Study of ion-ion fusion mechanisms at sub-barrier energies for nuclear astrophysics

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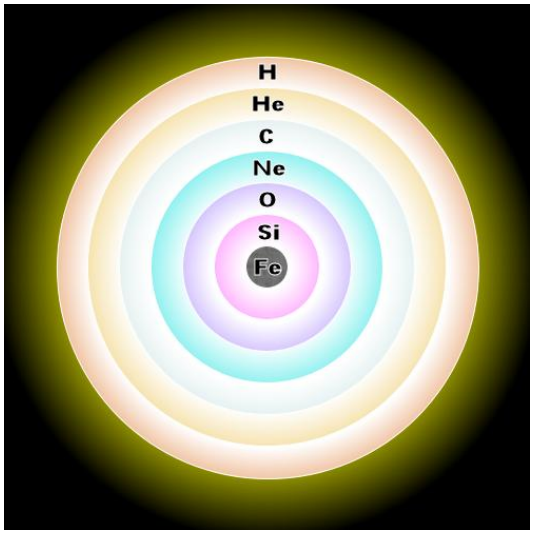
Key Reactions in Nuclear Astrophysics (KRINA) Virtual Workshop 2021

Motivation

- In stellar nucleosynthesis, many of the important reactions are those of capture of very light particles: p, n, a.
- There are also a few crucial reactions between light ions heavier than ^{4}He, among them those involving ^{12}C and ^{16}O.



- Such reactions occur at very low energies, well below the Coulomb barrier.
  - this makes them difficult to study experimentally
  - understanding the fusion mechanism at such energies becomes very important in order to correctly extrapolate at the low energies of interest

EXPERIMENTAL SOLUTIONS
Direct measurements

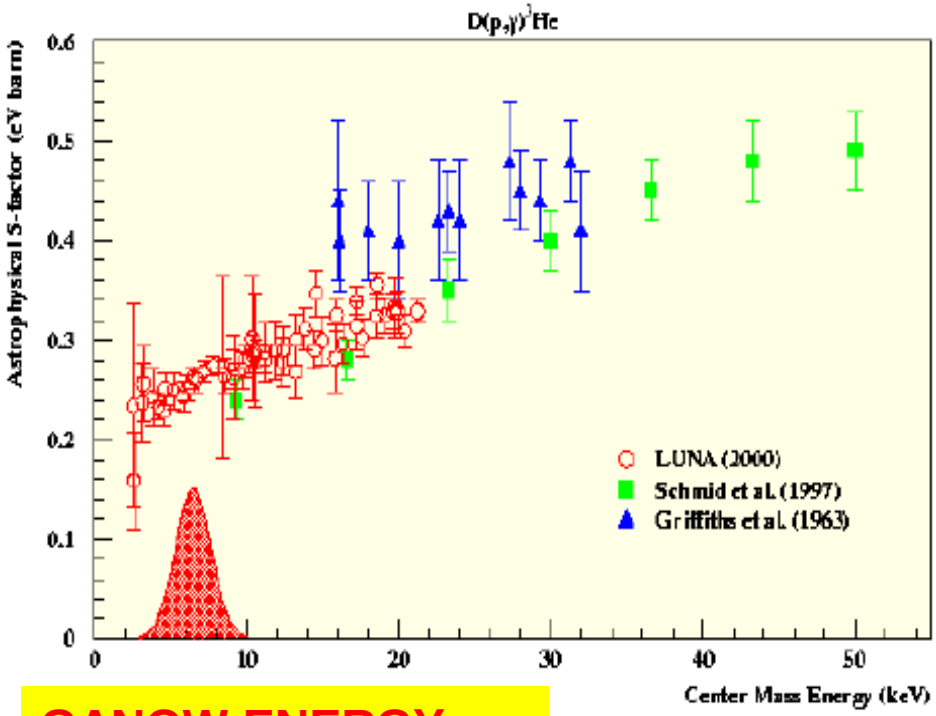
IMPROVEMENTS TO REDUCE THE BACKGROUND

-(UNDERGROUND LABORATORY)

Use of laboratory with natural shield

(underground physics-for instance **LUNA experiment at LNGS-Italy**)

