STUDY OF ION-ION FUSION MECHANISMS AT SUB-BARRIER ENERGIES FOR NUCLEAR ASTROPHYSICS

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Nuclear astrophysics with direct and indirect methods at IFIN-HH

Activities and results of nuclear astrophysics research at IFIN-HH Bucharest-Magurele in the last few years. Mostly from the Nuclear Astrophysics Group (NAG), which continued the two basic types of experimental activities:

Direct measurements at low and very low energies with beams from the local *3 MV tandetron accelerator.*

Competitive for *measurements into the Gamow window* of reactions induced by light ions and alphas.

Extra sensitivity is provided by the *ultra-low background laboratory in a salt mine* and by BEGA.

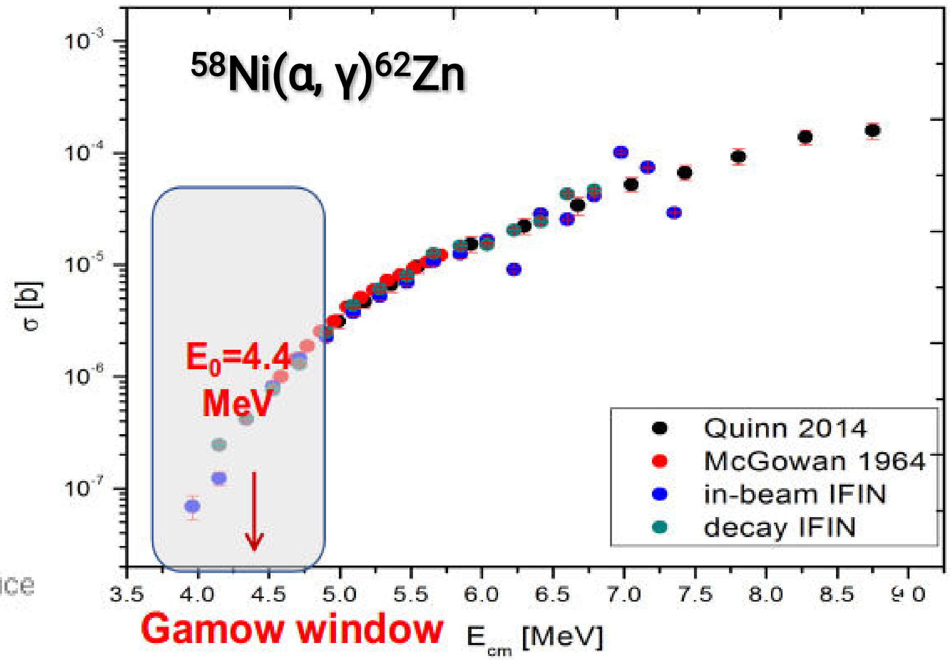
- Indirect measurements done with beams at *international facilities with radioactive beams*: TAMU, RIKEN

860A Sputter Source

$^{11}B^{3+}$	>50 eμA
$^{12}C^{3+}$	>80 eμA
$^{16}O^{3+}$	>80 eμA
$^{28}Si^{3+}$	>70 eμA
$^{31}P^{3+}$	>70 eμA
$^{58}Ni^{3+}$	>20 eμA
$^{63}Cu^{2+}$	>20 eμA
$^{75}As^{2+}$	>10 eμA
$^{197}Au^{2+}$	>80 eμA

Direct Measurements

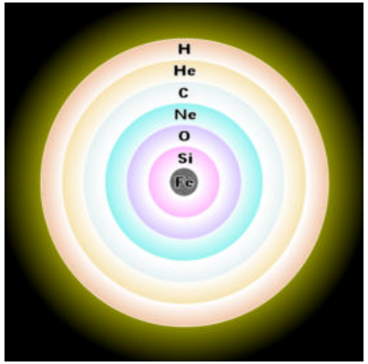
- Program-guided – *study of ion-ion fusion mechanism below Coulomb barrier*
  - aim for $^{12}C+^{12}C$, $^{12}C+^{16}O$, etc using reactions between nearby nuclei
  - $^{13}C+^{12}C$ for E_{cm}=2.2 – 5.6 MeV, Phys Let B 801 (2020), NIM A (2020)
  - $^{13}C+^{16}O$ et al. – in progress
  - Complementary to indirect studies (e.g. THM ...)
    - collab with Lanzhou, Catania
- "opportunistic" - cases of NA interest that can use the properties of the lab at the salt mine (= long $T_{1/2}$ >1-2 hrs. activities)
  - Ni + α, Zr + α



Motivation

In stellar nucleosynthesis, many of the important reactions involve the capture of very light particles: p, n, α.

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.

