The Enge Split-Pole at ALTO: recent nucleosynthesis studies

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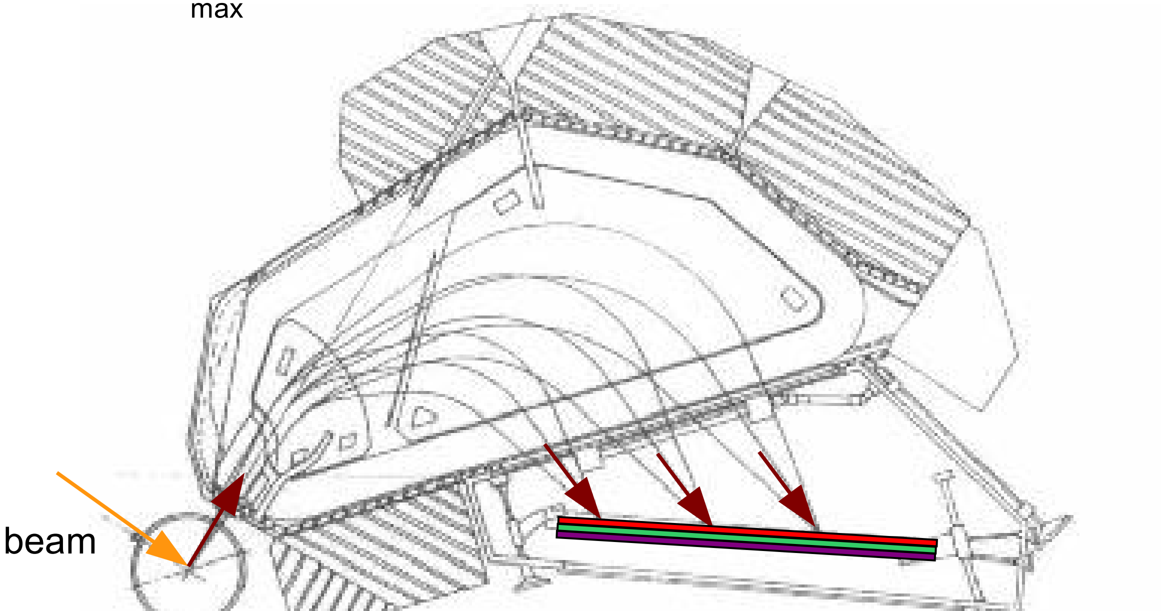
1st meeting of LIA – Subatomic Physics: from theory to applications,
São José dos Campos, June 12th – 13th, 2018

Split-Pole magnetic spectrometer

Enge Split-Pole:

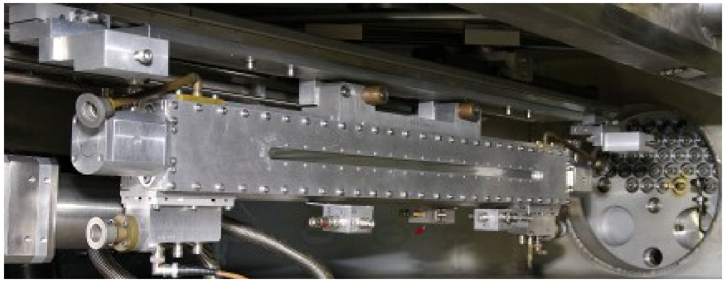
- $\Delta E/E = 5 \times 10^{-4}$
- $\Delta\Omega$ = 1.7 msr (or more, but aberrations)
- B_{max} = 1.8 T



Enge, NIM 162 (1979)
Spencer & Enge, NIM 49 (1967)

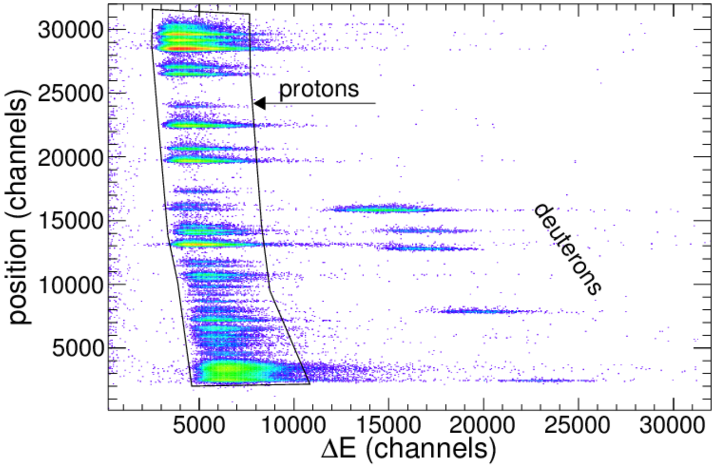
Focal-plane detector:

- Position sensitive gas chamber
- ΔE proportional gas counter
- E plastic scintillator



Markham & Robertson, NIM 129 (1975)

Particle identification:



Angular distribution measurement

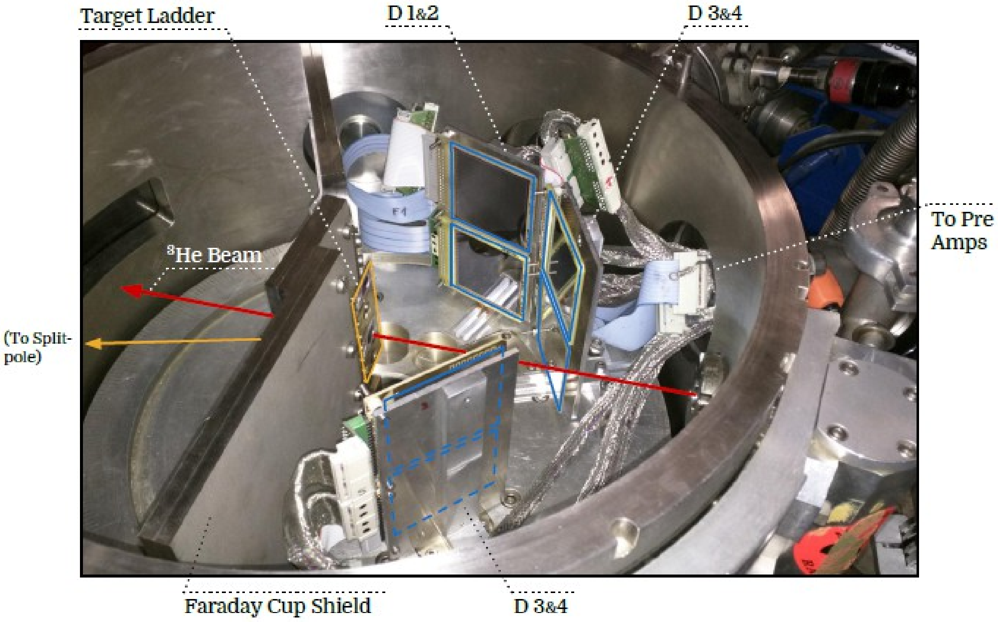
- Orbital angular momentum
- Spectroscopic factors → partial widths

DSSSD array in coincidence mode

(Orsay – Barcelona – York set-up)

Experimental conditions

- 6 W-type DSSSDs
  → 16 + 16 strips (ΔE ~ 20 keV FWHM)
- close geometry around the target
  → d ~ 11-12 cm, ε ~ 14%
- Very low background environment
- Thick shield to reduce induced background from faraday cup @ 0 degree
- Beam intensity up to **100 enA** (p, ^{3}He)

