

# Indirect Methods for Nuclear Astrophysics

L. Trache – IFIN-HH Bucharest-Magurele

NUSPRASEN Workshop on Nuclear Reactions  
Warsaw, Jan. 22-24, 2018

# Summary

## Indirect Methods in Nuclear Astrophysics

- a list with examples and problems
- approach:
  - methods and advantages/problems
  - not on astrophysical importance of reactions shown
  - not report of latest progress

ECT\* workshop on IMNA

ChETEC training school in IFIN-HH, April 10-20, 2018


Carpathian Summer School Physics (28<sup>th</sup>) Sinaia

# Nuclear Astrophysics

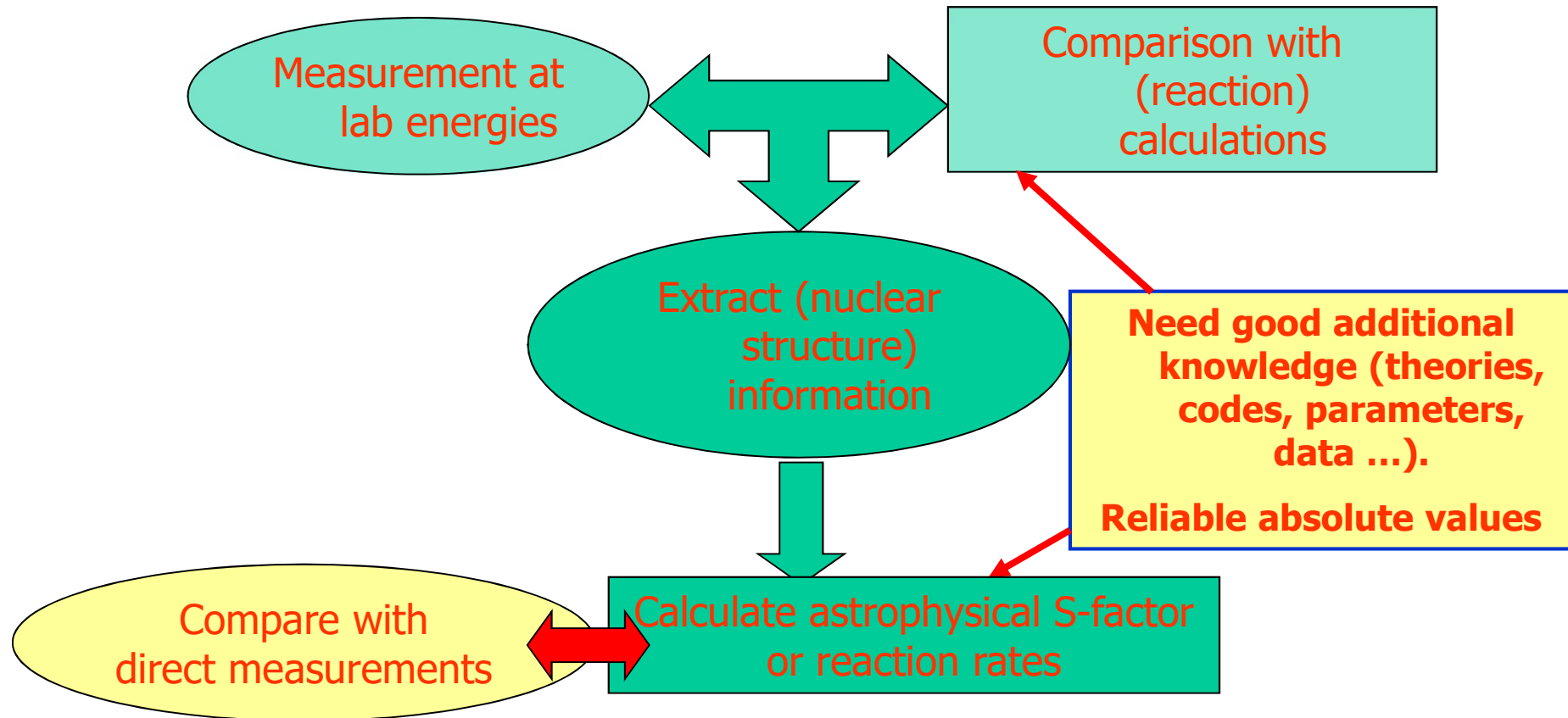
Indirect methods – measurements at lab energies  
→ cross sections at stellar energies

Experiments at 10, ... 100, 300 MeV/nucleon to  
assess cross sections at 10, 100, 300 keV

Indirect methods in NPA, mostly with RNB

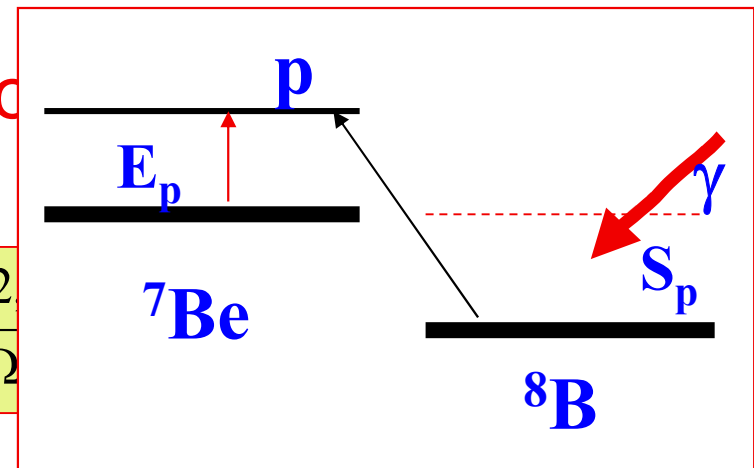
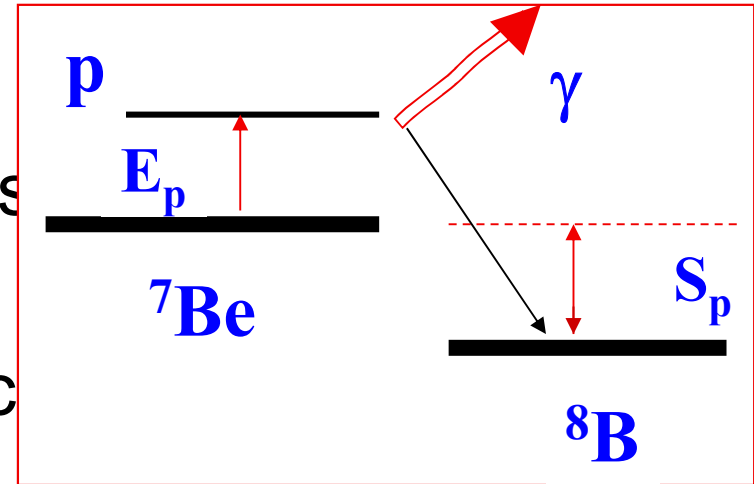
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- A. Coulomb dissociation
  - B. Transfer reactions (ANC method)
  - C. Breakup (nuclear) of loosely bound nuclei
  - D. Resonance spectroscopy –  $\beta$ -decay,  $\beta p$ -decay, transfer reactions, resonant elastic scattering, etc
  - E. Trojan Horse Method – see later, Aurora's talk

