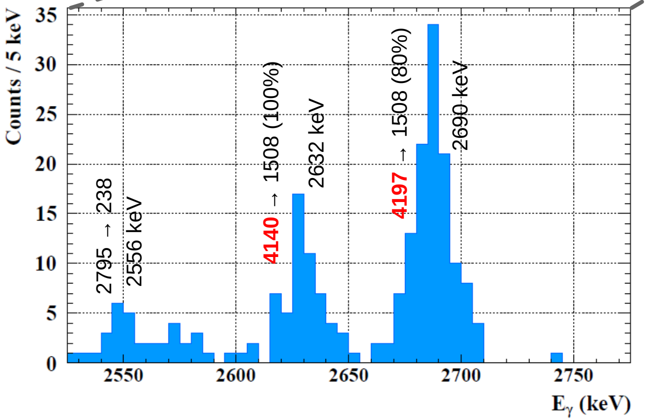
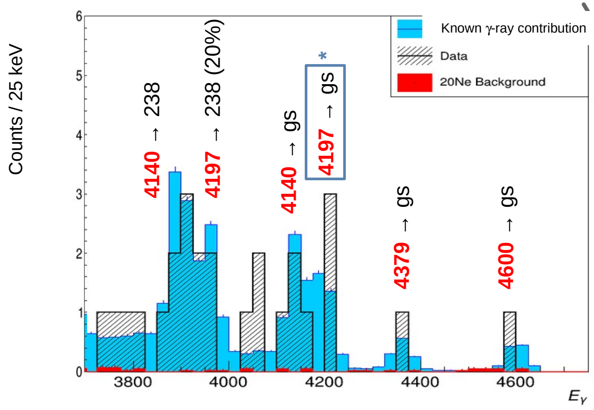


4033 keV state: $N = 2.2^{+2.9}_{-1.6}$ (1σ CL)

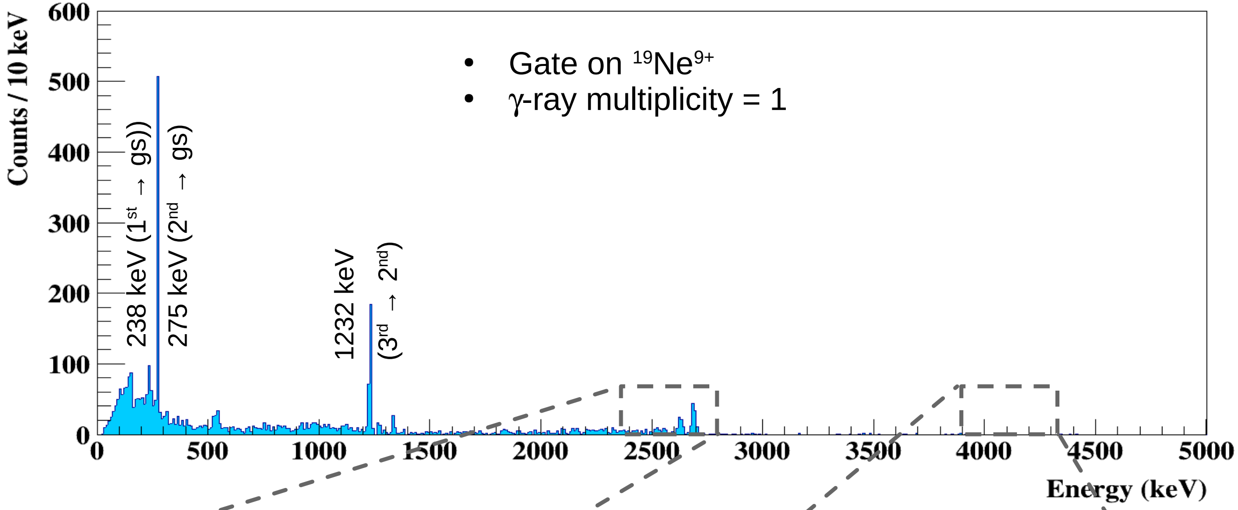


Source of background

- Compton events from high-energy γ-ray lines
- Small leaking (2.3%) of ^{20}Ne in VAMOS ^{19}Ne^{9+} selection

