Experimental determination of reaction rates in Classical Novae and X-ray bursts

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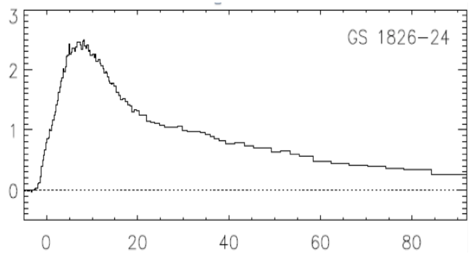
Outline

1. Explosive hydrogen burning
   a) Classical novae
   b) X-ray bursts
2. Thermonuclear reaction rates
3. Classical novae: the $^{18}F(p,\alpha)^{15}O$ case
4. X-ray bursts: the $^{15}O(\alpha,\gamma)^{19}Ne$ case

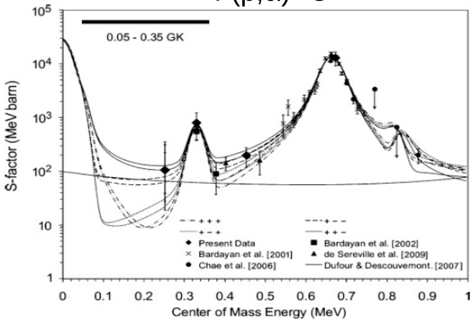
Classical nova

Nova Cygni 1992, HST

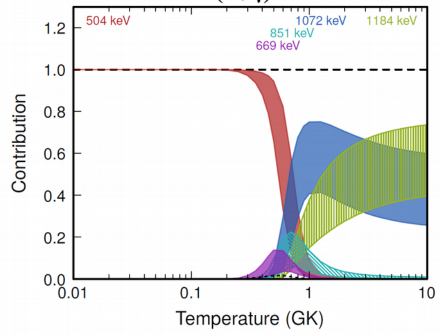


X-ray burst light curve

$^{18}F(p,\alpha)^{15}O$



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



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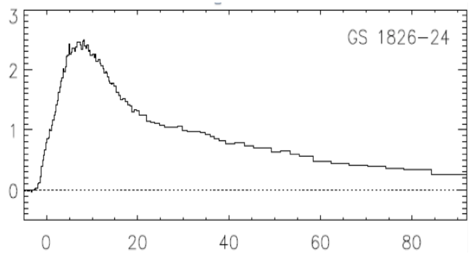

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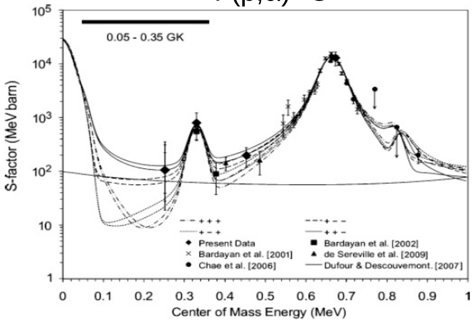
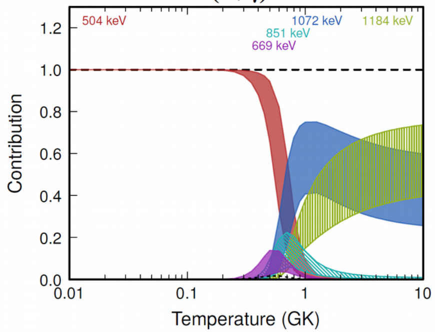


$^{15}O(\alpha,\gamma)^{19}Ne$



Explosive hydrogen burning in binary systems

Thermonuclear runaways in the white dwarf/neutron star component of close binary systems

Compact object: White Dwarf

Compact object: Neutron star

Classical novae outbursts

- Moderate rise times: < 1 – 2 days
- $L_{peak} \sim 10^4\ L_\odot$
- Recurence time: ~ 10^4 – 10^5 yr
- Frequency: 30 ± 10 yr^{-1}
- Mass ejected: 10^{-5} – 10^{-4} $M_\odot$

  (10^2 – 10^3 $km.s^{-1}$)

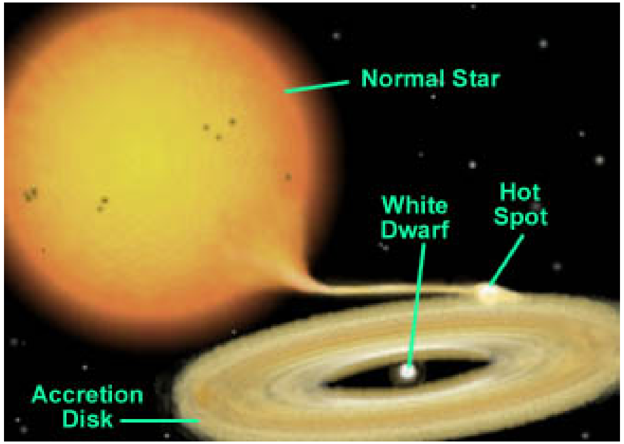
Type I X-ray outbursts

- Very fast rise times: 2 – 10 s
- $L_{peak} \sim 10^{38}$ erg s^{-1}

  (ccSN $L_{peak} \sim 10^{51}$ $erg.s^{-1}$)
- Short duration: 10 – 100 s
- Recurence time: ~ hours – days
- Mass ejected: unlikely

Classical novae explosions

Final evolution of a close binary system



	novae	ccSN
M_{ej} ($M_{\odot}$)	~ 10^{-5}	~ 10
f (yr^{-1} $galaxy^{-1}$)	~ 30	~ 10^{-2}
L ($L_{\odot}$)	~ 10^{5}	~ 10^{11}
Nucleosynthesis	^{13}C, ^{15}N, ^{17}O	"~ all"

Classical novae mechanism

- Accretion of H-rich material at the surface of a white dwarf (WD) from its companion star
- Ignition of the combustion at the base of the envelope in degenerated conditions
- Thermonuclear runaway in convective envelope (T_{peak} ~ 100 – 400 MK)
- Expansion and shell ejection
- Mechanism well established but:

  → ejected mass < observed mass

  → mixing between accreted and WD material

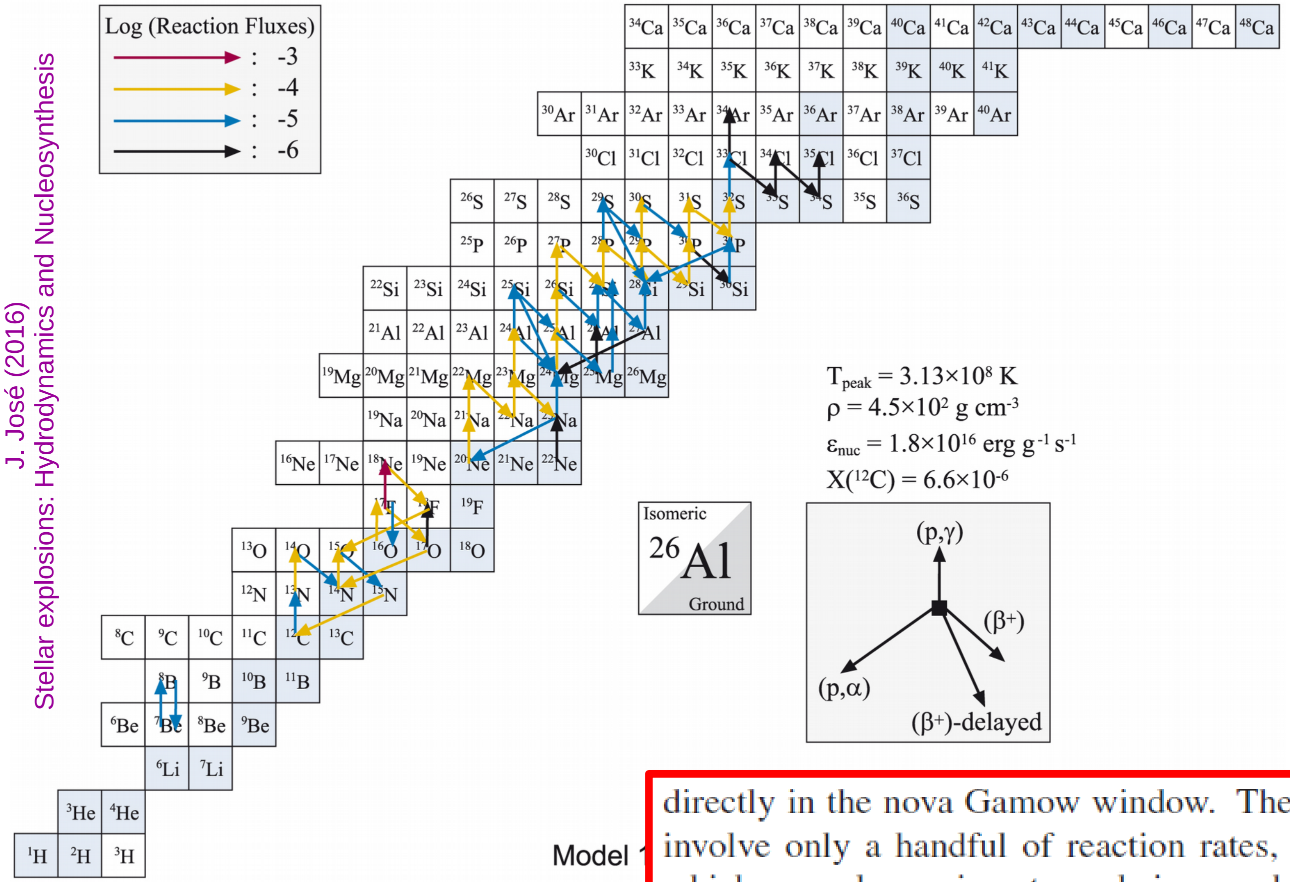
Classical nova

Nova Cygni 1992, HST

Classical novae types

- $^{12}C^{16}O$ and $^{16}O^{20}Ne$ (M_{WD} < 1.35 $M_{\odot}$)
- Different properties (nucleosynthesis...)

Nuclear network and uncertainties



J. José (2016) Stellar explosions: Hydrodynamics and Nucleosynthesis

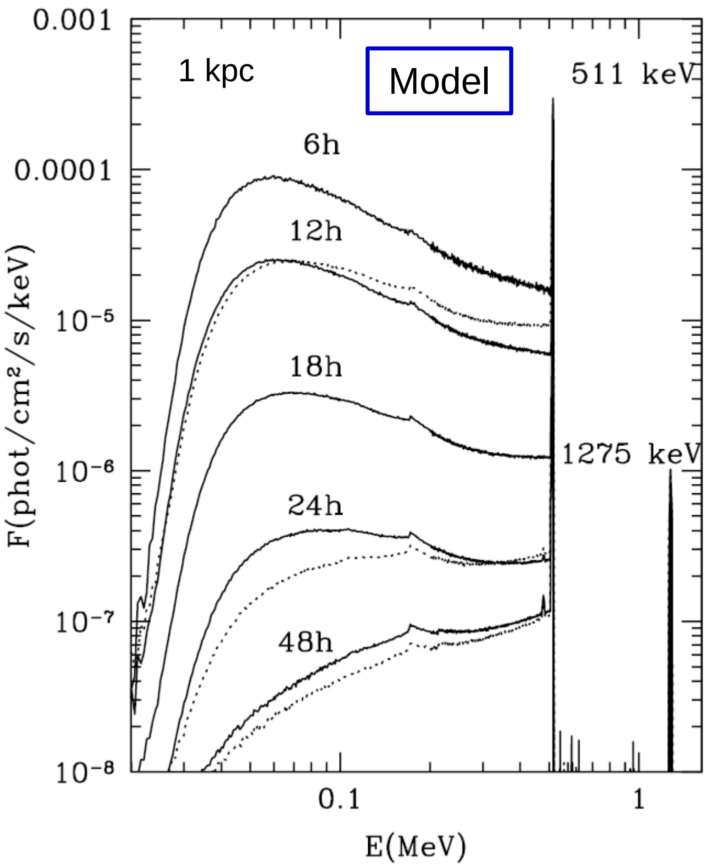
- Main nuclear path close to the valley of stability, and driven by (p,γ), (p,α) and β+ interactions
  - → ~ 100 nuclides
  - → ~ 180 reactions
- End point of nucleosynthesis: Ca
- Sensitivity studies allow to identify key reactions
- First stellar explosions for which all reaction rates will soon be based on experimental information

directly in the nova Gamow window. The remaining uncertainties for nova nucleosynthesis involve only a handful of reaction rates, particularly ^{18}F(p,α), ^{25}Al(p,γ) and ^{30}P(p,γ), for which several experiments are being conducted (or have been proposed) at different facilities

J. José (2007)

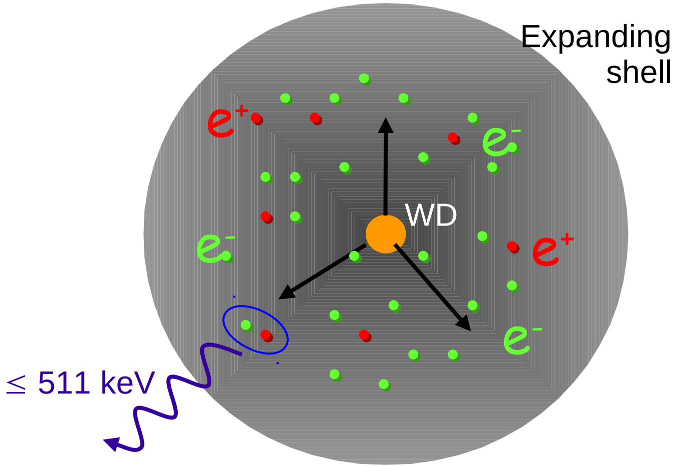
^{18}F – 511 keV line prediction – $^{18}F(p,\alpha)^{15}O$

ONe nova: 1.15 / 1.25 $M_\odot$ (solid/dashed)



M. Hernanz+ (2001)

Classical nova



e^+ - e^- interactions:

- Line @ 511 keV
- Continuum ≤ 511 keV
  - Comptonization
  - $e^+ + e^- \rightarrow 3\gamma$ (positronium)

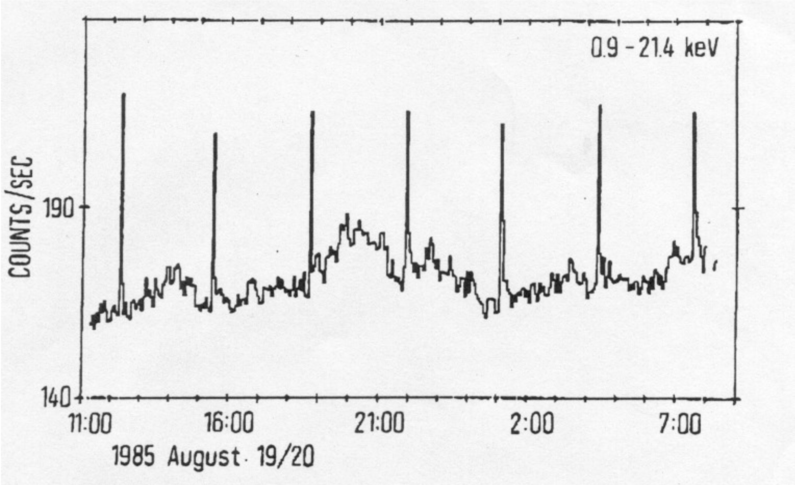
Properties of the expanding envelope

- $T_{1/2}(^{18}F)$ = 110 min
- Similar to the time for the shell to become transparent

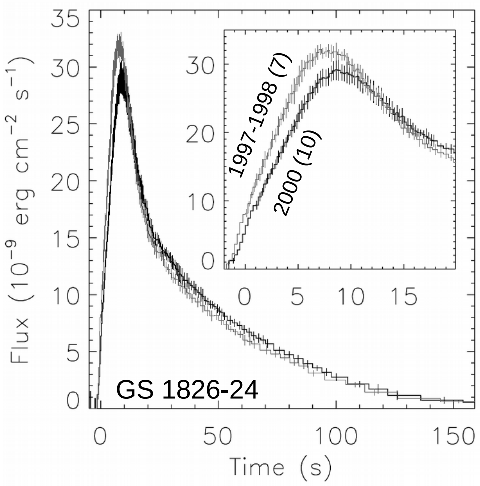
Predicted γ-ray flux directly depends on the $^{18}F(p,\alpha)^{15}O$ reaction

Type I X-ray bursts light curves

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



Precision X-ray observations

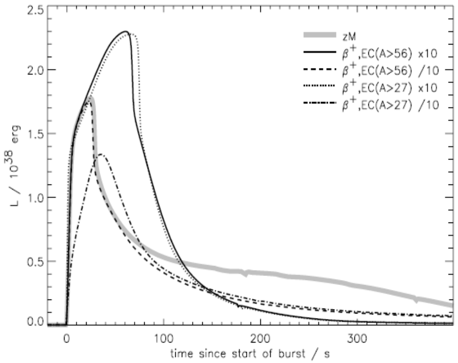


D. K. Galloway+ (2004)

Understand the luminosity profile: one of the most important challenge

- Sensitive to NS spin frequency (oscillations in rise part of light curve)
  → link to 2D flame propagation + NS properties (*M*, *R*)   S. Bhattacharyya+ (2007)
  J. Nattila+ (2017)
- Sensitive to nuclear network
  → composition of burst ashes (superburst) + burst ejecta (?)