$^2H(p,\gamma)^3He$

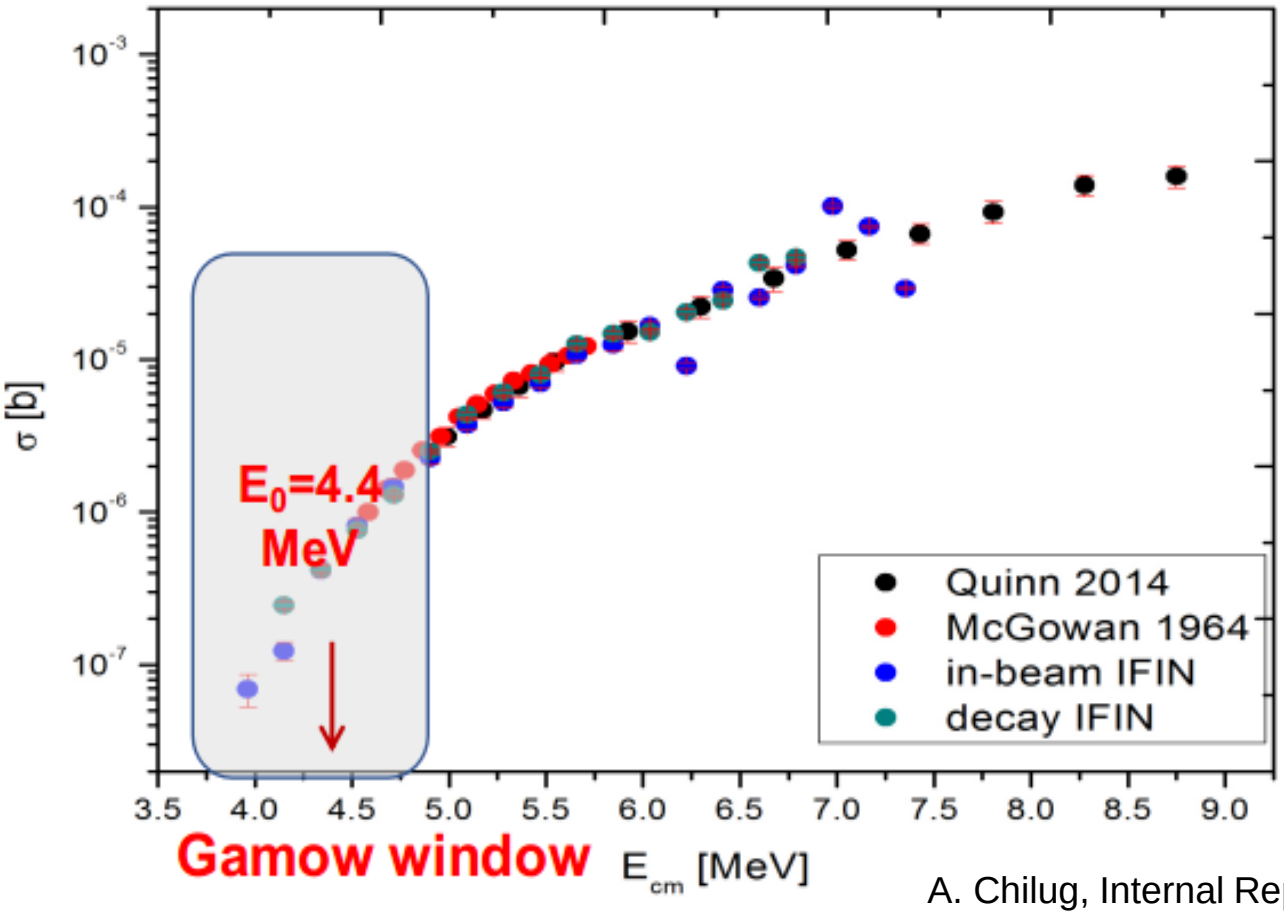


GANOW ENERGY

NO EXTRAPOLATION needed

$^{58}Ni(\alpha, \gamma)^{62}Zn$

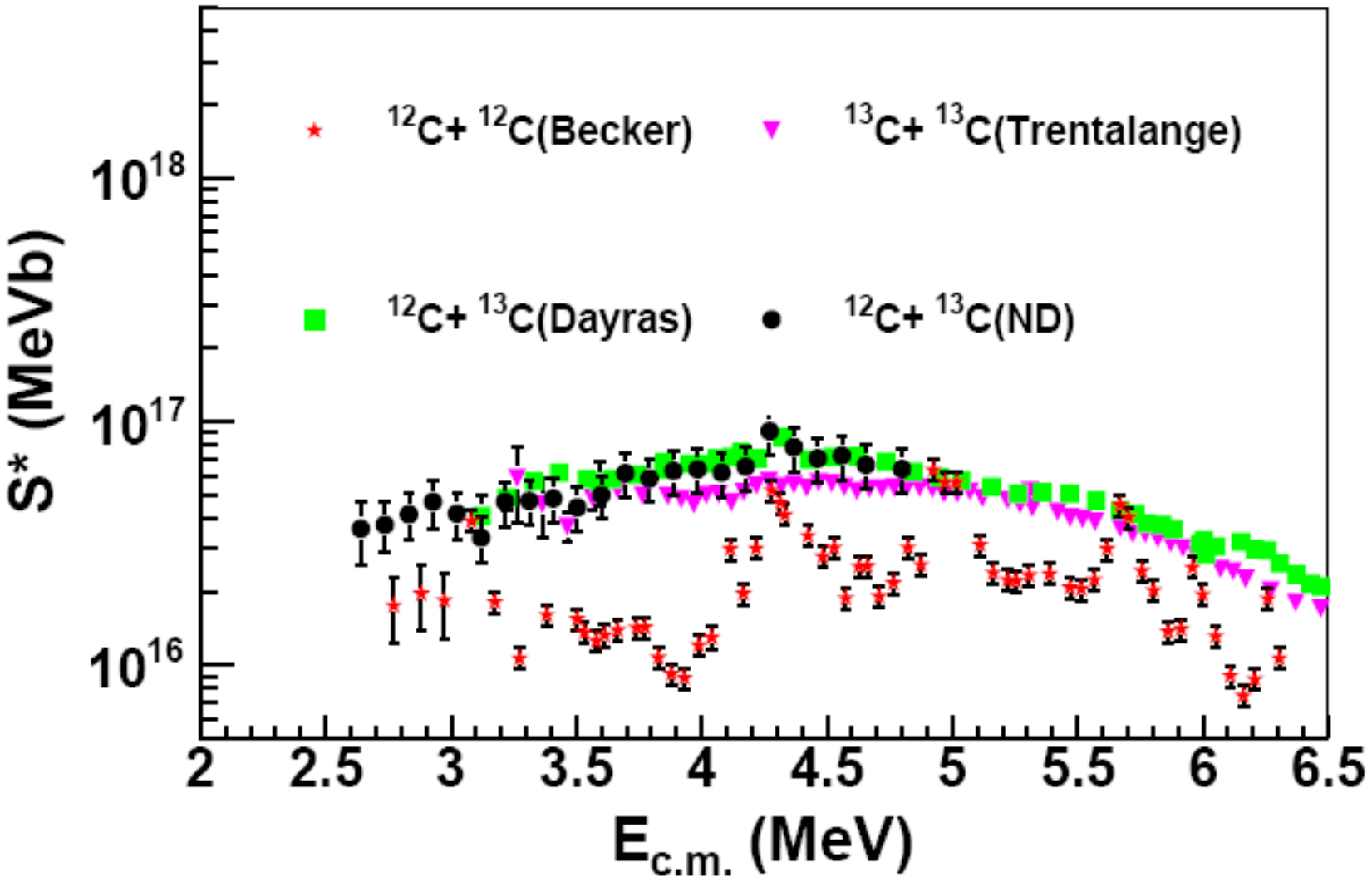
- important reaction for estimating the production of ^{62}Ni, ^{63}Cu and ^{64}Zn in type Ia supernovae.
- activation of Ni targets using an alpha beam



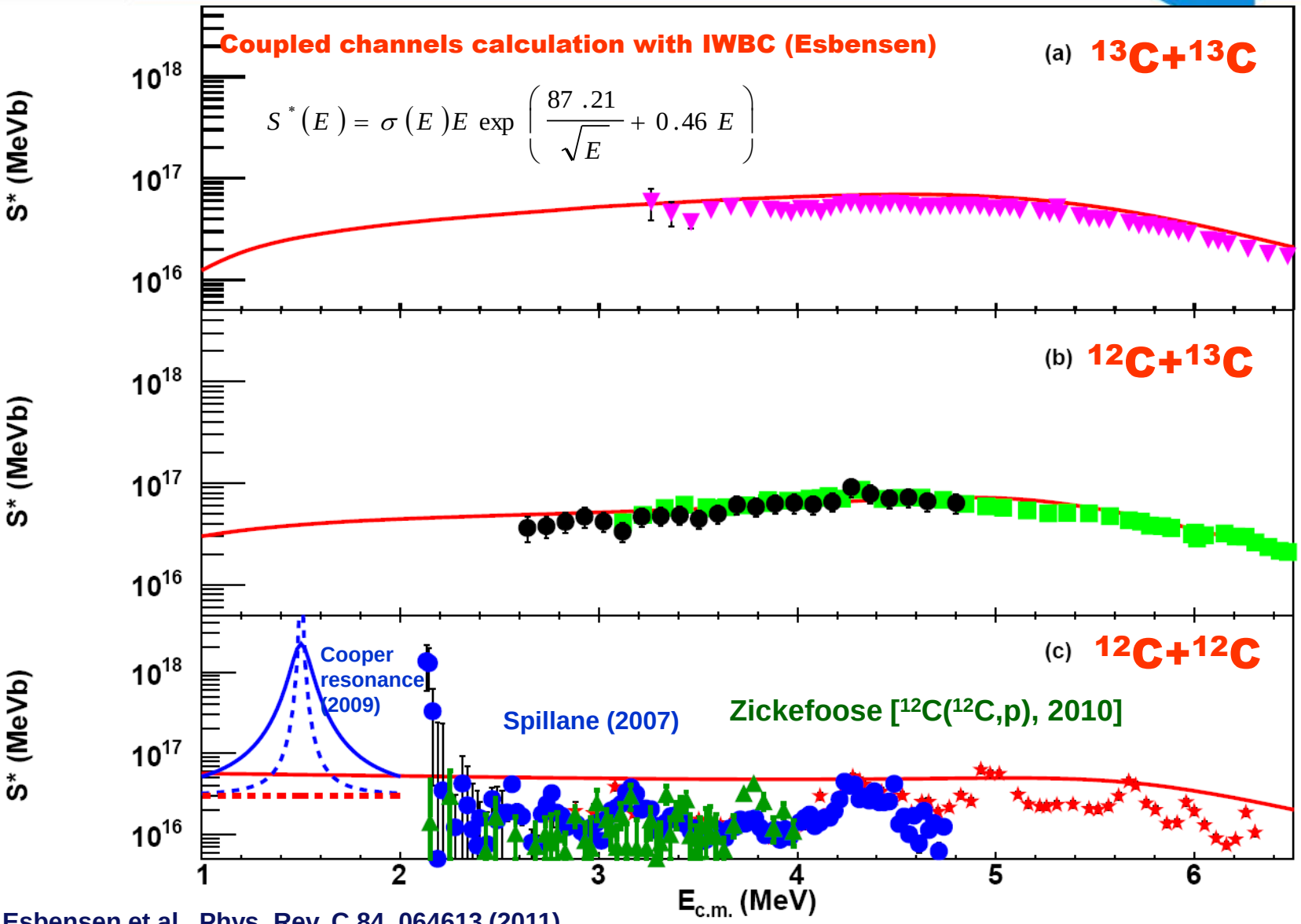
A. Chilug, Internal Report IFIN-HH

Ion – Ion fusion reactions

- For fusion reactions between light ions, the situation is more difficult because the Coulomb barrier is higher
- Three of the more crucial reactions involve ^{12}C and ^{16}O
  - $^{12}C + {}^{12}C$
  - $^{12}C + {}^{16}O$
  - $^{16}O + {}^{16}O$
- But other reactions can be studied as well, rxns that might not be very important astrophysically, but that can further our understanding of fusion mechanisms at low energies