* new transition

^{19}Ne – tritons – γ triple coincidences



- Gate on $^{19}Ne^{9+}$
- γ-ray multiplicity = 1

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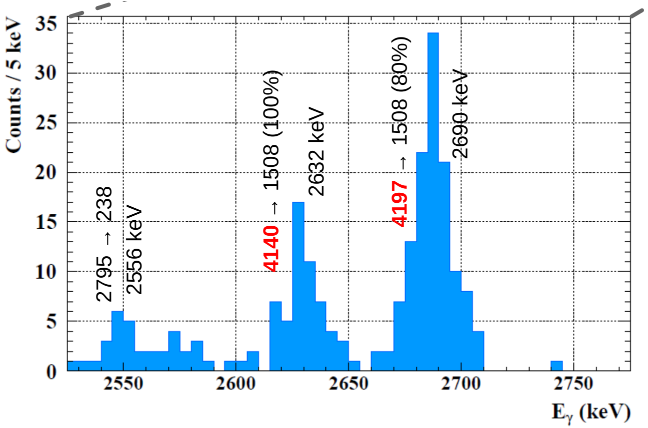

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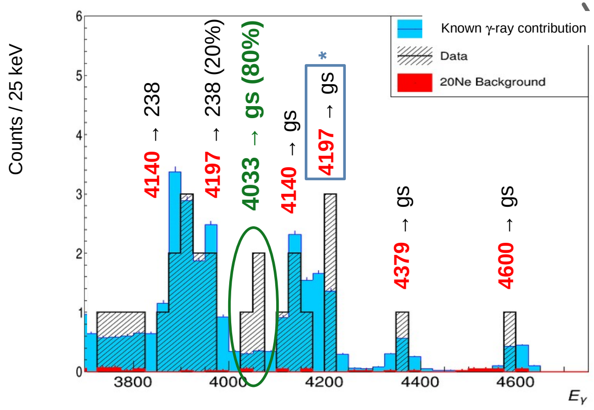

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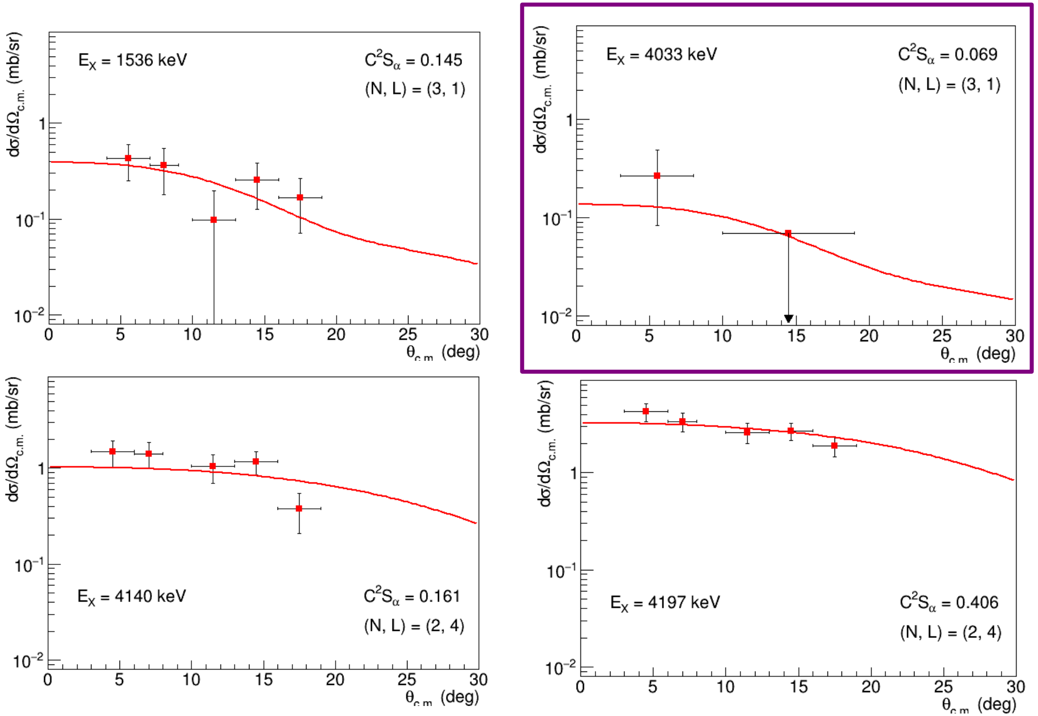
Angular distributions and α-particle spectroscopic factors