Effect of weak rates



S. E. Woosley+ (2004)

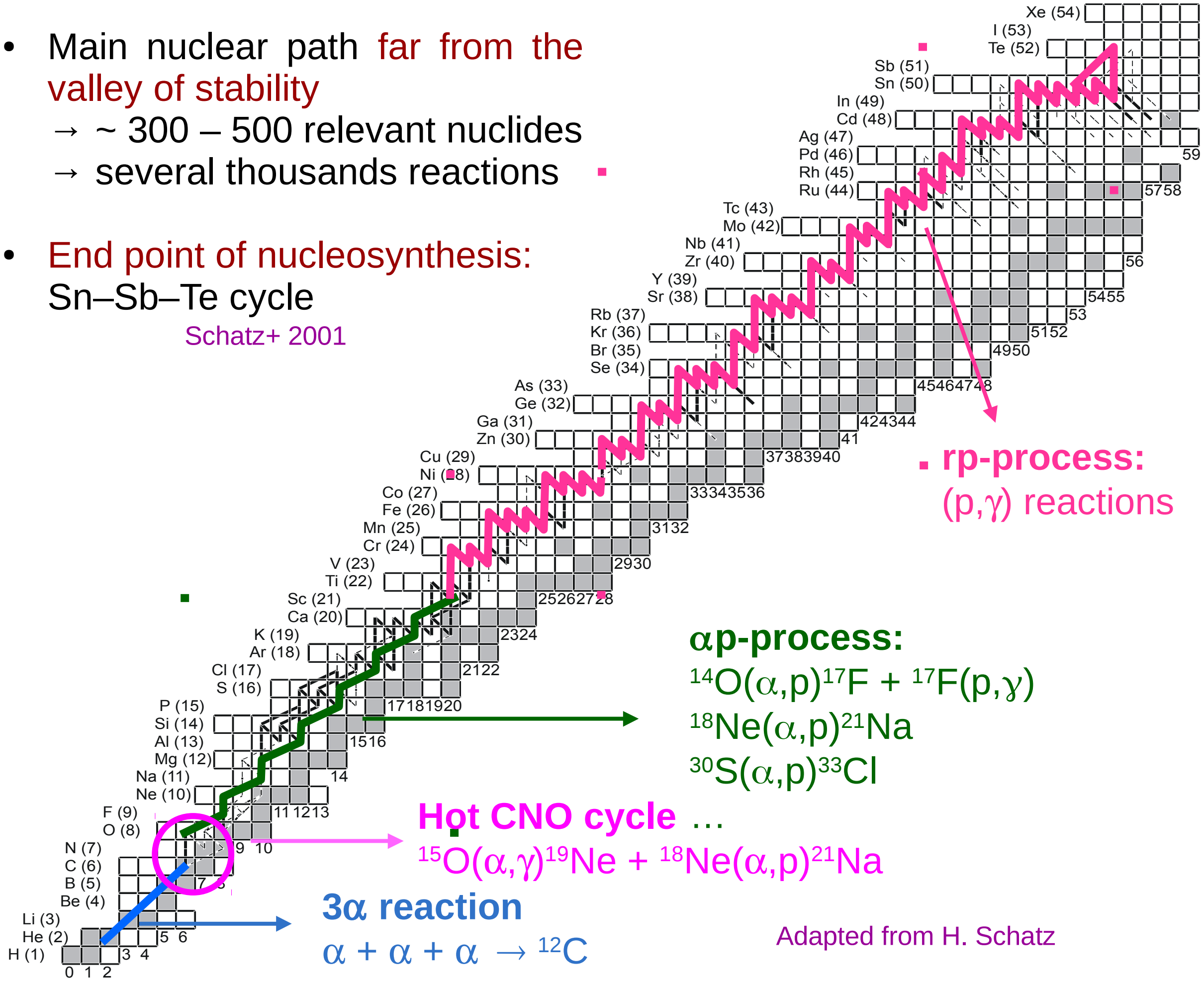
But…

- Very sensitive to nuclear input
- Nuclear physics inputs primarily based on theoretical models

Nuclear network and uncertainties

- Main nuclear path far from the valley of stability
  → ~ 300 – 500 relevant nuclides
  → several thousands reactions
- End point of nucleosynthesis: Sn–Sb–Te cycle

Schatz+ 2001



rp-process:
(p,γ) reactions

αp-process:
$^{14}O(\alpha,p)^{17}F$ + $^{17}F(p,\gamma)$
$^{18}Ne(\alpha,p)^{21}Na$
$^{30}S(\alpha,p)^{33}Cl$

Hot CNO cycle …
$^{15}O(\alpha,\gamma)^{19}Ne$ + $^{18}Ne(\alpha,p)^{21}Na$

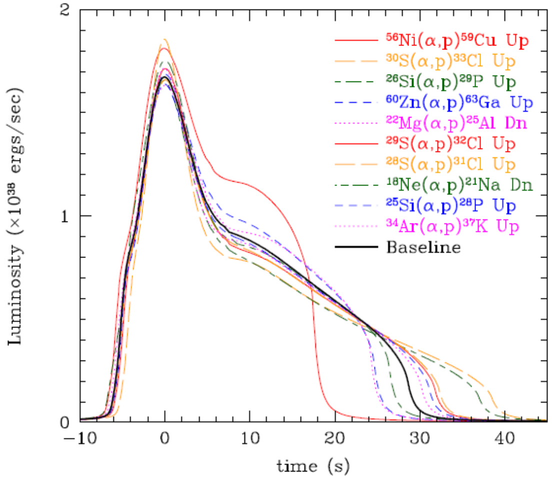
3α reaction
$\alpha + \alpha + \alpha \rightarrow {}^{12}C$

Adapted from H. Schatz

Nuclear Physics inputs

- Mass measurements along *rp*-process path
- Key reactions
- …

Sensitivity studies

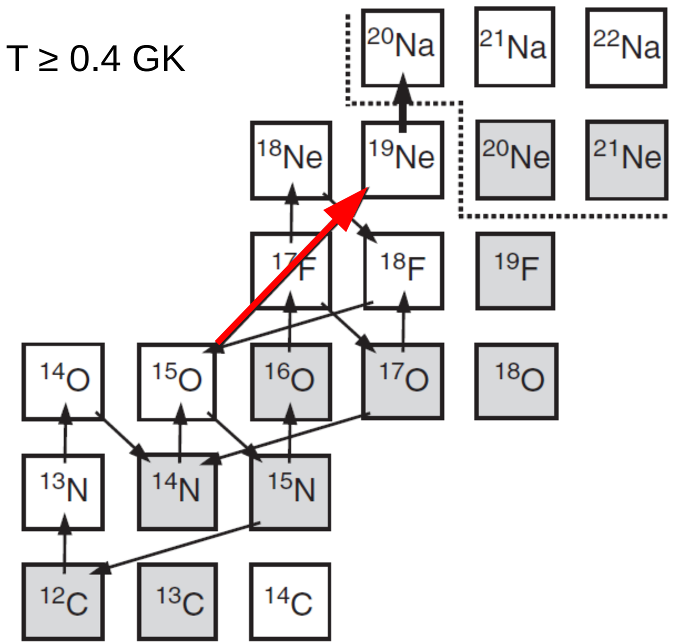


Cyburt+ 2016

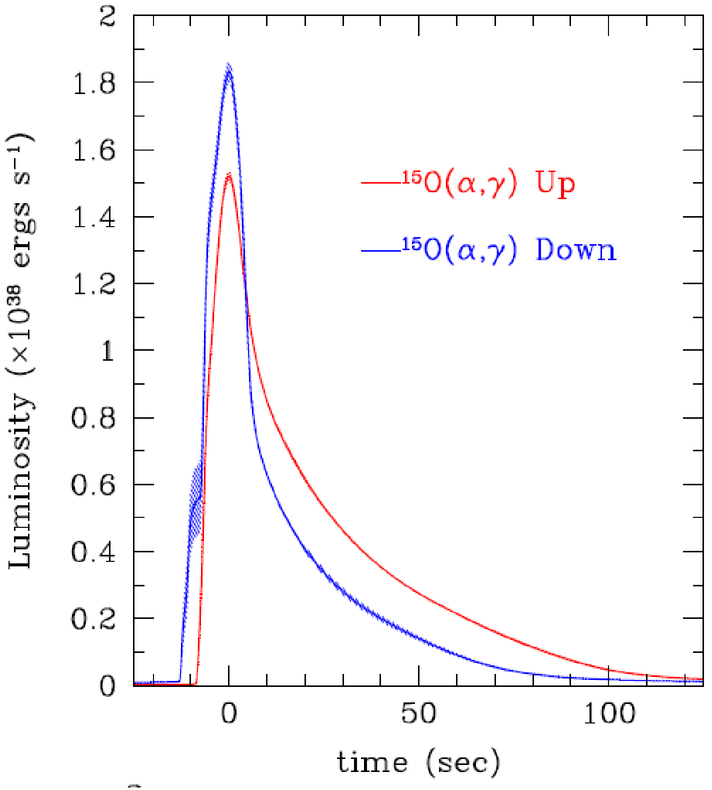
Only a few tens of key reactions are important

Role and impact of $^{15}O(\alpha,\gamma)^{19}Ne$

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



Cyburt+ 2016

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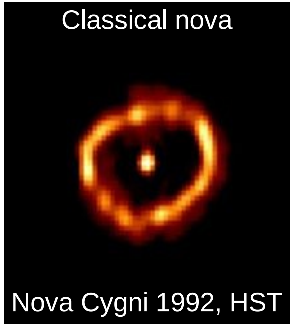
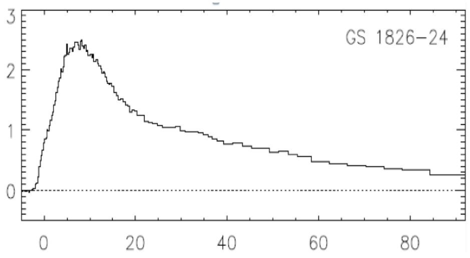
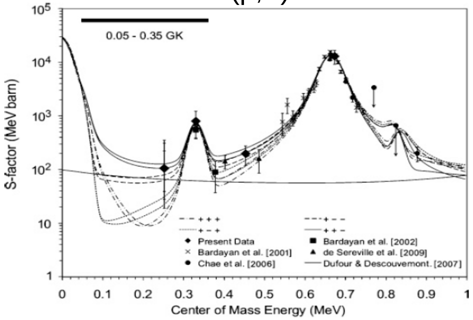


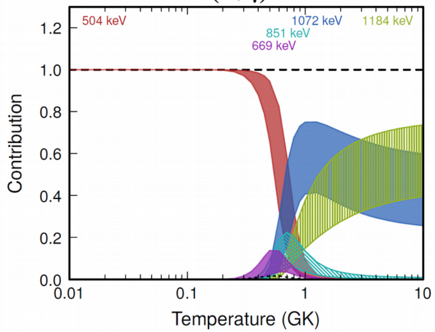


X-ray burst light curve

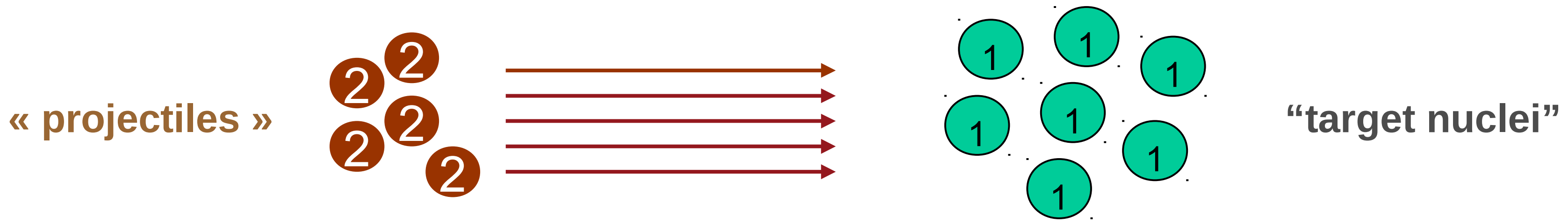
$^{18}F(p,\alpha)^{15}O$



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



Reaction rate



- The reaction rate is the number of reactions 1 + 2 → 3 + 4 [notation: **1(2,3)4**] per unit volume and time:

$$\boxed{r_{123} = \frac{dN_{12}}{dt} = \frac{N_1 N_2}{1+\delta_{12}} \int_0^\infty \sigma_{123}(v) v \phi(v) dv \equiv \frac{N_1 N_2}{1+\delta_{12}} \langle \sigma v \rangle_{123}}$$

where N_i is the density of particle i (cm^{-3}), $\sigma_{123}(v)$ the cross-section (probability that the nuclear reaction occur), $\varphi(v)dv$ the probability for the relative speed between 1 and 2 to be in the range [v,v+dv], and $<\sigma v>_{123}$ is the reaction rate per particle pair (cm^3 s^{-1}).

$1+\delta_{12} = 2$ if 1 ≡ 2, otherwise each pair would be counted twice.