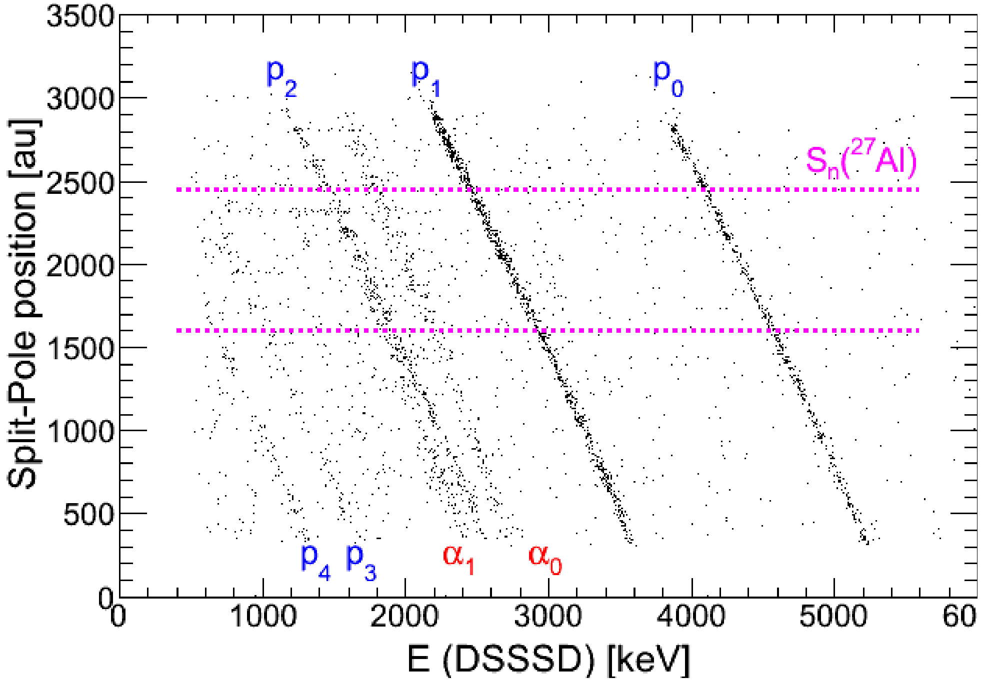


Event selection

- Split-Pole proton selection
- Time of flight between FP plastic and DSSSDs
- Energy front v.s. back in DSSSDs

Typical coincidence spectrum

- ^{27}Al(p,p')^{27}Al*(p|α)

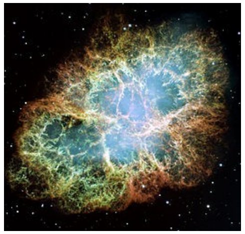


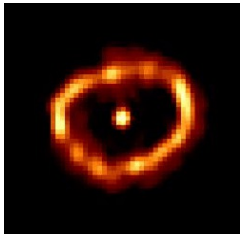
Angular correlation measurement: sensitivity to the spin, branching ratios

Experimental studies the last 10 years

Experimental study of nucleosynthesis

Topic	Beam	Status
Massive star evolution and fate	^{6}Li	A. Belhout et al. NPA793 (2007)
Neutron source in AGB stars	^{7}Li	M. G. Pellegriti et al. PRC77(R) (2008)
Massive star evolution and fate	^{7}Li	N. Oulebsir et al. PRC85 (2012)
^{7}Li problem & Big-Bang nucleosynthesis	^{3}He	F. Hammache et al. PRC88(R) (2013)
^{26}Al nucleosynthesis in massive stars	p	S. Benamara et al. PRC89 (2014)
^{26}Al nucleosynthesis in massive stars	p	P. Adsley et al., to be submitted
^{15}N nucleosynthesis in massive stars	p	P. Adsley et al., ongoing analysis
Classical novae and ^{18}F nucleosynthesis	^{3}He	J. Riley et al., to be submitted
Carbon fusion in massive stars	p	I. Stefan, V. Guimarães, ongoing analysis
Classical novae and ^{22}Na nucleosynthesis	^{3}He	V. Guimarães et al., ongoing analysis
Classical novae and ^{30}P nucleosynthesis	^{3}He	A. Meyer et al., ongoing analysis
Destruction of ^{7}Li	^{3}He	A. Belhout et al., PRC96 (2017)
^{13}C nucleosynthesis in massive stars	^{7}Li	A. Meyer et al., to be submitted



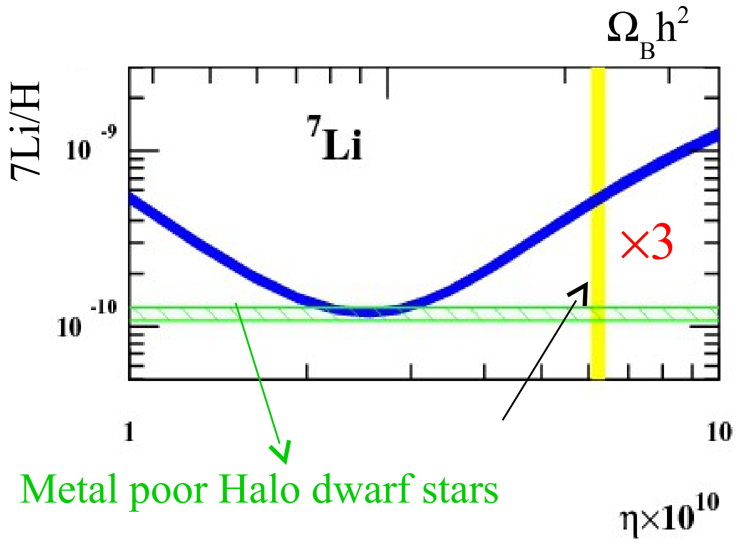


→ light ion beams used all the time

Collaborations:
IPNO – CSNSM + Brazil/USP-UNIFESP, York, Algeria, GANIL, Catania, Barcelona, Huelva

Big-Bang nucleosynthesis & ^{7}Li problem

Primordial nucleosynthesis (**BBN**) of light elements is one of the three observational pillars of the Big Bang model with the expansion of the Universe and the Cosmic Microwave Background radiation



When $T \leq 10^9$ K → BBN begins :

- D, ^{4}He, ^{3}He, ^{7}Li synthesized via nuclear reactions
- Abundances depend on $\Omega_B h^2$ (now fixed: WMAP, Planck)

(BBN+CMB) predictions agree with D, ^{3}He, ^{4}He observations

But: $(^7\mathrm{Li/H})_{\mathrm{BBN}} / (^7\mathrm{Li/H})_{\mathrm{obs}} \approx$ **3 !!! → ^{7}Li problem**

Possible explanations:

- Physics beyond standard model: super-symmetry, constant variation, ….
- ^{7}Li stellar destruction ? → need uniform destruction all over the Spite plateau region
- Nuclear physics: ^{7}Li produced via ^{7}Be EC & ^{3}He(^{4}He,g)^{7}Be known better than 15%

Missing ^{7}Be destruction channels? Chakraborty et al. (2011), Civitarese et al. (2013)

- ^{7}Be + ^{3}He → ^{10}C* hypothetical state at ~ 15 MeV (1-, 2-)
- ^{7}Be + ^{4}He → ^{11}C* hypothetical states at 7.8 MeV

Existence?

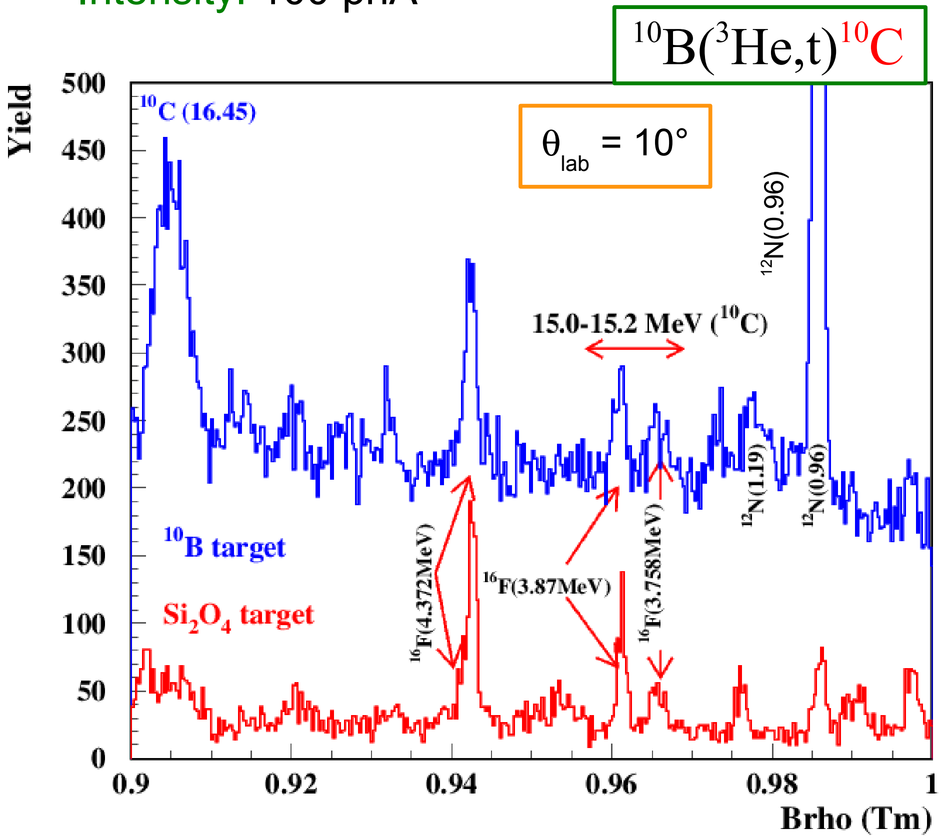
- ^{7}Be + d → ^{9}B* state at 16.71 MeV (5/2+)
- ^{7}Be + t → ^{10}B* state at 18.80 MeV (2+)