Comparison with analog states in ^{19}F

Preliminary

		^{19}Ne		^{19}F	
J$^\Pi$	Q=2N+L	E_x (keV)	C^2S_α	E_x (keV)	C^2S_α [a]
5/2-	8	1508	**0.25**	1346	0.20
3/2+	7	1536	**0.15**	1554	0.21
3/2-	8	1615	**0.23**	1459	0.20
9/2+	7	2794	**0.22**	2780	0.16
3/2+	7	**4033**	**0.064**	3908	≤ 0.09
(7/2-)	8	4140	**0.16**	3999	0.29
(9/2-)	8	4197	**0.41**	4033	
7/2+	7	4379		4378	
		4549		4556	
(5/2+)	7	4600		4550	

[a] F. de Oliveira Santos et al. (1996)

FR-DWBA analysis (FRESCO)

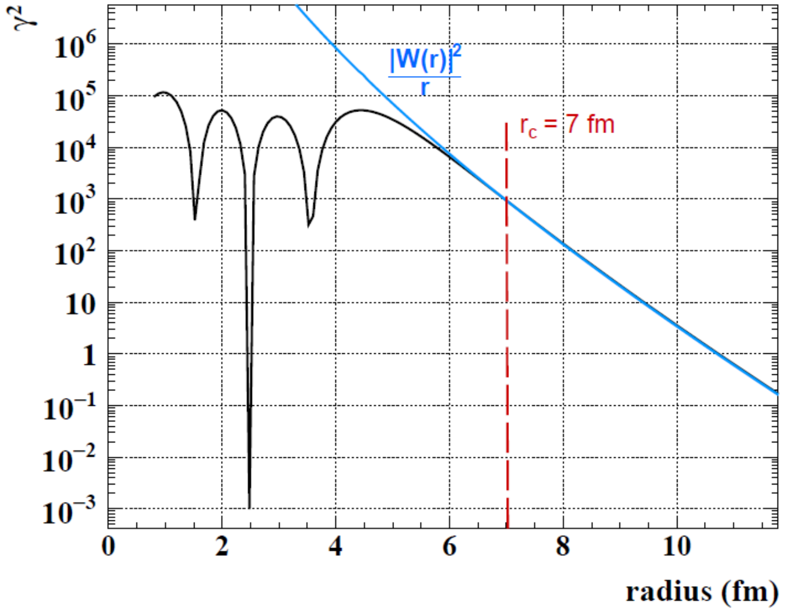
- Optical potentials from mirror reaction: ^{15}N(Li,t)^{19}F
  F. de Oliveira Santos et al. (1996)
- C^2S_α determination: prescription from Becchetti+ (1978)
  - $L \geq 2$: α-cluster bound by 50 keV
  - $L < 2$: C^2S_α extrapolation to actual α-separation energy
- Uncertainty due to optical potential ~ 40%

- Good agreement with analog states
- Small C^2S_α for the E_x(^{19}Ne) = 4033 keV state
- C^2S_α determined for the 2 components of the E_x(^{19}Ne) = 4140 + 4197 keV doublet