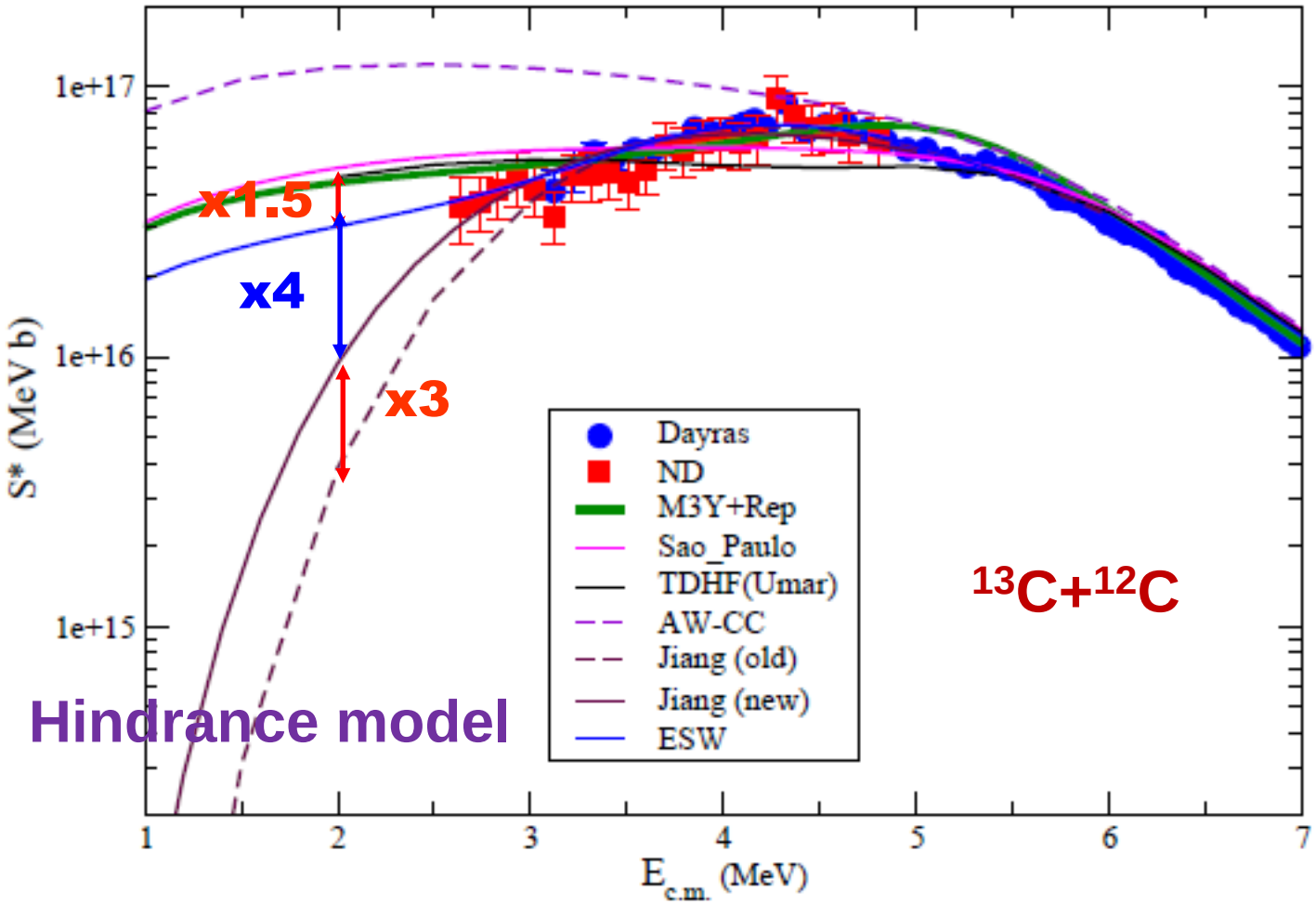

$^{12}C+ ^{12}C$(Becker)
$^{13}C+ ^{13}C$(Trentalange)
$^{12}C+ ^{13}C$(Dayras)
$^{12}C+ ^{13}C$(ND)
S* (MeVb)
10^{18}
10^{17}
10^{16}
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
$E_{c.m.}$ (MeV)

$^{12}C + ^{12}C$



H. Esbensen et al., Phys. Rev. C 84, 064613 (2011)
M. Notani et al., Phys. Rev. C 85, 014607 (2012)

Test of extrapolating models

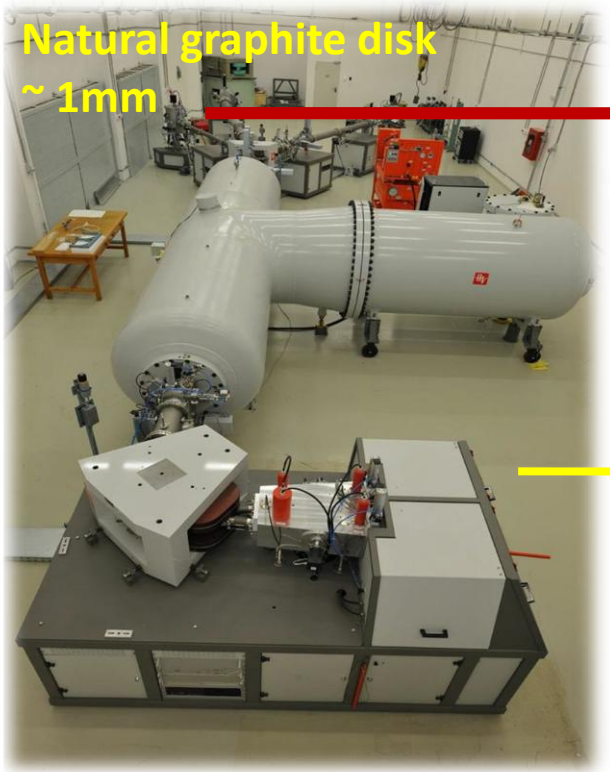


- **M3Y can be used to model the xsec by adding repulsive core.**
- **TDHF & Sao_Paulo predict similar behavior.**

$^{12}C + ^{12}C$

- Fusion mechanism with $^{13}C+^{12}C$ using thick target activation method in collaboration with IMP Lanzhou, China (Zhang et al., *Phys. Letters B* **801** (2020))