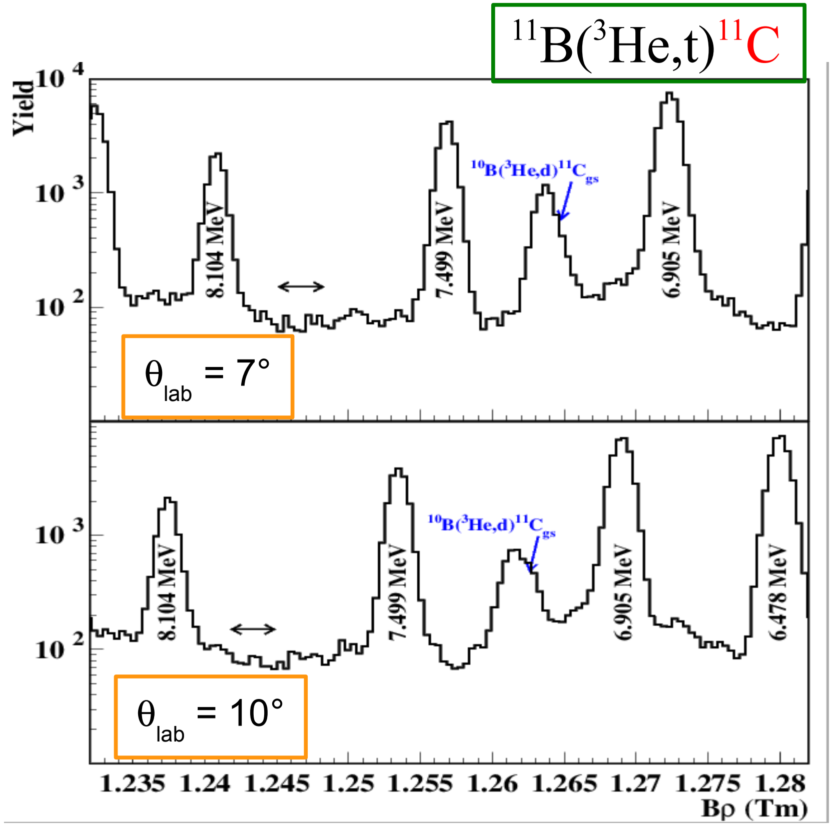
Unknown partial & total width

Search for missing ^{10}C and ^{11}C states

Reactions: $^{10}B(^3He,t)^{10}C$ & $^{11}B(^3He,t)^{11}C$@ 35 MeV (Tandem-Alto)
Targets: ^{10}B/Au, ^{nat}B (80% ^{11}B), ^{12}C, Si_2O_4, ^{197}Au

Intensity: 100 pnA





No additional state in ^{10}C at ~ 15 MeV

→ Contamination peaks due to ^{16}O
→ Same results at other angles (5º and 15º)

If present → Γ ≥ 590 keV (95% CL)

F. Hammache, A. Coc et al. PRC 88, 062802 (R) 2013

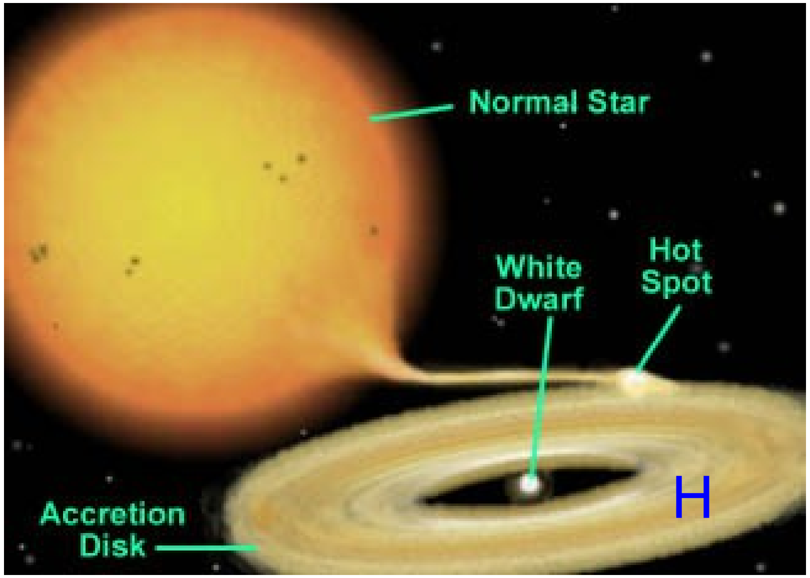
No additional state in ^{11}C at ~ 7.8 MeV

→ All known ^{11}B states below E_X = 12 MeV have their counterpart in ^{11}C mirror nucleus

Solution to ^{7}Li problem very likely must be found out of nuclear physics

Classical novae and γ-ray emission

Final evolution of a close binary system



- Accretion of H-rich material on the WD from its companion star
- Thermonuclear runaway in convective envelope
- Expansion and shell ejection

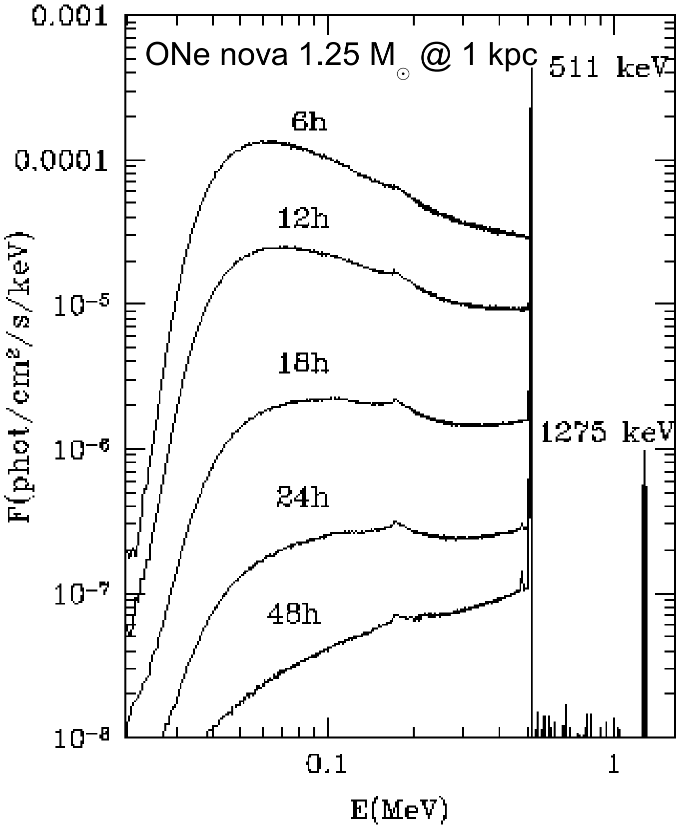
Constraints on models

- Multi wavelengths observations
- γ-ray observations
  → isotopic abundances
  → explosion mechanism, novae rate ejected shell properties ...

