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 (28th) Sinaia

Nuclear Astrophysics

Indirect methods – measurements at lab energies $\rightarrow$ 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

A. Coulomb dissociation

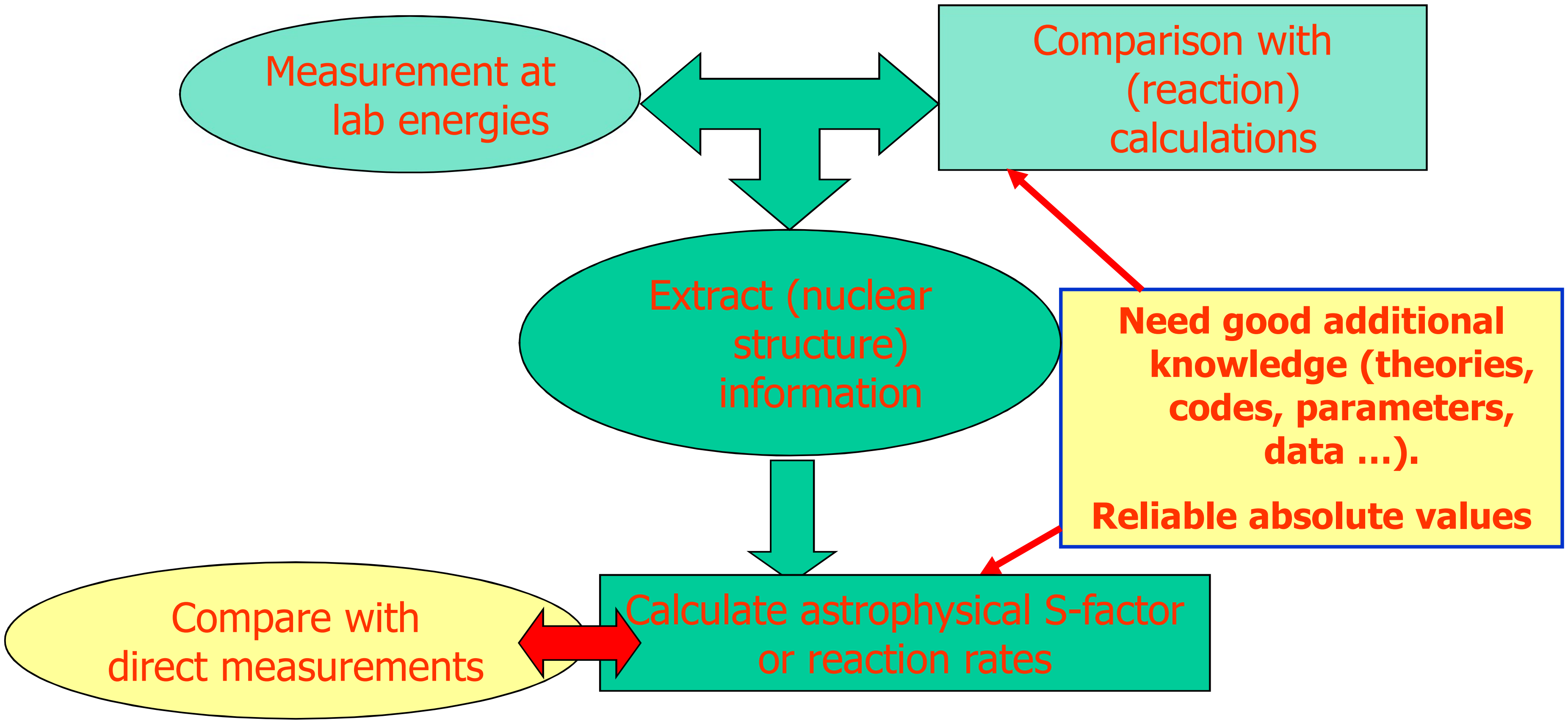
B. Transfer reactions (ANC method)

C. Breakup (nuclear) of loosely bound nuclei

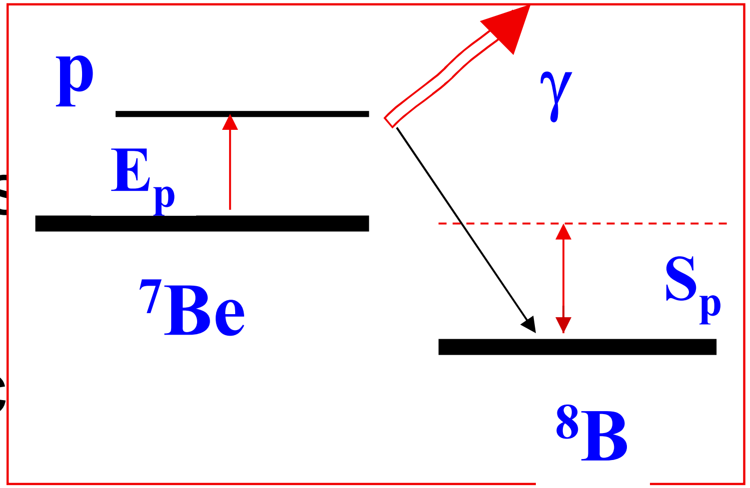
D. Resonance spectroscopy – β-decay, βp-decay, transfer reactions, resonant elastic scattering, etc

E. Trojan Horse Method – see later, Aurora's talk

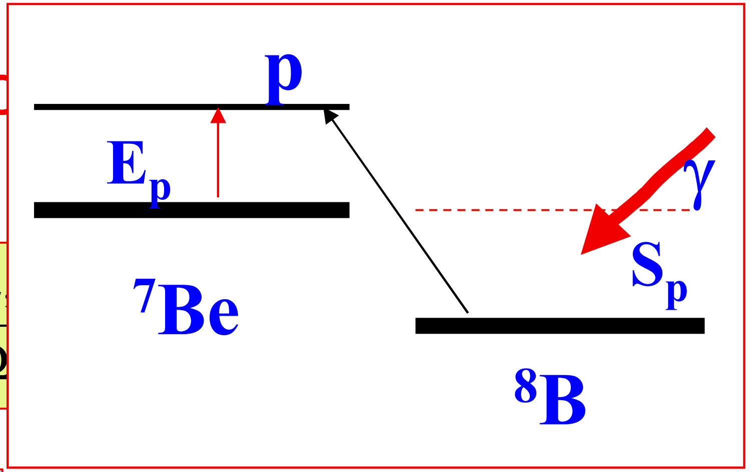
Indirect methods for nuclear astrophysics – general scheme