In beam irradiation, thick targets



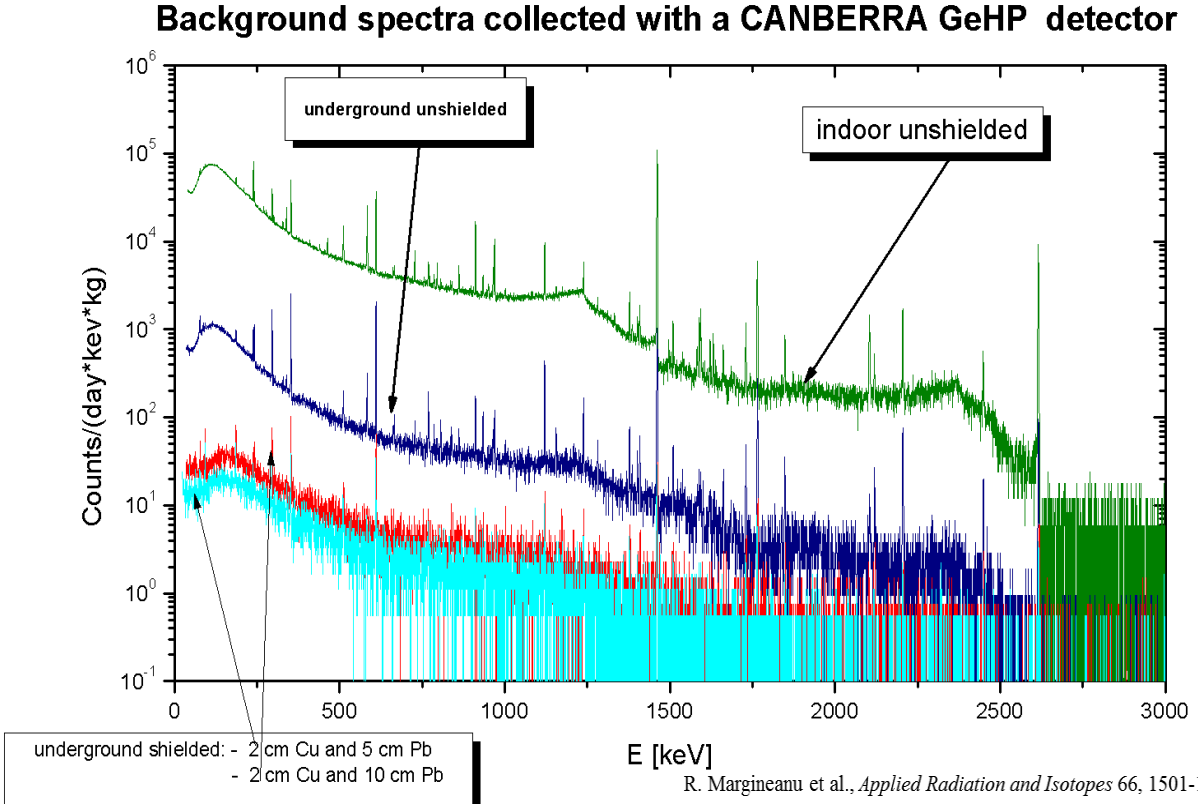
$^{12}C(^{13}C,p)\,^{24}Na$

$^{24}Na: T_{1/2} = 15$ h

$E_\gamma = 1369$ keV

^{13}C beam @ 10-15 pμA

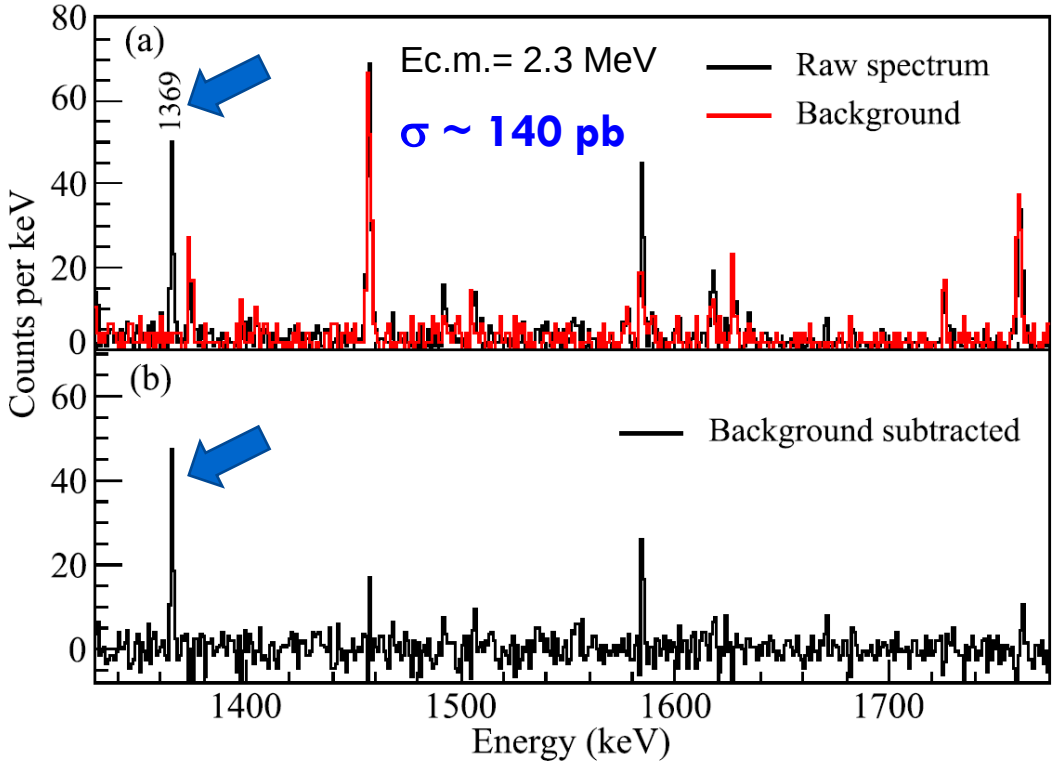
Ultra low background laboratory at Slanic Salt Mine



R. Margineanu et al., *Applied Radiation and Isotopes* 66, 1501-1506, 2008

$^{12}C + ^{12}C$

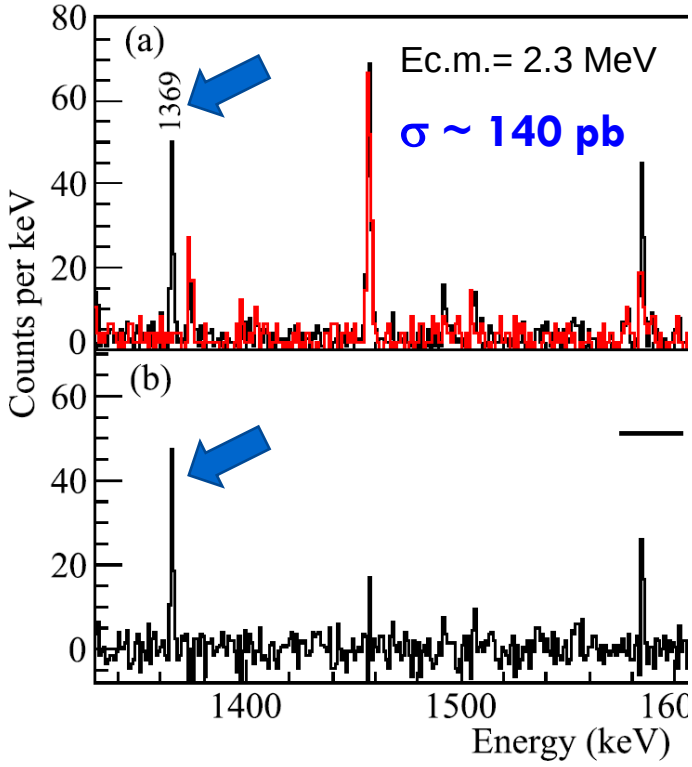
- Fusion mechanism with $^{13}C+^{12}C$ using thick target activation method in collaboration with IMP Lanzhou, China (result published in PLB by N. Zhang)



activation: 3 targets, total of ~3 days irradiation time
measurements: total of ~4 days

$^{12}C + ^{12}C$

- Fusion mechanism with 13C+12C using thick target activation method in collaboration with IMP Lanzhou, China (result published in PLB by N. Zhang)