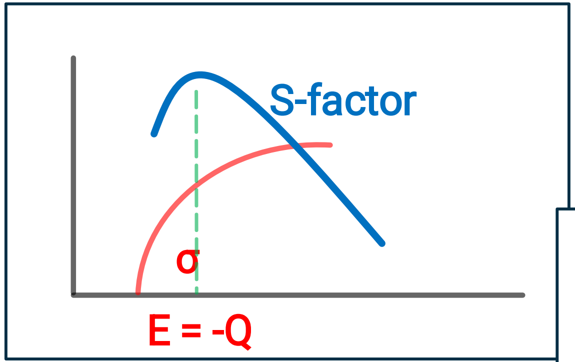
- this makes them difficult to study experimentally
- understanding the fusion mechanism at such energies becomes very important in order to correctly extrapolate at the low energies of interest

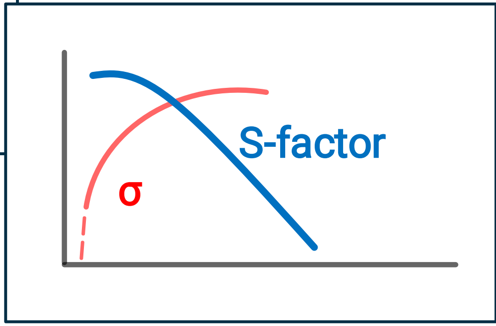
Ion-ion fusion near or below the Coulomb barrier

There are many models with different approaches (and variations...), among them:

- Time-dependent Hartree-Fock (TDHF)
  - no need to worry about which channels one should include because they are all automatically included at the mean field level
- Coupled-Channels (CC) - focuses on the influence on nuclear structure on heavy-ion fusion
  - different variations based on choice of ion-ion potential (WS, M3Y, M3Y-Repulsive, etc...)
- Hindrance - first reported in (2002) by Jiang
  - In medium-heavy mass systems, the fusion reaction
    - Q-value is always negative
  - Mathematically, S(E) must have a maximum

$$S(E) = E\sigma_{\text{fus}} \exp[2\pi(\eta - \eta_0)] \ \text{mb MeV.}$$



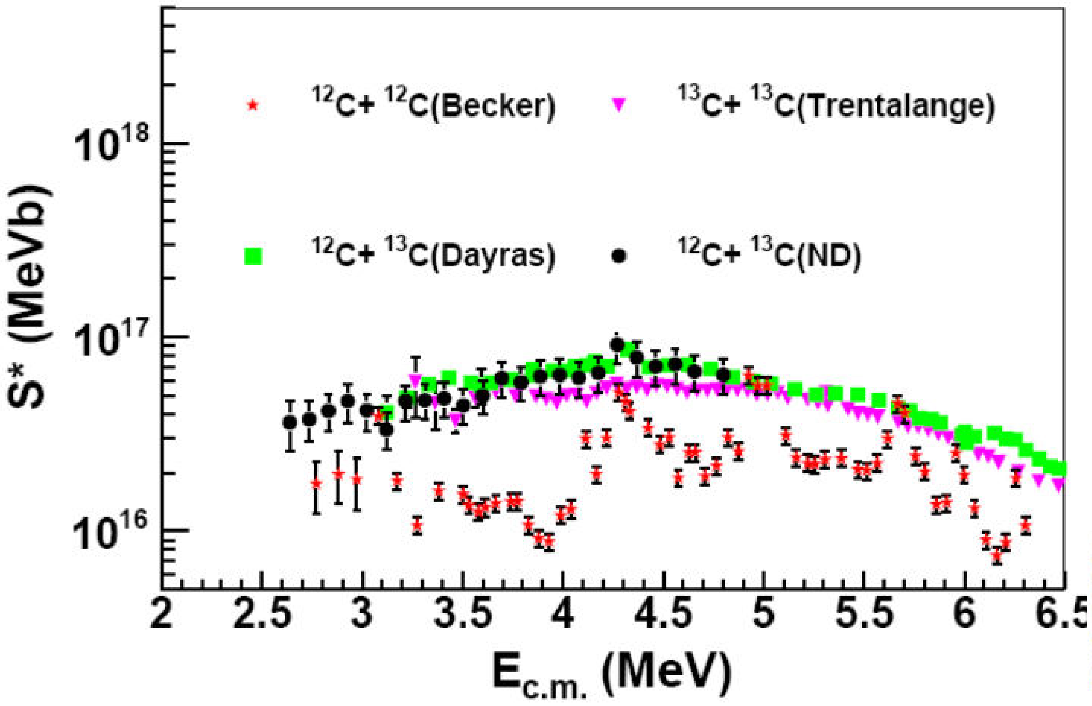


That's not the case for light-light and some light-medium systems, where the fusion Q-value > 0. There is no restriction on S(E) when E -> 0

