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Nuclear astrophysics with indirect approaches: ANC and Trojan Horse Method

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Outline of the talk

- ✓ **Why indirect approaches are useful in nuclear astrophysics (and beyond)**
- ✓ **Indirect methods: ANC & THM**
- ✓ **Some details about THM**
- ✓ **Two physical cases (with unstable and stable beams):**
  - ❑ **The $^{18}F(p,\alpha)^{15}O$ reaction**
  - ❑ **The $^{16}O(^{16}O,\alpha)^{20}Ne$ reaction**
- ✓ **Summary**

The Scientific Case

The purpose of nuclear astrophysics is to provide reliable nuclear physics input

Nuclear parameters (cross sections, …)

Astrophysical models: how a star works

Model input parameters: magnetic field, metallicity, …

Elemental yield → comparison with abundances observed in stars and meteorites to validate models

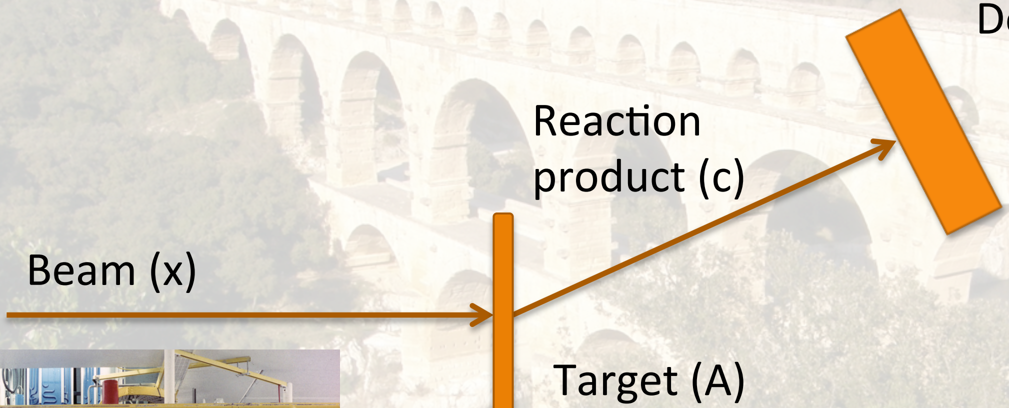
Change the model until observables are matched by predictions

Astrophysical models are very complex: assumptions on stellar structure and on stellar parameters (age, mass…) → need of multiple independent constrain

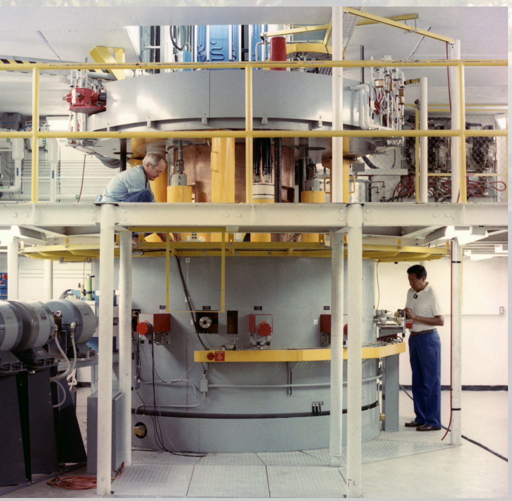
Key information: how does the mixing mechanism work? Mixing transports the produced nuclides from stellar inner layers to the surface where they are observed

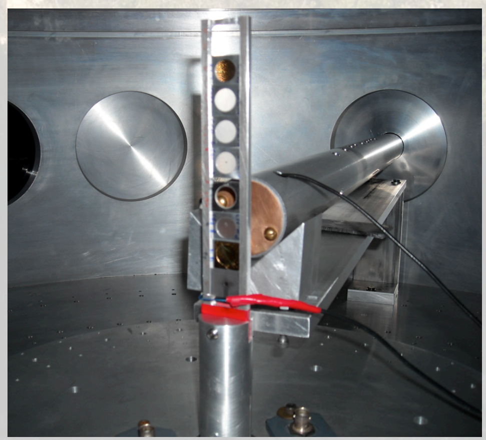
Direct…

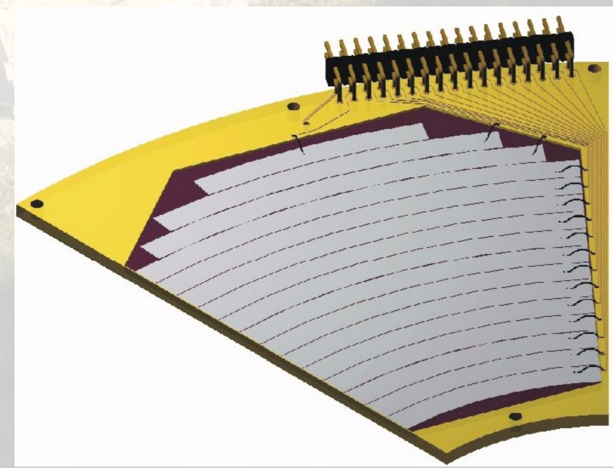
How to measure the A+x→c+C reaction in a *direct* way?



Detector → kinematic observables
- Energy
- Emission angle
+ Particle identification







It looks *quite* simple!

Pros and cons

Straightforward but complicated

✓ Coulomb barrier exponentially suppresses the cross section (E<100 keV)

→ low count rate and low statistics

→ high background and poor signal-to-noise ratio

→ no access to the low energy region

✓ Straggling

→ possible errors in energy calibration

→ poor energy and angular resolution

✓ Electron screening

→ trend of the bare-nucleus S-factor altered

→ systematic error due to poor knowledge of the process

… even in the few cases when the low-energy S-factor has been measured the bare-nucleus S-factor has not being determined accurately

…and indirect measurements

Entrance channel A+a → **several reaction mechanisms link the two channels** → **Reaction products C+c+…**

Complicated but rewarding

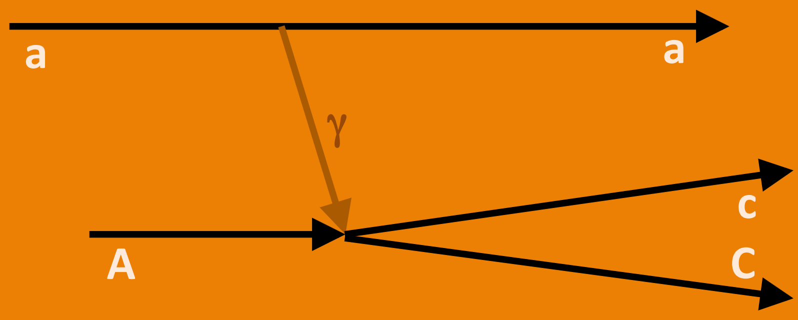
High energy experiments: up to several hundreds MeV