$\Rightarrow$ in practice $N_A<\sigma v>$ in cm^3 mol^{-1} s^{-1} is tabulated in litterature

Thermonuclear reaction rates

- In a stellar plasma, the kinetic energy of nuclei is given by the thermal agitation velocity

  $\Rightarrow$ thermonuclear reaction rate

- For a non-degenerate perfect gas, the velocity is given by the Maxwell-Boltzmann distribution:

$$\phi(v)dv = \left(\frac{\mu}{2\pi kT}\right)^{3/2} \exp\left(-\frac{\mu v^2}{2kT}\right) 4\pi v^2 dv$$

- One obtains for the reaction rate per particle pair (in $cm^3\ s^{-1}$) as a function of energy:

$$\boxed{\langle\sigma v\rangle_{123} = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{123}(E) E e^{-E/kT} dE}$$

The astrophysical S-factor

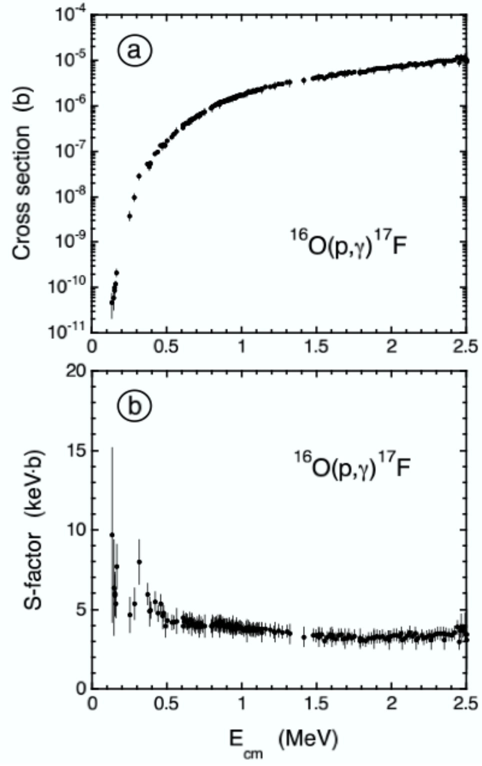
$$\sigma(E) \equiv \boxed{\frac{1}{E}} \times \boxed{e^{-2\pi\eta}} \times \boxed{S(E)}$$

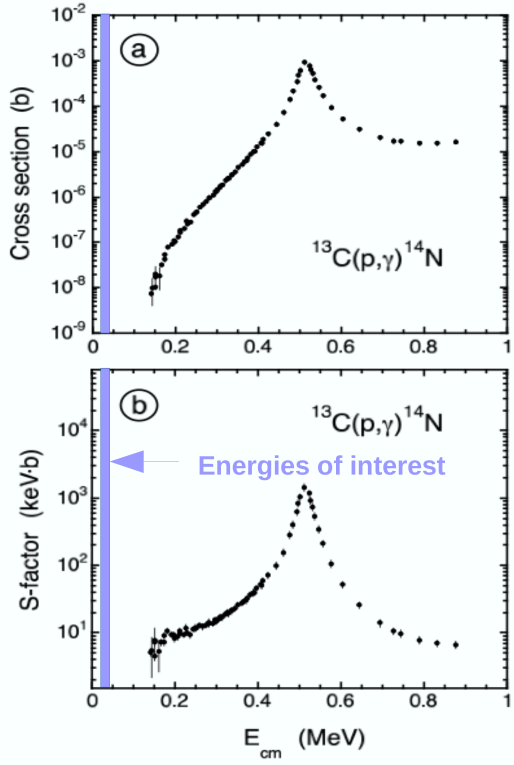
Correction of the effect $\sigma_{max} \propto 1/E$

Correction of the tunneling probability ($\ell = 0$)

- (sometimes) S(E) is a smoothly varying function
- Most of the cases, extrapolation to astrophysical energies needed!

S(E): astrophysical *S*-factor which contains all the nuclear effects for a given reaction





C. Iliadis (2015) , Nuclear physics of Stars

Gamow peak & non-resonant case

Reaction rate:

$$\langle \sigma v \rangle_{123} = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{123}(E) E e^{-E/kT} dE$$

If the *S*-factor is smoothly varying ("non-resonant"):

$$S(E) = \sigma(E)\, E\, e^{2\pi\eta} \cong S_0$$

$$\langle \sigma v \rangle_{123} = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(kT)^{3/2}} S_0 \int_0^\infty \boxed{e^{-2\pi\eta} e^{-E/kT}} dE$$

Gamow peak is the energy range where most reactions between 1 and 2 occur

Approximation by a Gaussian curve:

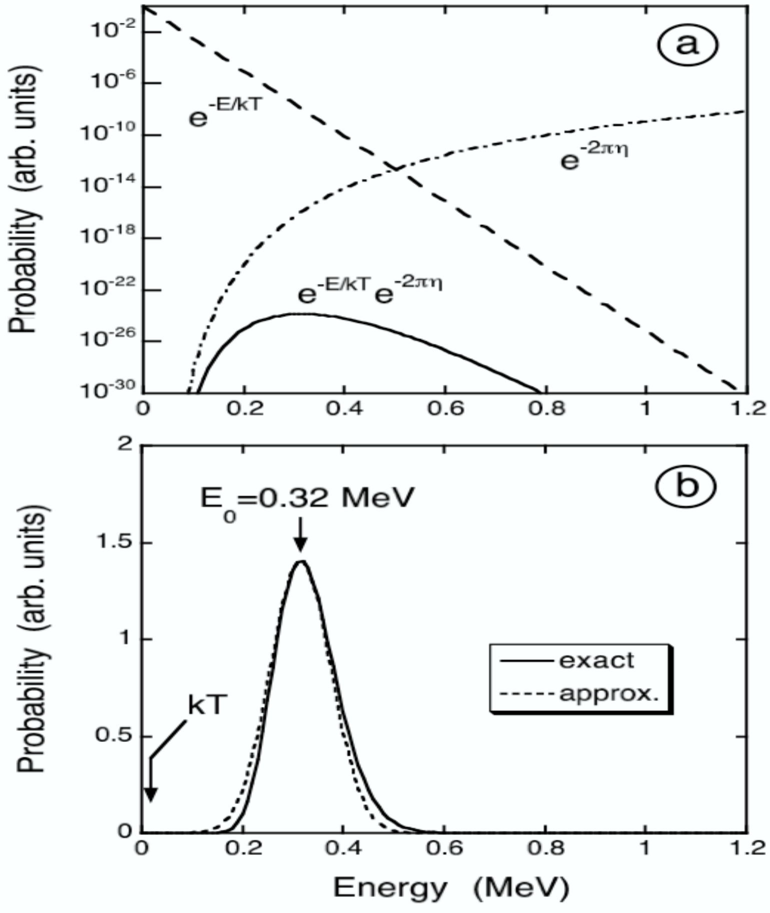
$$\exp(-2\pi\eta - E/kT) = I_{max} \exp\left[-\left(\frac{E - E_0}{\Delta/2} \right)^2 \right]$$

$$E_0 = \pi k T \eta(E_0) = 1.22 \left(Z_1^2 Z_2^2 \mu_{amu} T_6^2 \right)^{1/3} \quad \text{keV}$$

$$\Delta = 4\sqrt{E_0 kT/3} = 0.749 \left(Z_1^2 Z_2^2 \mu_{amu} T_6^5 \right)^{1/6} \quad \text{keV}$$

[Δ: total width at 1/e; $T_6 \equiv T$ (MK)]

$^{12}C(\alpha,\gamma)^{16}O$, T = 0.2 GK



C. Iliadis (2015) , Nuclear physics of Stars

The narrow resonance case

- Contribution to the reaction rate of a resonance at the energy E_R close to E_0:

$$\langle \sigma v \rangle_{123} = \sqrt{\frac{8}{\mu\pi}} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{BW}(E) E e^{-E/kT} dE$$

with $$\sigma_{BW}(E) = \pi^2 \omega \frac{\Gamma_a \Gamma_b}{(E - E_R)^2 + (\Gamma/2)^2}$$

- For a narrow resonance: Maxwell-boltzmann distribution ~ constant

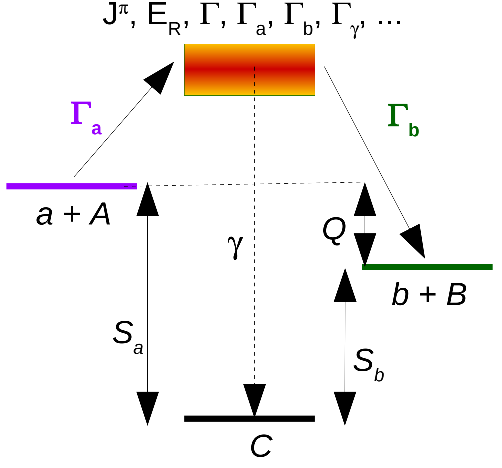
$$\langle \sigma v \rangle_{123} = \sqrt{\frac{8}{\mu\pi}} \frac{E_R e^{-E_R/kT}}{(kT)^{3/2}} \int_0^\infty \sigma_{BW}(E) dE$$

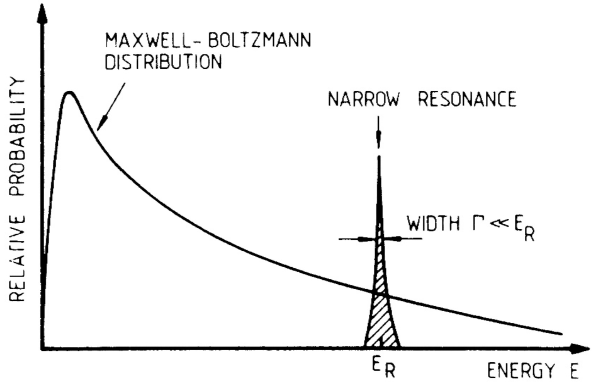
- If the partial widths (Γ_i) are constants over Γ << E_R:

$$\boxed{\langle \sigma v \rangle_{123} = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 \, \omega\gamma \, e^{-E_R/kT}}$$

$$\omega\gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma}$$ is the resonance strength $$\left[\omega = \frac{2J_R + 1}{(2J_a + 1)(2J_A + 1)}\right]$$

Reaction $a + A \rightarrow C \rightarrow b + B$

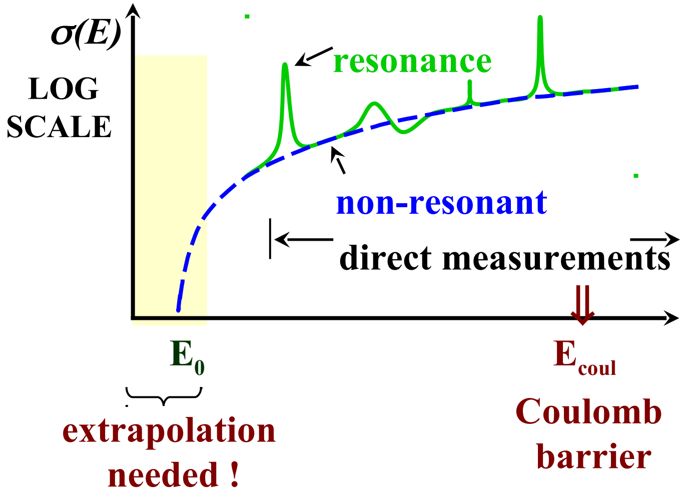




Experimental strategy

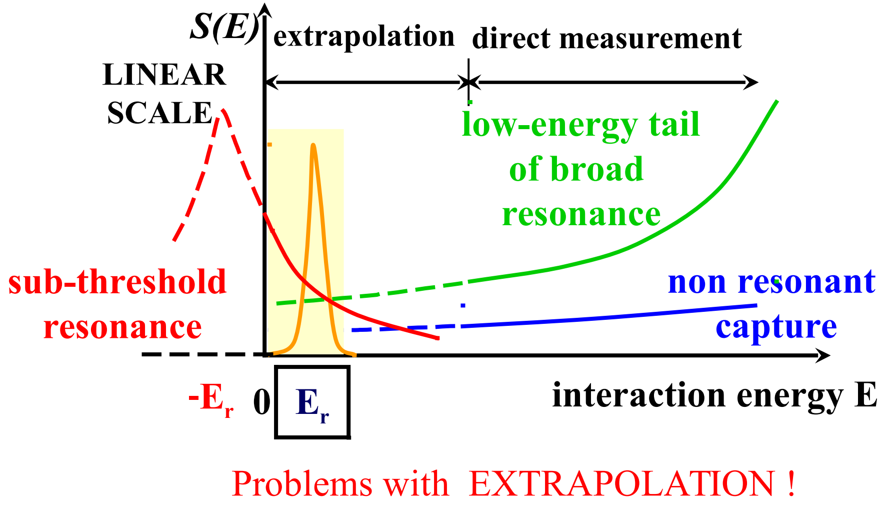
Cross section

$$\sigma(E) = \frac{1}{E}\, S(E)\, \exp\left(-2\pi\eta\right)$$



Astrophysical *S*-factor

$$S(E) = E\,\sigma(E)\, \exp\left(2\pi\eta\right)$$



- Measurement of cross section at higher energies and extrapolation to astrophysical energies E_0
  → direct measurement approach
- Determination of resonant state properties (E_R, partial widths Γ_i, J^π)
  → indirect measurement approach

Direct measurements: requirements and challenges

Low cross section → low yields → poor signal-to-noise ratio

Sources of background

- Beam induced
  - Reactions with impurities in the target
  - Reactions on beam collimators/apertures

see lecture from C. Bruno on Saturday

- Non beam-induced
  - Interaction from cosmic muons with detection setup
  - Charged particles / γ-rays from natural background
  - Neutron induced reactions

Requirements & challenges → Improving signal-to-noise ratio

- Improving signal
  - Very long measurements (weeks, months…)
  - High beam intensities: heating effects on target (limitation)
  - Thicker targets (?): exponential drop of the cross section
  - High detection efficiency

- Reducing noise/background
  - Ultra pure targets: difficult
  - Dedicated experimental setup →
    - Coincidence measurements (STELLA…)
    - Recoil mass separator (DRAGON…)
    - Underground laboratory (LUNA, Felsenkeller...)

Indirect measurements

Cross-section of astrophysical interest not measured directly

see lecture from A. Spyrou on Friday

Main idea:

- Perform experiments above the Coulomb barrier at high energy (~ few – 10's of MeV/u)
  → higher cross sections than for direct measurements

Pros and Cons:

- ✔ Experimental conditions are relatively less constraining than for direct measurement (not necessarily true with RIB studies)

- ✖ Results are model dependent
- Results depend on the uncertainties relative to the different model parameters

- Examples of indirect methods:
  - **Transfer reactions**, Asymptotic Normalization Coefficient (ANC) method, Trojan Horse Method (THM), surrogate method, Coulomb dissociation...