# Indirect methods for nuclear astrophysics – general scheme



# A. Coulomb dissociation

- **Radiative capture** - direct process
  - $X(p,\gamma)Y$
- **Photodissociation** - inverse process
  - $Y(\gamma,p)X$
  - Use detailed balance theorem
- virtual photons – **Coulomb Dissociation**



$$\frac{d^2\sigma}{dE_\gamma d\Omega}(E_\gamma, \theta) = \frac{1}{E_\gamma} \left[ \frac{dN(E1, E_\gamma)}{d\Omega} \sigma_{E1}^{photo}(E_\gamma) + \frac{dN(E2, E_\gamma)}{d\Omega} \sigma_{E2}^{photo}(E_\gamma) \right]$$

$$\sigma^{radcap}(E_{rel}) \propto \sigma_{E1}^{photo}(E_\gamma)$$

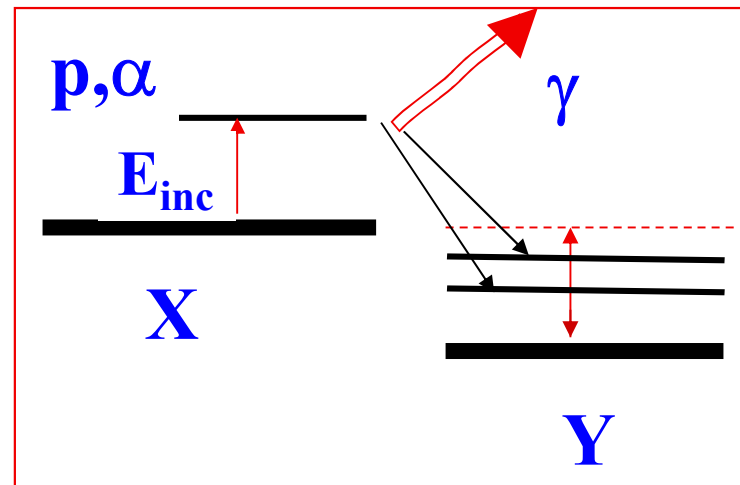
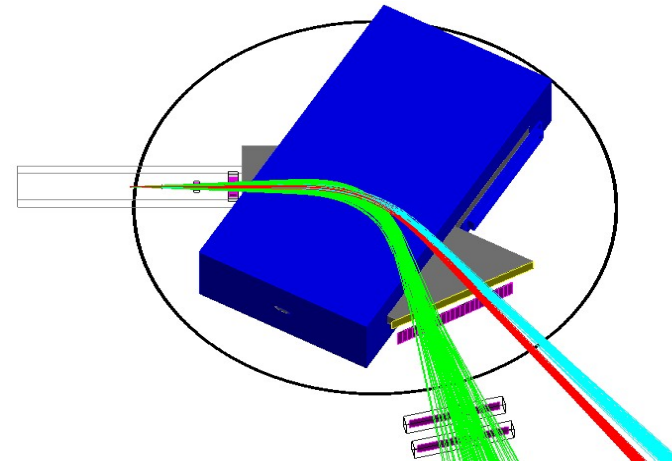
$$E_\gamma = E_p + S_p$$

# CD

Problems:

- theory: ?! nuclear – Coulomb interference
- exp: it is difficult to disentangle the multipoles

Extra: not all radiative capture processes can be studied by photodissociation (including with virtual photons = CD)!



# Example: $^9\text{C}$ breakup @ RIBF

## exp. NP1412-SAMURAI29R1

- Exp at RIKEN, at the RIBF facility using SAMURAI.
- Primary beam:  $^{18}\text{O}$  @ 230 A.MeV and 200 pA
- Secondary beam:  $^9\text{C}$  @ 200 A.MeV and  $10^5$  pps
- Coulomb and nuclear breakup

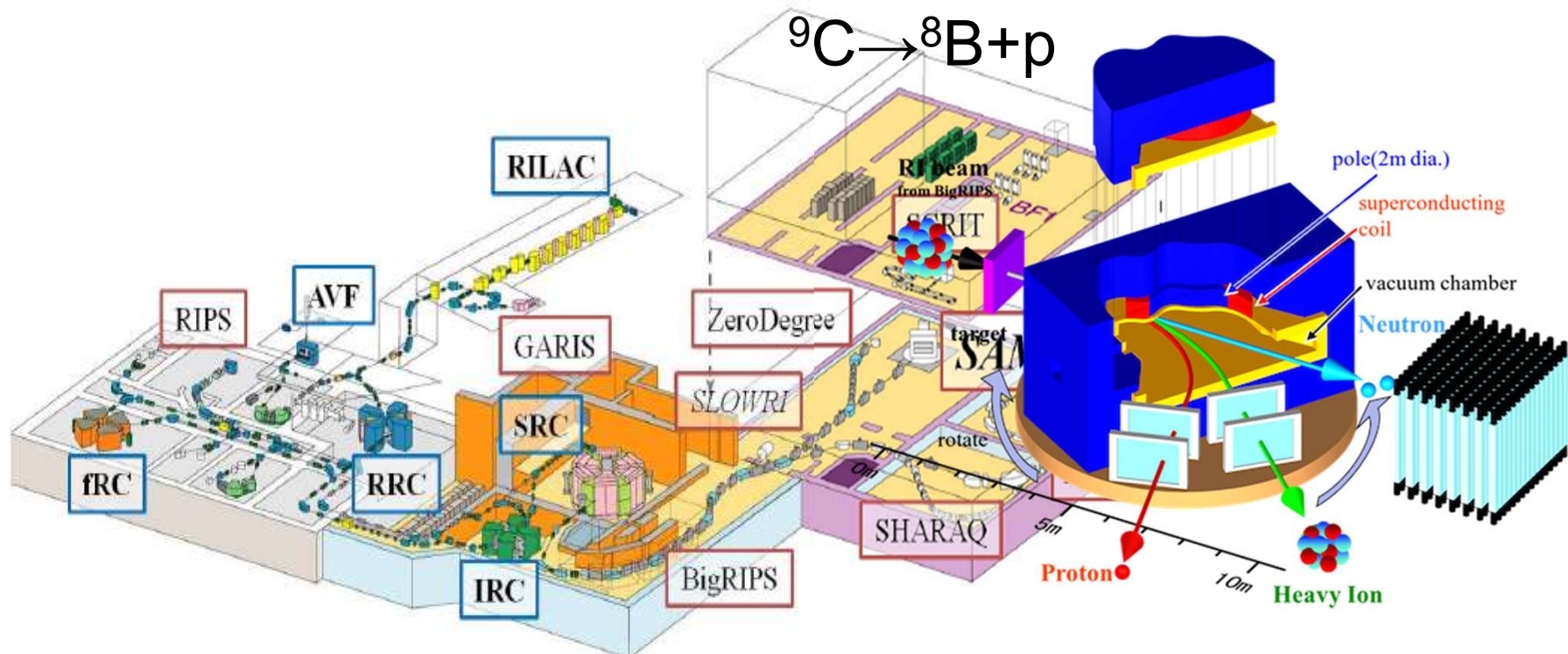
Exp demanding: sec beam quality typically lower, setup complex, beamtime scarce ...