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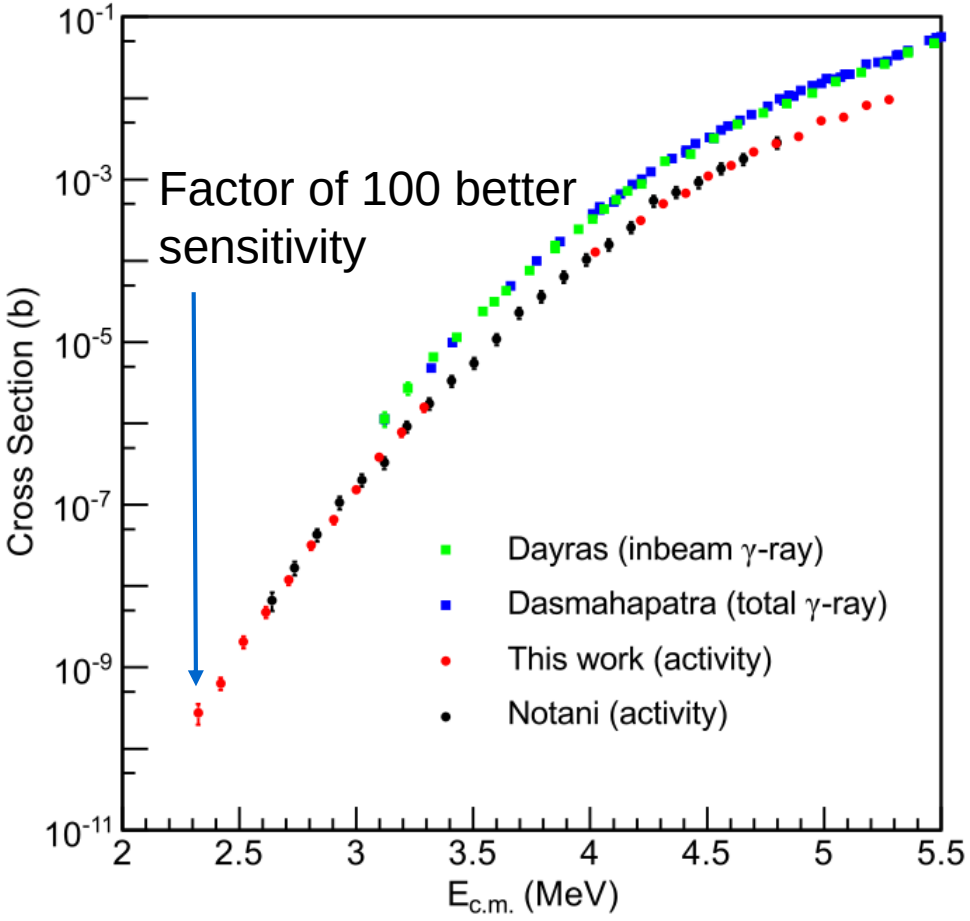
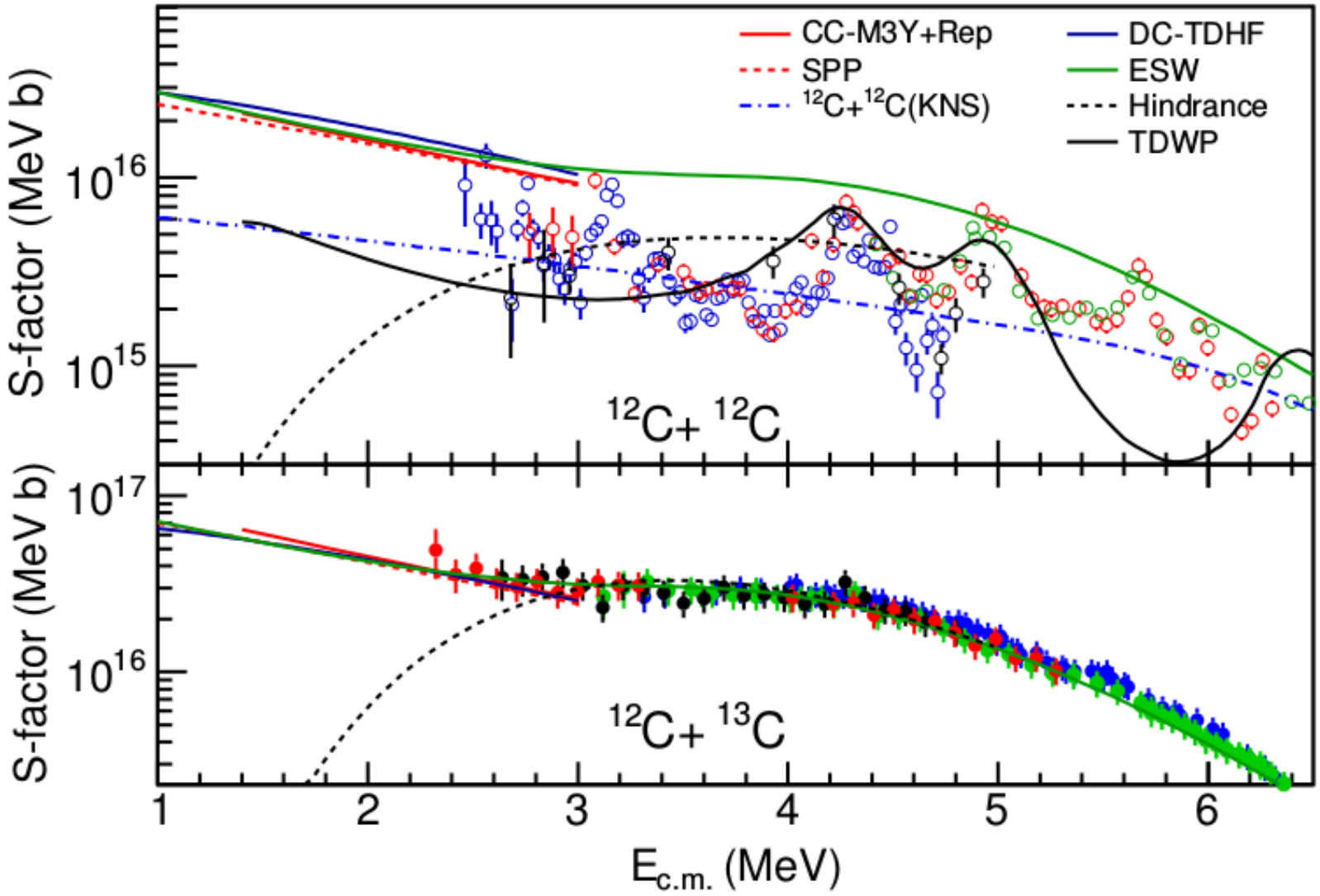


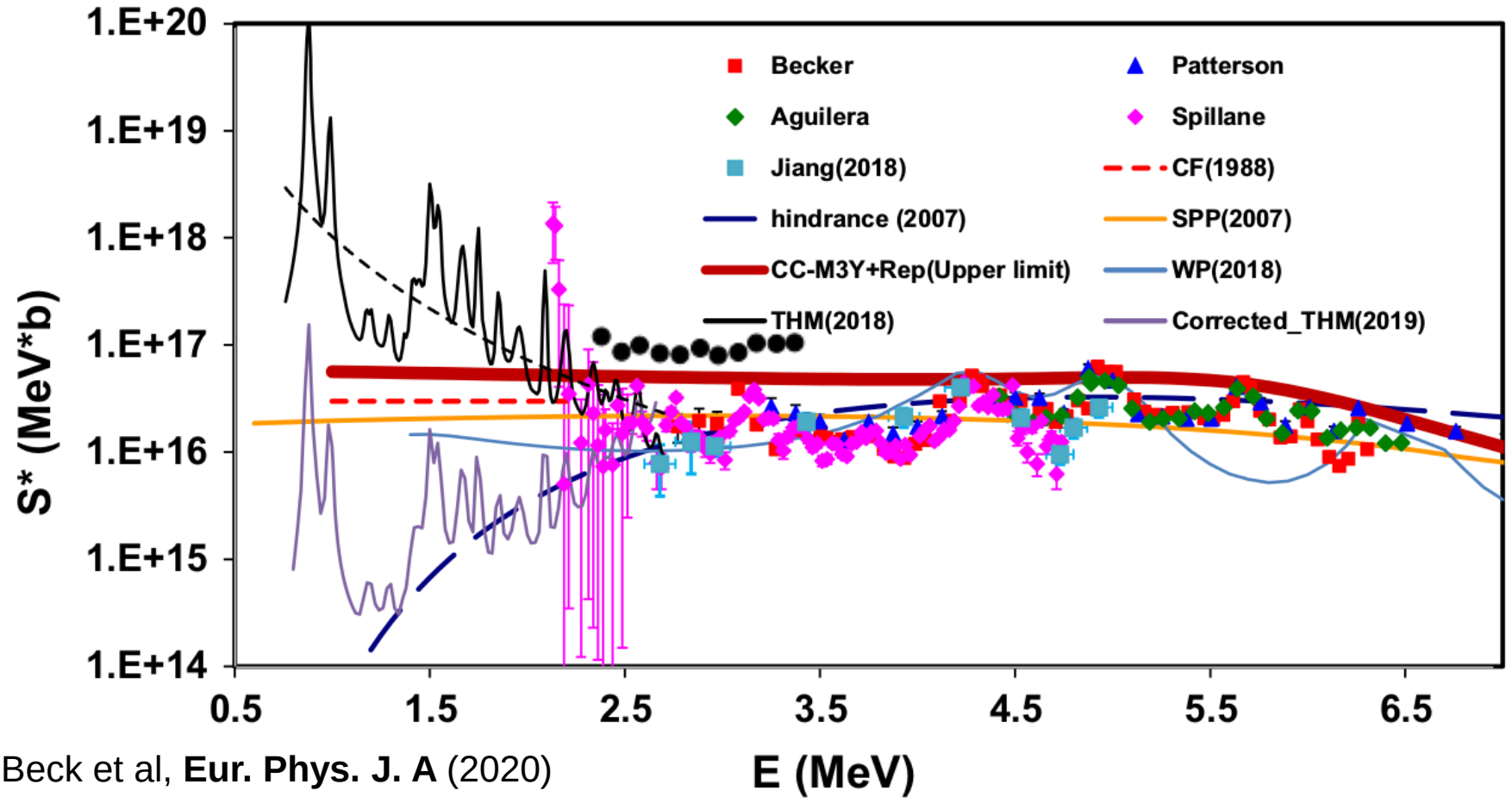
Zhang et al., *Phys. Letters B* **801** (2020)