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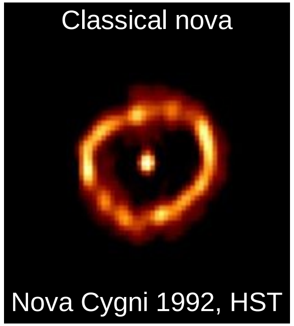
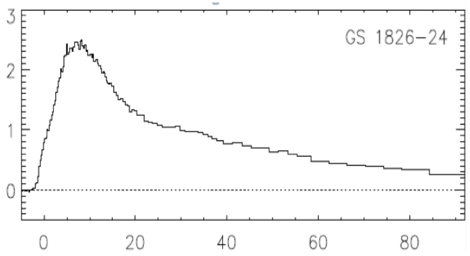
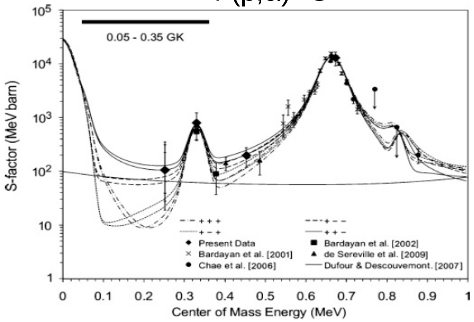


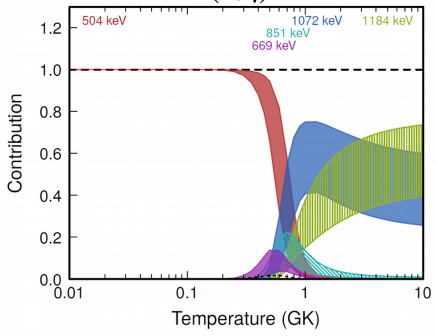


X-ray burst light curve

$^{18}F(p,\alpha)^{15}O$



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



^{19}Ne and ^{19}F spectroscopy

Useful information:

- $^{18}F + p \rightarrow {}^{19}Ne \rightarrow \alpha + {}^{15}O$
  (1+) (1/2+) (0+) (1/2-)
- Compound nucleus: ^{19}Ne
- $\ell_p = 0$ resonances: $J^\pi = 1/2^+, 3/2^+$
- $S_p = 6.410$ MeV; $S_\alpha = 3.528$ MeV

Gamow window:

- $T_9 = 0.1 \rightarrow E_0 = 112$ keV; $\Delta = 72$ keV
- $T_9 = 0.4 \rightarrow E_0 = 282$ keV; $\Delta = 228$ keV
- Center of mass: [76 keV; 396 keV]
- ^{19}Ne excitation energy: [6.486 MeV; 6.638 MeV]

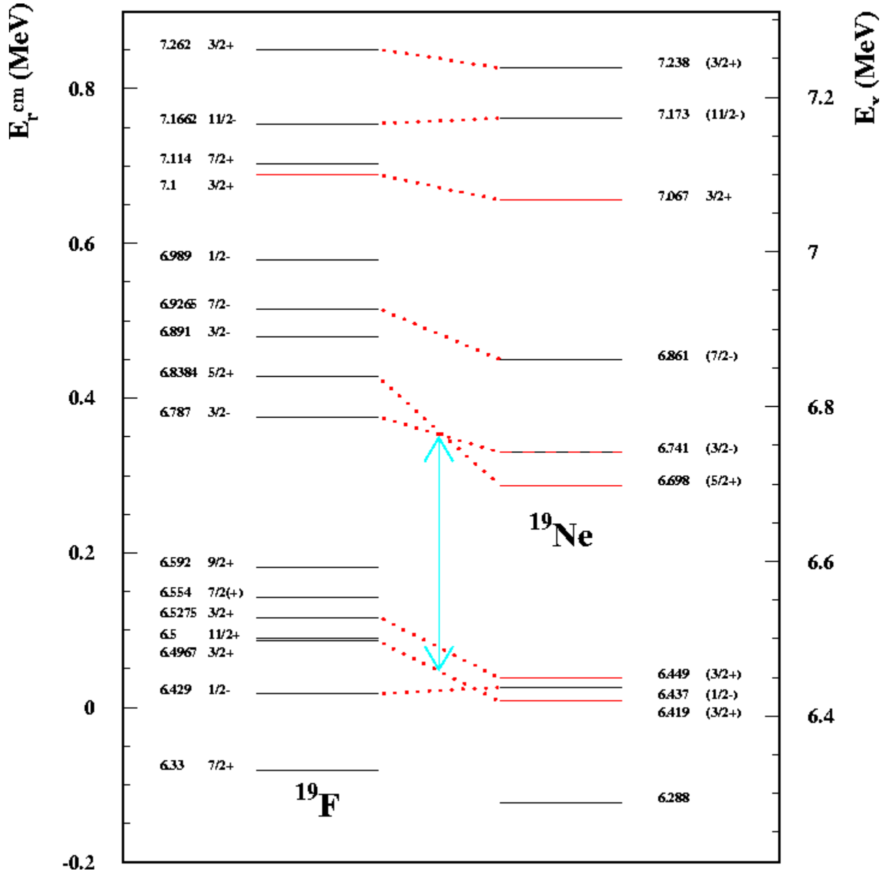
Mirror nuclei: ^{19}Ne $\leftrightarrow$ ^{19}F

- Swapped number of protons and neutrons

Analog states:

- Similar properties (J^π, Γ_i ...)

status beginning of 2000



$^{18}F(p,\alpha)^{15}O$ astrophysical S-factor

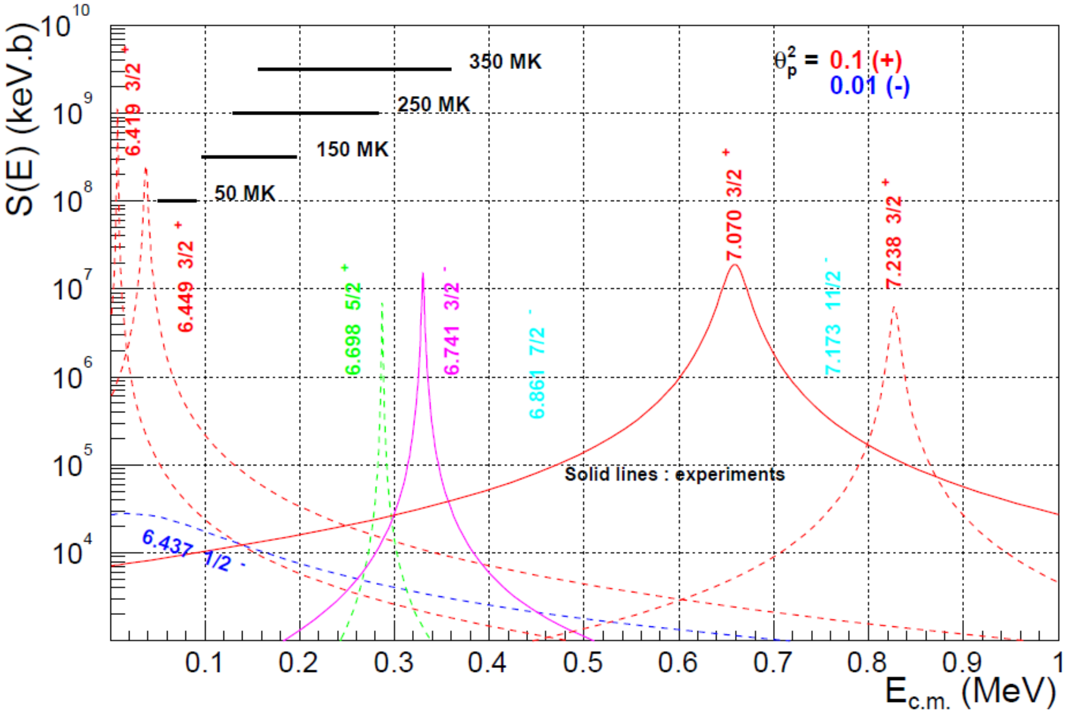
Main questions:

- Existence of close to threshold $3/2^+$? How many? Properties?
- Interference effect between $3/2^+$ states?
- Existence of sub-threshold $1/2^+$ state?
- Interference between $1/2^+$ states?

What to measure?

- $\omega\gamma = \omega \dfrac{\Gamma_p \Gamma_\alpha}{\Gamma}$
- Low-lying resonances: $\Gamma_p \ll \Gamma \Longrightarrow \omega\gamma \approx \omega\Gamma_p$
- Interferences → direct measurement

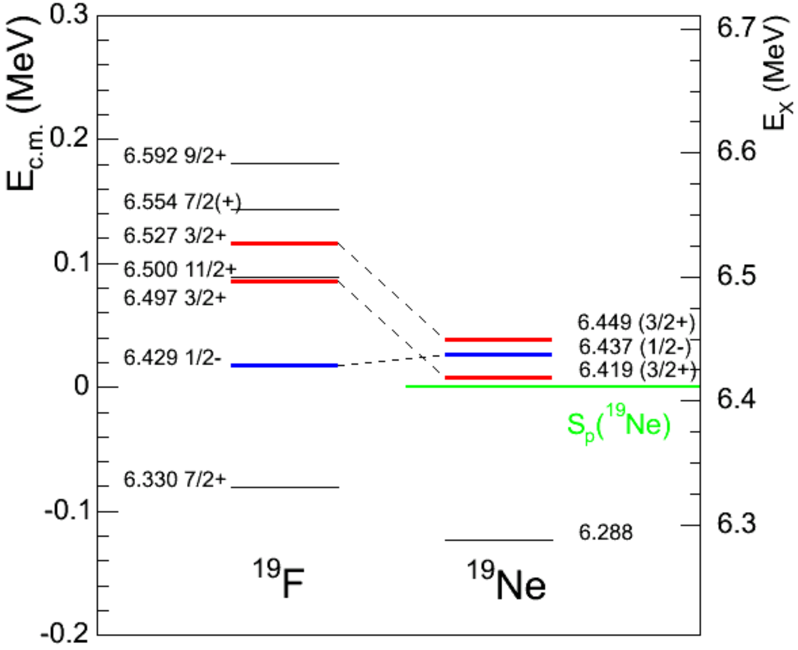
status beginning of 2000



Experimental method

- ^{18}F + p: direct measurement impossible!
  - E_R = 40 keV << B_C = 2.6 MeV
  - $\omega\gamma < 10^{-11}$ eV << $\omega\gamma$(330 keV) = 1.48 eV

- Rely on information concerning analog levels in ^{19}F ($3/2^+$ states separated by 30 keV) S. Utku+ (1998)



- Neutron transfer reaction:

  d(^{18}F,p)^{19}F*

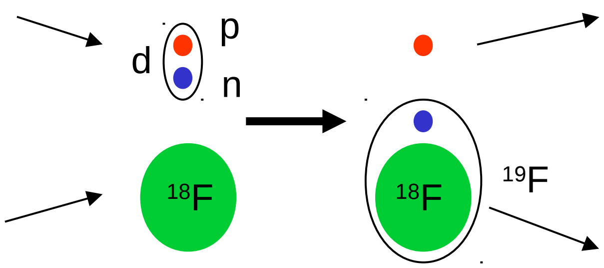
- DWBA (Distorted Wave Born Approximation) analysis:

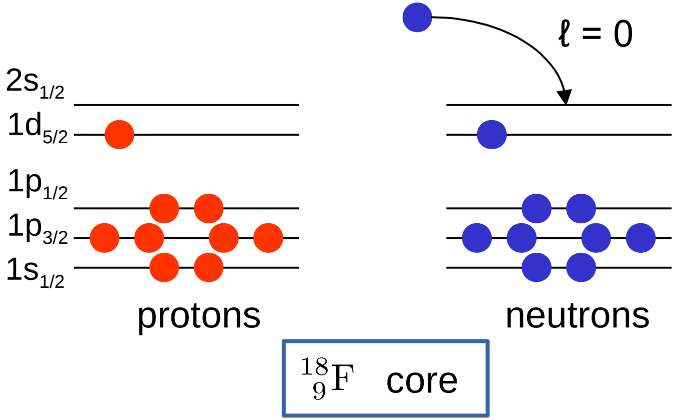
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S \left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \quad \text{and} \quad \Gamma_p = C^2 S \times \Gamma_{s.p.}$$

$S_{n,p}$: spectrosopic factor
C: isospin factor (= 1 here)
$\Gamma_{s.p.}$: single-particle width (calculation)

Transfer reactions in a nutshell

Example of the $^{18}F(d,p)^{19}F$ transfer reaction





DWBA: Distorted Wave Born Approximation

- The simplest theoretical model to describe a transfer reaction

DWBA main assumptions

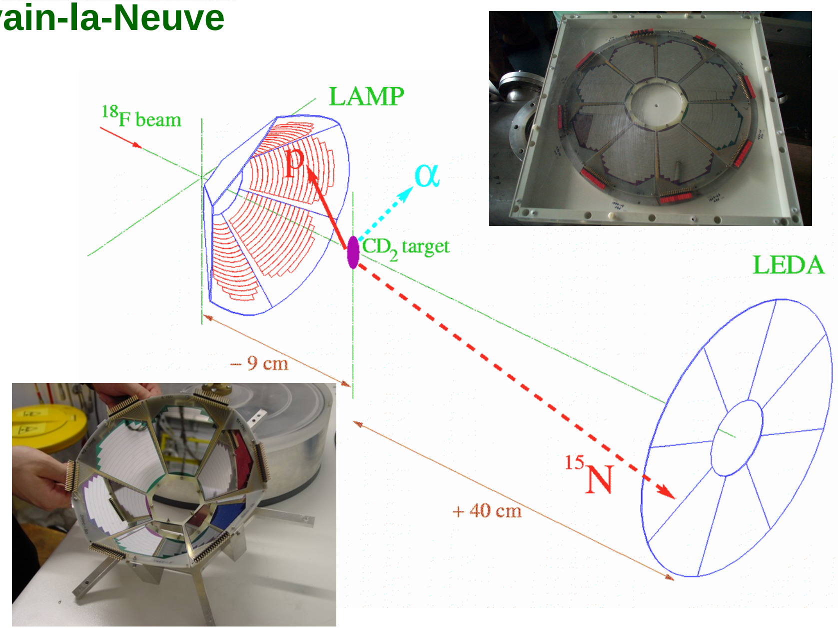
- The transferred nucleon/cluster is directly deposited on its orbital
  → no nucleon rearrangment in the final nucleus (^{19}F)
- The entrance and exit channels are dominated by elastic scattering → Distorted Wave
- The transfer process is weak enough to be treated as a first order perturbation → Born Approximation

Experimental setup

N. de Séréville+ (2007)

CRC
Louvain-la-Neuve

$d(^{18}F,p)^{19}F^* \rightarrow \alpha + {}^{15}N$

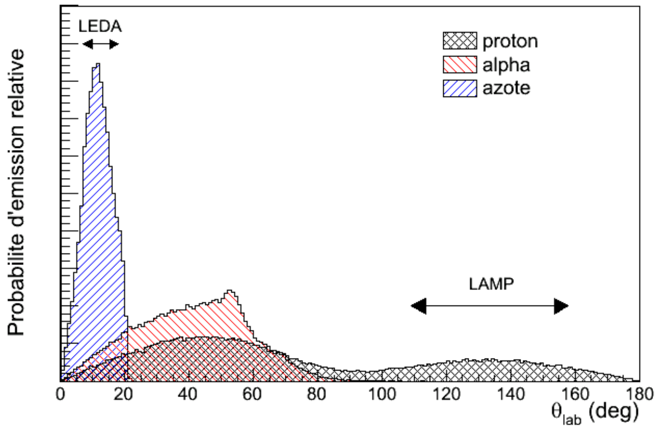


LEDA – LAMP in coincidences

- Protons at forward angles in the c.o.m
- ^{15}N at forward angles in the laboratory

Detector positioning

- LAMP: solid angle
- LEDA: coincidence efficincy (20%)



LEDA & LAMP detectors

Davinson+ (2000)

- Single sided Silicon detectors
- Sectors with 16 annular strips
- Energy resolution ~ 30 keV (FWHM)

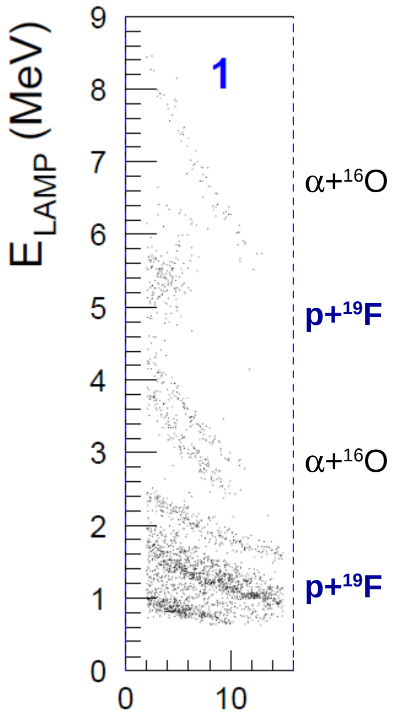
Target thickness (CD_2 = 100 μg/cm^2)