Observations and predictions

- E_γ > 100 MeV (FERMI/LAT) Abdo et al. Science (2010)
- γ-ray lines (^{7}Be, ^{18}F, ^{22}Na, ^{26}Al)

^{18}F ($T_{1/2}$ = 158 min) predicted emission

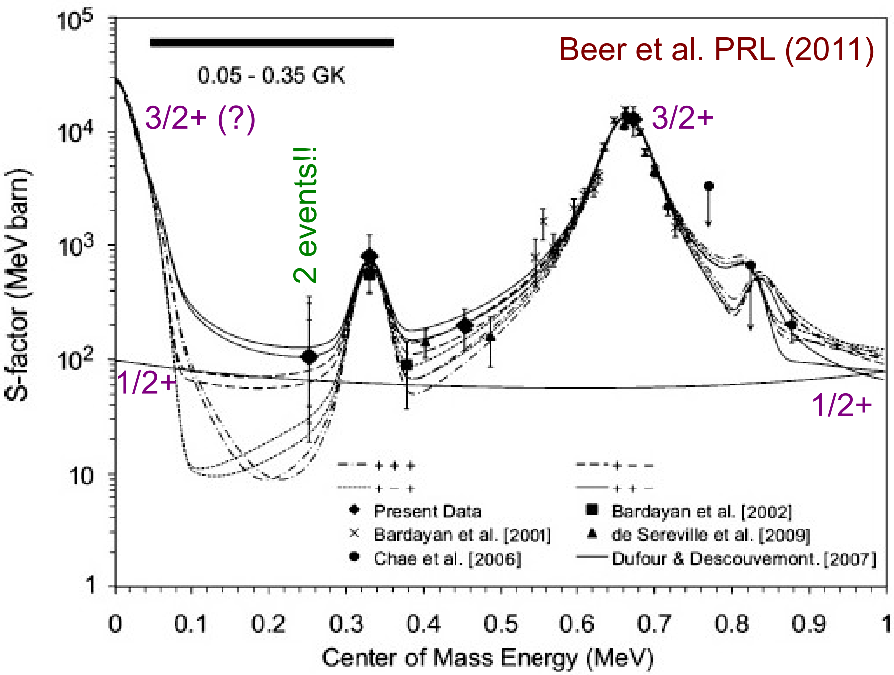


Hernanz, Gomez-Gomar, José (2001)

^{18}F yield depends crucially on uncertain ^{18}F(p,α)^{15}O reaction

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

$^{18}F(p,\alpha)^{15}O$ is the focus of intensive investigation since more than two decades


Beer et al. PRL (2011)

Direct measurement in Gamow peak

- Large error bar (statistics)
- Need for lower energy data

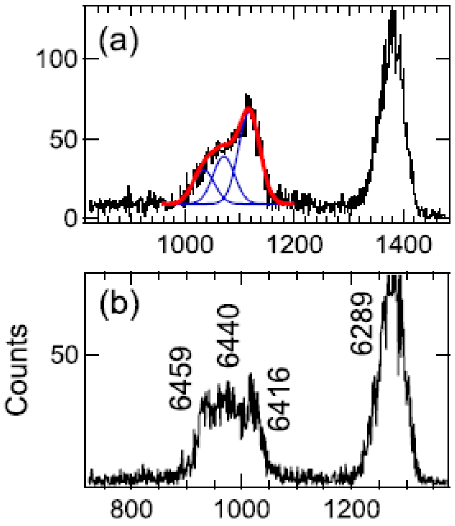
Interference effects in Gamow peak

- 3/2+ resonances: “8, 38keV” and 665 keV
- 1/2+ resonances: sub-threshold + 1.45 MeV

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

- 3 states above p+^{18}F
  - 5 keV (3/2-, 5/2+)
  - 29 keV (11/2+)
  - 48 keV (5/2-)

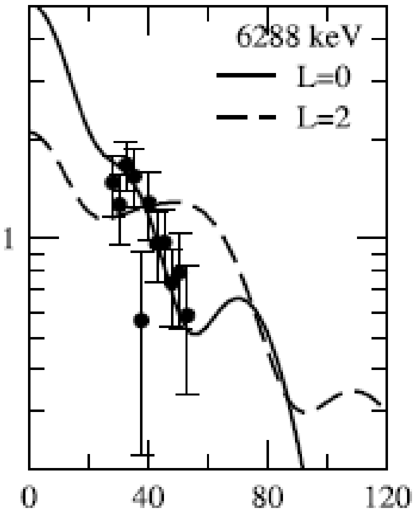
  → no 3/2+!


Laird et al. PRL (2013)

$^{20}Ne(p,d)^{19}Ne$ @ HRIBF

- J^{Π} = 1/2+ (ℓ = 0) for subthreshold resonance at -122 keV
- Maybe a doublet or high spin state (J > 3/2)

Laird et al. PRL (2013)

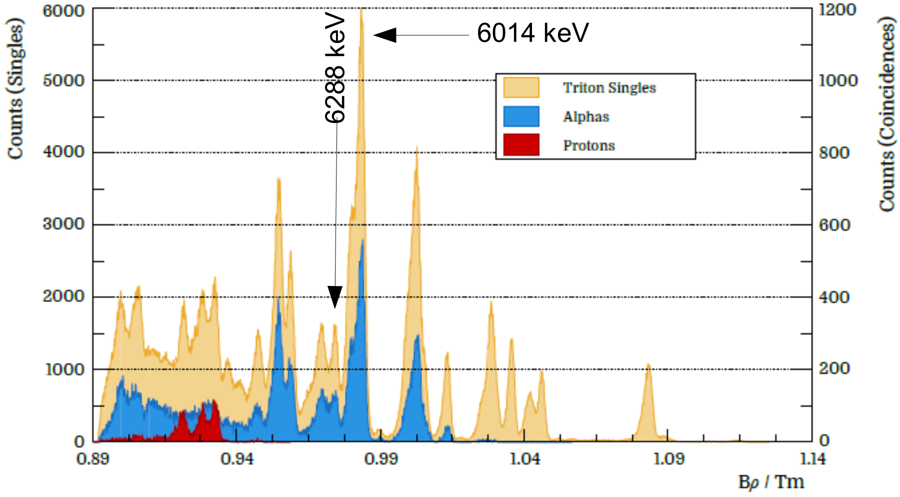

Bardayan et al. PLB (2015)

Experiment and results

Experimental set-up:

- The $^{19}F(^{3}He,t)^{19}Ne^{*}$ charge exchange reaction has already shown to be very little selective in populating ^{19}Ne excited states.
  → Split-Pole spectrometer
- Coincidence measurement, ^{19}Ne states decay via α/p emission.
  → DSSSD array

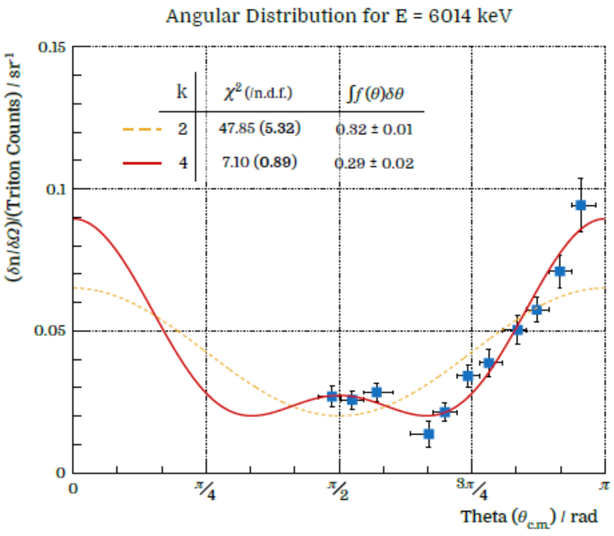
Split-Pole focal plane gated on tritons



Angular correlations (t + α)

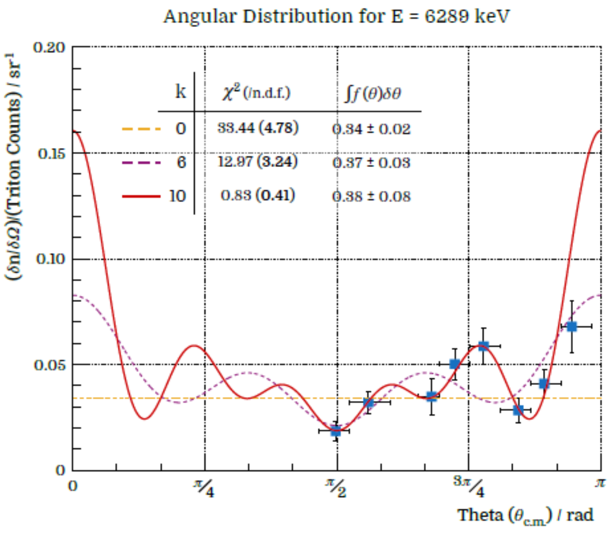
Legendre polynomial governed by J^{π}

J^{π}	$k_{max} = 2l$
1/2-	0
1/2+	2
3/2+	2
3/2-	4
5/2-	4
5/2+	6
7/2+	6
7/2-	8



E_X = 6014 keV

- Test case, known 3/2- state
- In agreement with J^{Π} = 3/2-



E_X = 6289 keV (E_R = -122 keV)