A. Coulomb dissociation



- Radiative capture - direct proces
  - X(p,γ)Y
- Photodissociation - inverse proc
  - Y(γ,p)X
    - **Use detailed balance theorem**
- virtual photons – Coulomb Disso



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

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

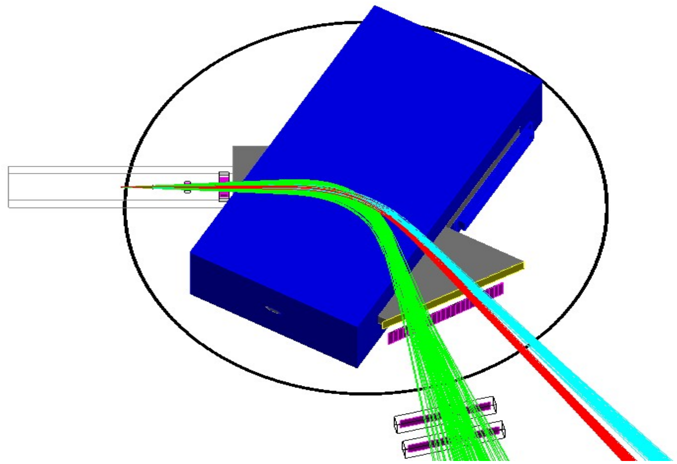
$$E_\gamma = E_p + S_p$$

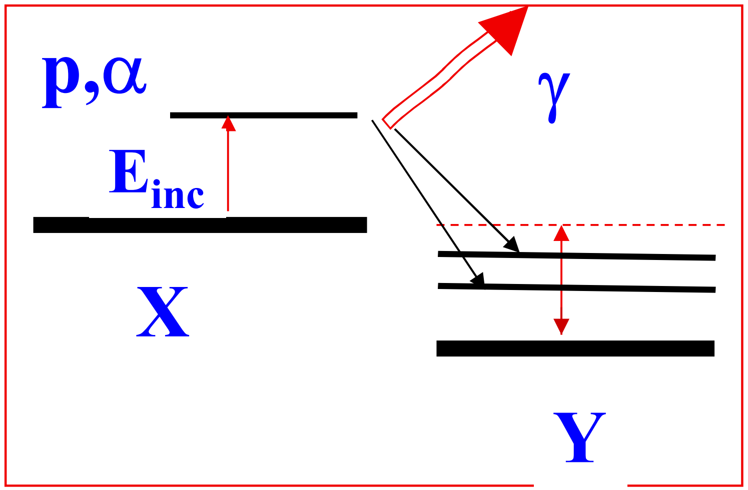
CD

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}C breakup @ RIBF
exp. NP1412-SAMURAI29R1

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

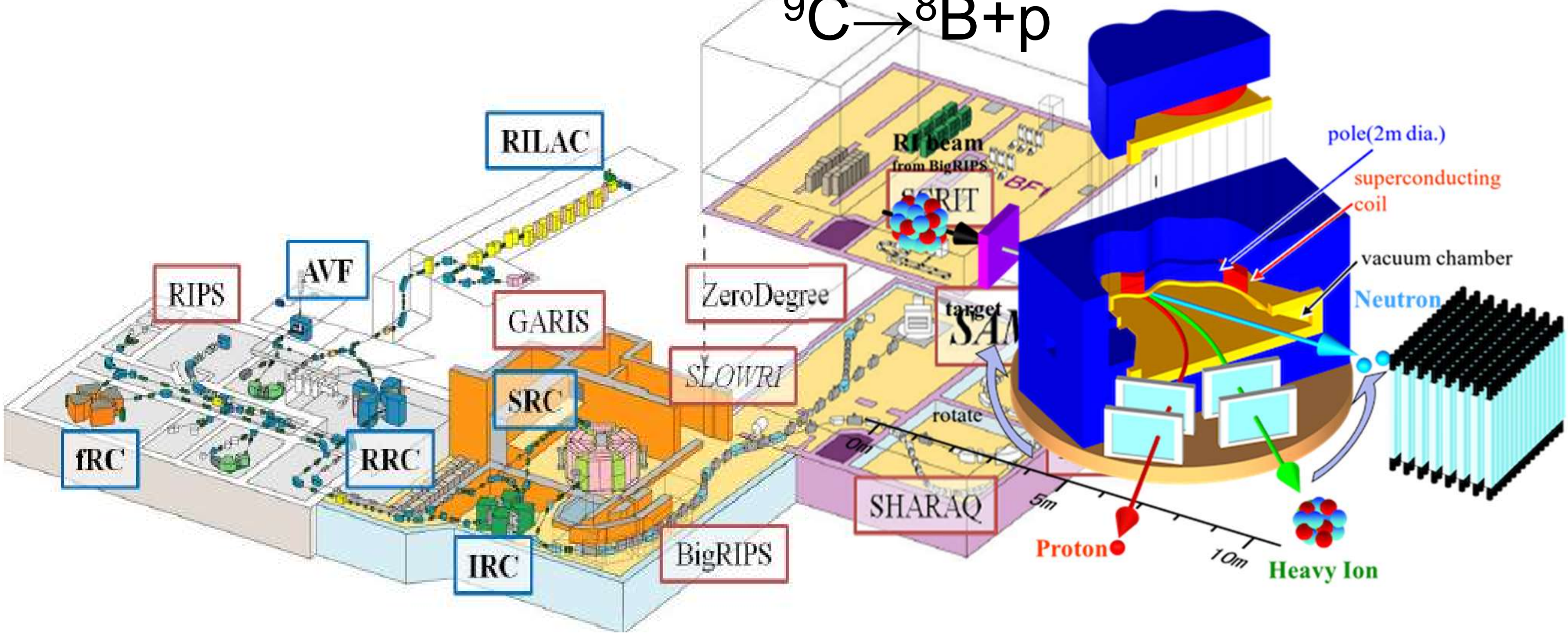
Exp demanding: sec beam quality typically lower, setup complex, beamtime scarce …