- → no Coulomb barrier suppression
- → negligible straggling
- → no electron screening

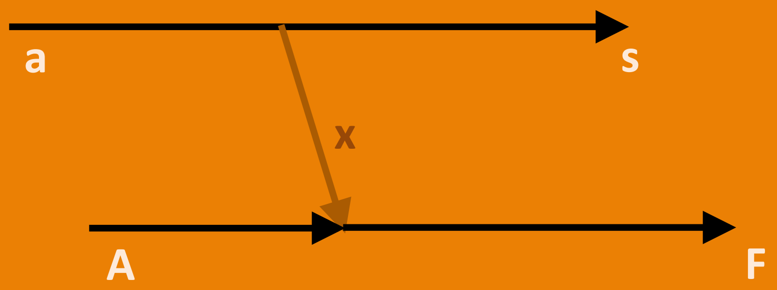
The reaction mechanism of interest has to be singled out to apply **nuclear reaction Theory**

→ **Only a fraction of the data is used during the analysis**

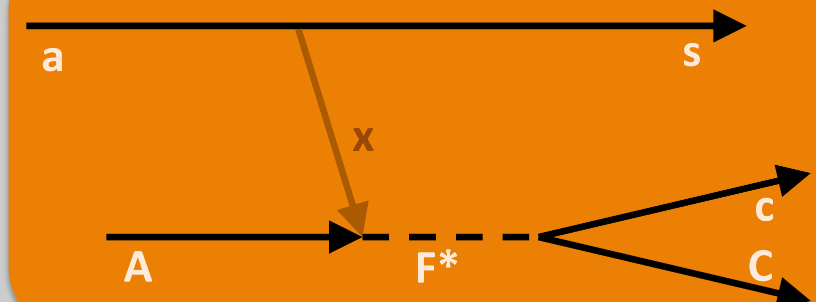
The Methods [see Rep. Prog. Phys. 77 (2014) 106901]



In the **Coulomb dissociation**, a virtual photon beam is used to a photodisintegration reaction; the detailed balance principle is then used to recover the cross section of the relevant radiative capture reaction



In the **Asymptotic Normalization Coefficient (ANC) approach**, a transfer reaction to a bound state is measured to deduce the normalization constant of the bound state wave function, prop. to the A(x,γ)F c.s.



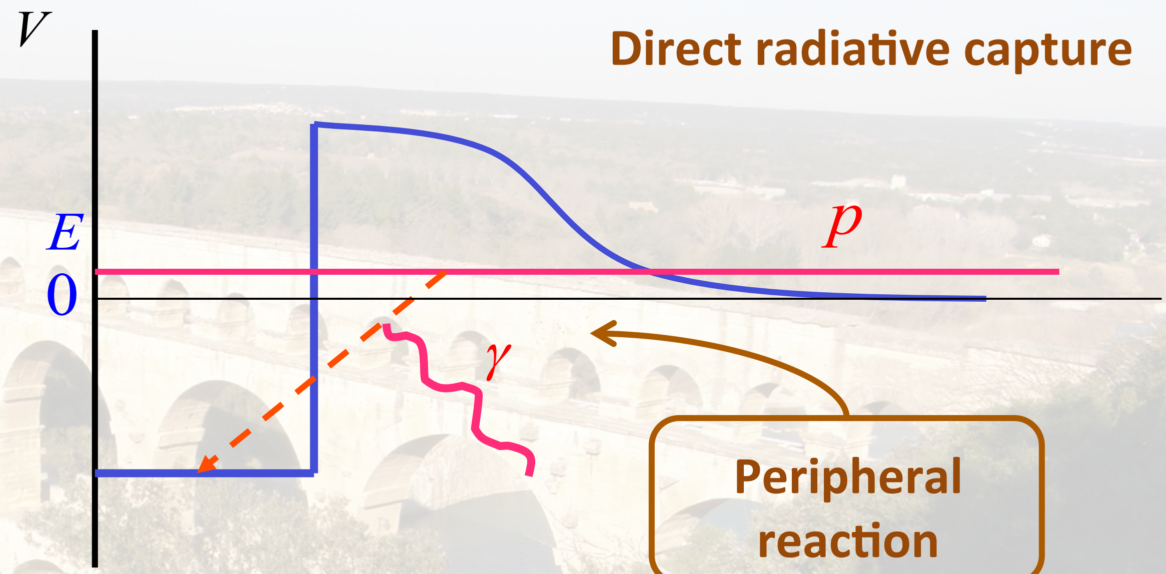
In the **Trojan Horse Method**, a transfer reaction to an unbound system is used to measure the c.s. of the A(x,c)C process. C and c can be charged or neutral particles (no photons)

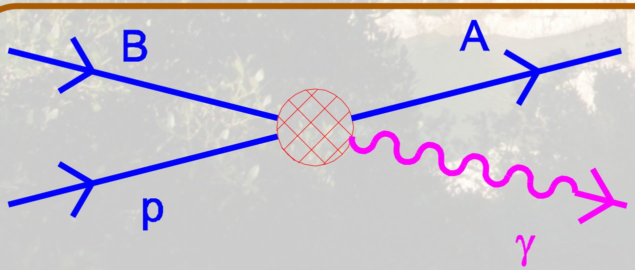
Few words about ANC

Radiative *p* (α) capture at stellar energies

- low energies → capture at large radii
- very small cross sections

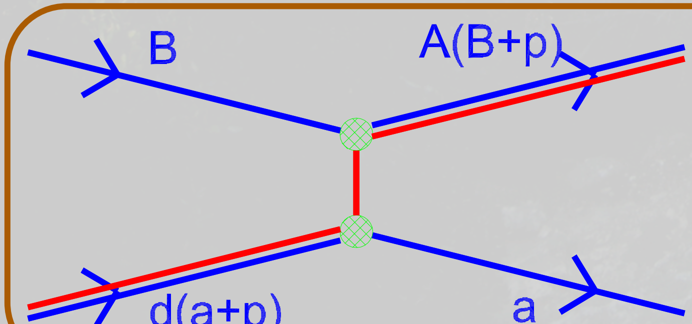
The cross section is determined by ANCs





In radiative capture reactions to loosely bound states the cross section is proportional to ANCs