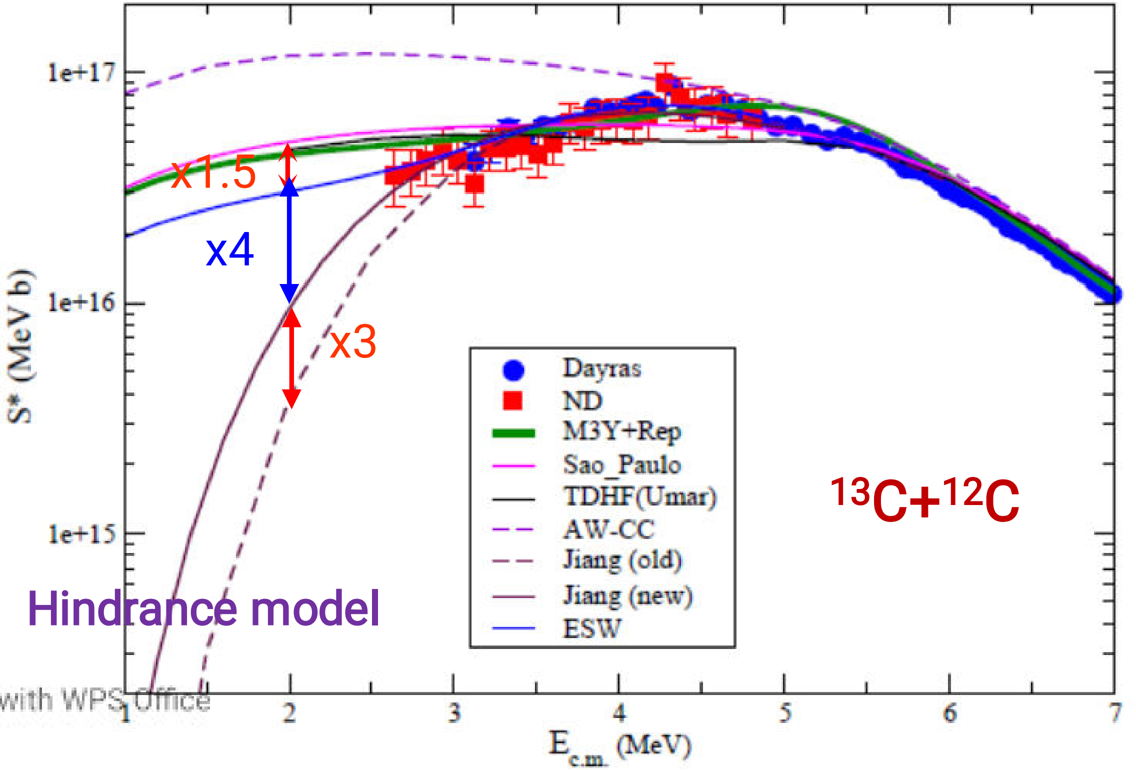
Other phenomena can have an influence too:

- Excitations of surface modes, barrier distribution, breakup reactions, transfer reactions, ...

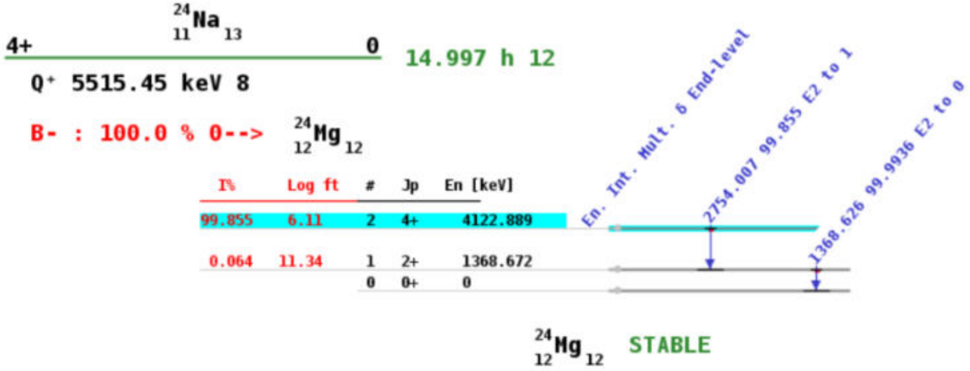
$^{12}C + ^{12}C$



Test of extrapolating models



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



24 Na 11 13
4+
0
14.997 h 12
Q+ 5515.45 keV 8
B- : 100.0 % 0-->
24 Mg 12 12
I% Log ft # Jp En [keV]
99.855 6.11 2 4+ 4122.889
0.064 11.34 1 2+ 1368.672
0 0+ 0
En. Int. Mult. & End-level
2754.007 99.855 E2 to 1
1368.626 99.9936 E2 to 0
24 Mg 12 12 STABLE