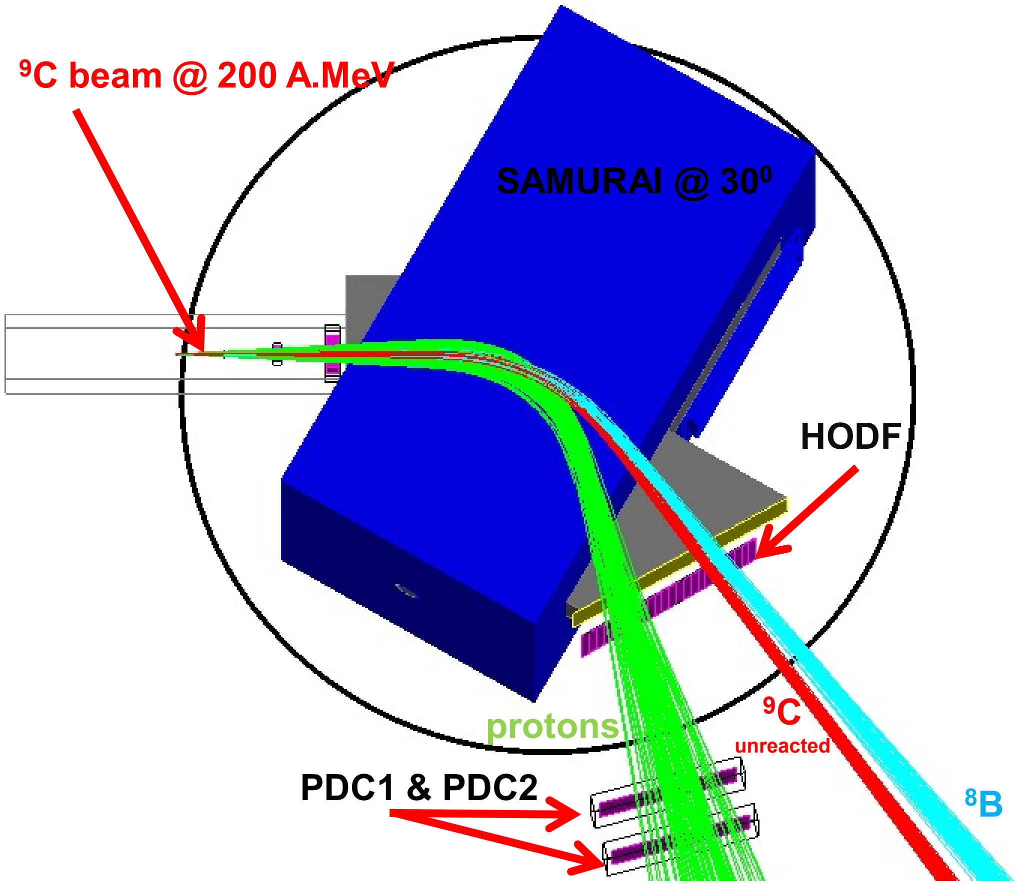
Main problem: GET BEAMTIME!

- 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

$^{9}C \rightarrow {}^{8}B+p$





⁹C beam @ 200 A.MeV
SAMURAI @ 30⁰
HODF
protons
⁹C
unreacted
PDC1 & PDC2
⁸B

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 rea... peripheral (absorption)

- Transfer matrix element

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

$$\frac{d\sigma}{d\Omega} = \sum \left[S\, S \left(\frac{d\sigma}{\ldots} \right) \right]$$

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

$$\frac{d\sigma}{d\Omega} = \sum (C^{A}_{Bpl_Aj_A})^2 (C^{d}_{apl_dj_d})^2 \frac{\sigma_{l_Aj_Al_dj_d}}{b^2_{Bpl_Aj_A}\, b^2_{apl_dj_d}}$$

ANC - independent on binding potential geometry!

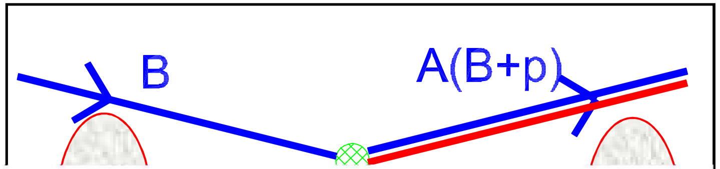
OMP knowledge crucial for reliable absolute values!

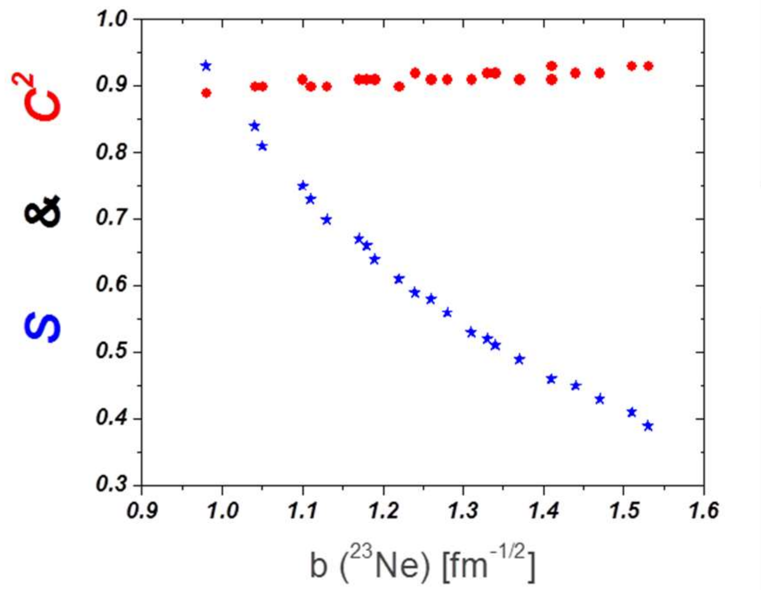
Semi-micr proc. JLM interaction (LT ea, PRC, 2000)

NA: proton-nucleus also peripheral

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

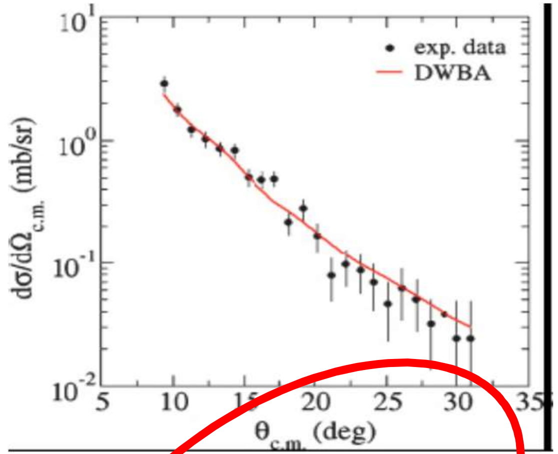
(Christy and Duck, 1963
Parker and Tombrello, 1964)