$$\sigma_{capture} \propto (C^{A}_{Bp})^2$$

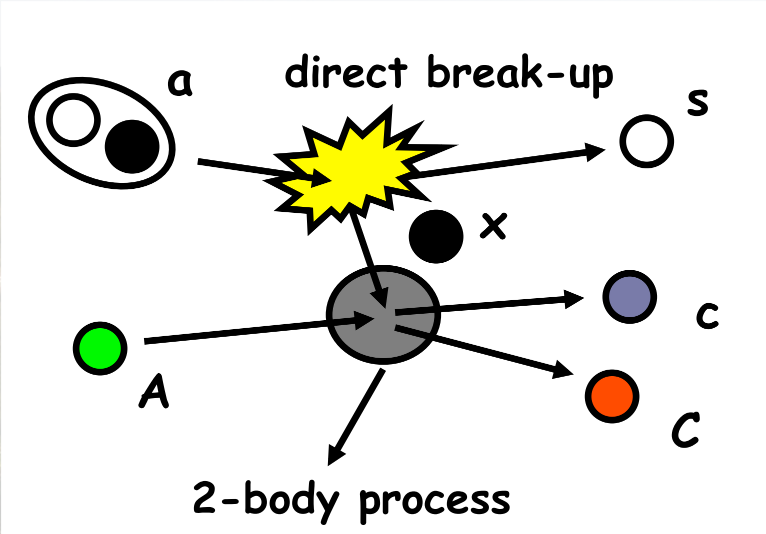


The same coefficient enters into the cross section of the transfer process

$$\frac{d\sigma}{d\Omega} = (C^{A}_{Bpl_A j_A})^2 (C^{d}_{apl_d j_d})^2 \frac{\sigma^{DW}_{l_A j_A l_d j_d}}{b^2_{Bpl_A j_A} b^2_{apl_d j_d}}$$

THM: basic features

THM reaction



From

A+a(x⊕s) → c+C+s @ 10-60 MeV

A + x → c + C @ 5-20 keV

By selecting the QF contribution

Though E_A >> V_{Coul} it is possible to measure at the Gamow peak since:

$$E_{c.m.}=E_{A-x}-Q_{x-s}$$

<u>Pros:</u>

- reduced systematic errors due to straggling, background…
- magnifying glass effect

<u>Cons:</u>

- off-shell cross section deduced (x → virtual particle)
- no absolute units

In **PWIA** we get:

$$\frac{d^3\sigma}{dE_C d\Omega_C d\Omega_c} \propto \mathrm{KF}\,|\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\mathrm{off}}$$

From the experiment

Evaluated through a MC code

HOES 2-body cross section

How it looks like in the general case

R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

This accounts for:

- HOES effects
- Normalization

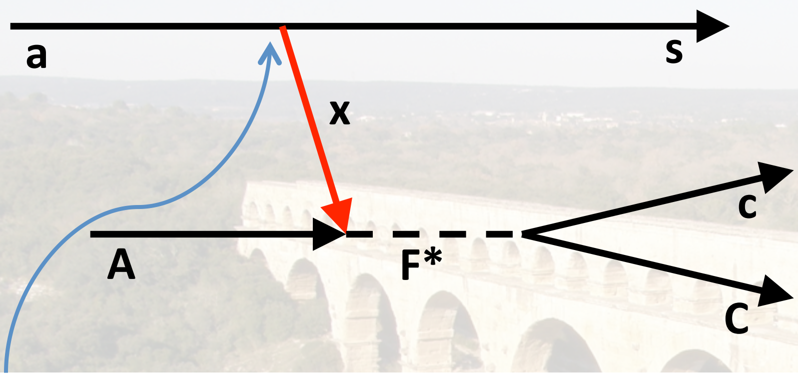
Moreover:
Possible generalization to CDCC & DWBA

However → Very complicated!

$$
\begin{aligned}
M^{\mathrm{PWA(prior)}}(P, \boldsymbol{k}_{aA}) \;=\; & (2\pi)^2 \sqrt{\frac{1}{\mu_{bB} k_{bB}}}\, \varphi_a(\boldsymbol{p}_{sx}) \\
\times & \sum_{J_F M_F j' l l' m_{j'} m_l m_{l'} M_n} i^{l+l'} \langle j m_j l m_l | J_F M_F \rangle \langle j' m_{j'} l' m_{l'} | J_F M_F \rangle \\
\times & \langle J_x M_x J_A M_A | j' m_{j'} \rangle \langle J_s M_s J_x M_x | J_a M_a \rangle\, \mathrm{e}^{-\mathrm{i}\delta^{hs}_{bBl}} Y_{l m_l}(-\hat{\boldsymbol{k}}_{bB}) \\
\times & \sum_{\nu,\tau=1}^{N} [\Gamma_{\nu bBjlJ_F}(E_{bB})]^{1/2} [\boldsymbol{A}^{-1}]_{\nu\tau} Y^{*}_{l' m_{l'}}(\hat{\boldsymbol{p}}_{xA}) \\
\times & \sqrt{\frac{R_{xA}}{\mu_{xA}}} [\Gamma_{\nu xAl'j'J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA}, R_{xA}) (j_{l'}(p_{xA} R_{xA}) \\
\times & [(B_{xAl'}(k_{xA}, R_{xA}) - 1) - D_{xAl'}(p_{xA}, R_{xA})] \\
+ & 2 Z_x Z_A e^2 \mu_{xA} \int_{R_{xA}}^{\infty} \mathrm{d}r_{xA} \frac{O_{l'}(k_{xA}, r_{xA})}{O_{l'}(k_{xA}, R_{xA})} j_{l'}(p_{xA} r_{xA})).
\end{aligned}
$$

Let's skip the math…

THM equations in a special case: resonant reactions



Upper vertex: direct *a* breakup
$M_i(E)$ is the amplitude of the transfer

Using the kinematics of three body reactions:

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - \frac{p_s^2}{2\mu_{sF}} + \frac{\mathbf{p}_s \cdot \mathbf{p}_A}{m_x + m_A} - \varepsilon_{sx}$$

It is possible to achieve negative energies in the A-x channel…
Out of reach for direct measurements

How to deal with negative energies?
Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual → Modified R-Matrix is introduced instead (A. Mukhamedzhanov 2010)

In the case of a resonant THM reaction the cross section takes the form:

$$\frac{d^2\sigma}{dE_{Cc}\, d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\, |M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