- Compromise between energy resolution and counting rate

Identification of $3/2^+$ states in ^{19}F

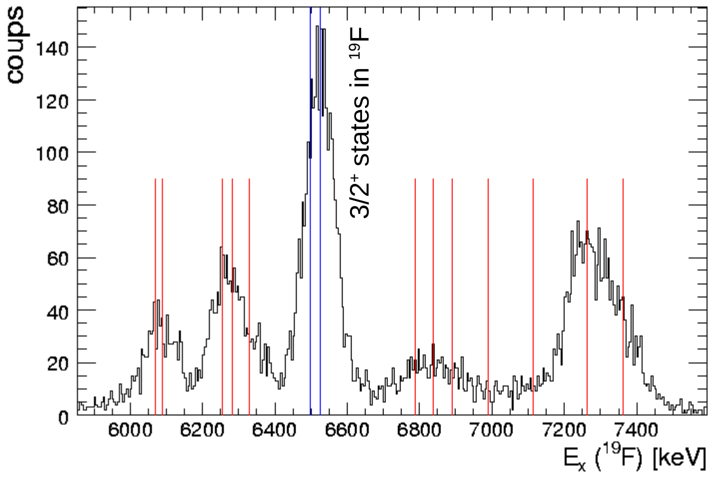
N. de Séréville+ (2007)

Kinematic lines



Different slopes indicate **different 2-body reactions**

Reconstructed excitation energy

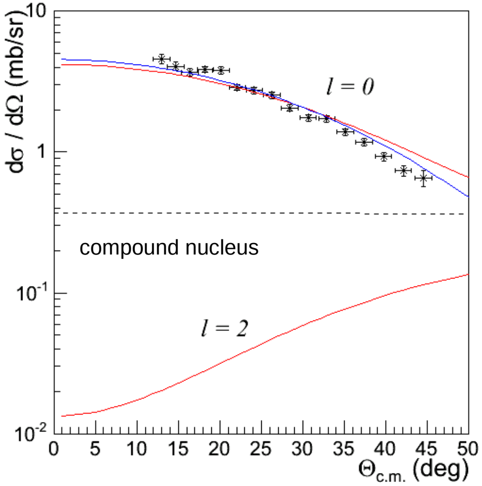


- Conservation of energy and momentum
- Known beam energy + (E_p, θ_p)

→ **calculation of excitation energy**

(FWHM ≈ 100 keV)

Angular distribution + DWBA



- Direct mechanism → $\ell_p = 0$
- $C^2S_p = 0.21$
- **Importance of $3/2^+$ states**

Search for ^{19}Ne 3/2$^+$ states

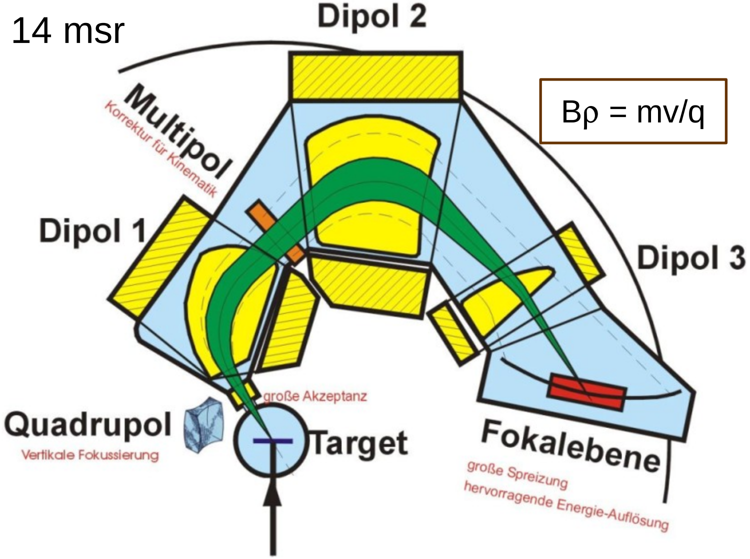
A. M. Laird+ (2013)
A. Parikh+ (2015)

$^{19}F(^3He,t)^{19}Ne$

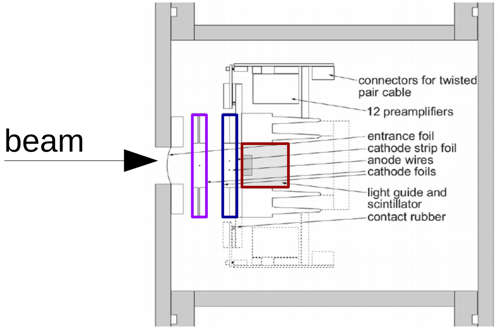
(^{3}He,t) reaction not selective at low energy

Q3D magnetic spectrograph

- $\Delta E/E = 2\ 10^{-4}$
- $\Delta\Omega$ = 14 msr



Focal plane cross-section



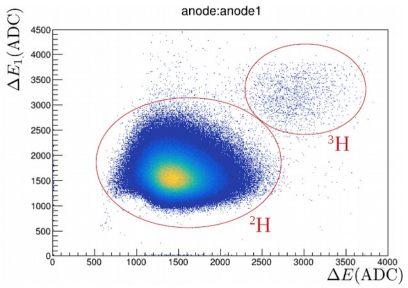
Wirth (1991), PhD

- ΔE: multi-wire proportional counter (MWPC)
- ΔE & position: MWPC with stripped cathode
- E: plastic scintillator

Experimental conditions

- ^{3}He beam @ 25 MeV, 200 enA
- Targets CaF_2 (50 µg/cm^2) + ^{12}C (7 µg/cm^2)
- 7 detection angles between Θ_{lab} = 10° and 50°
- ~14 keV resolution (FWHM)

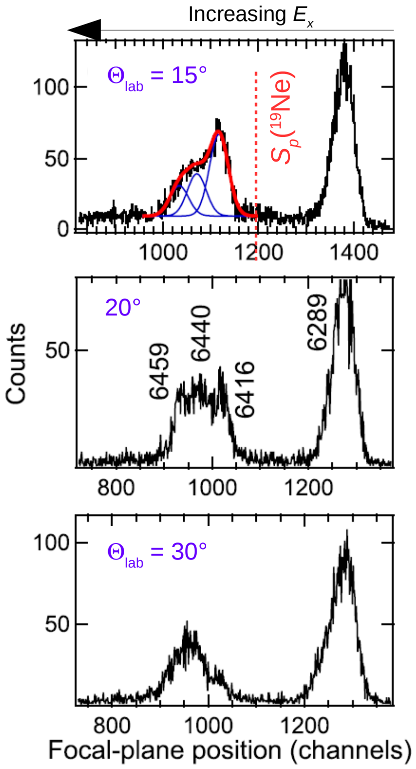
Particle Identification



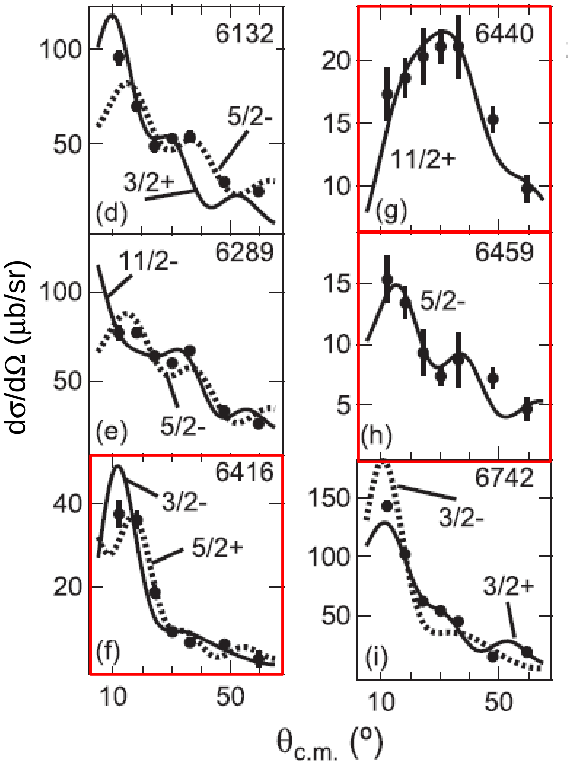
Where are the 3/2$^+$ states?

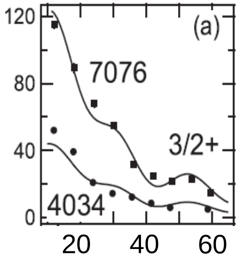
A. M. Laird+ (2013)
A. Parikh+ (2015)

Triton magnetic rigidity spectra



(^{3}He,t) angular distributions





- **Triplet of states** just above the p+^{18}F threshold [instead of doublet]
- **Very different angular distributions**
  → different spin/parity
- **DWBA analysis not "straightforward"**
  → 2 steps (^{3}He,d)(d,t)
  → assumes information on intermediate states in ^{20}Ne

- Compare angular distribution with known 3/2$^+$ state

Improving on energy resolution

M. R. Hall+ (2019)

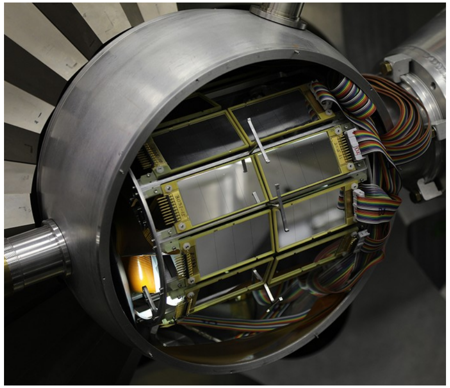
$^{19}F(^{3}He,t)^{19}Ne^{*}(\gamma)^{19}Ne_{g.s.}$ @ 30 MeV, 2.5 pnA, CaF2 (~1 mg/cm^2)

GODDESS

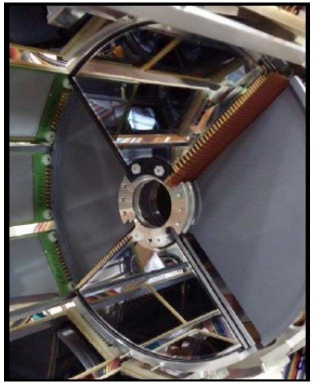
- Use of efficient γ-ray array → compact geometry
  → **GAMMASPHERE** (92 HPGe + BGO shield)
- Need to tag the reaction channel → triton detection
  → **ORRUBA** (silicon array)
  - SX3/BB10 barrel of resistive strip detectors
  - QQQ5 endcaps with striped detectors

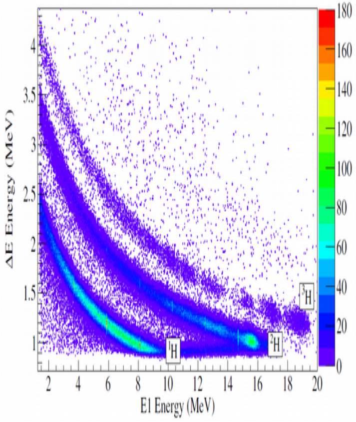
GAMMASPHERE

BB10 / SX3 (65 μm + 1 mm)



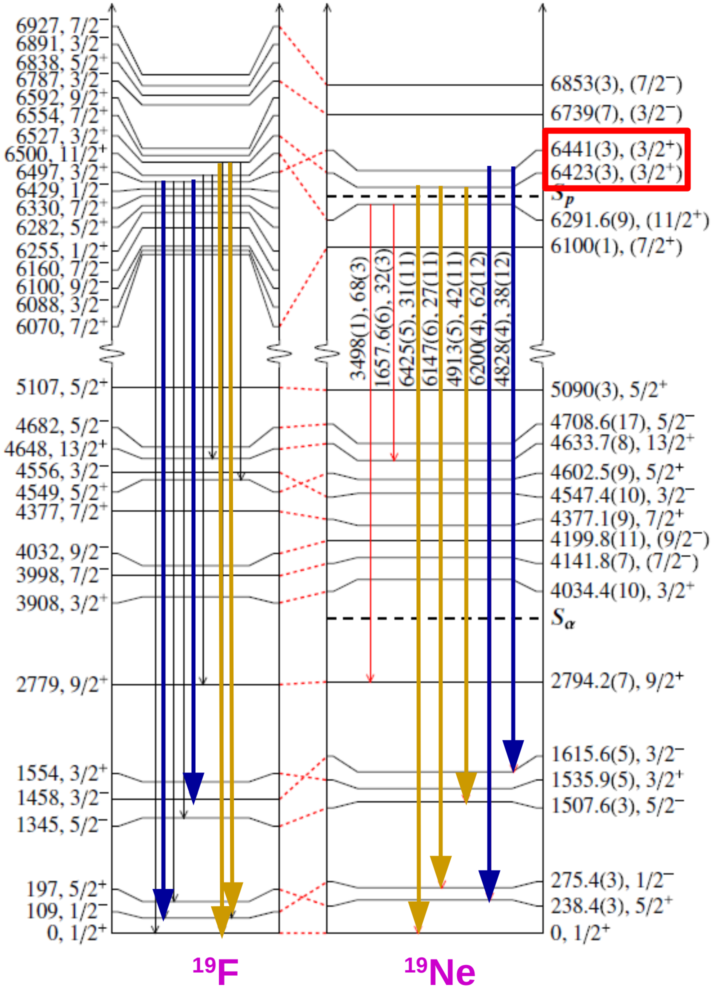
QQQ5 (100 μm + 1 mm)

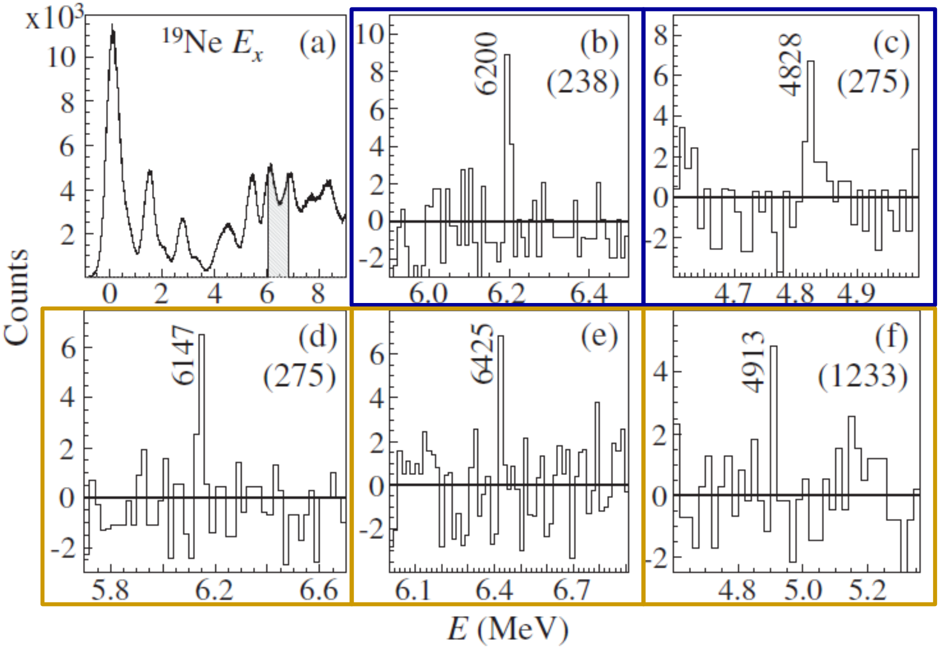




Indication of 3/2$^+$ states in ^{19}Ne?