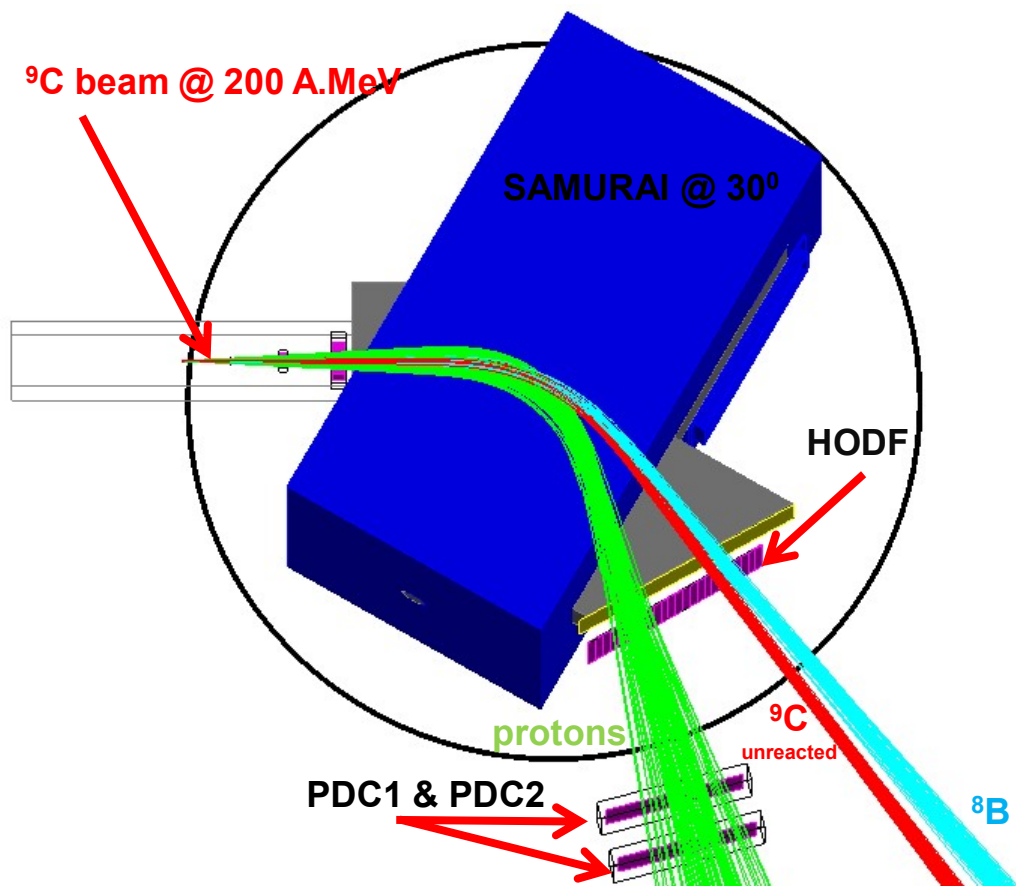
**Main problem: GET BEAMTIME!**

- measure relative breakup angle, while extreme forward focus

=> large granularity det = many channels; huge dynamic range (1-3000), ...

Solutions: dedicated detectors, compact electronics using ASICs







# B. Transfer reactions

- Used to find structural information (fermionic structure)
- Find states
- Characterize them:
  - location
  - Spin, parity
  - Spectroscopic factors, etc...
- Difficulties and problems:
  - Lower resolutions with RNB
  - Uncertainties in calculations – mech, parameters ...
  - (May not be able to determine) OMP

## B. Transfer reactions: the ANC method

Depend on OMP  
\* n Factors !!!

Transfer reactions are peripheral (absorption)

- Transfer matrix element

$$M = \langle \chi_f^{(-)} I_{Bp}^A | \Delta V | I_{ap}^d \chi_i^{(+)} \rangle$$

$$\frac{d\sigma}{d\Omega} = \sum [ S S ] \left[ \frac{d\sigma}{d\Omega} \right]$$

Depend on geom ( $r_0, a$ ) of  
proton-binding potential < 20-40%

$$\frac{d\sigma}{d\Omega} = \sum (C_{Bp l_A j_A}^A)^2 (C_{ap l_d j_d}^d)^2 \frac{b_{Bp l_A j_A}^2 b_{ap l_d j_d}^2}{b_{Bp l_A j_A}^2 b_{ap l_d j_d}^2}$$

ANC - independent on binding potential geometry!

OMP knowledge crucial for reliable absolute values!

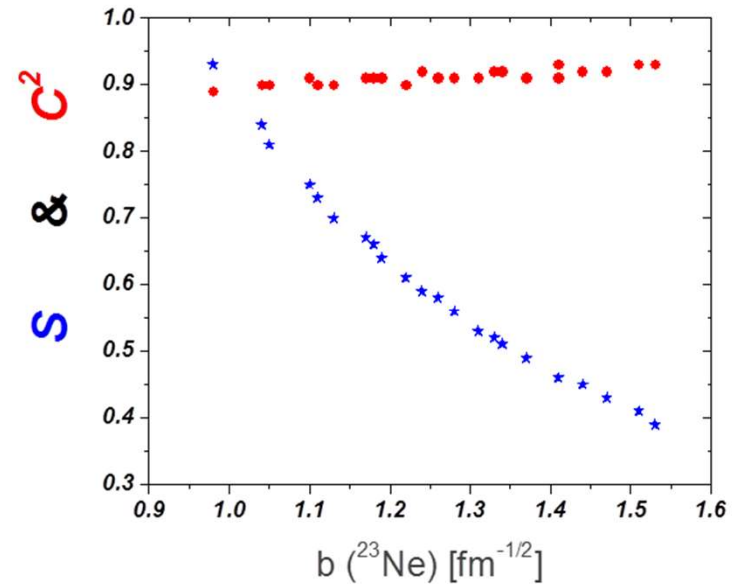
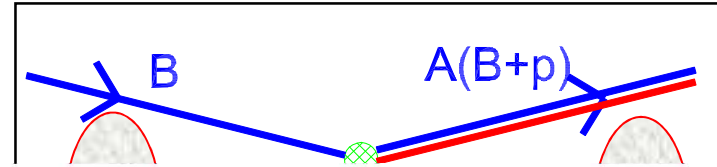
Semi-mic proc. JLM interaction (LT ea, PRC, 2000)

NA: proton-nucleus also peripheral

$$\sigma_{(p,\gamma)} \propto (C_{Bp}^A)^2$$

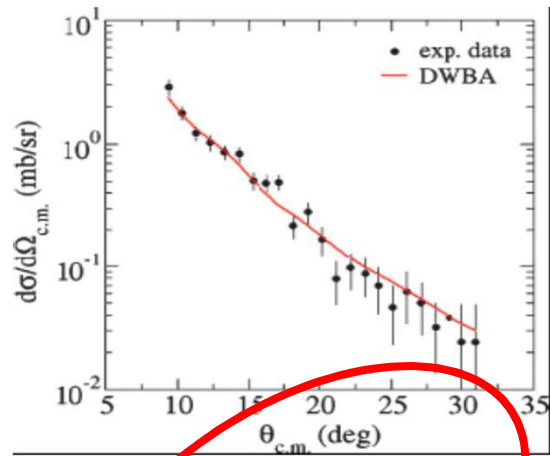
(Christy and Duck, 1963

Parker and Tombrello, 1964)