$^{12}C + ^{12}C$



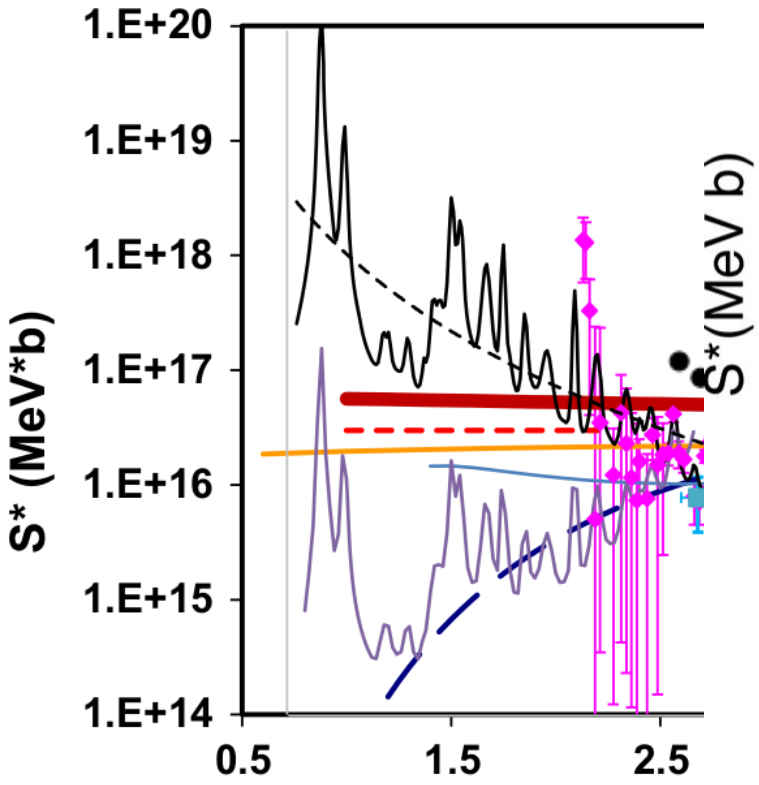
Zhang et al., *Phys. Letters B* **801** (2020)

$^{12}C + ^{12}C$

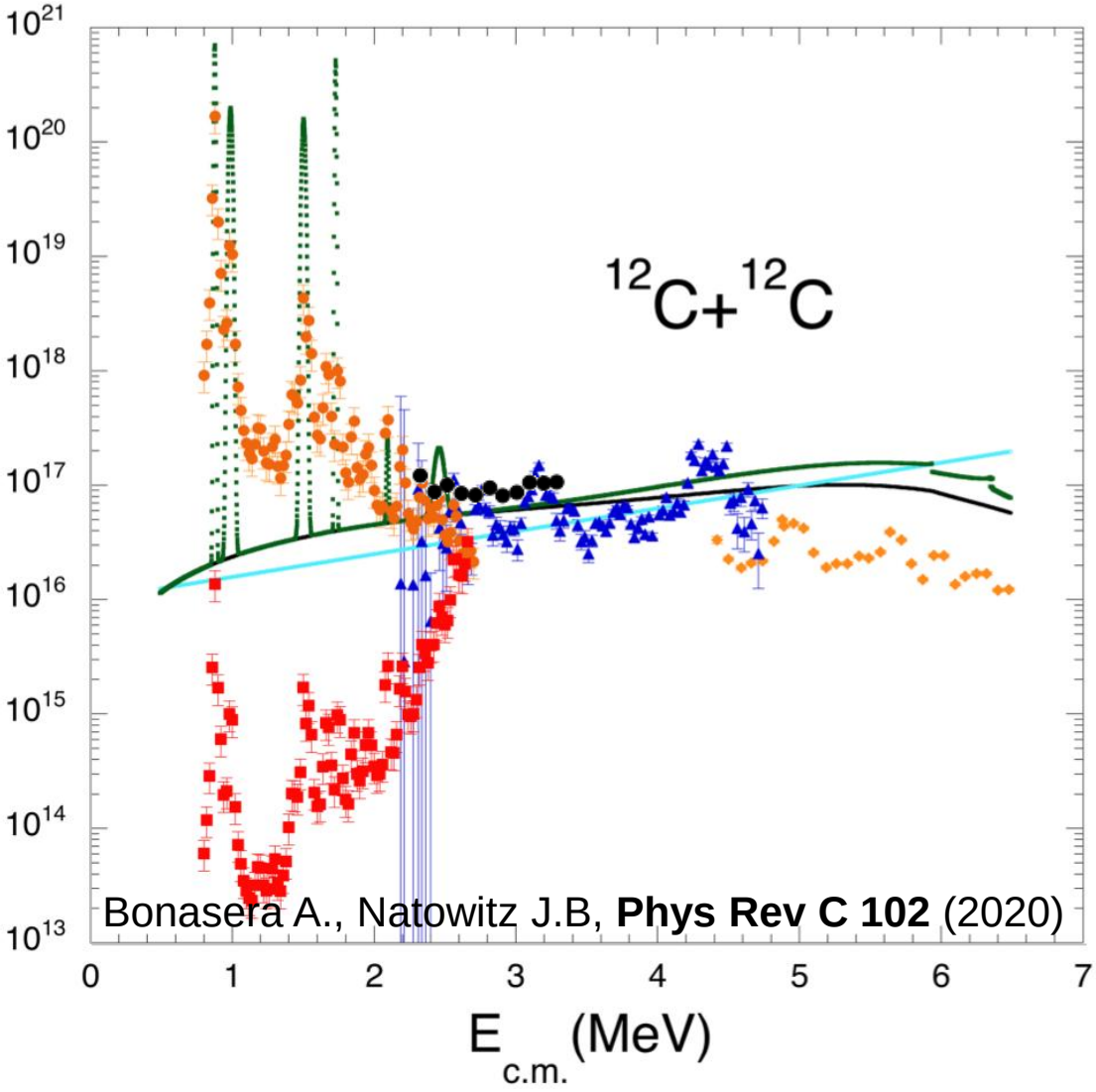


Beck et al, **Eur. Phys. J. A** (2020)

$^{12}C + ^{12}C$



Beck et al, **Eur. Phys. J. A** (2020)



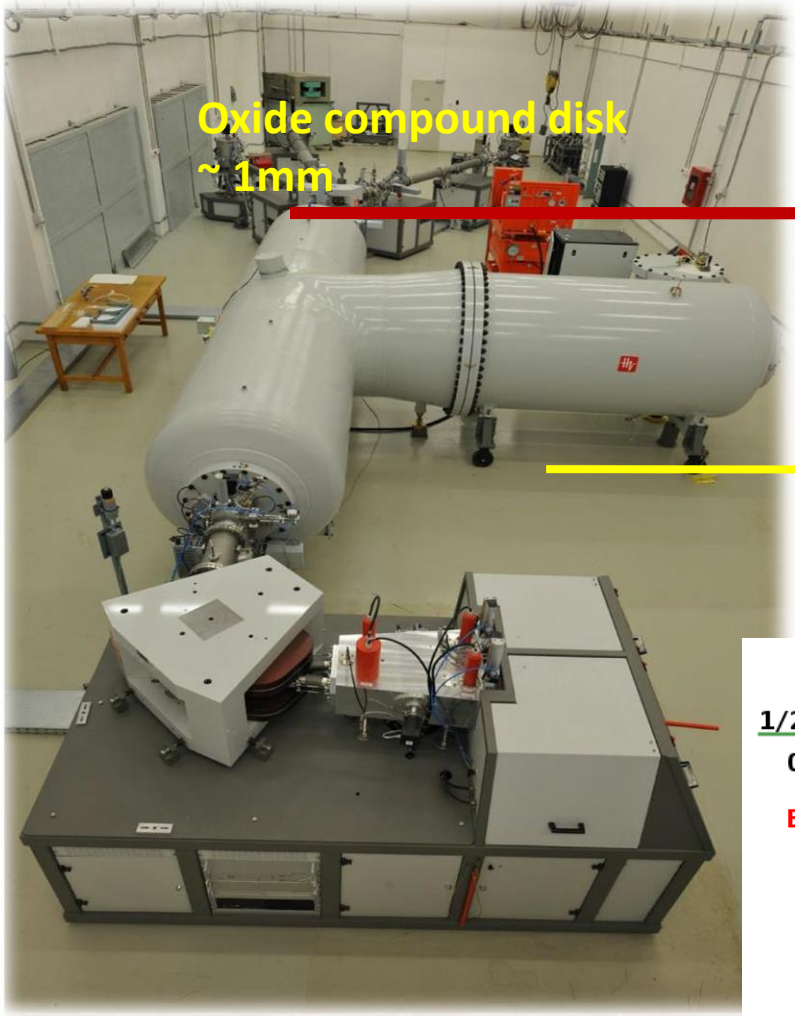
Bonasera A., Natowitz J.B, **Phys Rev C 102** (2020)

- Q: Can we extend this understanding by studying reaction mechanisms?
- Answer: Study other such reactions
- For example, $^{12}C + ^{16}O$ and $^{16}O + ^{16}O$
  - Along with their neighbors