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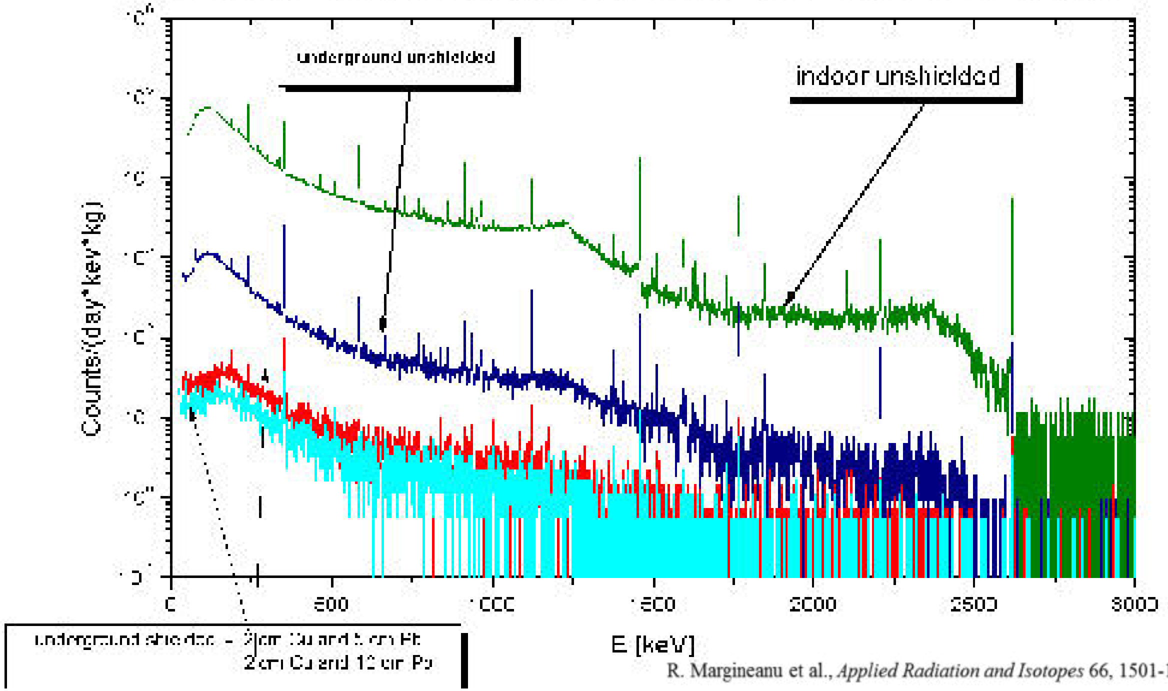
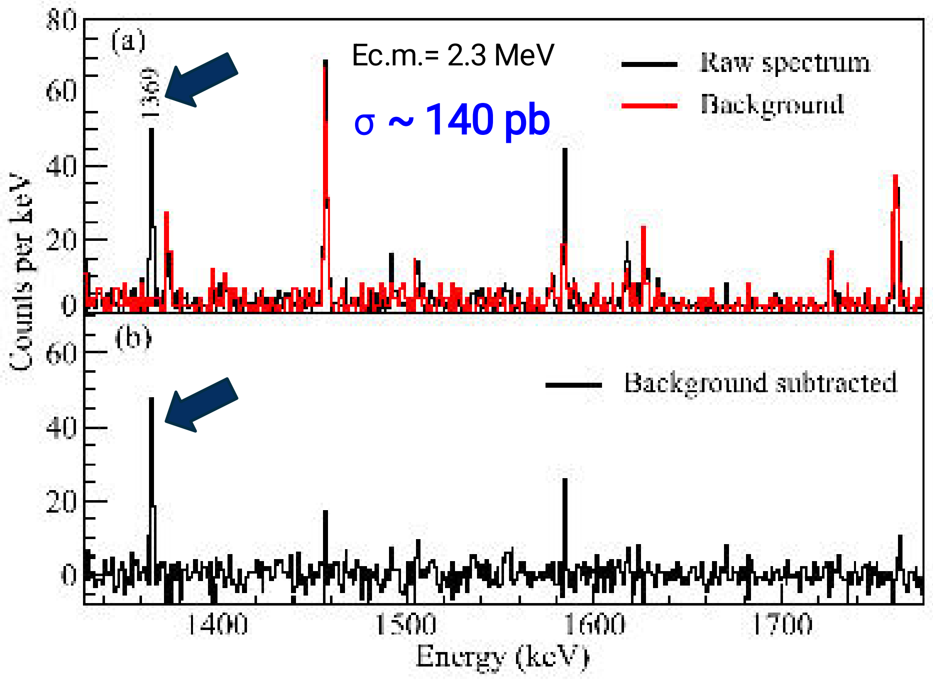
Ultra low background (μBq) laboratory at Slanic Salt Mine

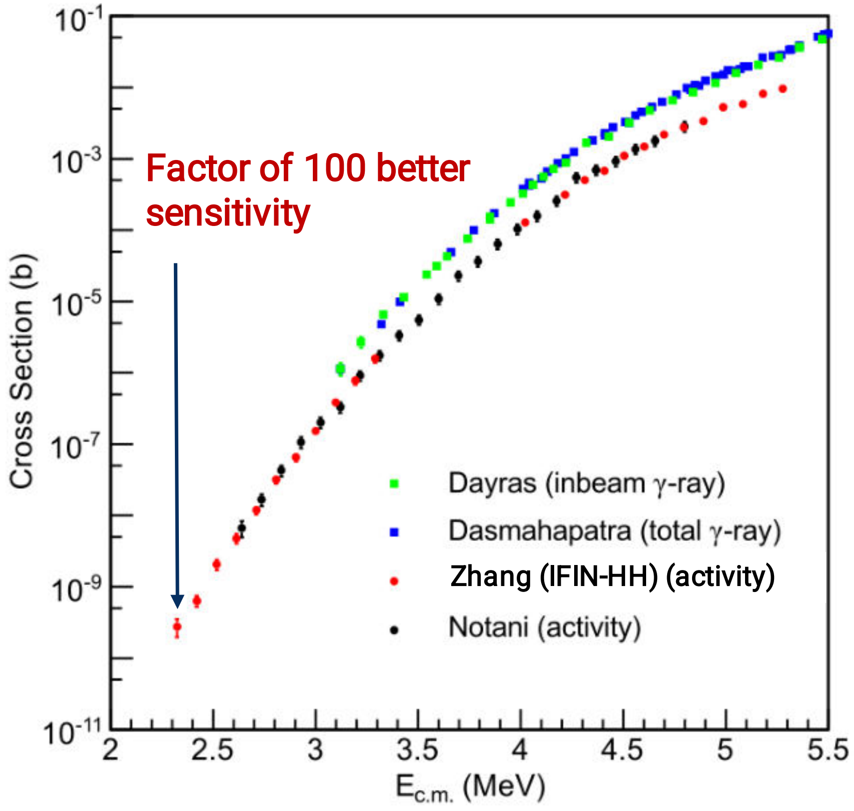
Background spectra collected with a CANBERRA GeHP detector