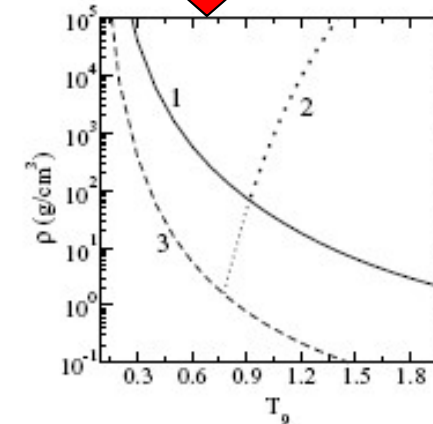
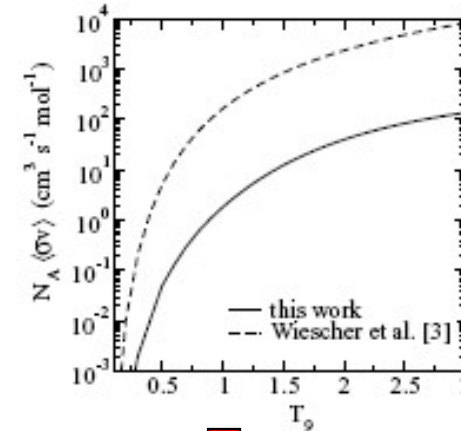
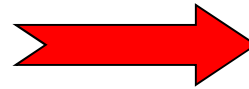


$$I_{Bp}^A \approx C_{Bp}^A \frac{W_{-n_A, l+1/2}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

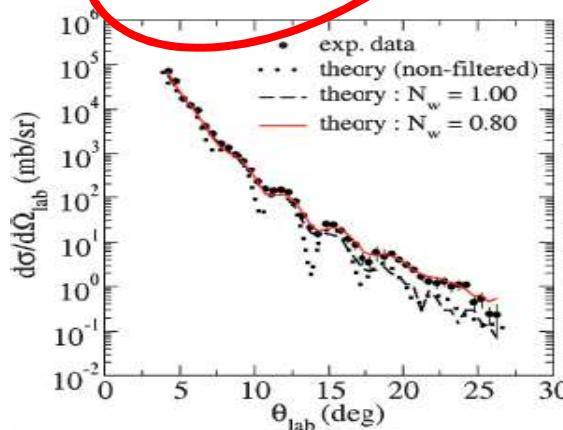
$^{14}\text{N}(^{12}\text{N}, ^{13}\text{O})$  proton-transfer react  $\Rightarrow$   $^{12}\text{N}(p, \gamma)^{13}\text{O}$  (rap I, II proc)



ANC, S-factor 0-2 MeV  
Reaction rate

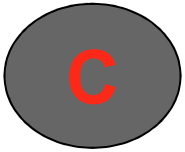


Transfer & elastic @12 MeV/u  
TAMU MARS  $^{12}\text{N}$  beam  $2 \cdot 10^5$  pps



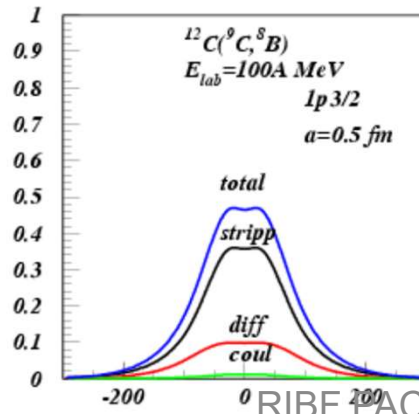
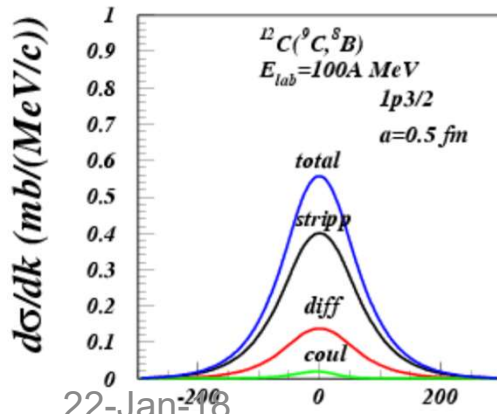
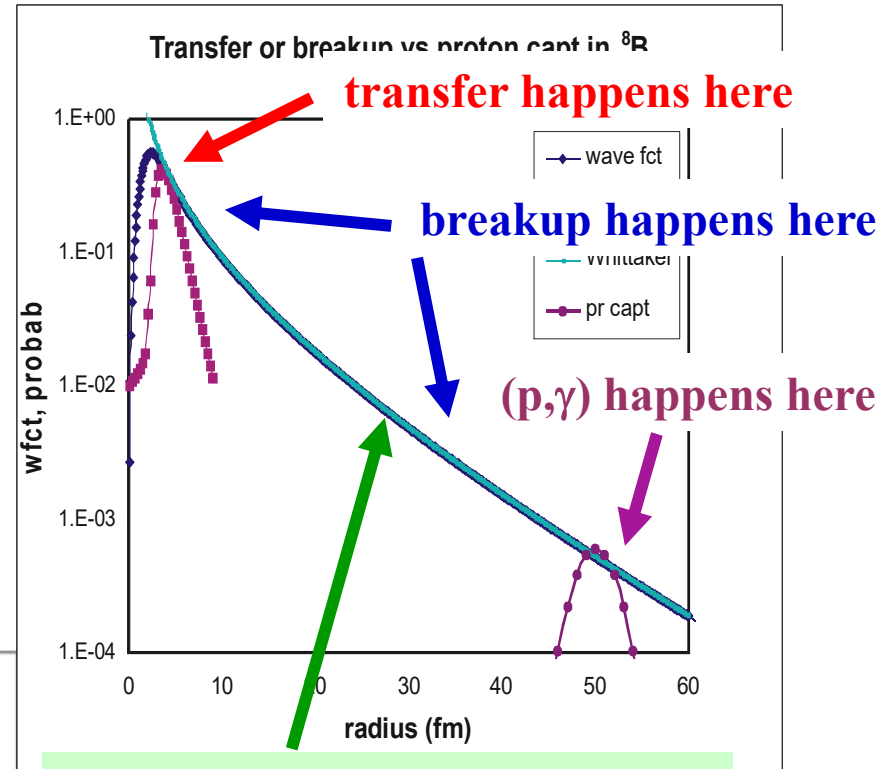
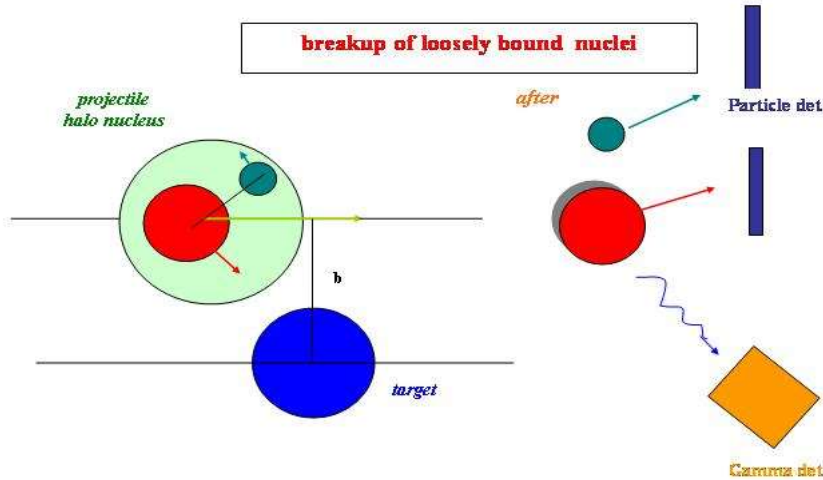
A. Banu et al, Phys Rev C 79, 025805 (2009)

FIG. 10. Temperature and density conditions at which the  $^{12}\text{N}(p, \gamma)^{13}\text{O}$  reaction may play a role. Curve 1 represents the equilibrium line between the rates for  $^{12}\text{N}$  proton capture and  $^{12}\text{N}$   $\beta$  decay. Curve 3 illustrates the same result as determined from Ref. [3]. Curve 2 shows the line of equal strength between the rate of the  $\uparrow\uparrow$  radiative proton capture to  $^{13}\text{O}$  and the rate for the inverse process,  $^{13}\text{O}$  photodisintegration. See text for details.