- Fusion mechanism with $^{13}C + ^{16}O$ (or $^{12}C + ^{17}O$) using thick target activation method

The $^{13}C+^{16}O$ Reaction

In beam irradiation, thick targets



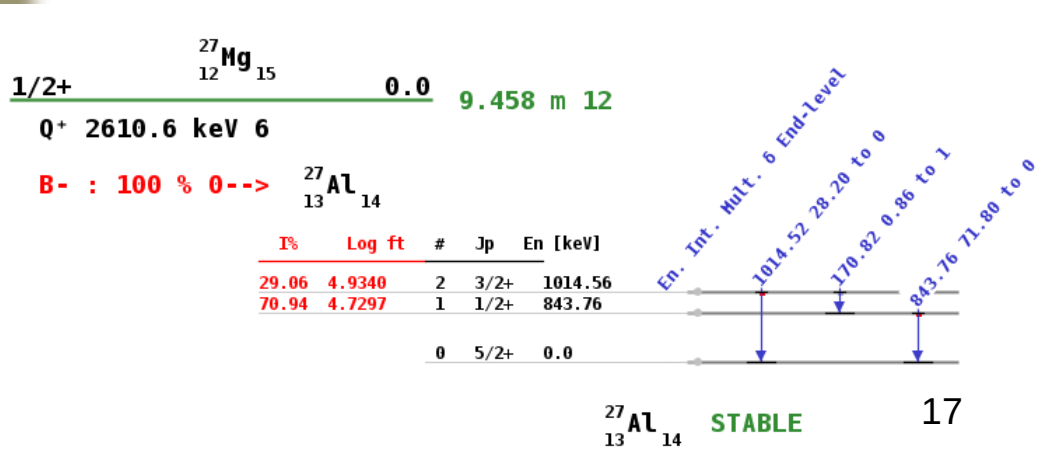
$^{16}O(^{13}C,2p)\,^{27}Mg$

$^{27}Mg: T_{1/2}$ =9.5 min

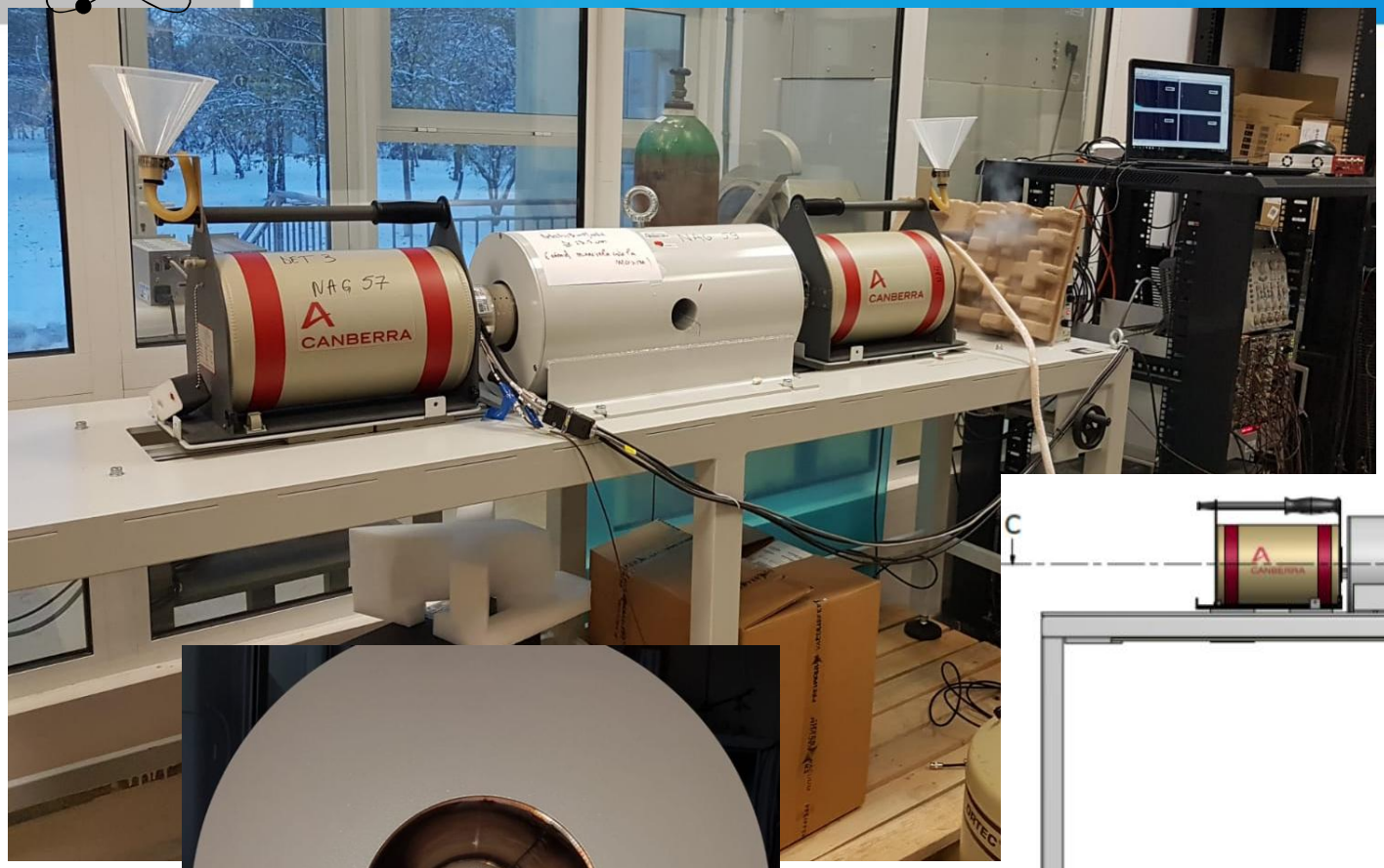
E_γ= 843.76 keV

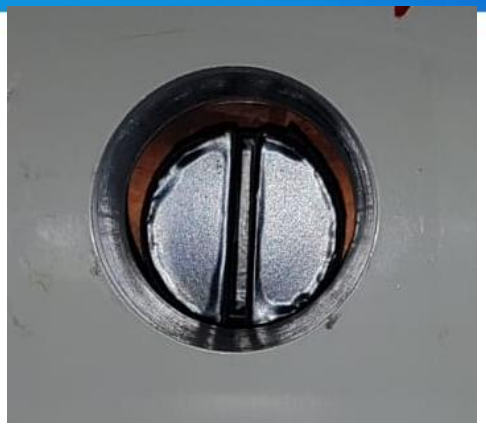
$^{13}C^{4+}$ beam @ 2-16 eμA

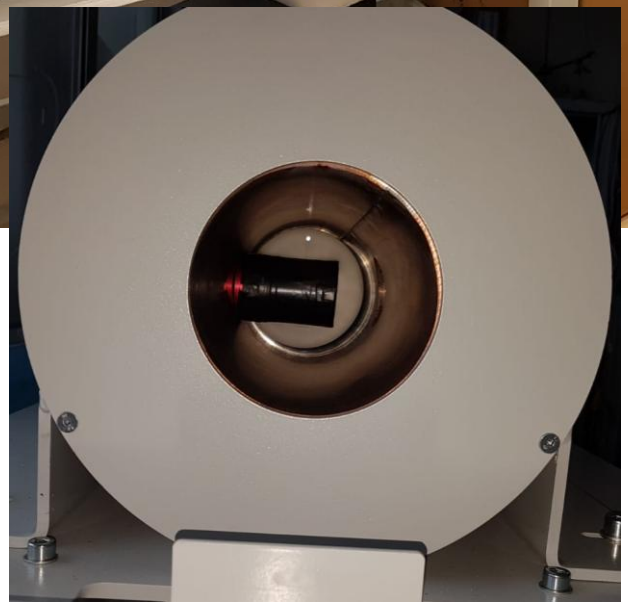
^{13}C beam energy 5 – 15. MeV

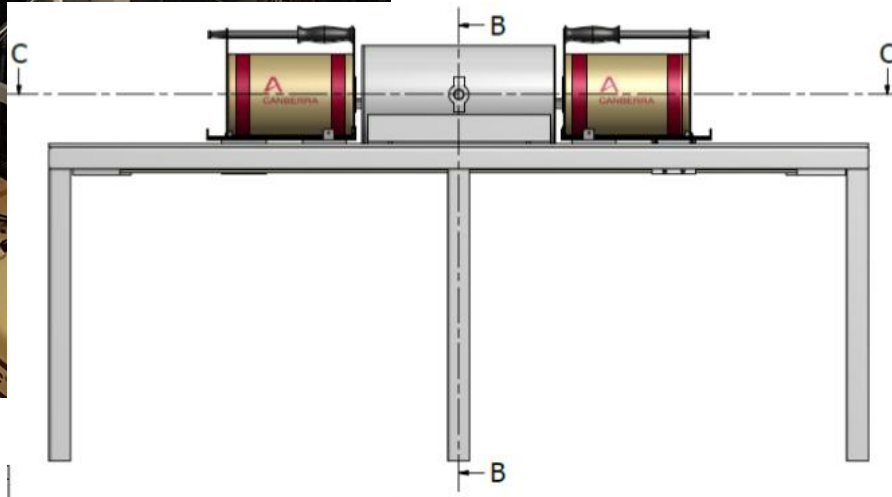


BeGa station (WIP)