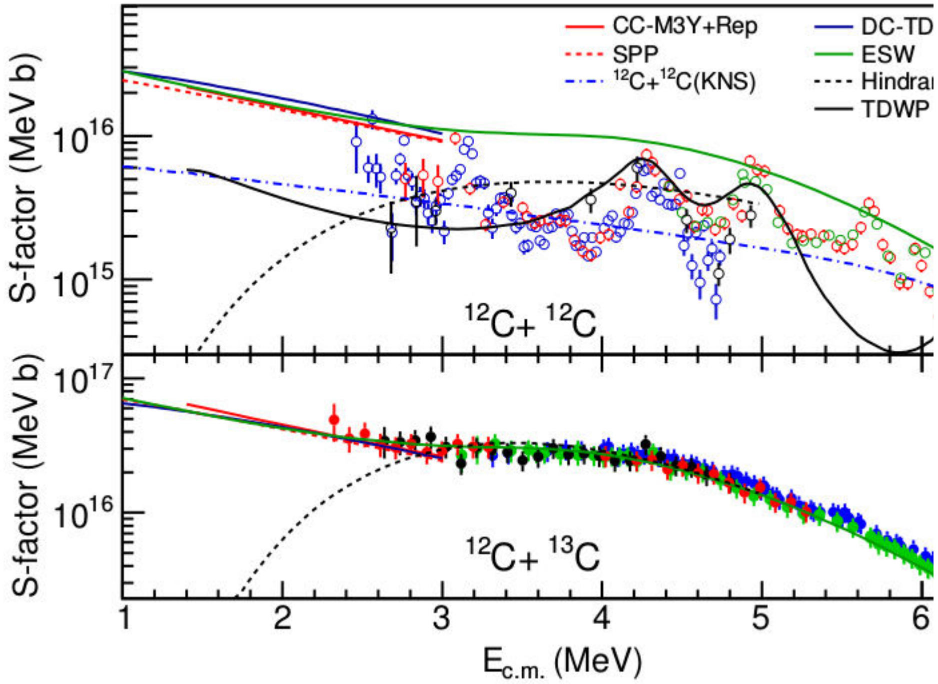
R. Margineanu et al., *Applied Radiation and Isotopes* 66, 1501-1506, 2008