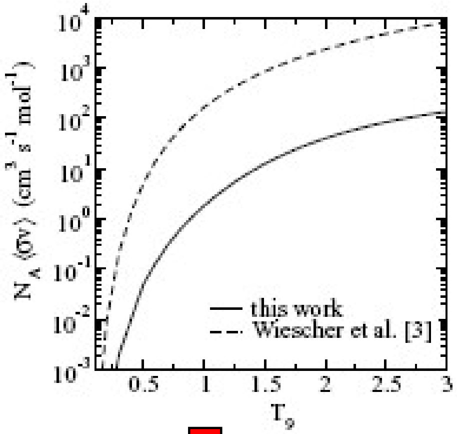


$$I^{A}_{Bp} \overset{r_{Bp}>R_N}{\approx} C^{A}_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

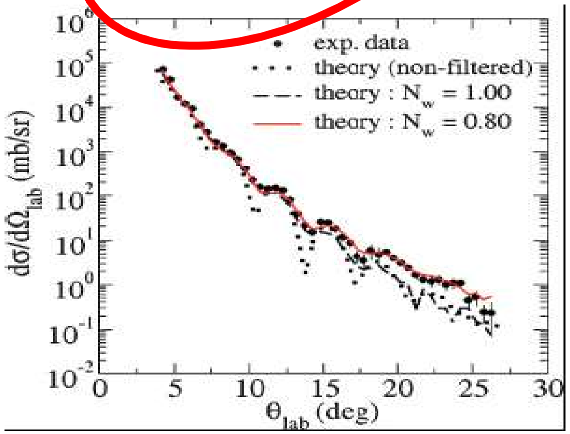
$^{14}N(^{12}N,^{13}O)$ proton-transfer react ⇒ $^{12}N(p,\gamma)^{13}O$ (rap I,II proc)



ANC, S-factor 0-2 MeV
Reaction rate



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



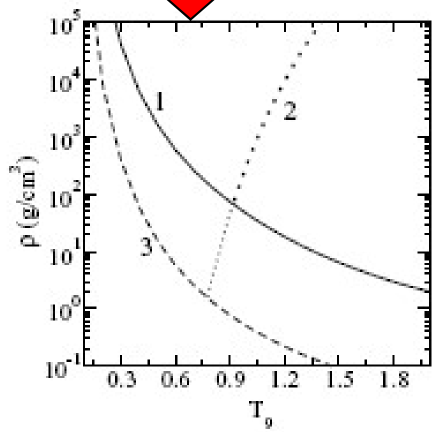
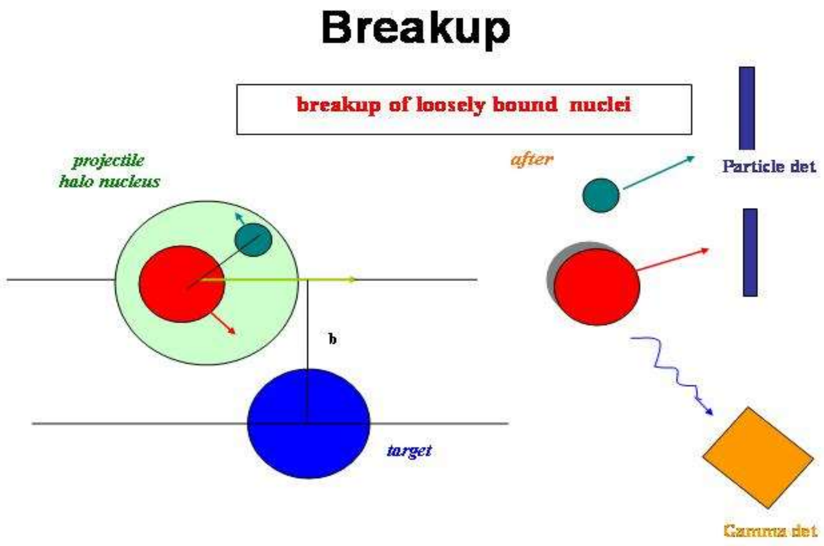
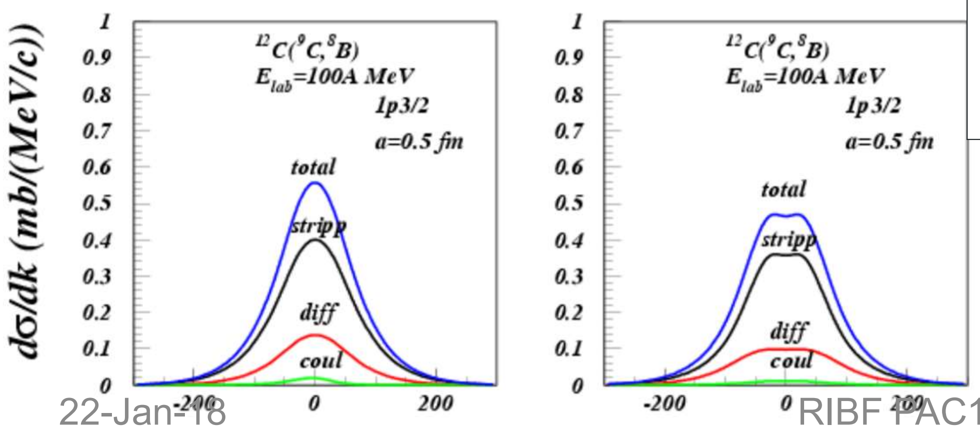