M^2 is proportional to the ANC of the F state populated in the transfer reaction

Merging together ANC and THM → deep connection of these two indirect methods

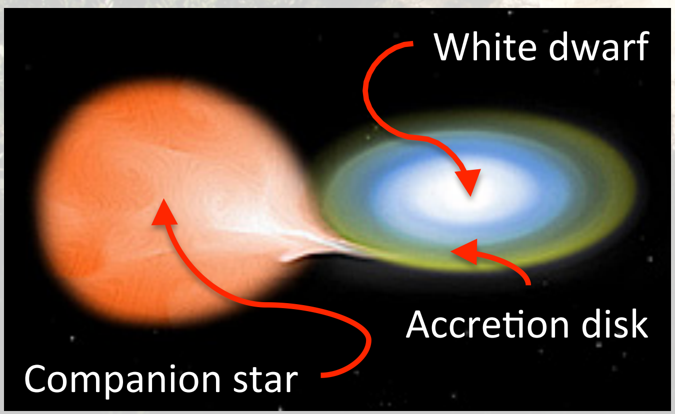
Recent Results: the $^{18}F(p,\alpha)^{15}O$ Reaction

PHYSICAL REVIEW C **92**, 015805 (2015)

First application of the Trojan horse method with a radioactive ion beam: Study of the $^{18}F(p,\alpha)^{15}O$ reaction at astrophysical energies

S. Cherubini,[1,2,*] M. Gulino,[1,3] C. Spitaleri,[1,2] G. G. Rapisarda,[1,2] M. La Cognata,[1] L. Lamia,[2] R. G. Pizzone,[1] S. Romano,[1,2] S. Kubono,[4,5] H. Yamaguchi,[5] S. Hayakawa,[1,5] Y. Wakabayashi,[5] N. Iwasa,[6] S. Kato,[7] T. Komatsubara,[8] T. Teranishi,[9] A. Coc,[10] N. de Séréville,[11] F. Hammache,[11] G. Kiss,[12] S. Bishop,[4,13] and D. N. Binh[5,14]

Scientific case



Hydrogen surface layer accumulates on white dwarf through accretion disk from the companion atmosphere

As more hydrogen is accreted, the temperature at the bottom of this surface layer increases until sufficient to trigger nuclear fusion reactions (about 0.2-0.4 10^9 K).

Thermonuclear runaway → explosive burning of hydrogen

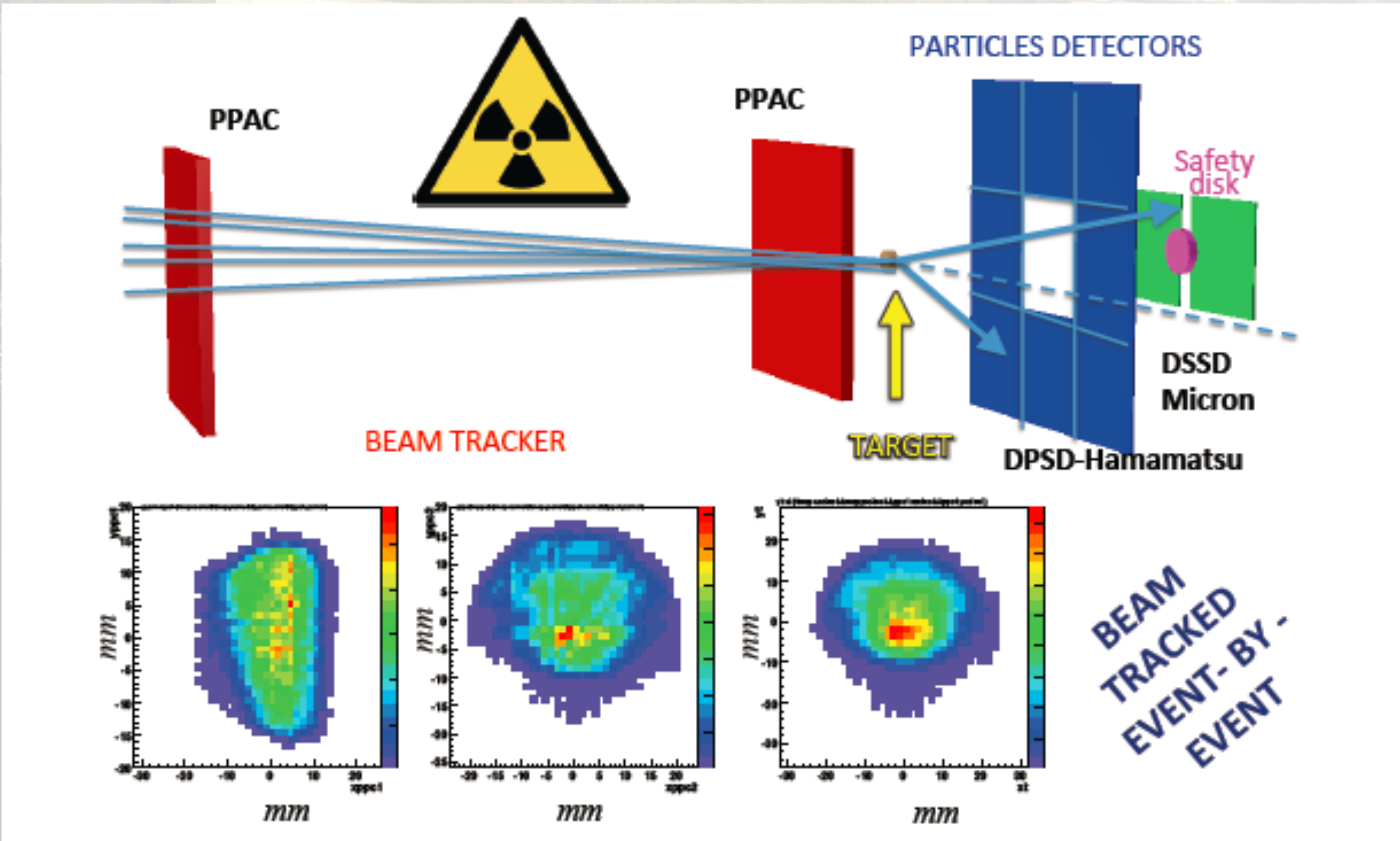
The γ-ray emission following the nova explosion is dominated by the 511 keV energy line, coming from the annihilation of positrons produced by the decay of radioactive nuclei. Among them, ^{18}F is the most important source