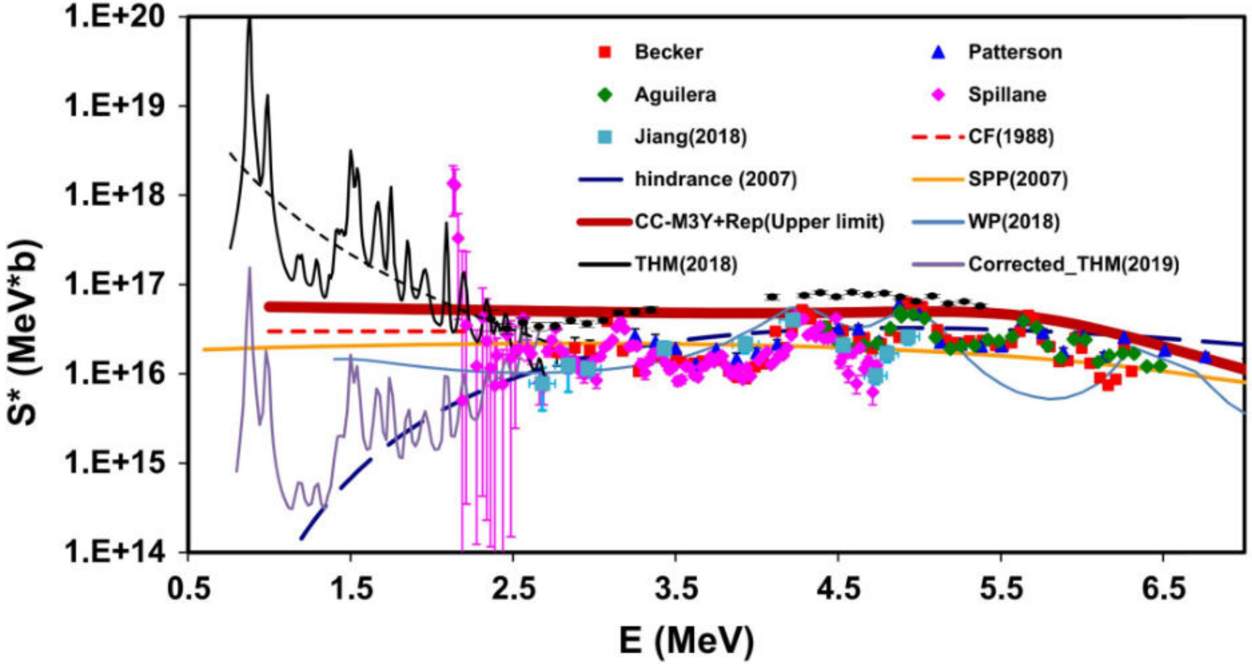
$^{12}C + ^{12}C$ - Results





$^{12}C + ^{12}C$ - Results





Extend study: approach used

- Direct measurements C+C, C+O, O+O extremely difficult or impossible to perform because the cross sections are very small
- Activation is most sensitive method, but all reactions lead to stable residuals
- Approach: study of nearby ion-ion fusion reaction mechanisms at sub-barrier energies
  - Worked for $^{12}C+^{12}C$, using $^{13}C+^{12}C$ down into Gamow window – avoids resonances
  - Similarly, study $^{12}C+^{16}O$ and $^{16}O+^{16}O$, using reactions involving their neighbors
- Fusion mechanism for $^{13}C+^{16}O$, $^{12,13}C+^{19}F$, ... using target activation method
  - Cannot go to salt mine, lifetimes too short, improve bkg reduction at home: BEGA
  - O targets: use oxides of heavy elements as targets (CeO_2, Ta_2O_5, WO_3)