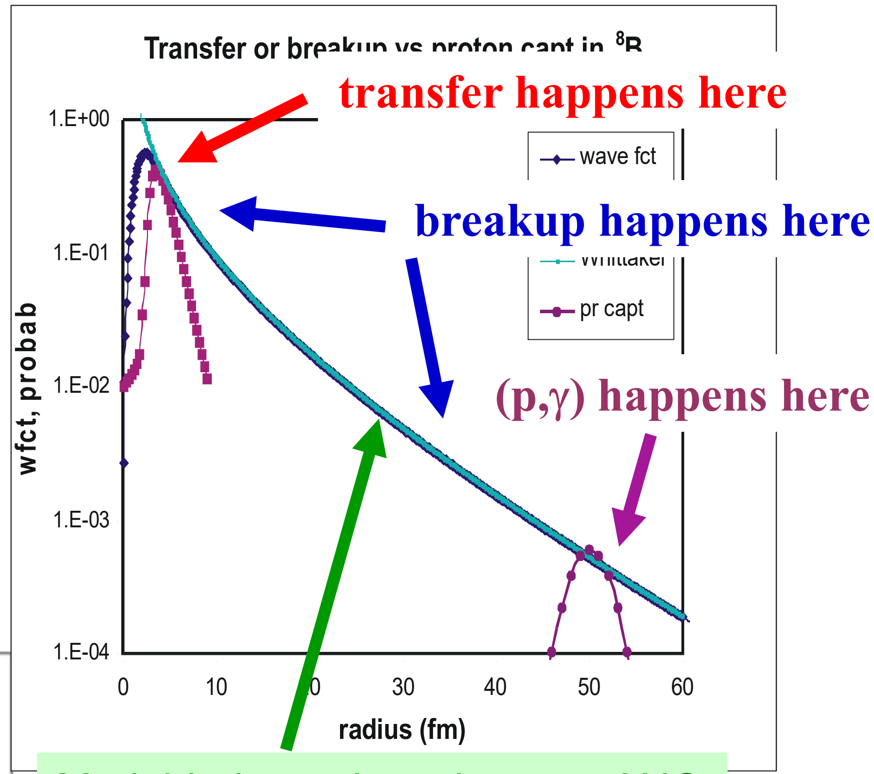
FIG. 10. Temperature and density conditions at which the $^{12}N(p,\gamma)^{13}O$ reaction may play a role. Curve 1 represents the equilibrium line between the rates for ^{12}N proton capture and ^{12}N β decay. Curve 3 illustrates the same result as determined from Ref. [3]. Curve 2 shows the line of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

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

Nuclear breakup: Y->X+p for X(p,γ)Y



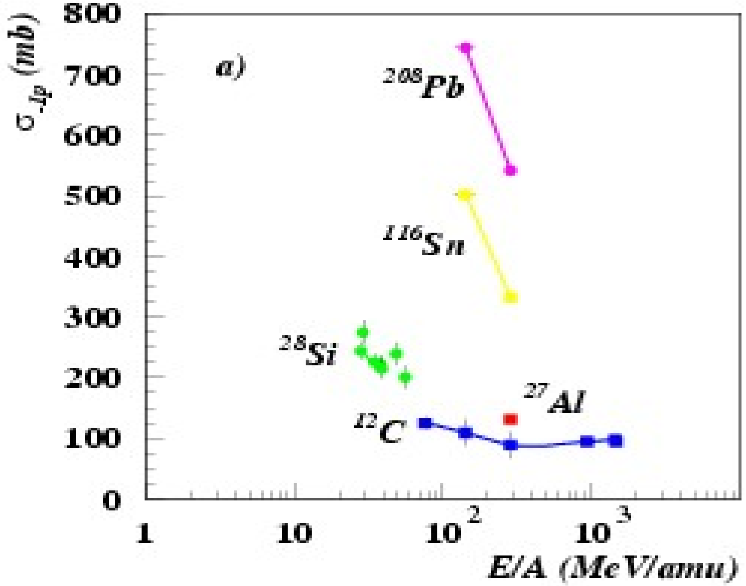




Model-independent shape w. ANC (Whittaker function)

Shape of mom distr => *nlj*
Cross section => ANC

Example: Summary of the ANC extracted from ^{8}B breakup with different interactions



Data from:

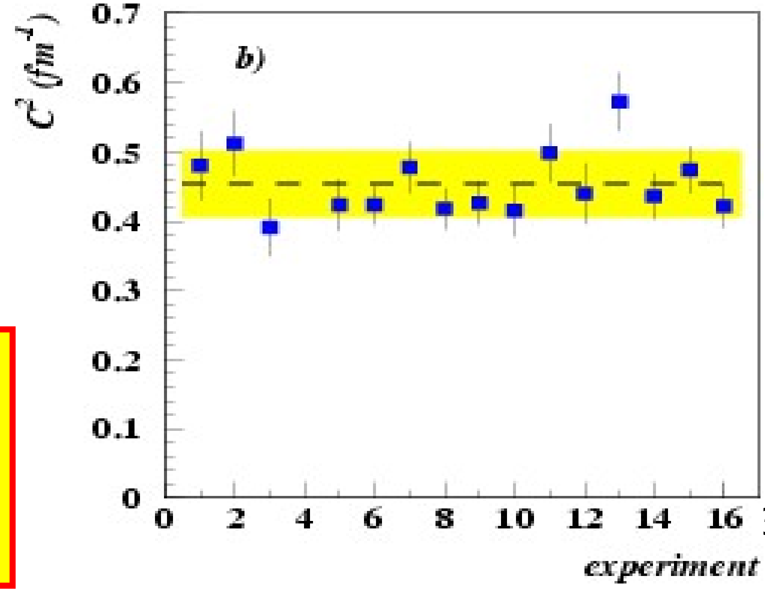
F. Negoita et al, Phys Rev C 54, 1787 (1996)

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

D. Cortina-Gil e a, EuroPhys J. 10A, 49 (2001).

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

J. Enders e.a., 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 ea, PRL 87, 2001

^{7}Be(p,γ)^{8}B (solar neutrinos probl.):
p-transfer: $S_{17}(0)=18.2\pm1.7$ eVb
Breakup: $S_{17}(0)=18.7\pm1.9$ eVb
Direct meas: $S_{17}(0)=20.8\pm1.4$ eVb