M. R. Hall+ (2019)





- Found γ-rays for **two potential 3/2$^+$ states in ^{19}Ne**
- Based on similar γ-ray decays for these 2 states as for 3/2$^+$ state γ-ray decays in mirror nucleus ^{19}F

Interferences between $3/2^+$ states

- Interferences between the E_R = 38 keV and 665 keV resonances

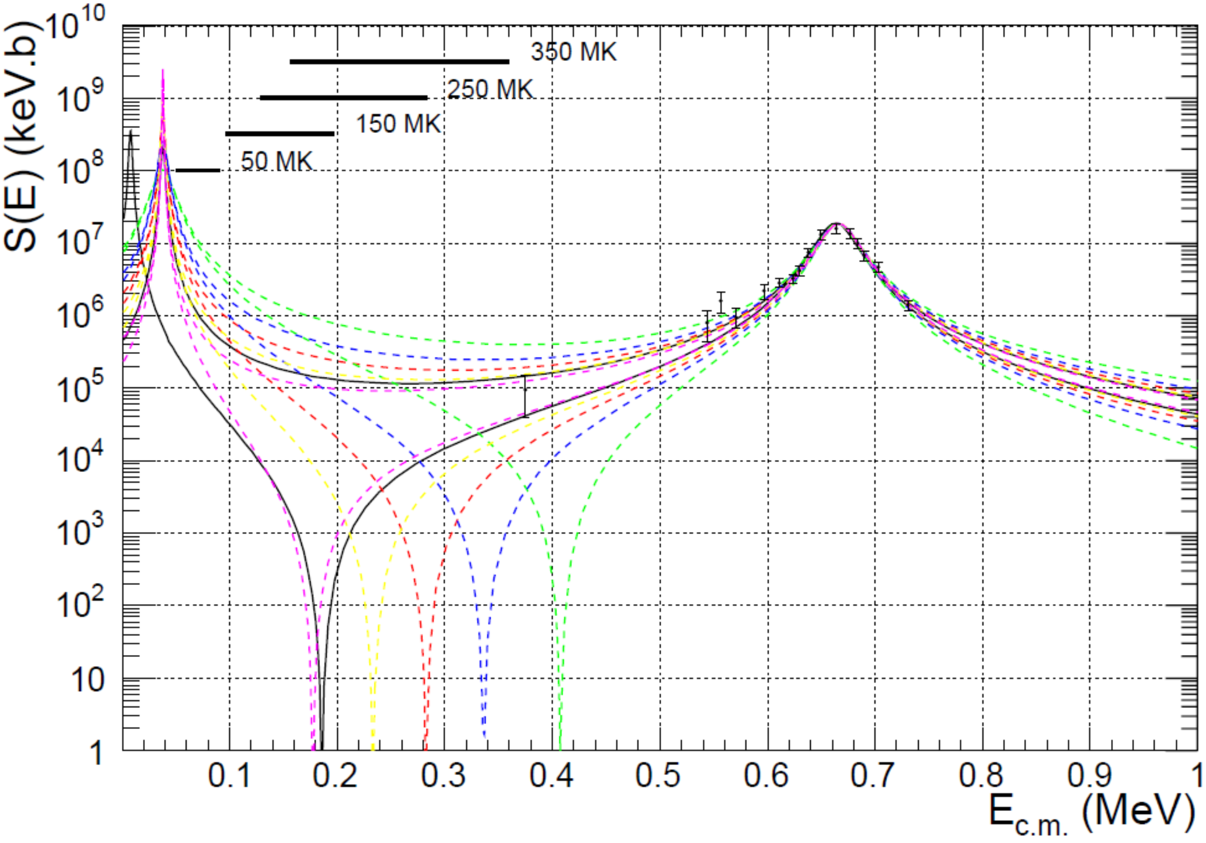
  → α-particle width is varied from Γ_α = 0.86 keV to 21.5 keV

- Destructive cases have strongest impact in Gamow window

- Existing data does not allow to discriminate between different cases

  D. Bardayan+ (2002)

  → direct measurements are needed

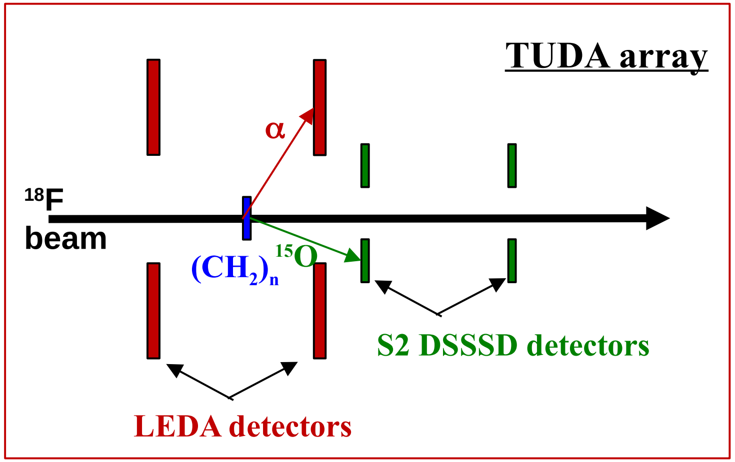


N. de Séréville+ (2005)

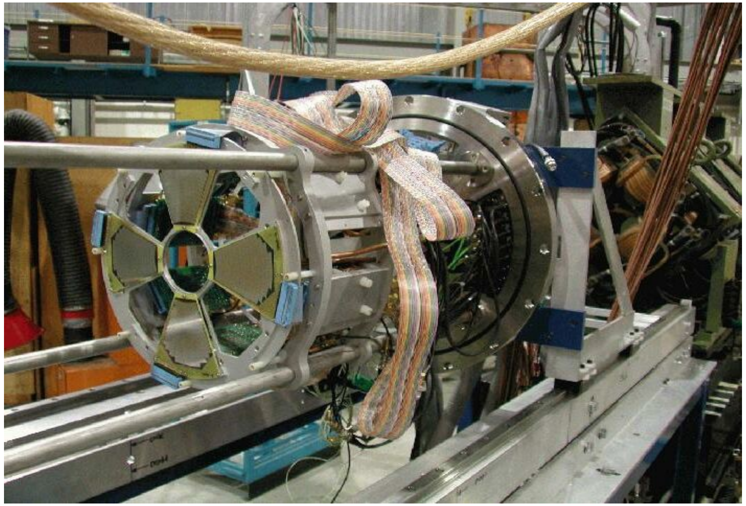
Direct measurement $^{1}H(^{18}F,\alpha)^{15}O$

C. E. Beer+ (2011)

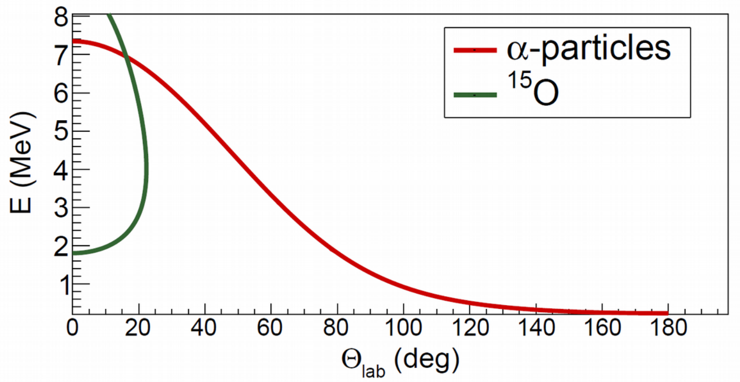
Experimental setup
→ coincident measurement



TUDA detectors



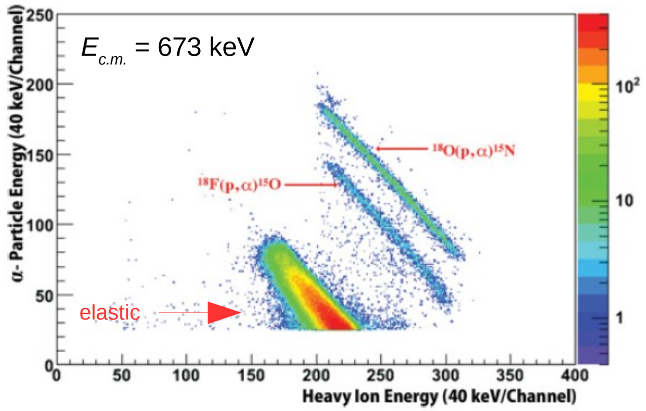
- Beam: ^{18}F (5×10^{6} pps) produced at ISAC (Isotope Separator & Accelerator; TRIUMF; Canada) by bombarding a thick target with 500 MeV proton (up to 100 μA)
- Target: 33 μg/cm^2 CH_2
- Charged particle detectors
  - TUDA → α-particles
  - S2 → ^{15}O

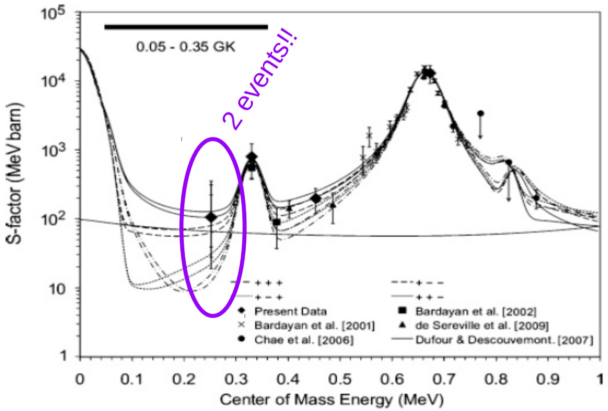


Constructive or destructive?

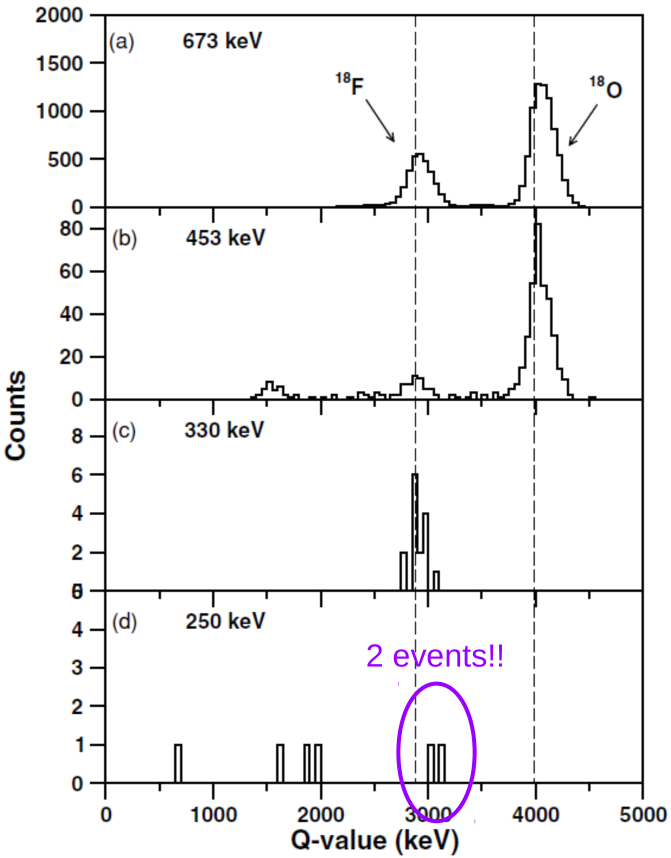
C. E. Beer+ (2011)

E(LEDA; α) v.s. E(S2; heavy)





Q-value spectrum



Improved statistics still needed to determine the sign of interference

→ **new experiment being setting up @ TRIUMF**

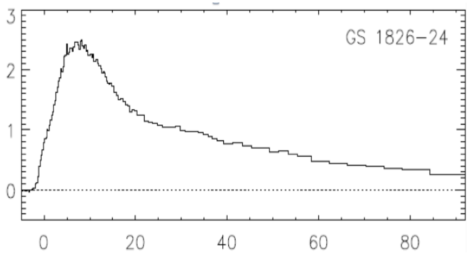
A. M. Laird+

Outline

1. Explosive hydrogen burning
   a) Classical novae
   b) X-ray bursts
2. Thermonuclear reaction rates
3. Classical novae: the $^{18}F(p,\alpha)^{15}O$ case
4. X-ray bursts: the $^{15}O(\alpha,\gamma)^{19}Ne$ case

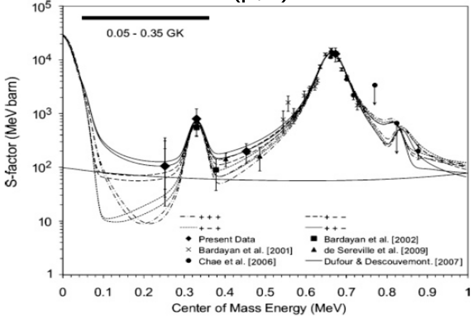
Classical nova

Nova Cygni 1992, HST

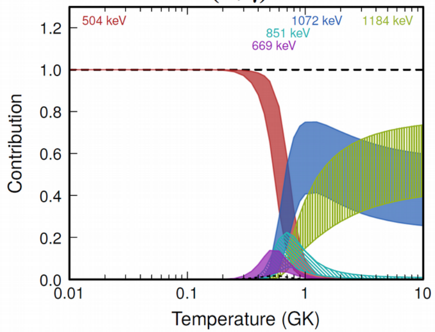


X-ray burst light curve

$^{18}F(p,\alpha)^{15}O$



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



^{19}Ne and ^{19}F spectroscopy

Useful information:

- $^{15}O + \alpha \rightarrow$ ^{19}Ne + γ
  (1/2-) (0+)

- Compound nucleus: ^{19}Ne
- $\ell_\alpha = 0$ resonances: $J = 1/2^-$
- $\ell_\alpha = 1$ resonances: $J = 3/2^+$
- $S_p = 6.410$ MeV; $S_\alpha = 3.528$ MeV

Gamow window:

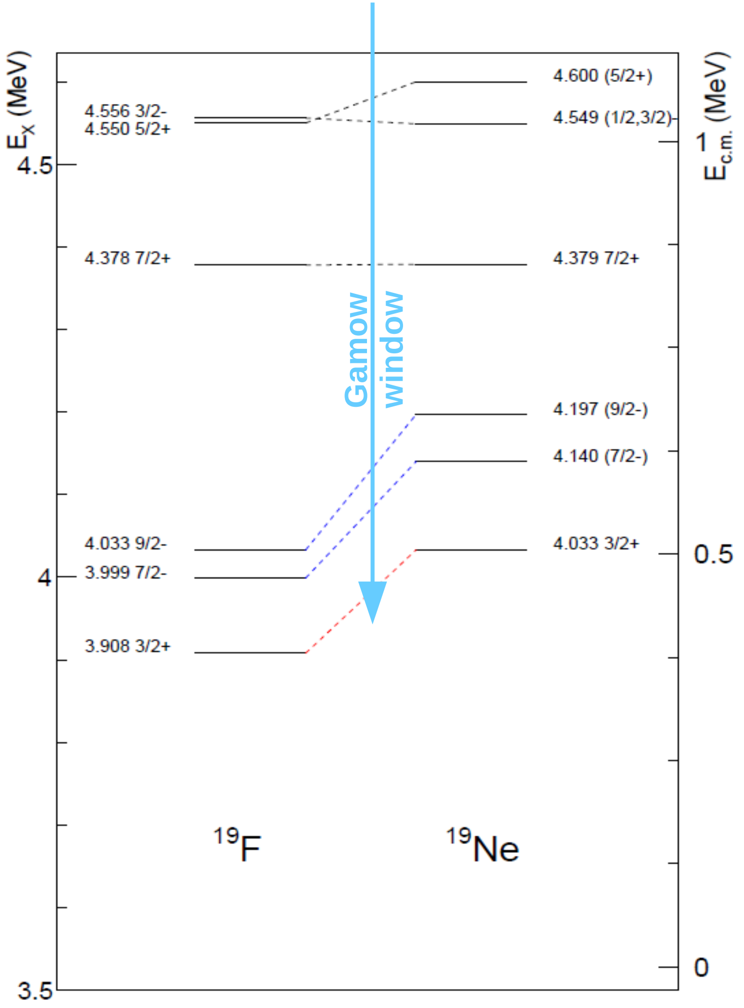
- $T_9 = 0.4 \rightarrow E_0 = 617$ keV; $\Delta = 337$ keV
- $T_9 = 1 \rightarrow E_0 = 1137$ keV; $\Delta = 723$ keV
- Center of mass: [450 keV; 1500 keV]
- ^{19}Ne excitation energy: [3.980 MeV; 5.027 MeV]

Mirror nuclei: ^{19}Ne $\leftrightarrow$ ^{19}F

- Swapped number of protons and neutrons

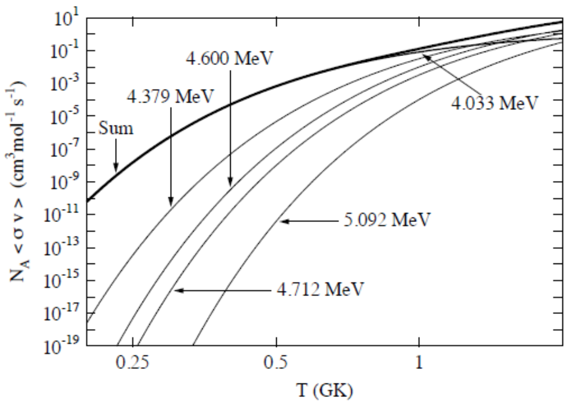
Analog states:

- Similar properties (J^π, Γ_i ...)