# Nuclear breakup: $Y \rightarrow X + p$ for $X(p, \gamma)Y$

## Breakup



Model-independent shape w. ANC (Whittaker function)

Shape of mom distr  $\Rightarrow nlj$   
 Cross section  $\Rightarrow \text{ANC}$

# Example: Summary of the **ANC** extracted from **$^8\text{B}$ breakup** with different interactions

Data from:

F. Negoita et al, Phys Rev C 54, 1787 (1996)

B. Blank et al, Nucl Phys A624, 242 (1997)

D. Cortina-Gil et al, EuroPhys J. 10A, 49 (2001).

R. E. Warner et al. – BAPS 47, 59 (2002).

J. Enders et al., Phys Rev C 67, 064302 (2003)

All available breakup cross sections on targets from C to Pb and energies 27-1000 MeV/u give consistent ANC values!

Summary of results:

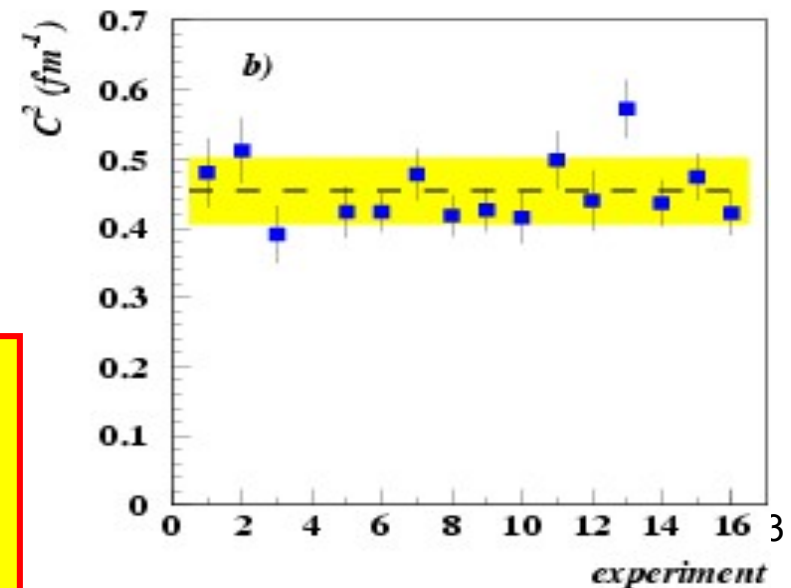
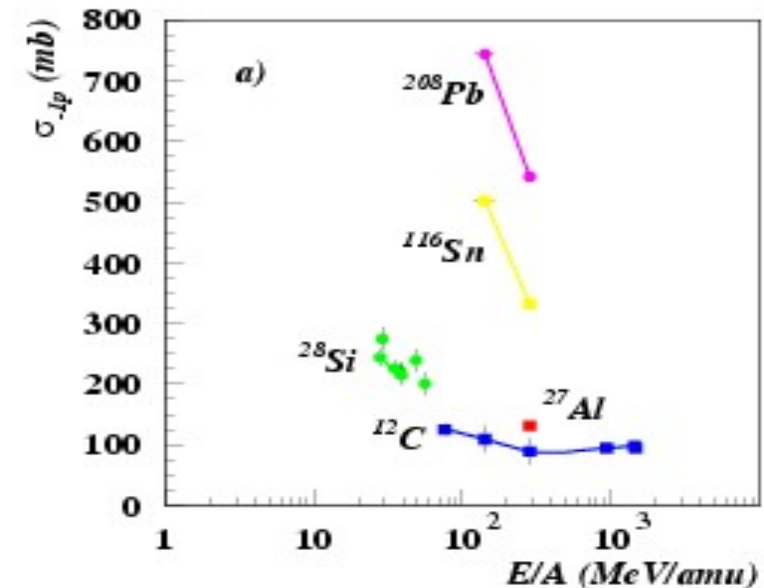
LT et al, PRL 87, 2001

**$^7\text{Be}(p,\gamma)^8\text{B}$  (solar neutrinos probl.):**

**p-transfer:  $S_{17}(0)=18.2\pm 1.7$  eVb**

**Breakup:  $S_{17}(0)=18.7\pm 1.9$  eVb**

**Direct meas:  $S_{17}(0)=20.8\pm 1.4$  eVb**



## D. Resonance Spectroscopy

\* **Resonant** reaction is a two-step process.

$$\sigma_{\gamma} \propto \left| \langle E_f | H_{\gamma} | E_r \rangle \right|^2 \left| \langle E_r | H_f | A + p \rangle \right|^2$$

\* The cross section (Breit-Wigner):

$$\sigma(E) = \frac{\lambda}{4\pi} \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_p \Gamma_{\gamma}}{(E - E_r)^2 + \left(\frac{\Gamma}{2}\right)^2}$$

\* The contribution to the reaction rate:

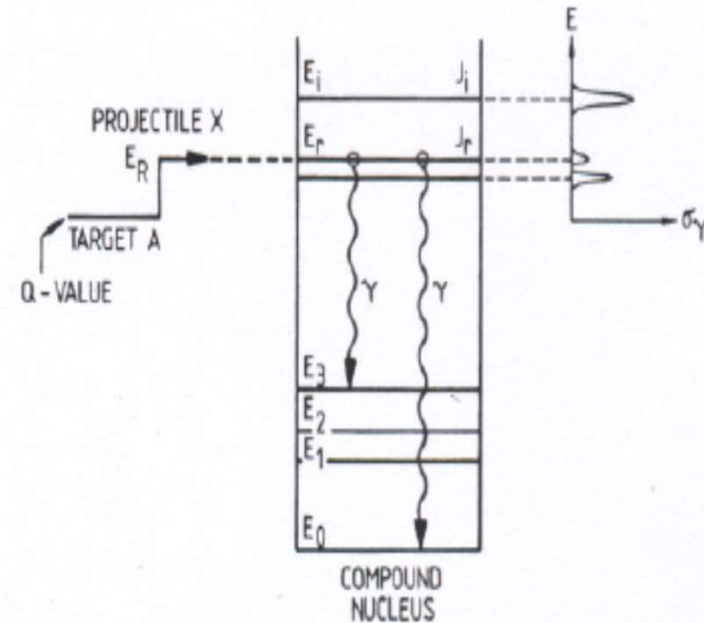
$$\langle \sigma v \rangle_{res} = \left( \frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 \omega \gamma \exp\left(-\frac{E_r}{kT}\right)$$

where

$$\omega \gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_t + 1)} \frac{\Gamma_p \Gamma_{\gamma}}{\Gamma_{tot}}$$