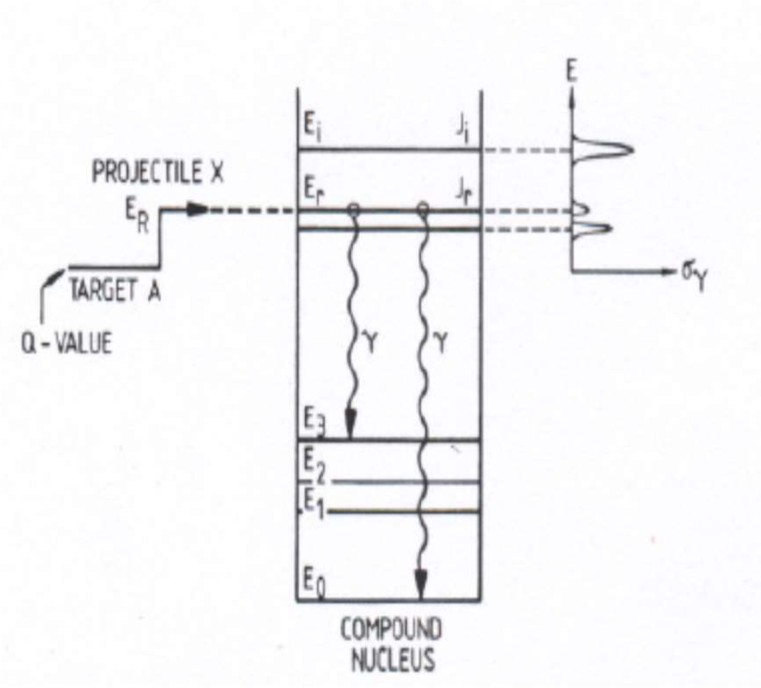
D. Resonance Spectroscopy

* **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):**

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



* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.

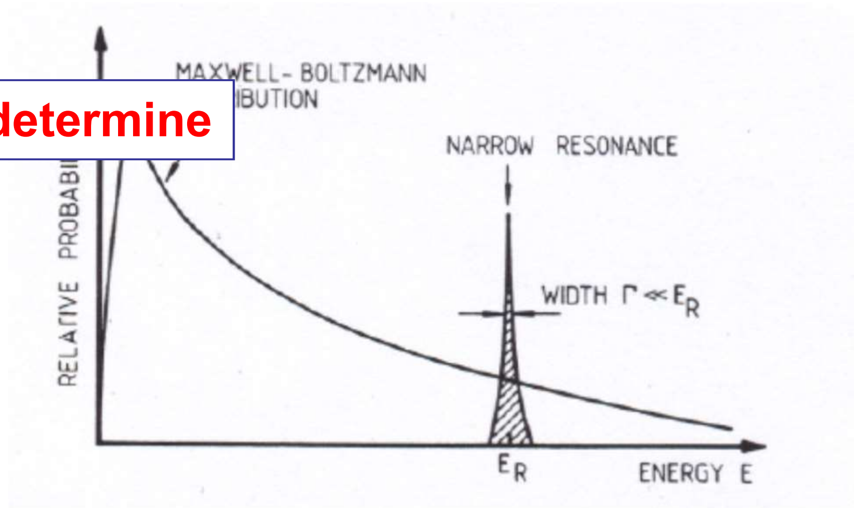
* **The contribution to the reaction rate:**

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

to determine

where

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



ωγ= resonance strength

D. Spectroscopy of resonances

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

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

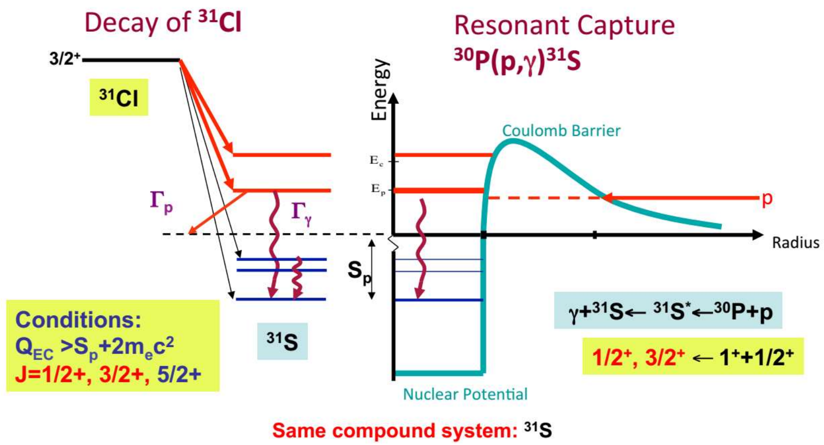
Difficulties:

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

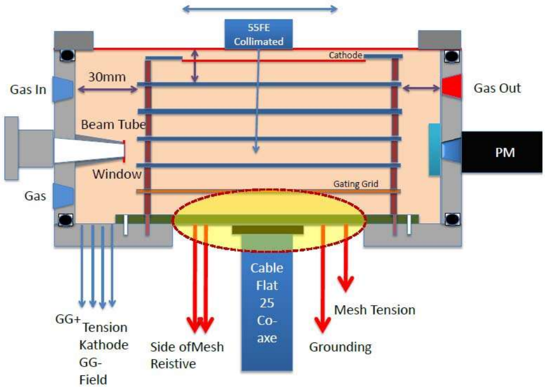
β-decay and β-delayed proton-decay

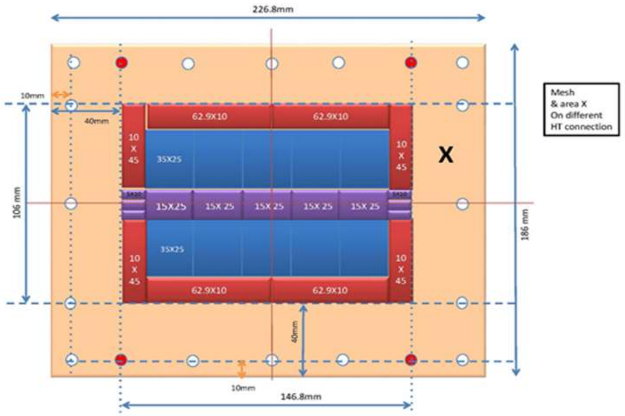
Another line of research motivated by NA: **spectroscopy of resonances:**

- 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}Al, ^{31}Cl, ^{35}K using ASTROBOX2 at TAMU (oct 2016, Oct 2017)



ASTROBOX2

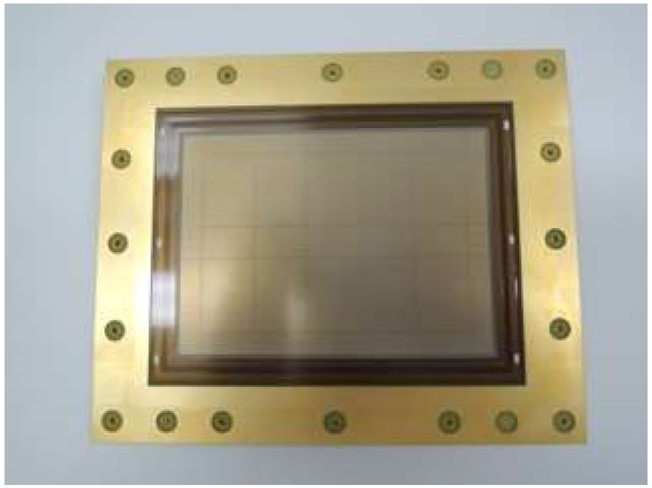




- Top left: chamber uses gas for detection and micromegas for signal amplification.