The $^{12}C+^{16}O$ Reaction

X. Fang et al, PHYSICAL REVIEW C 96, 045804 (2017)

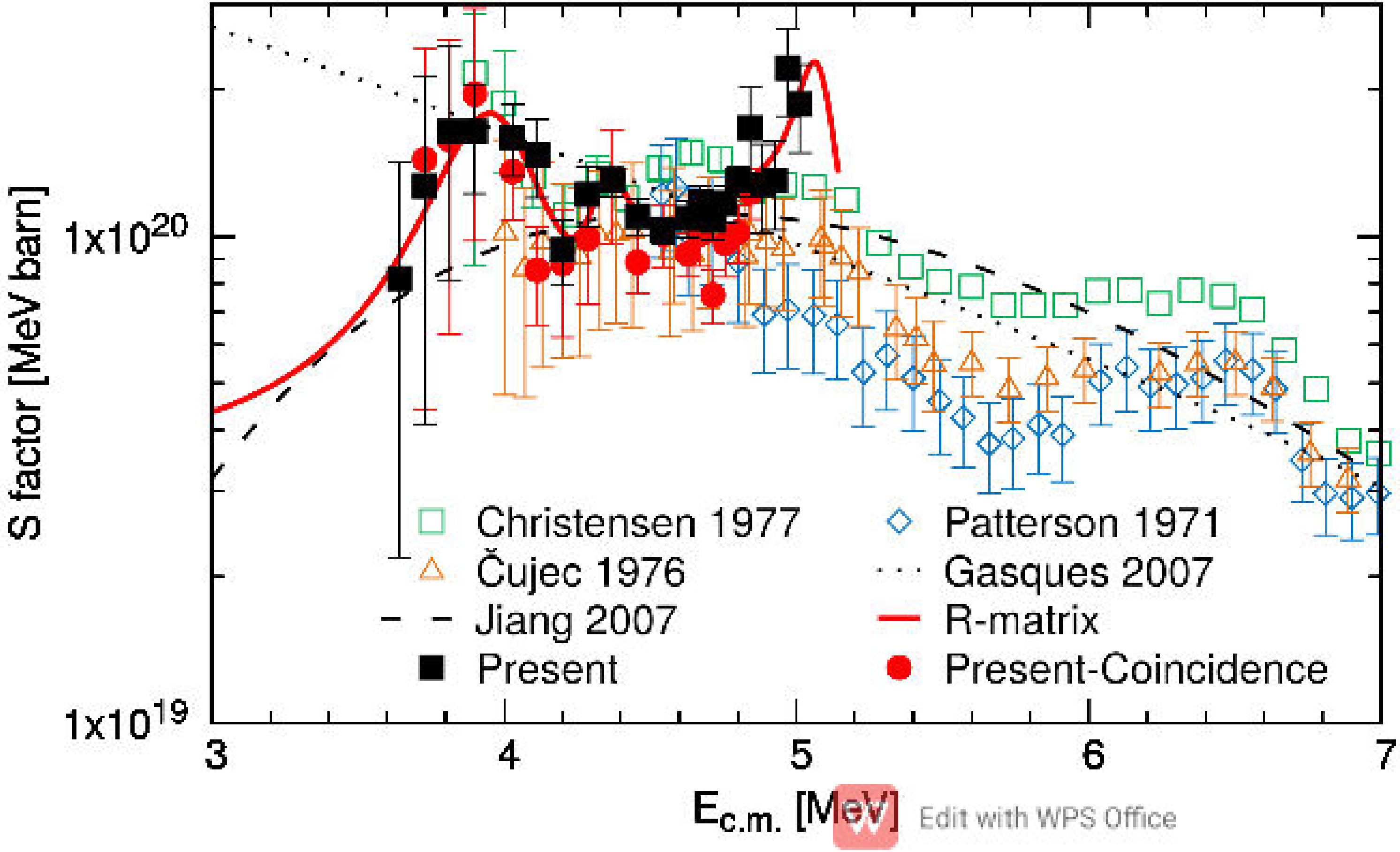
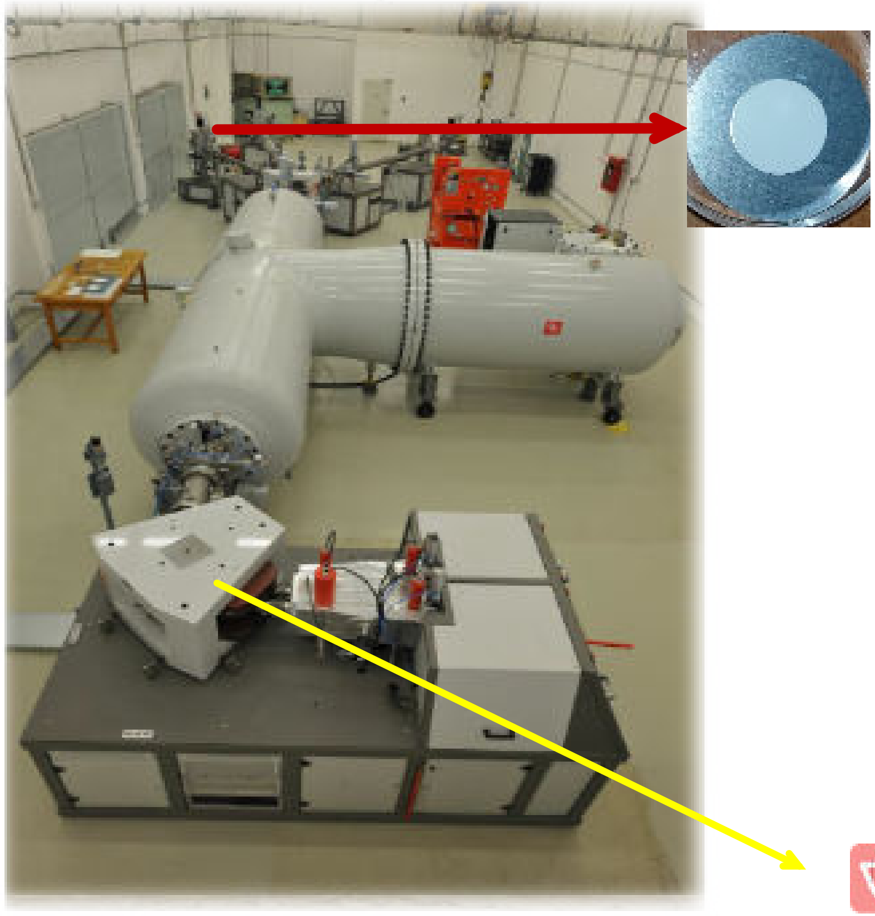
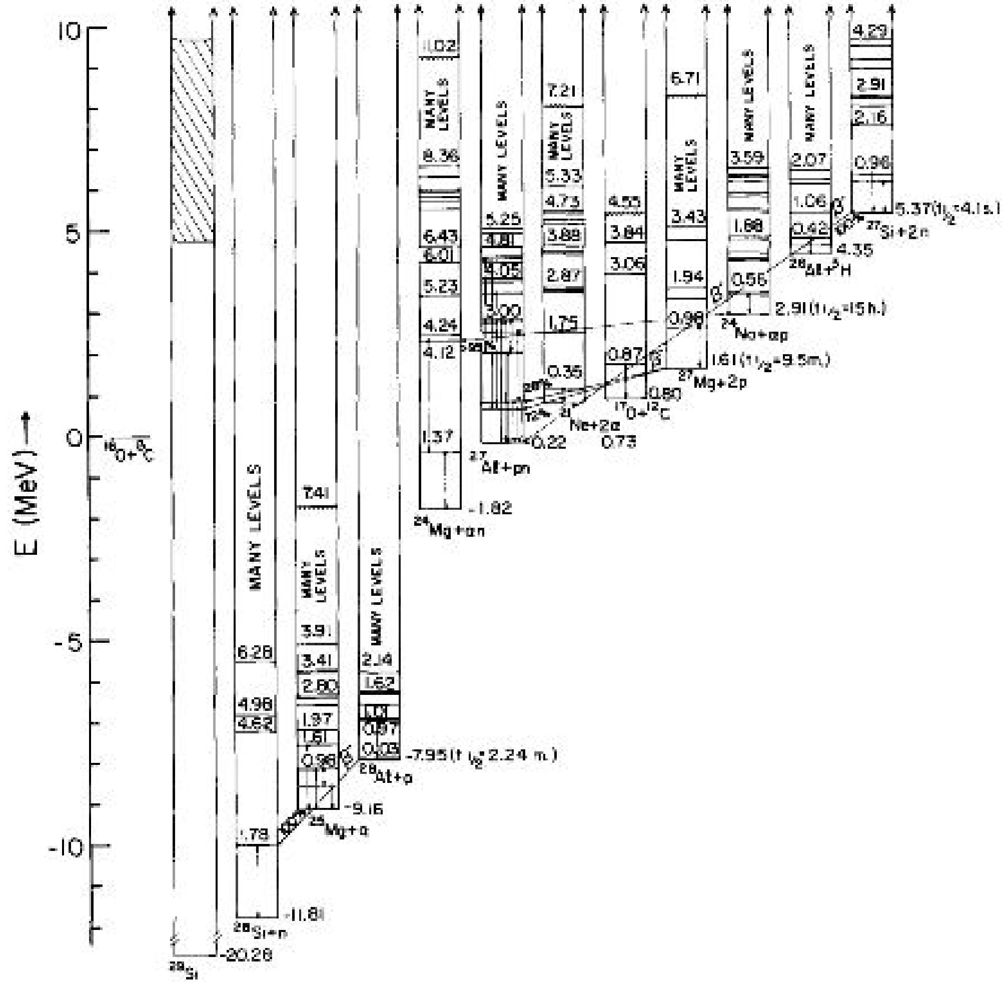