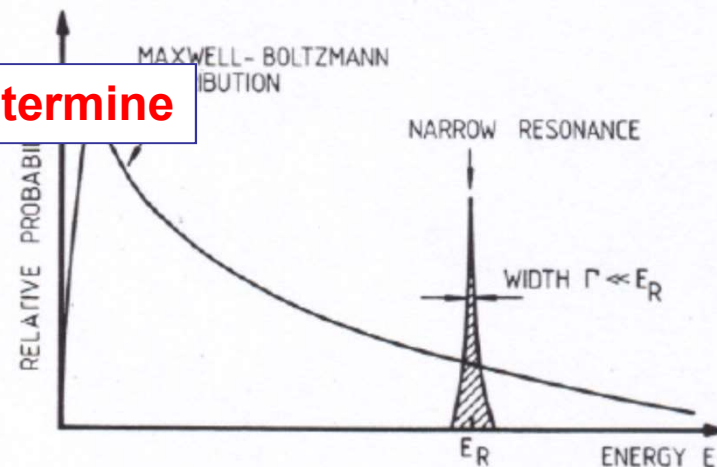
$\omega \gamma =$  resonance strength

22-Jan-18



\* C. Rolfs and W. Rodney, "Cauldrons in the Cosmos".

to determine



# D. Spectroscopy of resonances

Any spectroscopic method that would populate the states in same CN:

- Determine location  $E_r$
- Determine resonance strength  $\omega\gamma$ 
  - $\beta$ -decay,  $\beta$ -delayed p-decay
  - transfer reactions
  - resonant elastic scattering
  - etc...

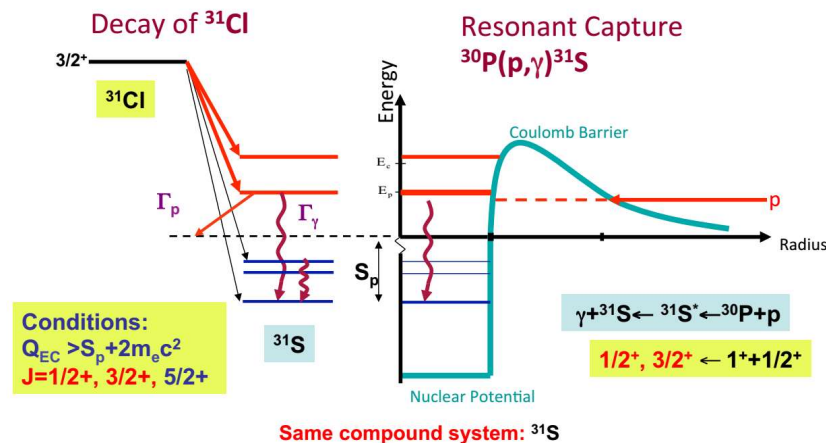
Difficulties:

- Find the appropriate mechanism to populate the resonance(s)
- Most difficult: determine the width ( $\omega\gamma$ )

# $\beta$ -decay and $\beta$ -delayed proton-decay

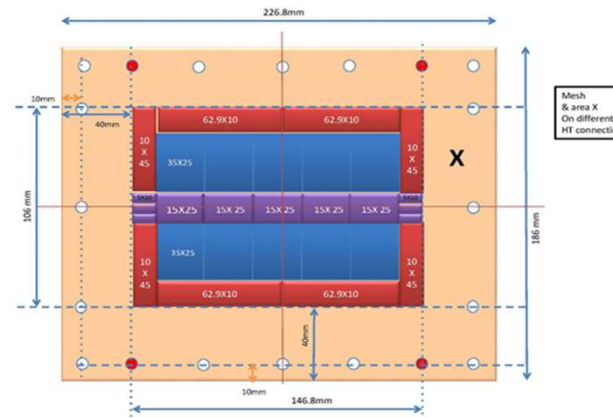
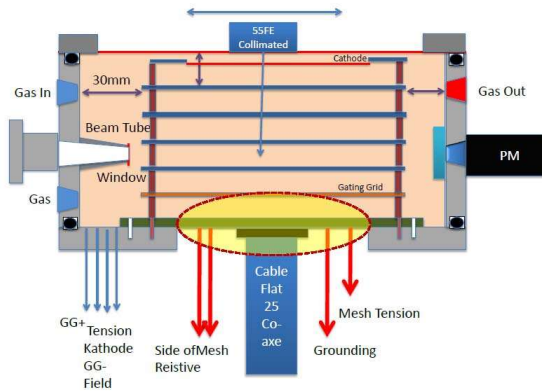
Another line of research motivated by NA: **spectroscopy of resonances:**

- Find and characterize (position and resonant strength) the states that are resonances in proton radiative capture
- Method used: beta-delayed proton decay of some proton-rich nuclei
- Lower proton energies (100 – 500 keV) most important, but very difficult:
  - lower branching
  - increased exp difficulties (det windows, background, etc...) => Need special methods and detectors
- Studied:  $^{23}\text{Al}$ ,  $^{31}\text{Cl}$ ,  $^{35}\text{K}$  using ASTROBOX2 at TAMU (oct 2016, Oct 2017)





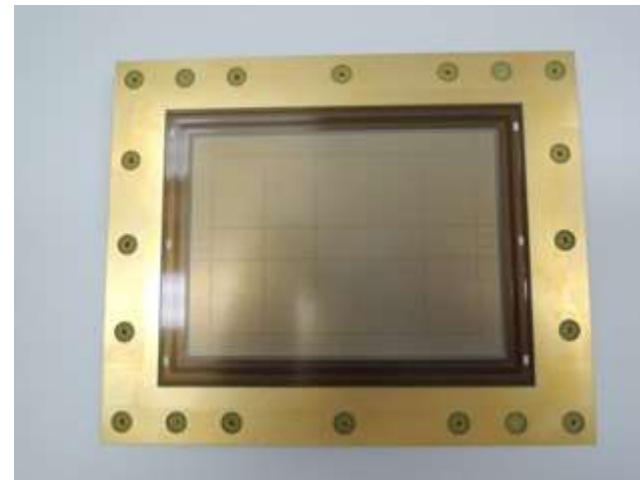
# ASTROBOX2



- Top left: chamber uses gas for detection and micromegas for signal amplification.