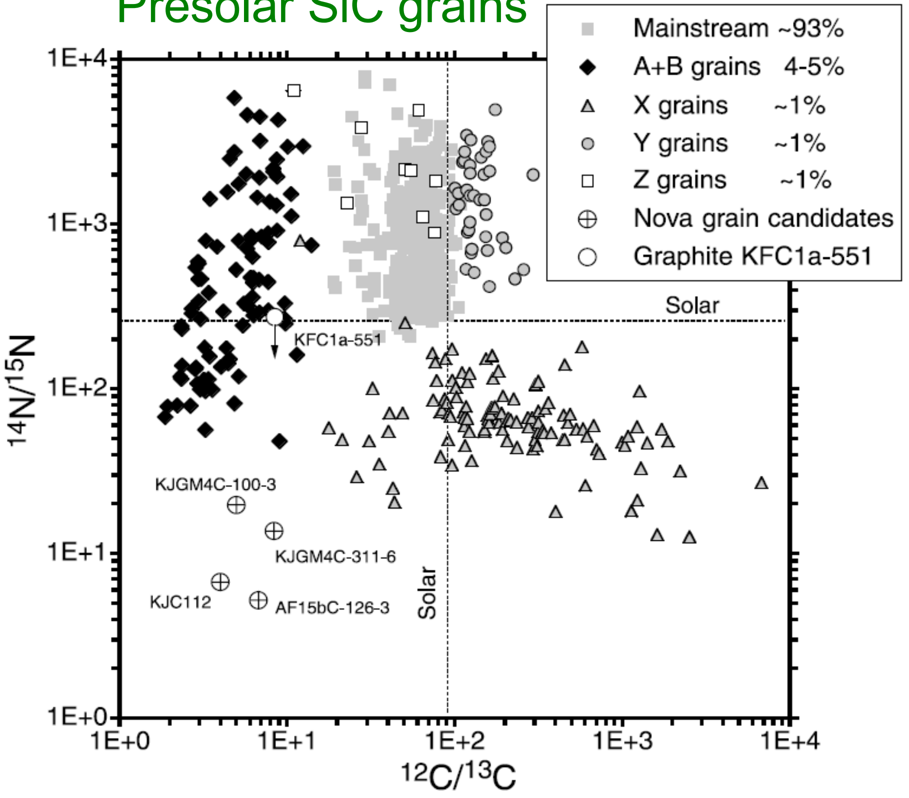
- Not compatible with single 1/2+ state
- Would indicate high spin or multiplet

J. Riley, A. M. Laird et al., to be submitted

Presolar grains and classical novae

- Primitive meteorites hold several types of dust grains that condensed in stellar winds or ejecta of stellar explosions
- These grains carry isotopic anomalies which are used as a signature of the stellar environment in which they formed

Presolar SiC grains



Amari et al., ApJ 551 (2001)

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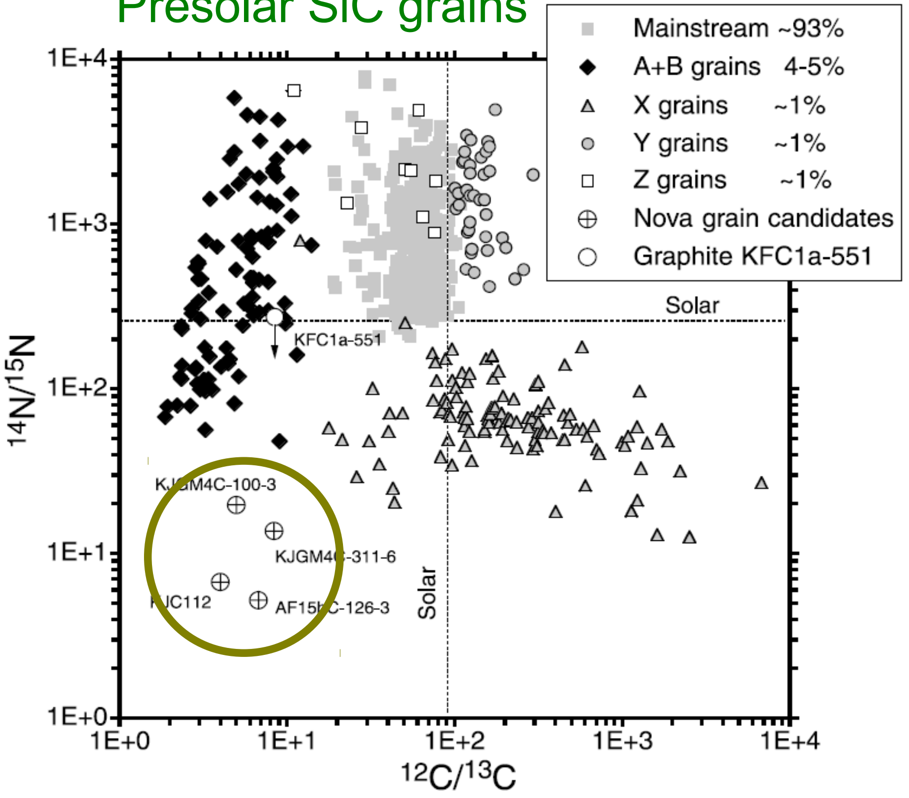

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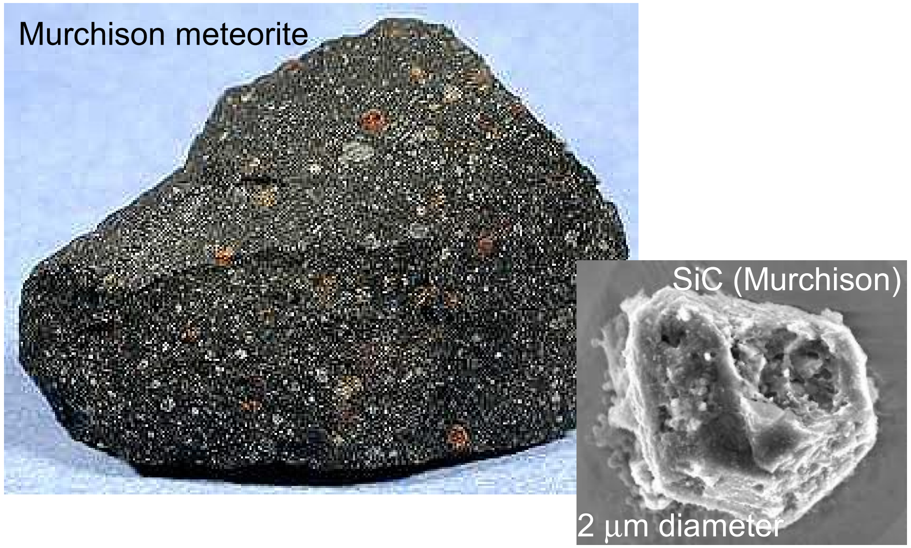