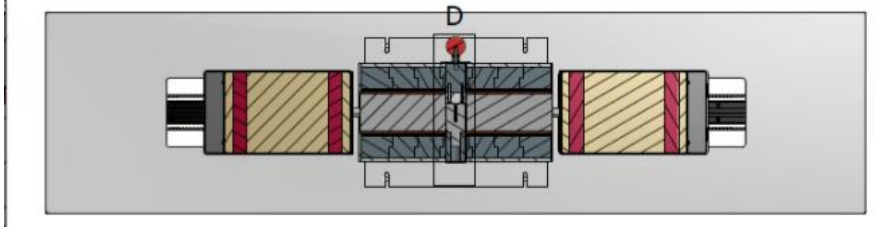








C-C (1 : 10)



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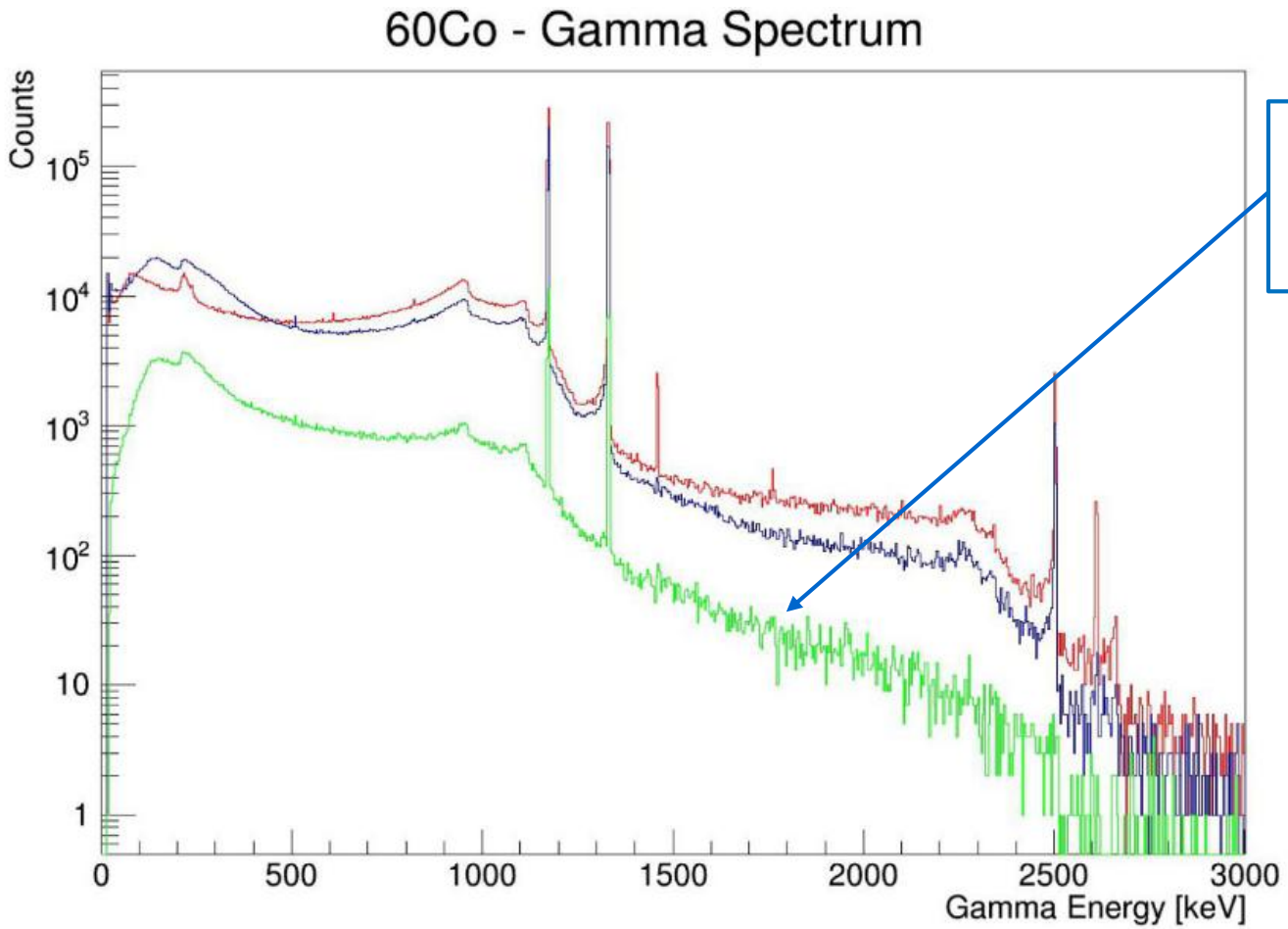
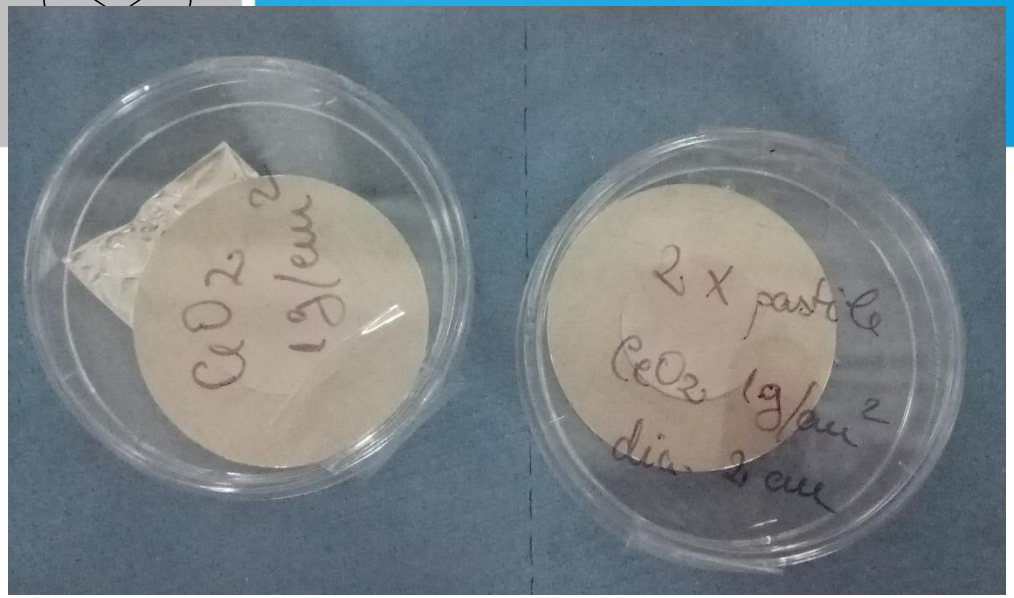


~ factor of 70 background reduction

Figure 5. ^{60}Co spectrum with detector unshielded (red line), shielded and with beta-gamma coincidence (blue and green lines).

Issues so far



Summary and future plans

- Thick target activation method + Salt mine/BEGA can be used to do measurements near the Gamow window
  - $^{13}C+^{16}O$ – experiment to be performed later this year
  - $^{13}C+^{19}F$ – experiment to be proposed at PAC for next year
- This study of ion-ion fusion reactions has been proposed and accepted to receive funding from the Romanian government through a Post-Doctoral grant (PD)
- The goal is to obtain experimental information about interaction mechanisms in light ion-ion fusion reactions
  - General effects
  - Nuclear structure effects: clusterization, deformations, level densities
  - At theory level: info on interaction potentials (OMP) for very low energies

Thank you!