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 γ

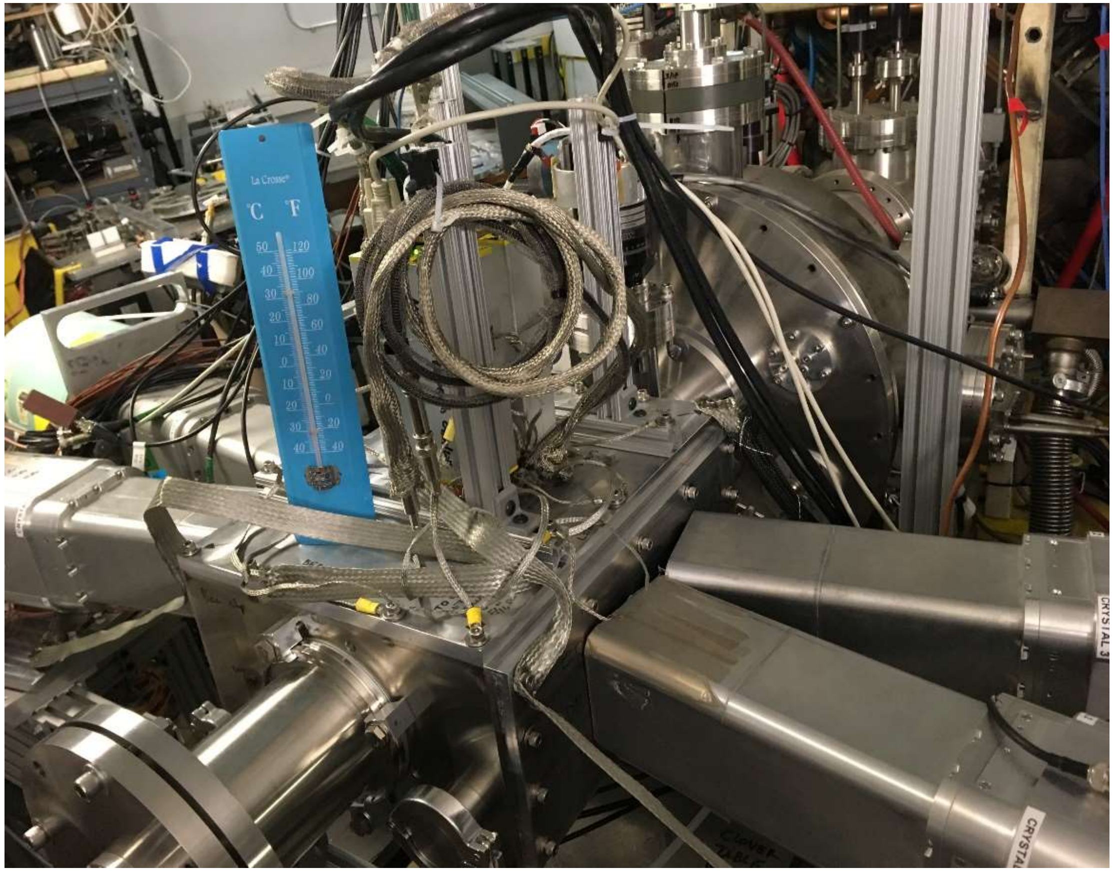


Figure 8. Photo of the setup showing ASTROBOIX2 and the 4 clover Ge detectors

Best result for ^{31}Cl βp-decay

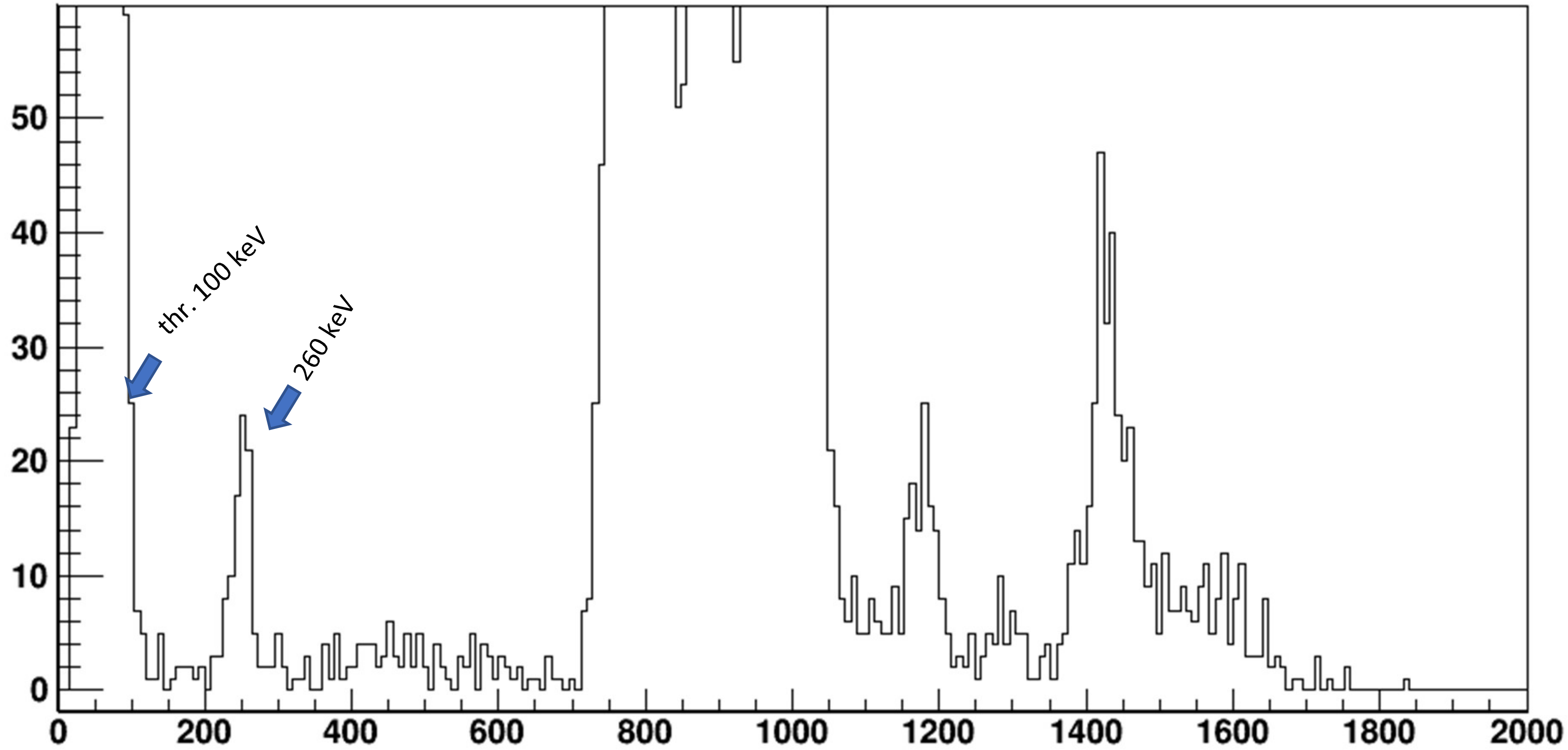


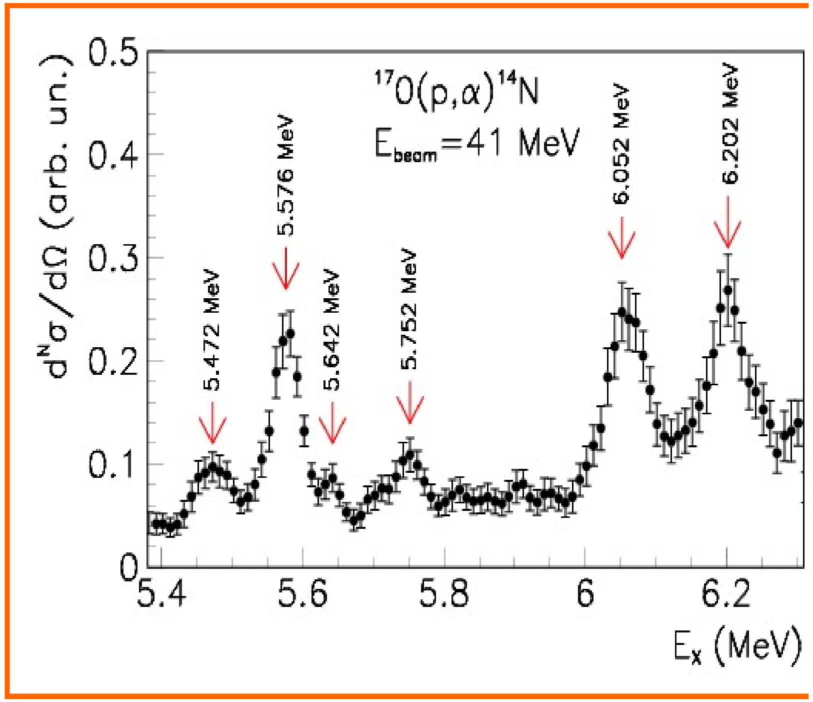
Figure 5. Proton spectrum from the βp-decay of ^{31}Cl. The horizontal axis is in keV.

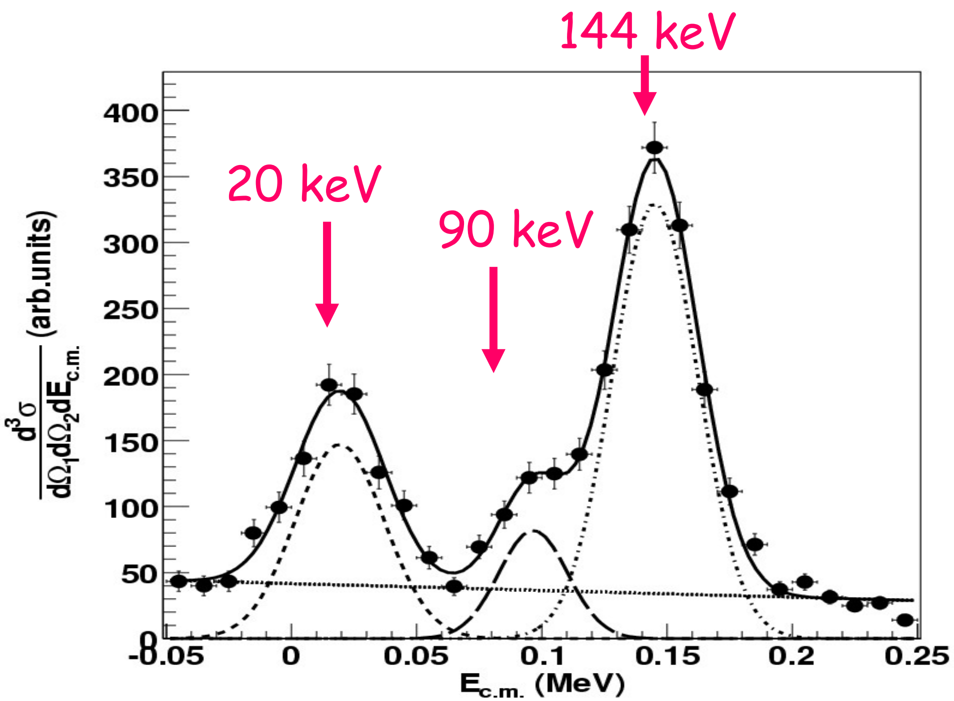
A. Saastamoinen et al., NPA8, Catania, June 2017

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

- The most direct from indirect methods!

$^{18}O + p \rightarrow \alpha_o + {}^{15}N$





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 meth**ods, 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
- 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) 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