Abundance determined by production vs. destruction rate → dominated by $^{18}F(p,\alpha)^{15}O$

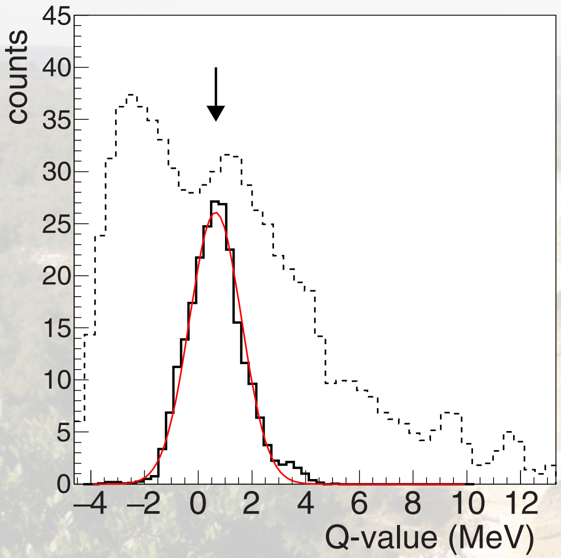
The $^{18}F(p,\alpha)^{15}O$ experiment

Experiment performed @ CRIB – CNS – RIKEN using a 18F RIB → first THM experiment with unstable beams

ASTRHO: Array of Silicons for TRojan HOrse



Selection of the $^2H(^{18}F,\alpha^{15}O)n$ channel and of the QF mechanism

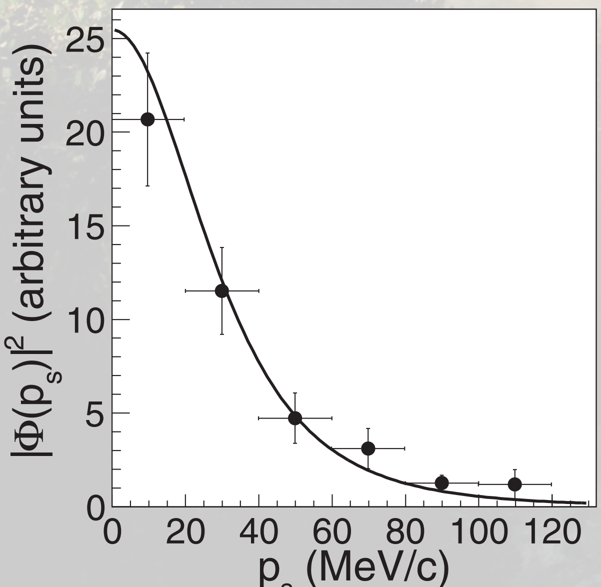


Experimental Q-value spectrum with no conditions (dashed line)

Q-value spectrum with particle selection (black solid histogram)

A single peak shows up, centered at the value 0.668 MeV, very close to the theoretical Q value (0.658 MeV) for the $^2H(^{18}F,\alpha^{15}O)n$ reaction

The arrow represents the theoretical Q value and the red line is a Gaussian fit with $\mu = 0.668$ MeV and $\sigma = 0.322$ MeV, in agreement with the expected theoretical value and the experimental resolution

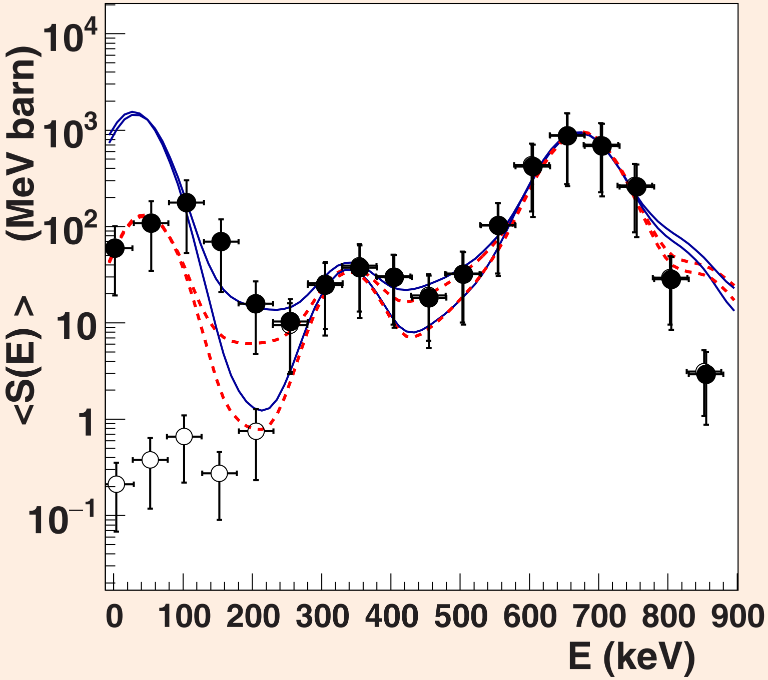


Solid circles: measured momentum distribution of the neutron inside deuteron using the $^2H(^{18}F,\alpha^{15}O)n$ reaction

Solid line: theoretical momentum distribution, given by the squared Hulthén function in momentum space

→ Good agreement implies that the reaction mechanism is QF and the THM equations can be applied to deduce the cross section of the $^{18}F(p,\alpha)^{15}O$ reaction from the one of the $^2H(^{18}F,\alpha^{15}O)n$ reaction

Recent Results: the $^{18}F(p,\alpha)^{15}O$ Reaction



The $^{18}F(p,\alpha)^{15}O$ astrophysical S factor from the present experiment.

<u>*Solid circles*</u>: THM experimental data with the assumption of $J^\pi = 3/2^+$ for the resonance at E=6460 keV (upper limit)

<u>*Open circles*</u>: $^{18}F(p,\alpha)^{15}O$ astrophysical S factor corresponding to the assumption of $J^\pi = 5/2^-$ (lower limit)

Blue solid and red dashed lines: calculations reported and discussed in Beer et al. PRC 83 (2011) 042801 smeared to the present experimental resolution (σ = 53 keV). The difference is given by the alternative interference pattern adopted in the calculations.