What to measure and how?

Thermonuclear reaction rate



B. Davids+ (2003)

- Dominant state at E_x = 4.033 MeV
  (E_R = 505 keV; J^π = 3/2$^+$; ℓ_α = 1)

Narrow resonance case

- $\mathcal{N}_A \langle \sigma v \rangle \propto \omega\gamma \; e^{-E_R/kT}$
- $\omega\gamma = 0.5 \times (2J_R + 1) \dfrac{\Gamma_\alpha \Gamma_\gamma}{\Gamma}$
- Close to α-particle threshold (case of E_x = 4.033 MeV state)

→ $\Gamma_\alpha \ll \Gamma_\gamma \;\Rightarrow\; \Gamma = \Gamma_\alpha + \Gamma_\gamma \approx \Gamma_\gamma$

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

→ resonance strength proportional to the α-particle width (smaller partial width)

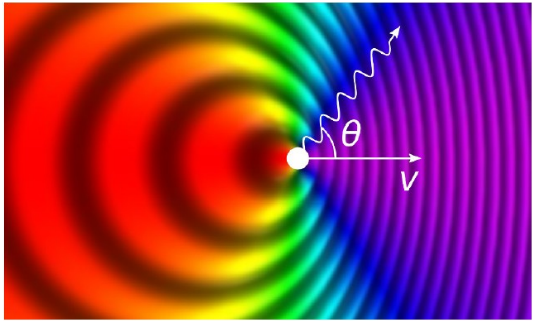
Experimental approaches

- Direct measurement: requires ~ 10^{10} pps of low-energy ^{15}O RIB [not available]
- Indirect approach: $\Gamma_\alpha = \dfrac{\Gamma_\alpha}{\Gamma} \times \Gamma = B_\alpha \times \Gamma$
  - Measurement of α branching ratio B_α
  - Measurement of state lifetime $\tau \propto 1/\Gamma$
- Transfer reaction approach: $\Gamma_\alpha = C^2 S_\alpha \times \Gamma_\alpha^{s.p.}$
  - Measurement of α spectroscopic factor C^2S_α

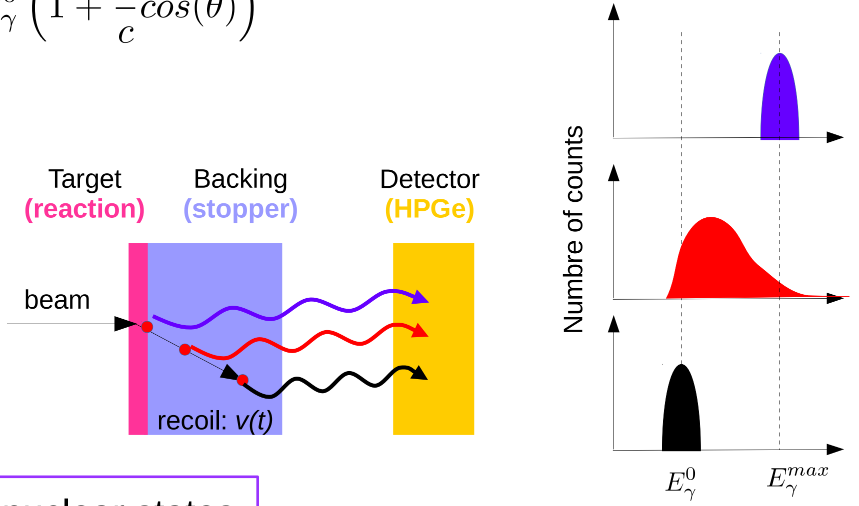
Doppler-Shift Attenuation Method

DSAM: Doppler-Shift Attenuation Method
→ lifetime of state infered from the measured decaying γ-ray energy distribution

Doppler effect



- Detected γ-ray energy (E_γ) depends on the speed (v) of the nucleus at emission time and on the angle (θ) between the observer and the emitting nucleus direction
- $E_\gamma = E^0_\gamma \left(1 + \frac{v}{c} cos(\theta)\right)$



DSAM principle

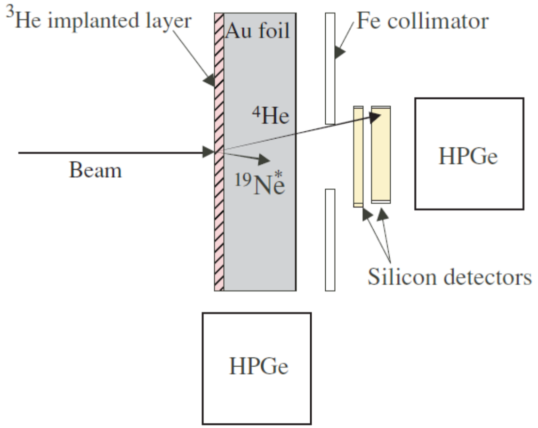
- Population of state of interest through a chosen nuclear reaction
- Slowing and stopping of recoil nucleus
- γ-ray emission at range of velocities

γ-ray line shape is sensitive to the lifetime of nuclear states

Lifetime measurement results

R. Kanungo+ (2006)

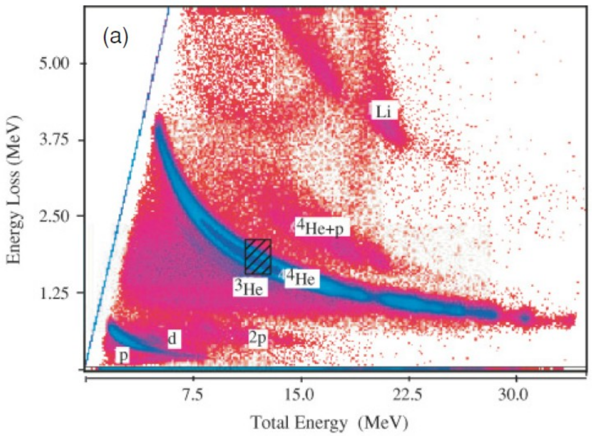
Experimental set-up



- ^{3}He(^{20}Ne,α)^{19}Ne* @ 34 MeV [TRIUMF]
- ^{3}He (6x10^{17} cm^{-2}) implanted in 12.5 μm Au foil
- 2 HPGe at 0° and 90°
- Δ*E* (25 μm) - *E* (500 μm) silicon detectors telescope

→ coincidence α-γ measurement

Reaction channel identification



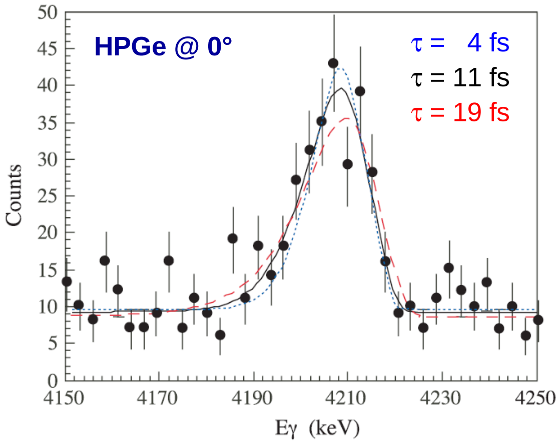
- Wide range of α–particle energy

→ fusion-evaporation ^{20}Ne + ^{12}C (contaminant)

- Hatched area [E_α = 11 – 13 MeV]

→ α-particles corresponding to population of 4.033 MeV state

E_γ = 4033 keV line shape



- $\boxed{\tau = 11^{+4}_{-3}\ \mathrm{fs}\ (1\sigma)}$
- Good agreement with existing works:
  - $\tau = 13^{+9}_{-6}\ \mathrm{fs}\ (1\sigma)$ W. P. Tan+ (2005)
  - $\tau = 6.9^{+1.5}_{-1.5} \pm 0.7\ \mathrm{fs}\ (1\sigma)$ S. Mythili+ (2008)

How to determine branching ratios

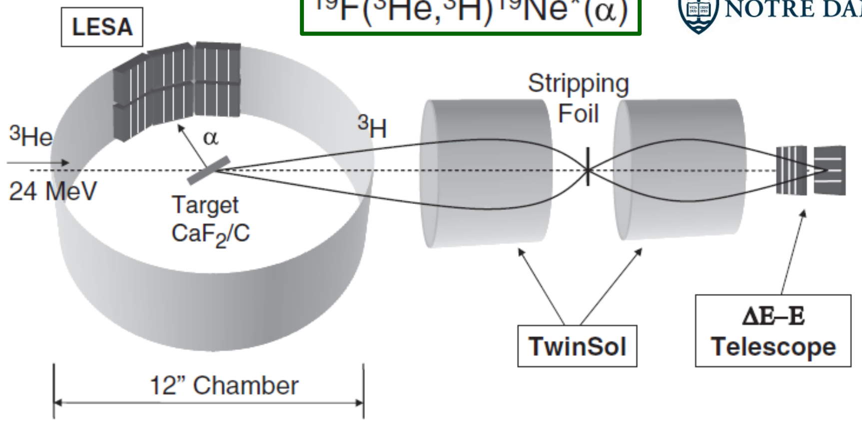
W. P. Tan+ (2007, 2009)

α-particle branching ratio $B_\alpha = \frac{\Gamma_\alpha}{\Gamma}$ is the probability for an unbound state to decay through α emission

Experimentally: coincidence measurement

- Detector close to 0° (silicon, spectrometer…)
  - Detection of particles allowing the identification of the reaction and states of interest (2-body kinematics)
    → "single" events $N_{singles}$
  - Strong alignment of magnetic substates
- Silicon detector array (stripped) surrounding the target
  - Detection of decaying particles
    → "coincident" events N_{coinc}
  - Angular correlation measurement
    → use to determine the number of decay N_{decays}
- Branching ratios $\boxed{B_\alpha = \frac{N_{decays}}{N_{singles}}}$

$^{19}F(^3He,^3H)^{19}Ne^*(\alpha)$



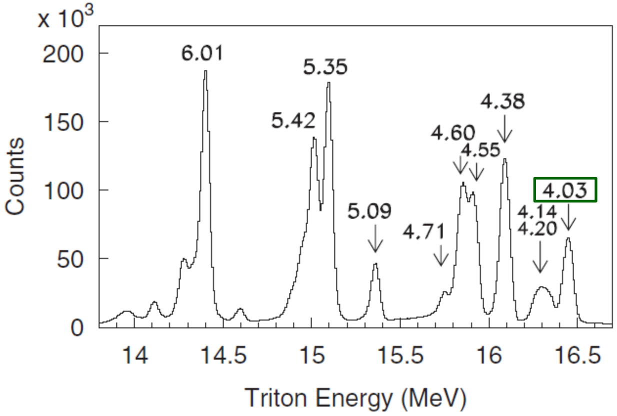
Challenge: low-energy α-particle (< 1 MeV)

- Thin target, thin detector dead layer, low electronic threshold

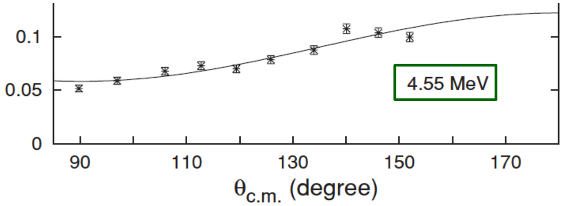
Branching ratio results

W. P. Tan+ (2007, 2009)

Triton energy spectrum (single)

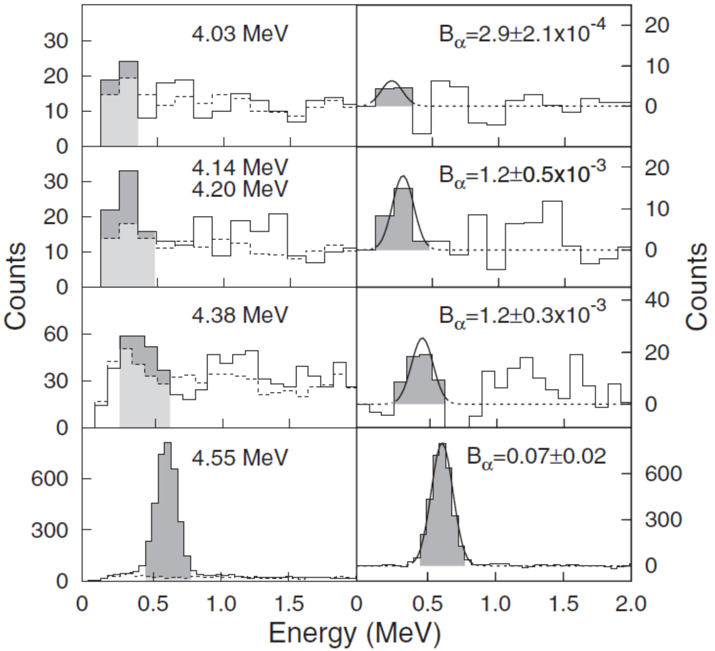


α-t angular correlation



$$W(\theta_{c.m.}) = \frac{1}{4\pi} \sum_{k=0}^{k_{max}} a_{2k} P_{2k}(cos(\theta_{c.m.}))$$

α-particle energy spectrum (α-t coincidence)



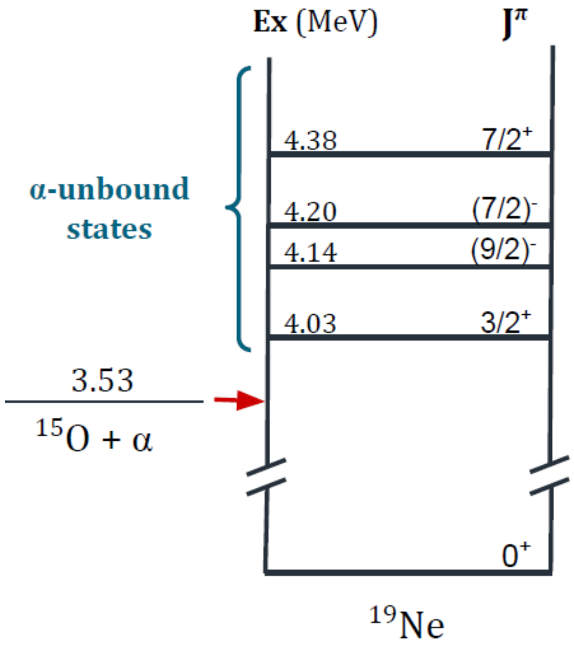
Left:
- Solid (all coincidences)
- Dashed (background)