RIB entering from left stops in the middle of detector, where it decays in gas (P10 at 800 torr)

- Top right: schematic design of the micromegas det (29 pads)
- Bottom right: photo of micromegas



# ASTROBOX2 & Ge-clovers for $\gamma$

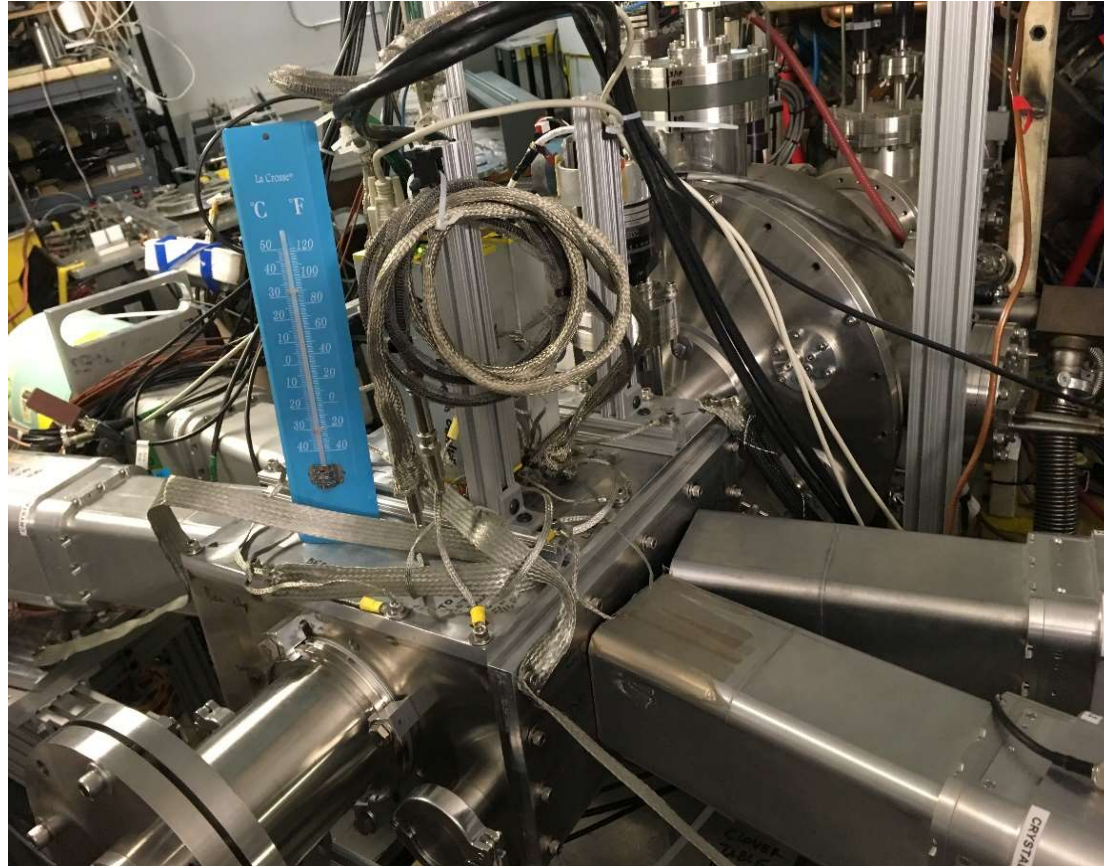


Figure 8. Photo of the setup showing ASTROBOX2 and the 4 clover Ge detectors

# Best result for $^{31}\text{Cl}$ $\beta\text{p}$ -decay

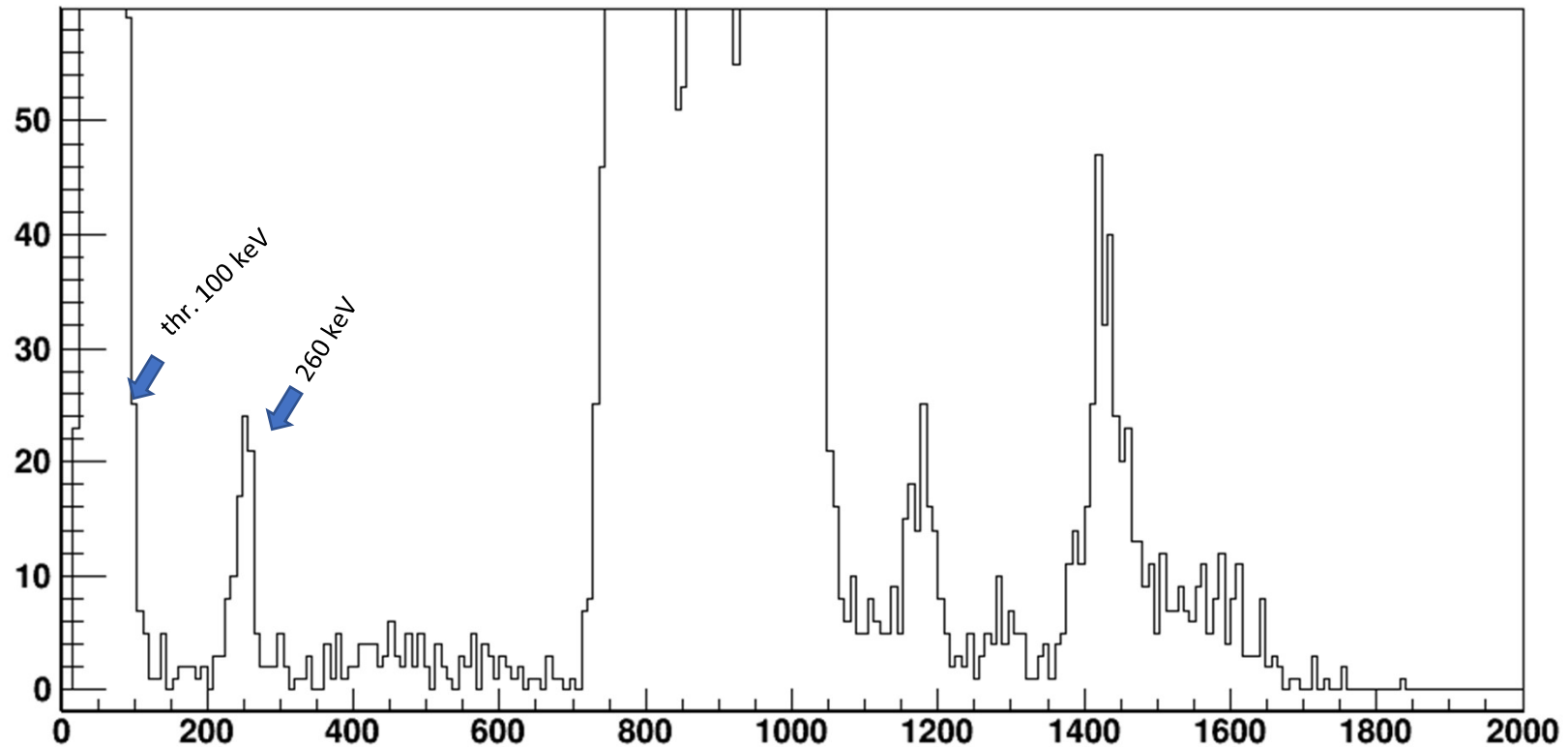
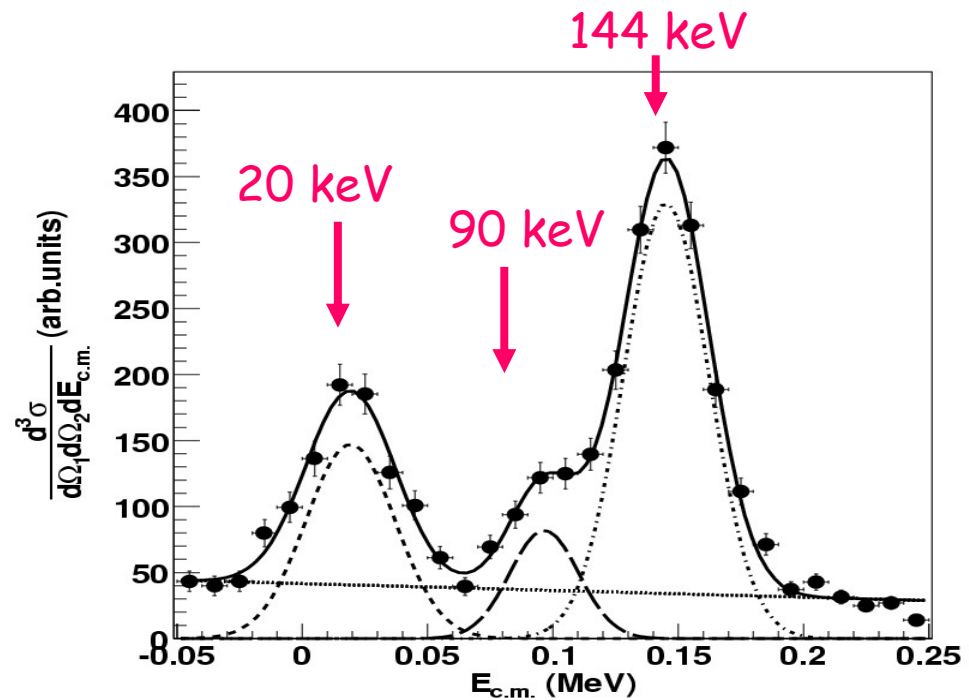
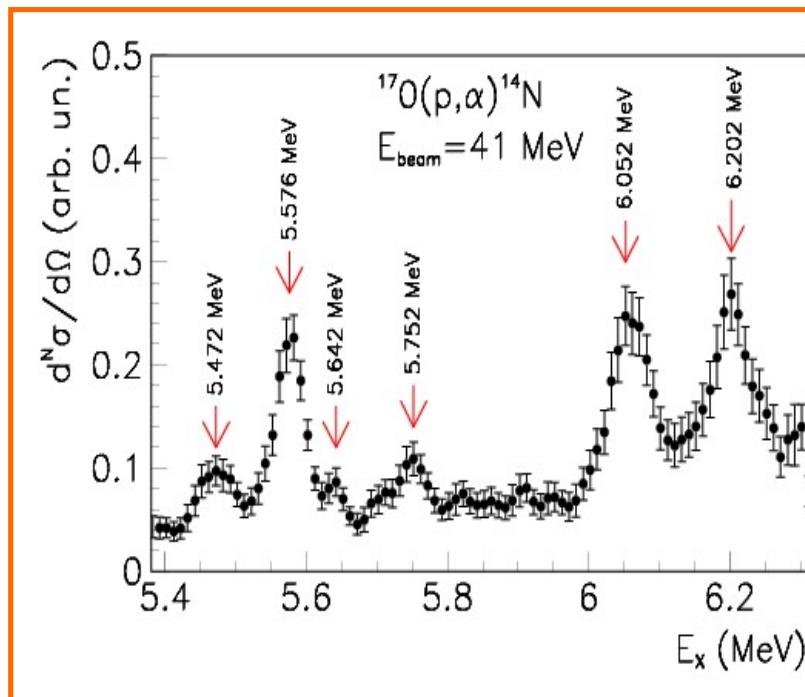