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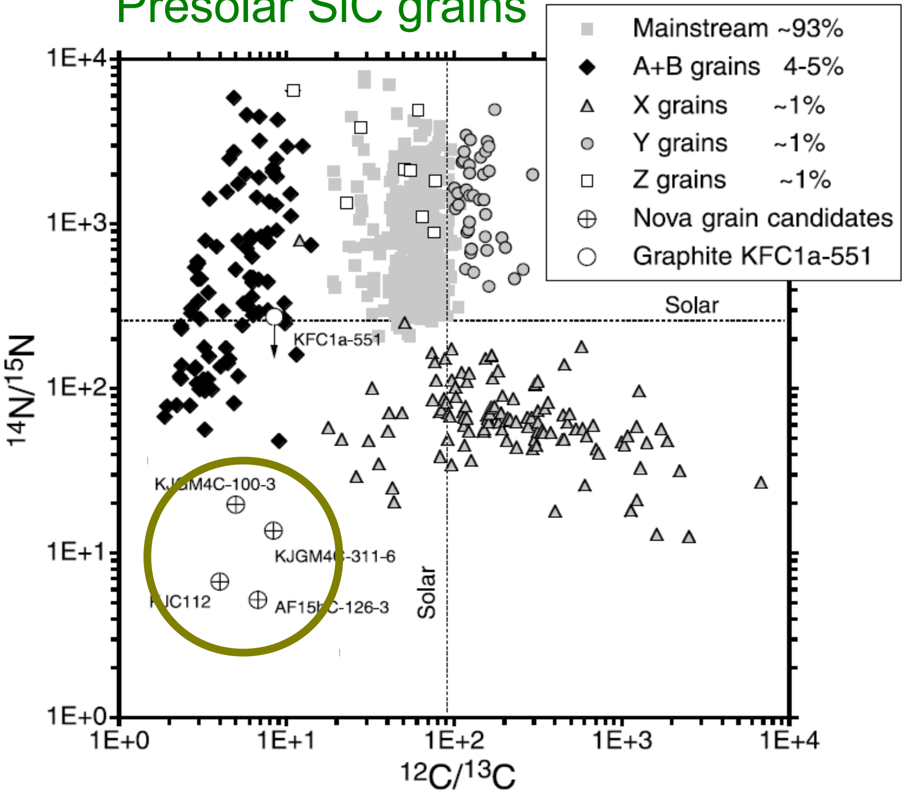


Amari et al., ApJ 551 (2001)

Classical novae José et al., ApJ 612 (2004)

- Extreme excesses of ^{13}C and ^{15}N
  → typical explosive H-burning signature
- High $^{30}Si/^{28}Si$ and close to (sub)solar $^{29}Si/^{28}Si$

^{30}Si yield depends crucially on uncertain $^{30}P(p,\gamma)^{31}S$ reaction

$^{30}P(p,\gamma)^{31}S$ experimental study

- Direct measurement impossible due to low ^{30}P beam intensities
- Reaction rate (narrow, isolated resonance):

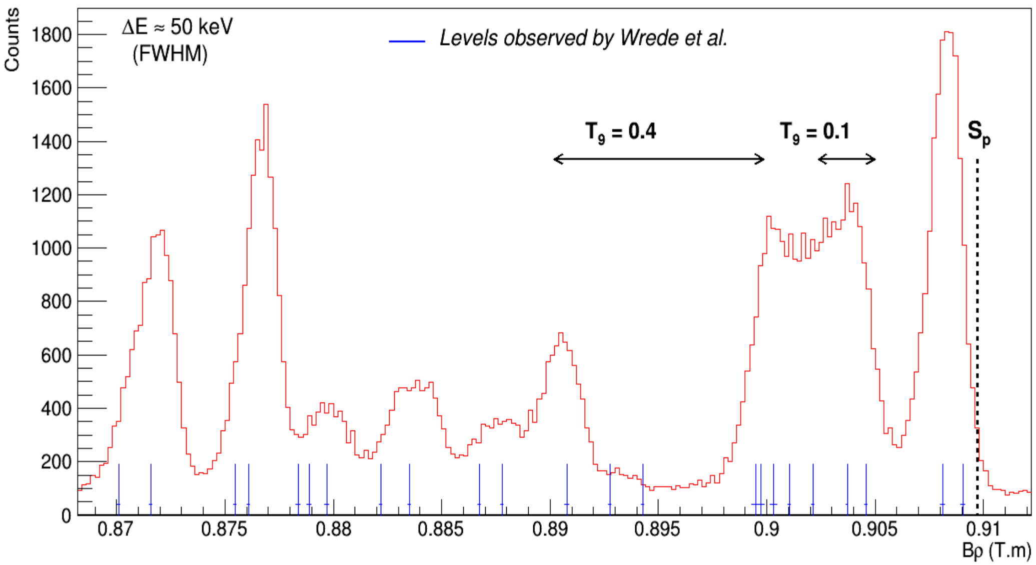
$$N_A\langle\sigma v\rangle\ \mu\ \omega\gamma = \Gamma_\gamma\Gamma_p/\Gamma_{tot}$$

→ Branching Ratio needed

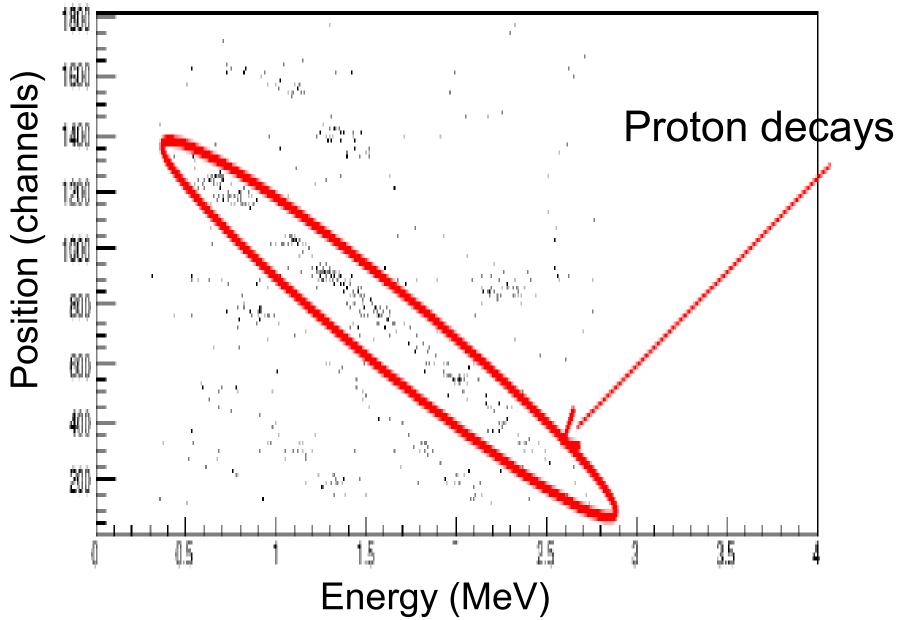
Experimental set-up:

- The $^{31}P(^{3}He,t)^{31}S^{*}$ charge exchange reaction has already shown to be very little selective in populating ^{31}S excited states.
  → Split-Pole spectrometer
- Coincidence measurement, ^{31}S states decay via proton emission.
  → DSSSD array

Split-Pole focal plane (singles) gated on tritons



Coincidence spectrum (1 W1)



Ongoing analysis: A. Meyer (PhD)