Each pair of curves represents the upper and lower limit for each calculation

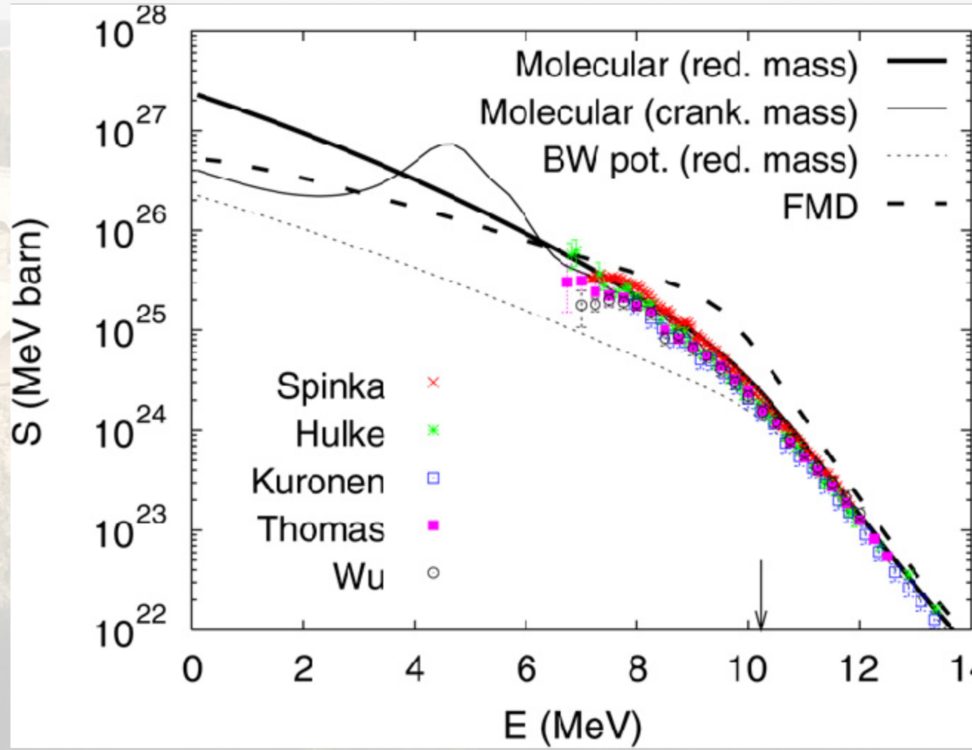
Around 700 keV: normalization region

Elsewhere: fair agreement with the dashed lines if $J^\pi = 3/2^+$ is assumed

Recent Results: the $^{16}O(^{16}O,\alpha)^{28}Si$ Reaction - Introduction (thanks to Dr. S. Hayakawa)

**$^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$ fusion... important in explosive carbon and oxygen burning phases in massive stars
(> 8 $M_{\odot}$ for $^{16}O+^{16}O$)**

- Timescale of the burning phase
- Nucleosynthesis productions



A. Diaz-Torres et al. / Physics Letters B 652 (2007) 255–258

Overview of astrophysical *S*-factor (1−4 GK ⇔ 3−12 MeV)

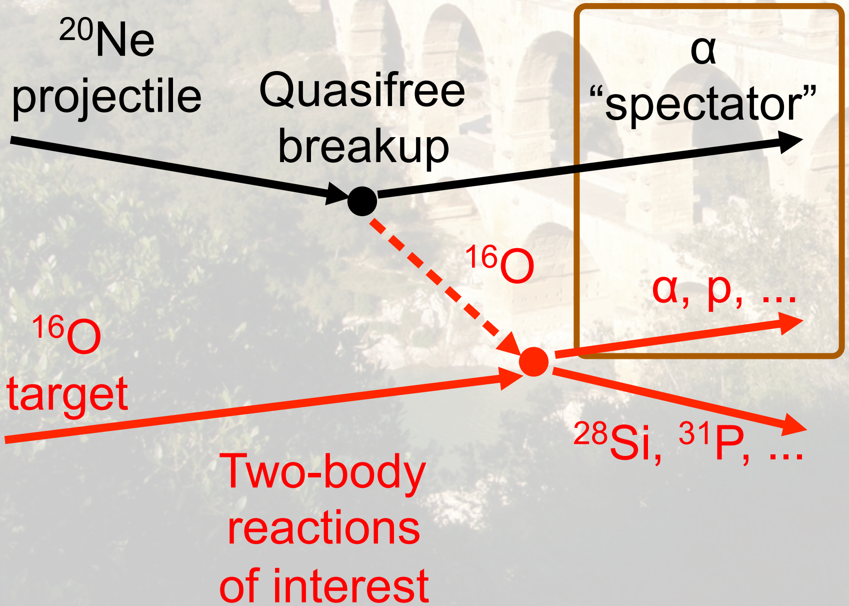
Main issues:
- Inconsistencies among different experiments at lower energies
- Inconsistencies among different theoretical extrapolations
- Lack of data below 7 MeV

1 order of magnitude uncertainty at low energies

Recent Results: the $^{16}O(^{16}O,\alpha)^{28}Si$ Reaction - THM approach

$^{16}O(^{20}Ne,\alpha\alpha)^{28}Si$
$^{16}O(^{20}Ne,p\alpha)^{31}P$
to study
$^{16}O(^{16}O,\alpha)^{28}Si$
$^{16}O(^{16}O,p)^{31}P$

E_{Ne} = 45 MeV ⇔ $E_{Ne\text{-}O}$ = 20 MeV
above Coulomb barrier (~17 MeV)
Incident energy is consumed to breakup ^{20}Ne into $^{16}O+\alpha$ ($E_{binding}$ = 4.73 MeV)
→ Two-body reaction could take place at low $^{16}O-^{16}O$ relative energies