Right:
- Backgound subtracted

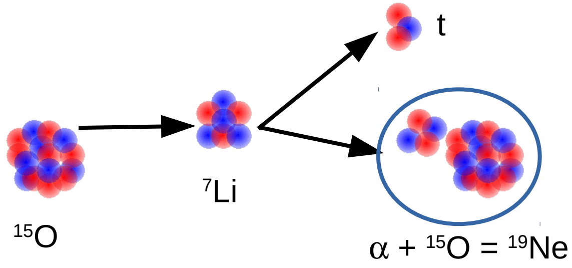
- B_α (4.033 MeV) = 2.9 ± 2.1 x 10^{-4}
- Compatible with previous upper limits
- Very low statistics (6 t-α on 20 background) with B_α compatible with 0 at the 2σ level

Experimental method

$\boxed{\text{Transfer reactions are a privileged tool to determine partial widths}}$



- α-particle transfer reaction commonly use **(^{7}Li,t) reactions [^{7}Li = α + t]**
- **Inverse kinematics** since ^{15}O is radioactive [not possible to produce targets]



- Comparison between experimental and theoretical differential cross-section

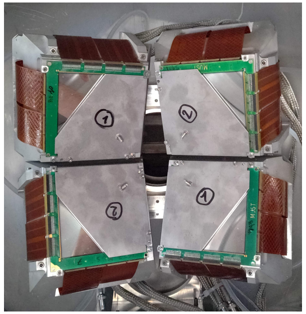
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = C^2 S_\alpha \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

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

Experimental set-up

J. Sanchez Rojo (2022 PhD)

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

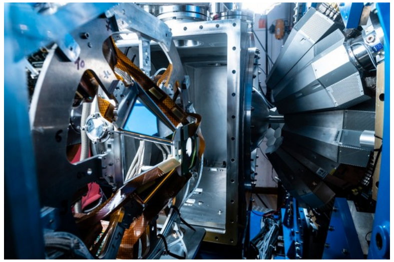


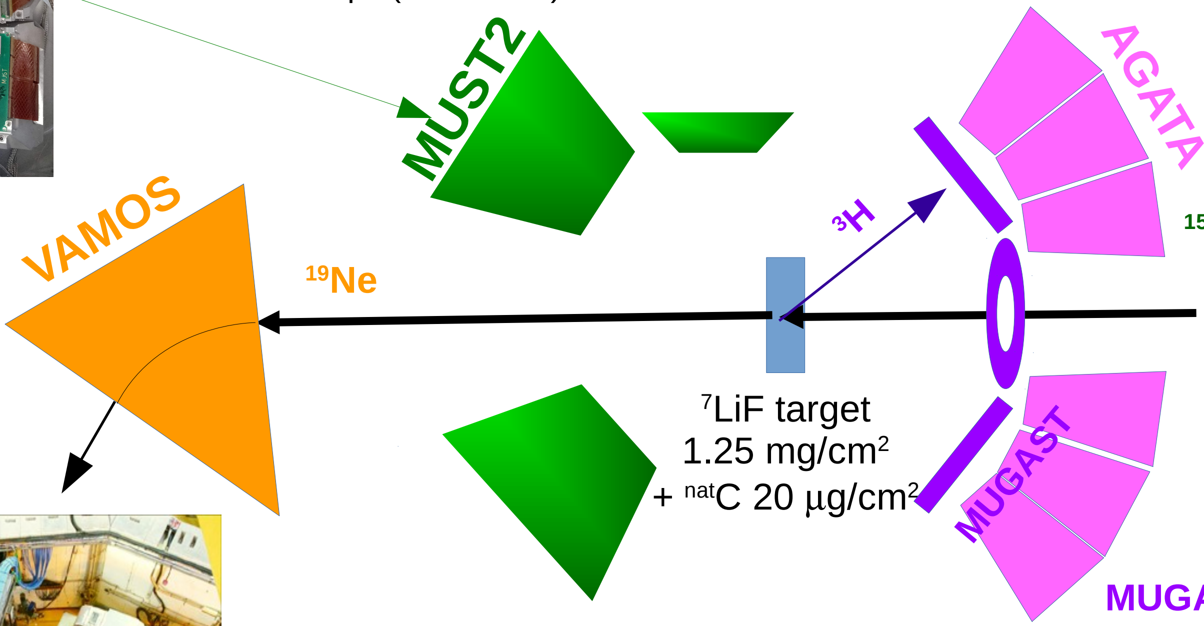
MUST2

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

AGATA @ 18 cm

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





^{15}O @ 4.7 MeV/u

- ~ 2x10⁷ pps
- SPIRAL1 beam
- ^{15}N contaminant < 0.5 %

VAMOS @ 0°

- ΔΘ ± 7°
- ΔBρ ± 10% (~)

MUGAST

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

Particle identification

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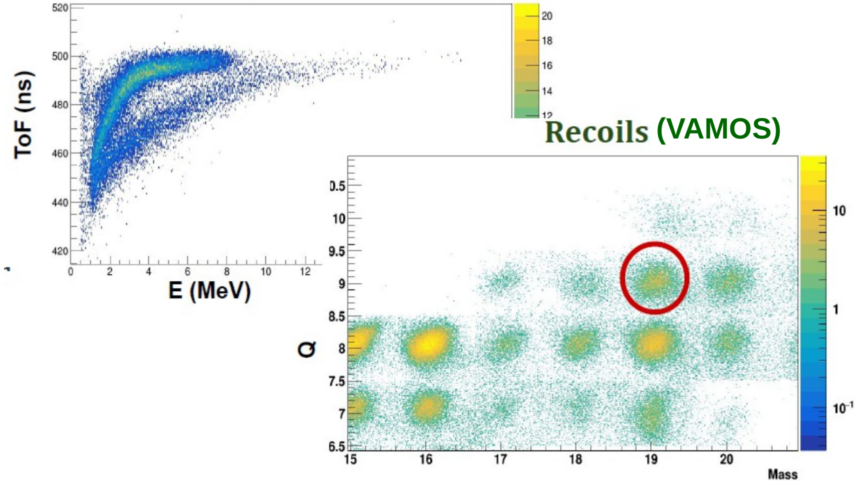
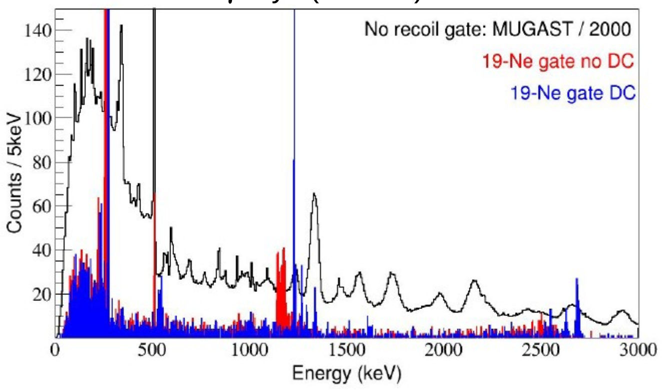
- VAMOS spectrometer (recoils)
  - Good selectivity of recoils: A, Z, Q
  - ^{19}Ne well identified
  - Crucial for background rejection

- 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)





^{19}Ne – t – γ triple coincidences

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Conditions

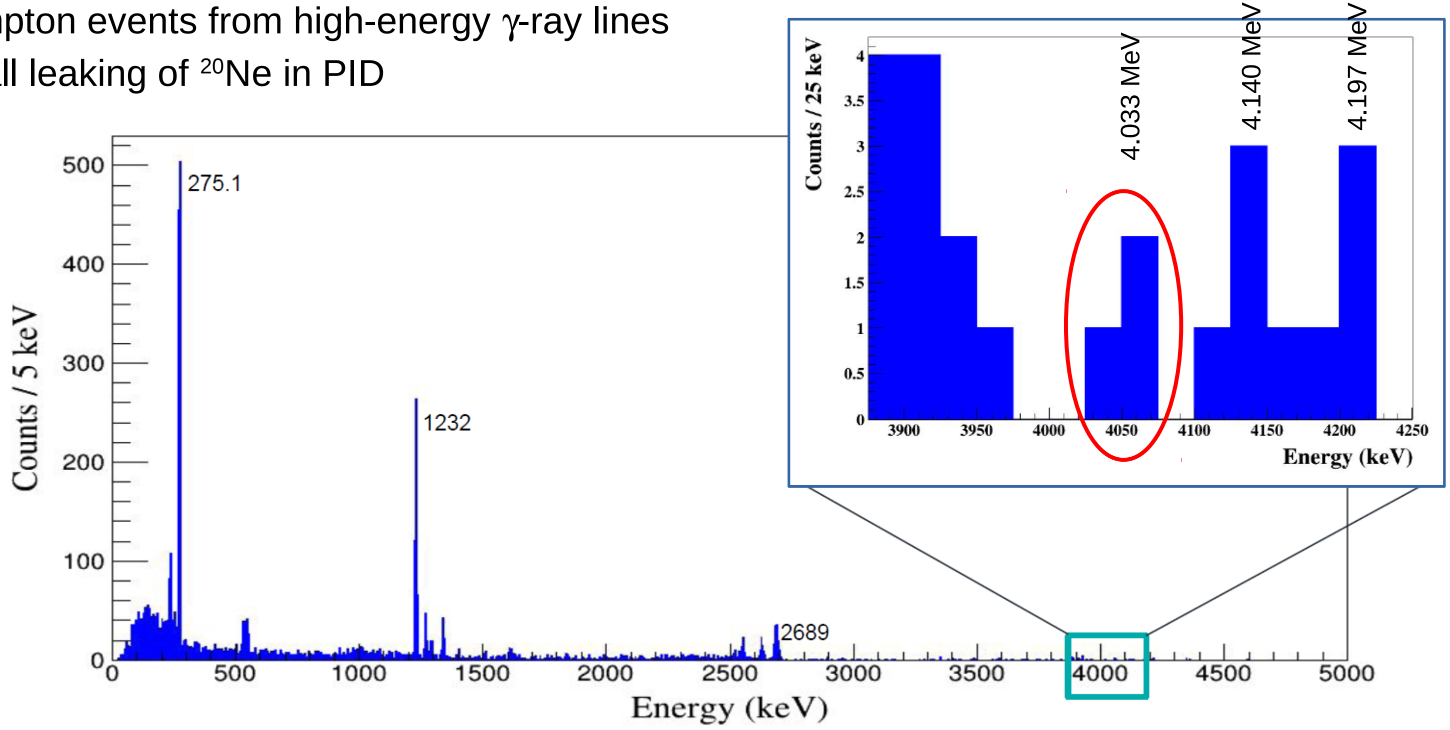
- Gate on $^{19}Ne^{9+}$
- γ-ray multiplicity = 1

Source of background

- Compton events from high-energy γ-ray lines
- Small leaking of ^{20}Ne in PID

Case of the 4.033 MeV state

- $N = 2.2^{+3.7}_{-1.9}$ (90% CL)
- NOT compatible with zero (unlike previous work)



Angular distributions and reaction rate

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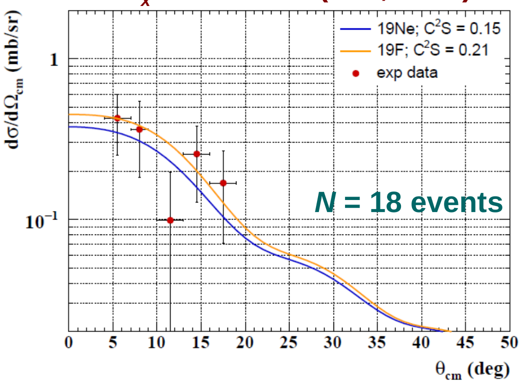
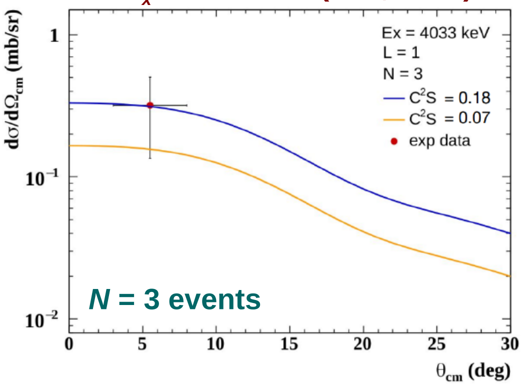
Selection of angular distributions

E_x = 1536 keV ($3/2^+$; ℓ = 1)

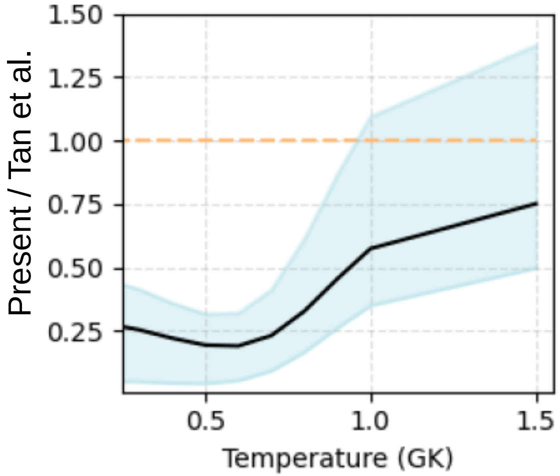


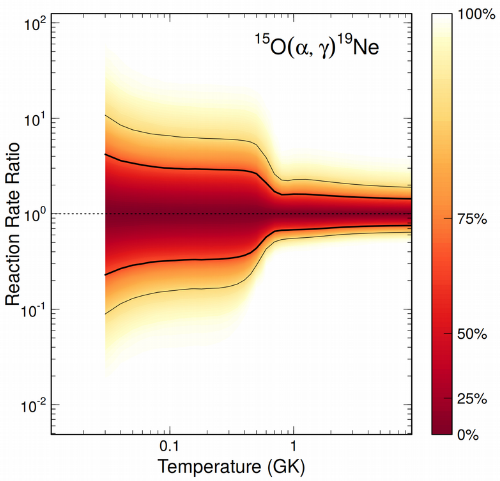
E_x = 4033 keV ($3/2^+$; ℓ = 1)



$$\Gamma_\alpha = 3.0^{+4.0}_{-2.2} \pm 1.4\ \mu\text{eV}$$

$^{15}O(\alpha,\gamma)^{19}Ne$ reaction rate





- Reaction rate significantly smaller than previous evaluation
  → factor 2 to 4
- Evaluation of a meaningful statistical uncertainty
  → factor 2 to 3 (1 sigma)
- Impact on X-ray bursts explosion in progress...

Summary

- Classical novae and type I X-ray bursts are fascinating objects
  - Classical novae: thermonuclear rates of few reactions still needed (but very difficult!)

    → close to valley of stability → stable + radioactive beams
  - Type I X-ray bursts: a few tens of (α,p) + (p,γ) reactions to study

    → relatively far from the valley of stability → mostly radioactive beams

- $^{18}F(p,\alpha)^{15}O$ and $^{15}O(\alpha,\gamma)^{19}Ne$
  - Same nucleus can be important for different reactions (compound ^{19}Ne), but different states are involved (different temperatures in astrophysical sites)
  - For a single reaction, **several experimental methods and techniques** (direct measurement, transfer reactions, charge exchange reactions, branching ratios, lifetime measurement...) **are needed** with a **wide variety of detectors** (magnetic spectrometer, charged particles and γ-ray detectors…) using **stable and radioactive ion beams**
  - Don't forget to look at the miror nucleus (if possible)!

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THANK YOU FOR YOUR ATTENTION