Massive stars: hydrogen ingestion in He burning shell

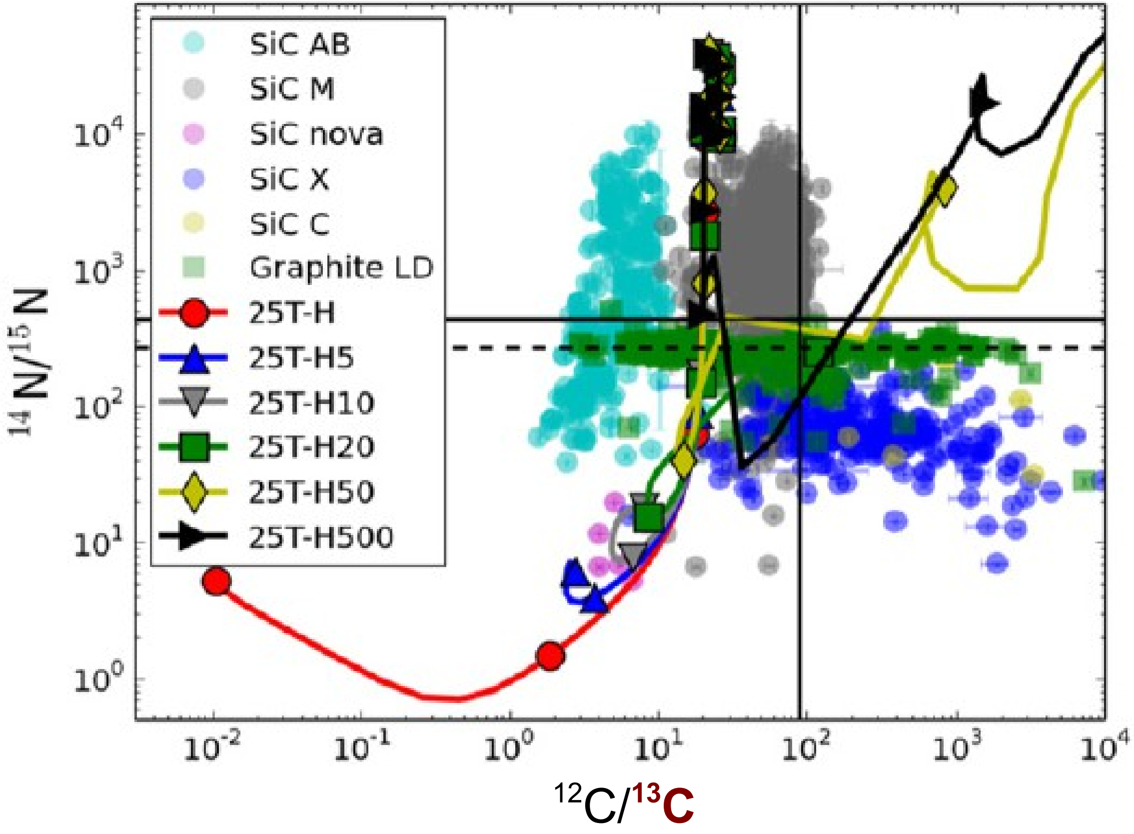
Hydrogen ingestion mechanism

- After end of central C burning, the convective He shell becomes unstable
  → **H from above the He shell is ingested into the He-rich region**

- The onset of core O burning completely deactivates the convective He shell until ccSN explosion
  → **He-rich layer left with 1.2% H**

Explosive nucleosynthesis in the He burning shell carries H burning signature

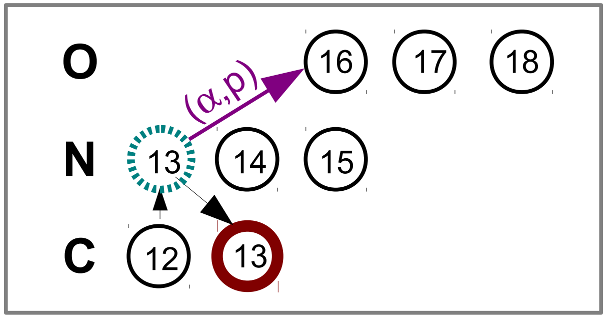
Models: 25 $M_\odot$, Z = 0.02, with (T,ρ) from 15 $M_\odot$



Pignatari et al., ApJL 808 (2015)

Comparison of models with grains data depends on ^{13}C abundance

- ^{13}C has a radiogenic origin from ^{13}N
- ^{13}N produced by $^{12}C(p,\gamma)^{13}N$ reaction
- ^{13}N destroyed by **$^{13}N(\alpha,p)^{16}O$** reaction

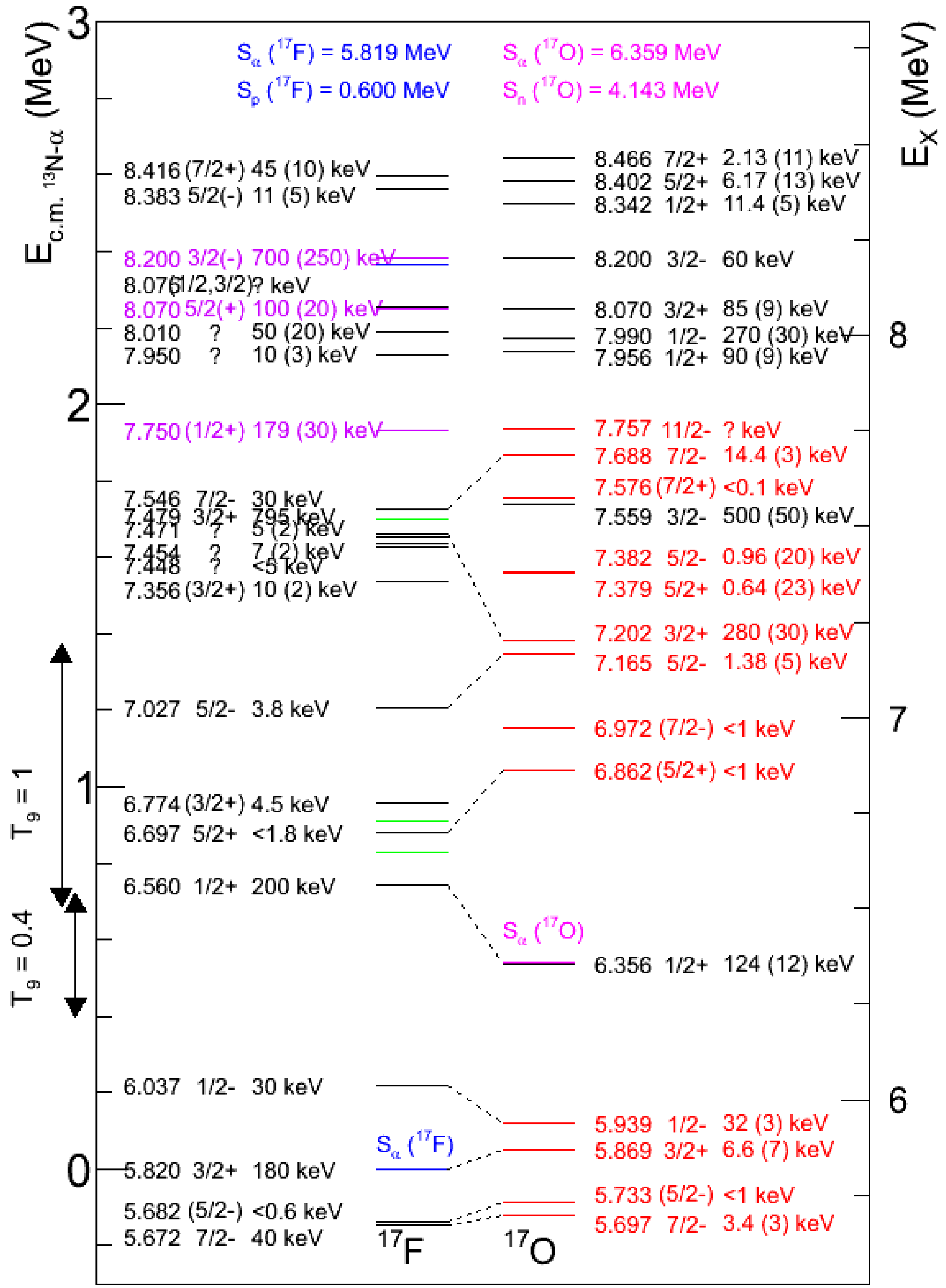


$^{13}N(\alpha,p)^{16}O$: experimental status

- Still no direct experimental data
- Cross section should be estimated from contribution of individual states in compound nucleus ^{17}F
- ^{17}F spectroscopy in the 60's using the $^{16}O(p,p)^{16}O$, $^{16}O(p,p')^{16}O$, $^{16}O(p,\alpha)^{13}N$ reactions
  - → E_R, Γ_{tot} measured
  - → J^Π mostly known

Salisbury et al., PR126 (1962)
Dangle et al., PR133 (1964)

- $N_A\langle\sigma v\rangle \mu \omega\gamma = \Gamma_\alpha\Gamma_p/\Gamma_{tot}$
  - → partial width (Γ_α, Γ_p) missing
- Since $S_\alpha(^{17}F) > S_p(^{17}F)$, for most states of interest $\Gamma_\alpha << \Gamma_p$
- Use mirror nucleus ^{17}O to derive α-widths → study of the $^{13}C(^{7}Li,t)^{17}O$ α-transfer reaction