Detected in the experiment

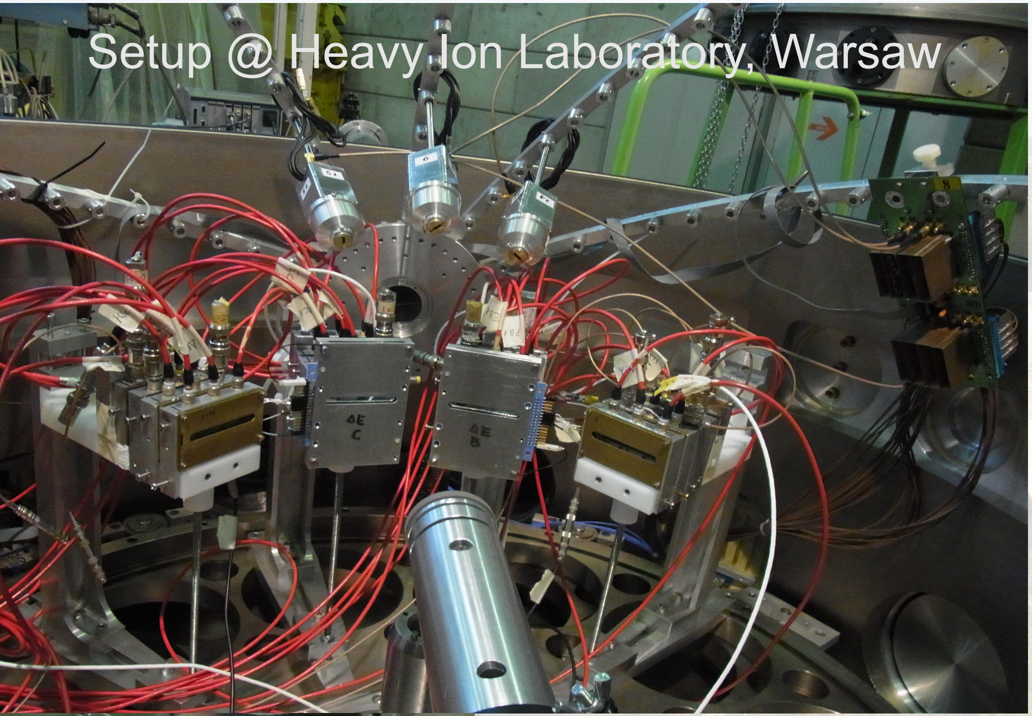
<u>Three particles in the exit channel:</u>
All the kinematic variables can be calculated from the energies and the emission angles of two of them → we choose the most convenient!

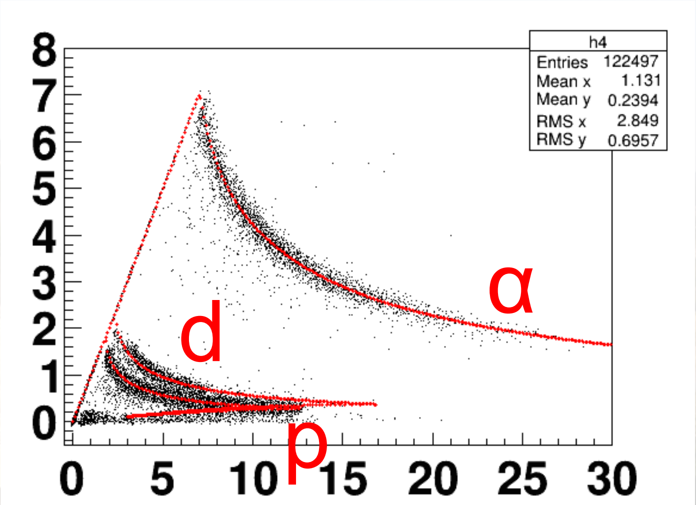
2 Performed measurements:

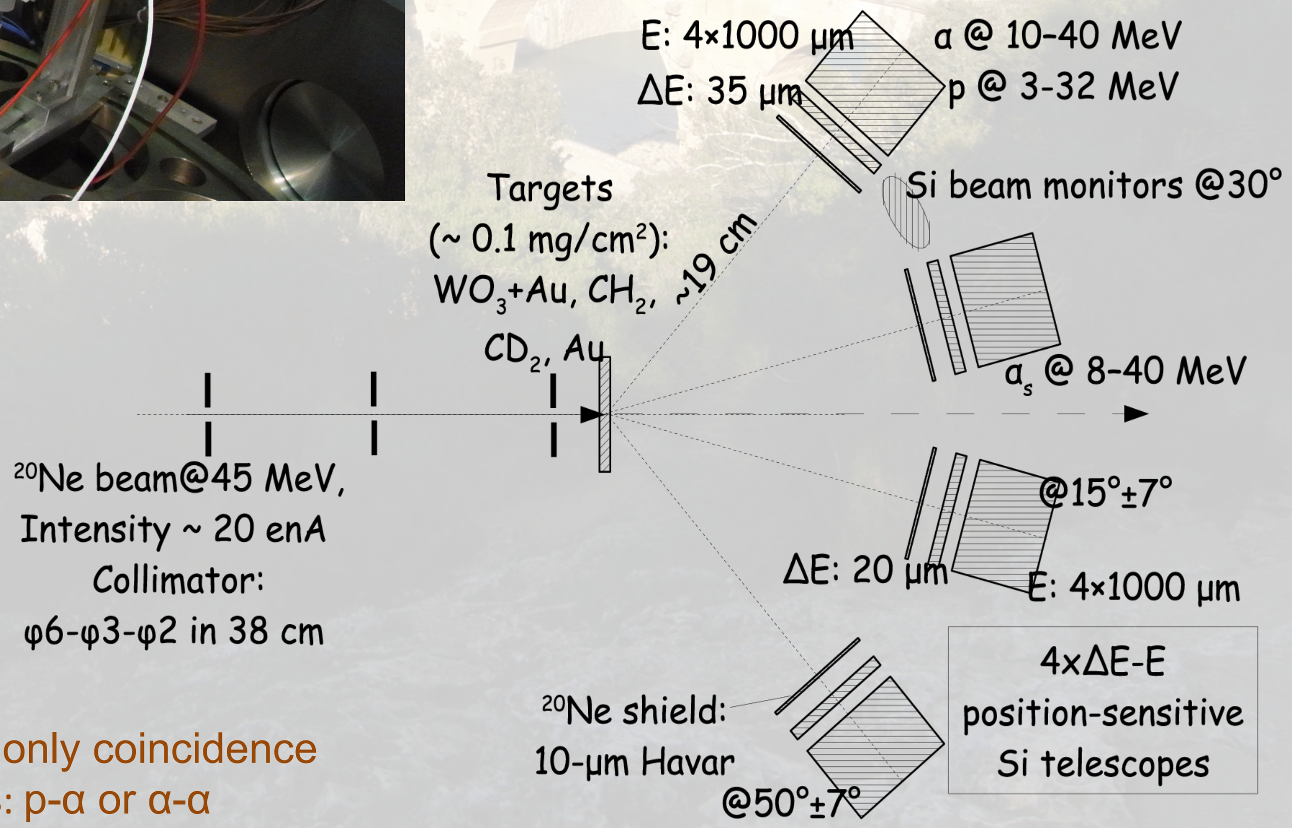
(a) E_{20Ne} = 45 MeV @Heavy Ion Lab., Warsaw
→ For normalization of the two-body cross section to the direct data