Figure 5. Proton spectrum from the  $\beta\text{p}$ -decay of  $^{31}\text{Cl}$ . The horizontal axis is in keV.

# E. THM (see Aurora Tumino's talk after)

- The most direct from indirect methods!



# Conclusion: Indirect methods are powerful and useful tools for NA!

Dedicate an ECT\* workshop:

Title: **Indirect Methods in Nuclear Astrophysics**

ECT\* Trento, Nov. 5-9, 2018

- It is one of the activities included on the NUSPRASEN @ ENSAR2 agenda, aiming at strengthening the relations between experimentalists and theoreticians, nuclear physicists and astrophysicists, etc.
- In addition to **listing the indirect methods**, new and old, will discuss
  - need for related *theories, codes and parameters*,
  - needs for nuclear data for astrophysics
  - stellar dynamics
  - nucleosynthesis
  - newest Rare Ion Beam facilities and their plans in NA.
- Organizers L. Trache, A Bonaccorso, C Bertulani, Tohru Motobayashi, Zs. Fullop. Contact [livius.trache@nipne.ro](mailto:livius.trache@nipne.ro)
- It is now in the list on the ECT\* website: <http://www.ectstar.eu/next-year/activities/taxonomy/term/21> .

# ChETEC training school in IFIN-HH

## April 10-20, 2018

ChETEC (Chemical Elements as Tracers of the Evolution of Cosmos) is a COST Action ([www.cost.eu](http://www.cost.eu)) aiming to increase networking of specialists in nuclear astrophysics, star dynamics, nucleosynthesis and observational astronomy – <http://chetec.eu>. Participants are from 29 countries. lead Raphael Hirschi, Keele Univ., UK

- **Title: "An experiment of Nuclear Physics for Astrophysics using direct methods"**  
IFIN-HH of Bucharest-Magurele, Romania will host a ChETEC training school in nuclear astrophysics of 11 days duration, consisting in classes and hands-on activities:
  - In a target laboratory
  - Performing an experiment at the 3 MV tandetron (7 days around the clock)
  - Gamma-ray measurements at the 9 MV tandem and the ROSPHERE array
  - De-activation measurements in an underground laboratory microBequerel in the Slanic-Prahova salt mine.
- **Lecturers (as of Oct. 27, 2017):**
  - Prof. Marialuisa Aliotta (Univ. of Edinburgh) – Introduction to Nuclear Astrophysics
  - Dr. Gyorgy Gyurky (ATOMKI Debrecen, TBC) – Experimental methods in NA: direct measurements
  - Prof. Silvia Leoni (Univ. of Milano) – Gamma-ray spectroscopy in NA
  - Mihai Straticiuc, R. Margineanu, Raluca Marginean – IFIN-HH

# European Network of Nuclear Astrophysics Schools: next is Carpathian SSP18

St. Tecla School of Experimental Nuclear Astrophysics

Carpathian Summer Schools of Physics  
2018 “Nuclear/Particle Astrophysics (VII)”  
July 1-14, 2018 in Sinaia, Romania

The 9<sup>th</sup> European Summer School on Experimental Nuclear Astrophysics

September 17-24, 2017  
Santa Tecla, Sicily, Italy



Big Bang and Stellar Nucleosynthesis, Plasmas in Stars and Laboratories, Direct and Indirect Measurements, Detectors and Facilities for Nuclear Astrophysics, Experiments with RIB

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**Carpathian Summer School of Physics 2016**  
Exotic Nuclei and Nuclear/Particle Astrophysics (VI)  
Physics with small accelerators

June 26 - July 9, 2016 Sinaia, Romania

**topics**

- Exotic nuclei
- Nuclear physics with RIBs
- Nuclear physics for astrophysics
- Stellar evolution, Compact stars and supernovae
- Astroparticle physics
- Stellar and laser induced plasmas
- Physics at ELI-NP
- Applications of small accelerators
- Nuclear astrophysics with small accelerators
- Instrumentation
- Accelerators for medical treatments, radioisotope production and industrial applications




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