Experiment and results

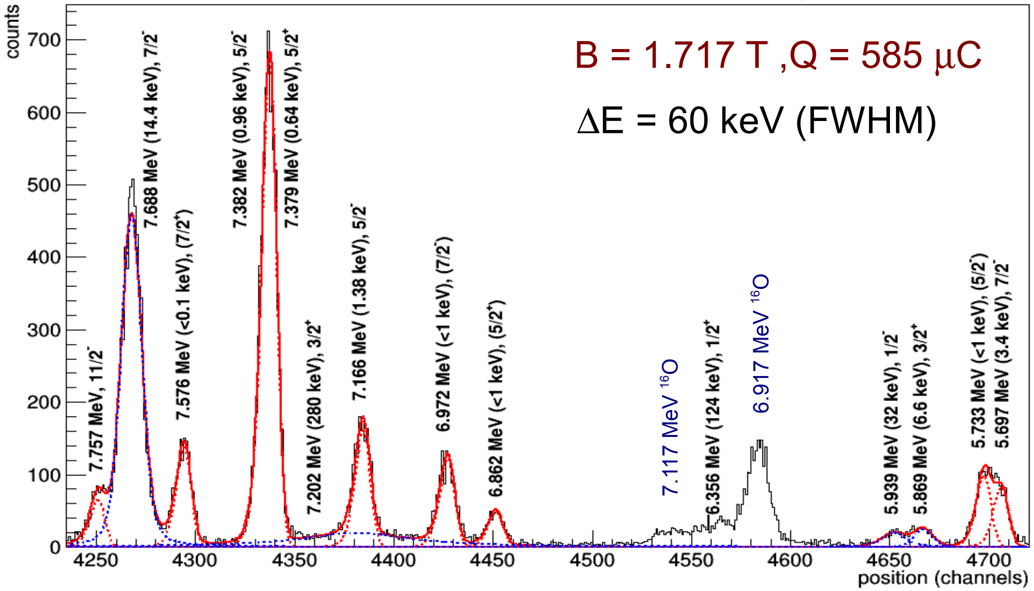
Study of the $^{13}C(^{7}Li,t)^{17}O$ α-transfer reaction (Orsay)

- Initially to study sub-threshold 6.356 MeV state for $^{13}C(\alpha,n)^{16}O$

Pellegriti et al., PRC77 042801 (R) (2008)

- Extending analysis at higher excitation energies

$^{13}C(^{7}Li,t)^{17}O$ triton spectrum, Θ_{SP} = 7°



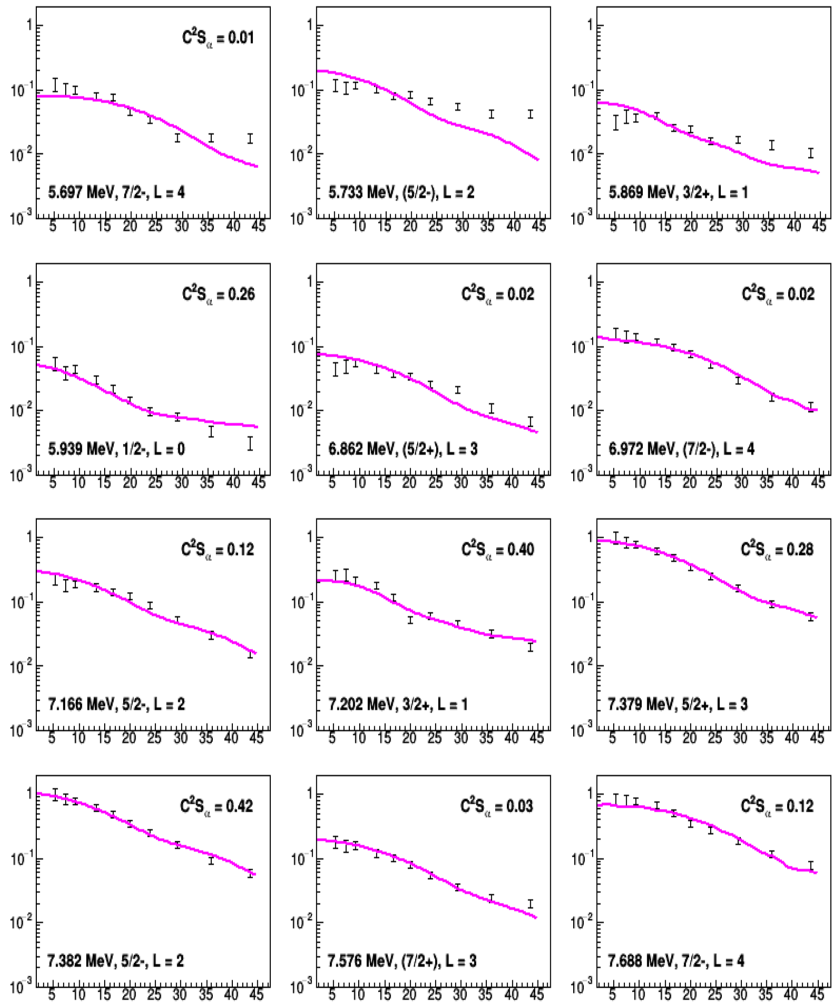
B = 1.717 T ,Q = 585 μC

ΔE = 60 keV (FWHM)

Broad state $E_X(^{17}O)$ = 7.202 MeV

→ Γ_{tot} = 300 (20) keV, (NNDC Γ_{tot} = 280 (30) keV)

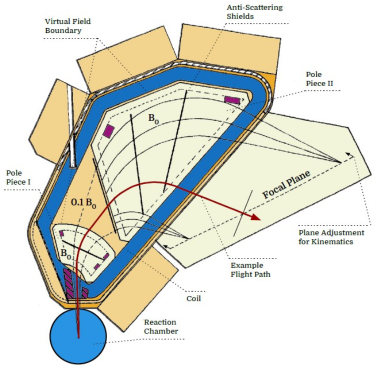
Angular distribution (FR-DWBA analysis)



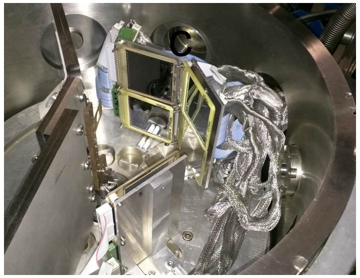
New reaction rate close (within a factor of 2) to CF88 in temperature range of interest

A. Meyer, N. de Séréville et al., to be submitted

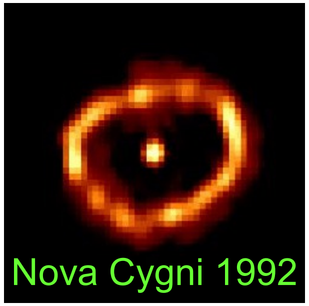
Summary



- Magnetic spectrometers (SP, ...) at TANDEM facilities well suited for indirect nuclear astrophysics studies
  - high-energy resolution measurements
    → discovery of new levels
  - angular distribution measurements
    → constrain orbital angular momentum
    → determine spectroscopic factors

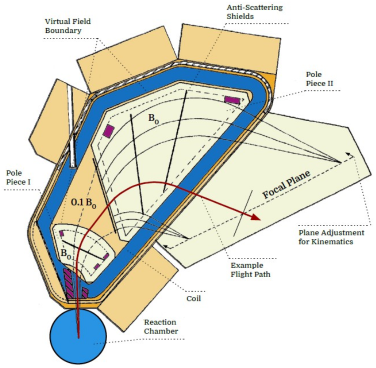


- Efficient (~15%) silicon array coupled to Split-Pole
  → angular correlation measurements
  → spin and BR determination


Nova Cygni 1992

- Scientific program
  - Quiescent nucleosynthesis – SP single measurement
    → asymptotic giant branch stars, massive stars
  - Explosive nucleosynthesis – SP coincident measurement
    → classical novae, core collapse supernovae

Summary



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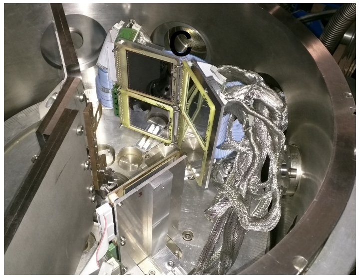

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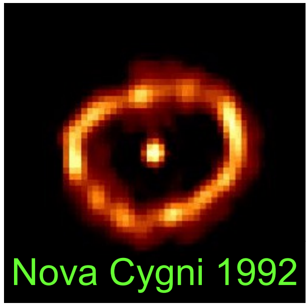
Collaborations are welcome



- Scie n
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    classical novae, core collapse supernovae

Collaborators

IPN
ORSAY

F. Hammache, N. de Séréville, I. Stefan...

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P. Adsley, A. M. Laird, S. Fox, J. Riley...

UPC

A. Parikh

USP

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V. Guimarães / M. Assunção

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Department of Neutron Physics