α-particle partial widths in ^{19}Ne

Determination of Γ_α for ^{19}Ne unbound states

- $\Gamma_\alpha = 2P_l(r, E_r)\dfrac{\hbar^2 r}{2\mu}C^2 S_\alpha|\phi(r)|^2$
- Radius determined when asymptotic behavior of α + ^{15}O radial wave function is reached



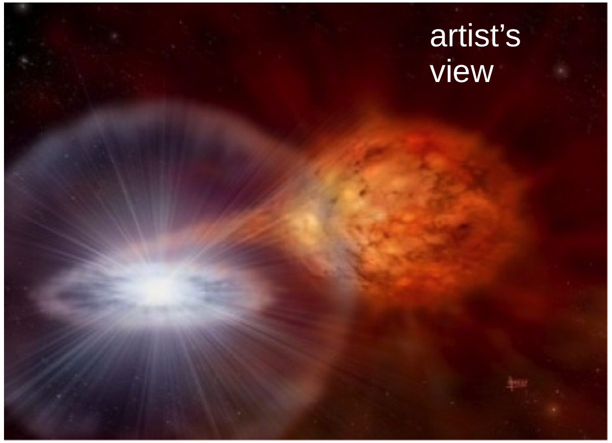
Comparison with existing data Preliminary

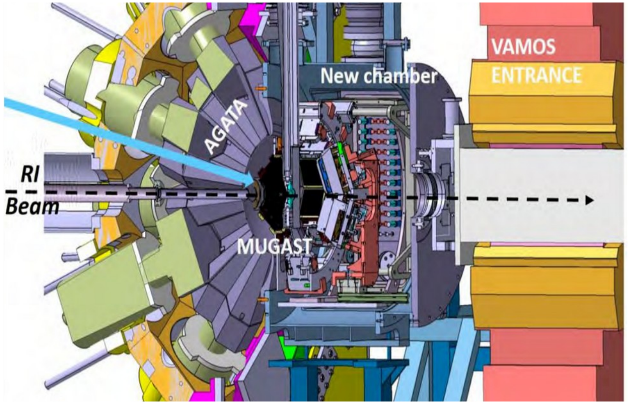
	Present work		Tan+ (2009)			Fortune+ (2010)	
E_x (keV)	Γ_α (μeV)	B_α (x 10^{-4})	Γ_α (μeV)	B_α (x 10^{-4})	τ (fs)	Γ_α (μeV)	τ (fs)
4033	**11.0 (4.4)**		**17 (13)**	2.9 (2.1)	13^{+9}_{-6}	**24 (18)**	7.9 (1.5)
4140	**1.0 (0.4)**	0.3 + 8.2	**44 (20)**	**12 (5)**	18^{+2}_{-3}		
4197	**12.6 (5.2)**		**18 (9)**		43^{+12}_{-9}		

- 4033 keV state: Γ_α = 11.0 ± 4.3 μeV
  (so far, uncertainty from DWBA only)
- 4140 keV + 4197 keV doublet
  → α-particle partial width for each component

compatible with existing results BUT obtained from a direct determination of the α-particle width

Summary





- $^{15}O(\alpha,\gamma)^{19}Ne$ is one of the key hot-CNO break-out reaction playing a crucial role in Type I X-ray bursts
- Thermonuclear reaction rate dominated by the 4.033 MeV state in ^{19}Ne for $T_9 > 0.4$
- The $^{7}Li(^{15}O,t)^{19}Ne^{*}(\gamma)^{19}Ne_{g.s.}$ was studied using the MUGAST + VAMOS + AGATA experimental setup at GANIL
- Alpha-particle widths were determined using an alpha-particle transfer reaction in inverse kinematics for the first time
  - 4033 keV strength compatible with previous determinations
  - 4140 + 4197 keV: individual contribution determined