(b) E_{20Ne} = 35 MeV @Inst. Nucl. Phys., Astana
→ Approach to lower energies

The $^{16}O(^{16}O,\alpha)^{28}Si$ via THM: the experiment

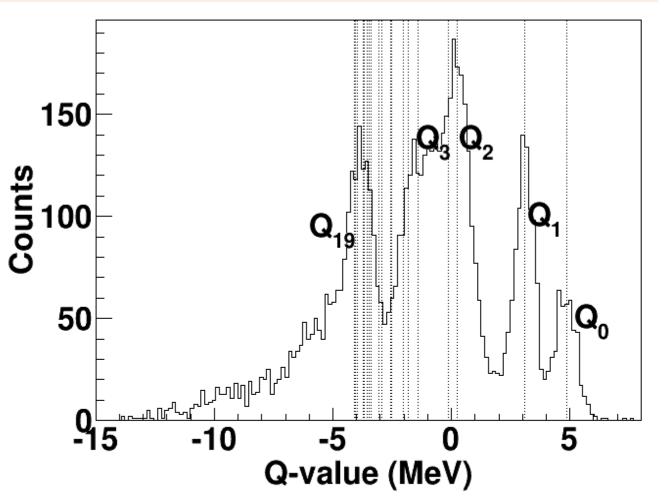






Taken only coincidence events: p-α or α-α

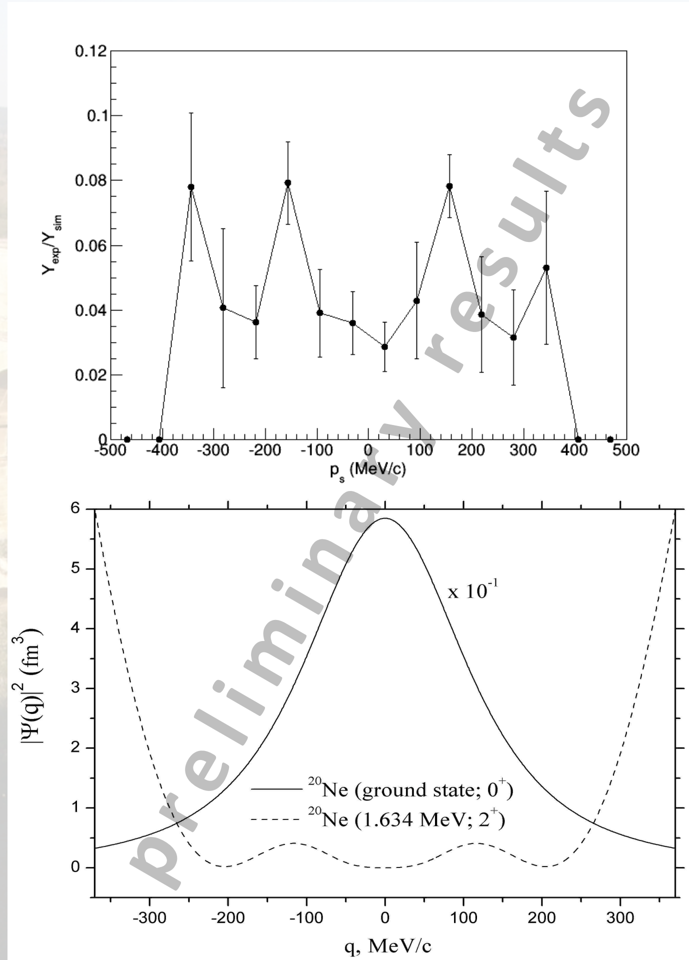
The $^{16}O(^{16}O,\alpha)^{28}Si$ via THM: preliminary results



Q-value = $E_{28Si} - E_{20Ne} + E_{\alpha 1} + E_{\alpha 2}$ (MeV)

- Corresponds well to the ^{28}Si excited levels
- Good reconstruction of three-body kinematics

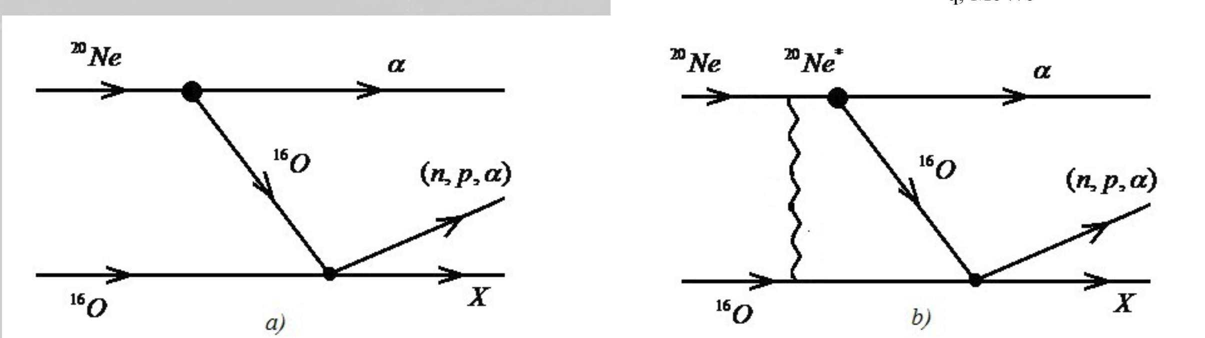
Evidence of the $^{16}O(^{20}Ne,\alpha\alpha)^{28}Si$ three-body channel



Experimental momentum distribution of α inside ^{20}Ne from Q_0 and Q_1 data

No single peak at 0 MeV/c
→ Evidence of a more complicated breakup mechanism

← Calculation by R. Yarmukhamedov



α-^{16}O breakup in two steps via the 1st excited state of ^{20}Ne?

Summary

- Nuclear astrophysics aims at supplying cross sections (astrophysical factors) for reactions of astrophysical importance to be included in nucleosynthesis, energy production and stellar evolution codes
- Since stars are "cold", low energies are generally involved making it difficult to measure such cross sections at astrophysical energies (signal-to-noise ratio approaching zero)
- Indirect methods such as THM and ANC (among others) have proved very effective in the measurement of such cross sections at low energies
- Over the last years, joint projects have been jointly run by Italian-French and Italian-Polish collaborations to tackle fundamental nuclear astrophysics questions
- In particular, we have discussed here the:

  (1) $^{18}F(p,\alpha)^{15}O$ Reaction → Novae nucleosynthesis

  (2) $^{16}O(^{16}O,\alpha)^{28}Si$ Reaction → nuclear burning in evolved massive stars