FIG. 13. The $S(E)$ factor of $^{12}C + ^{16}O$ fusion. In addition to the data of the present work (solid symbols) also previous data (open symbols) from the literature [15–17] are shown. Patterson's data [17] does not include the n channel. The dotted line denotes the calculations using the Sao Paulo potential [2,41]. The hindrance model fit [7] with all the data points is presented as the dashed line. An R-matrix calculation (solid line) based on the analysis of the proton channel is shown as well.

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

In beam irradiation, thick targets (CeO2 disk ~ 1 mm)





6 pμA and energy @ 7.6 – 15.6 MeV (Lab)

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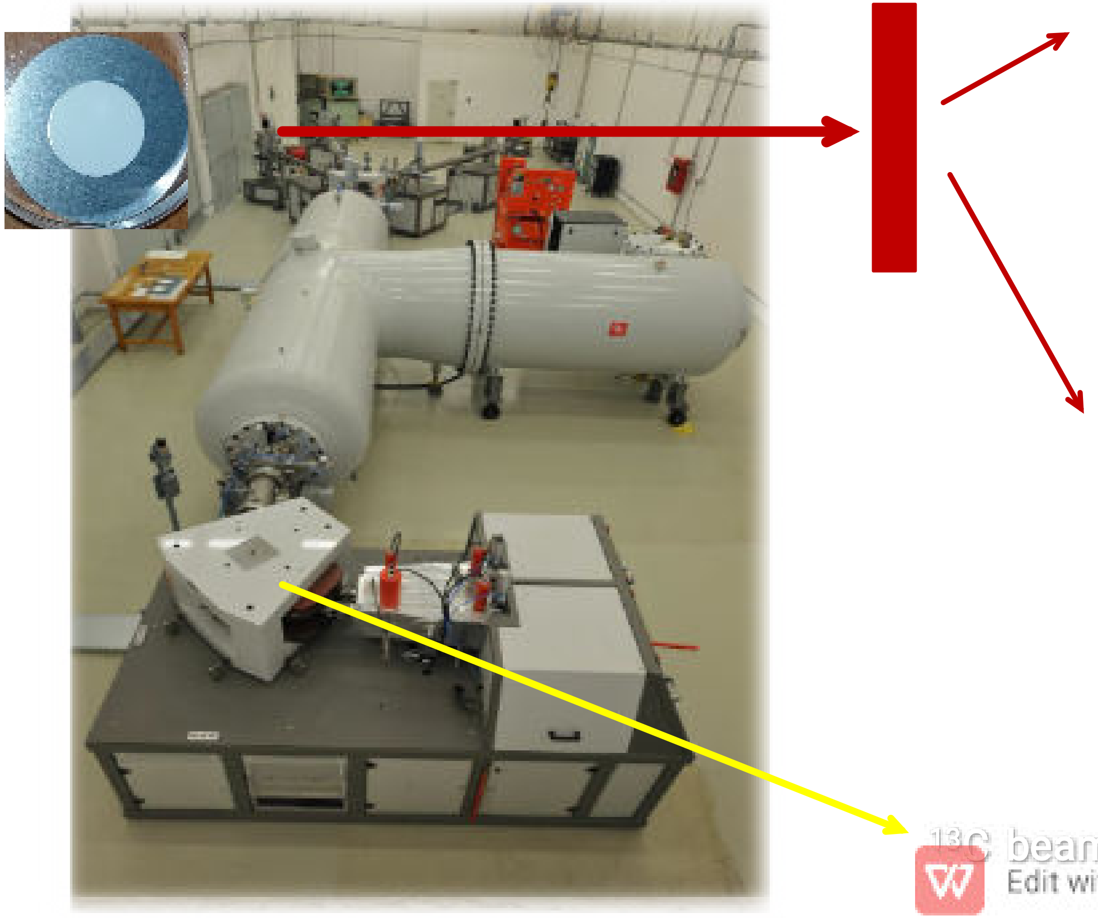
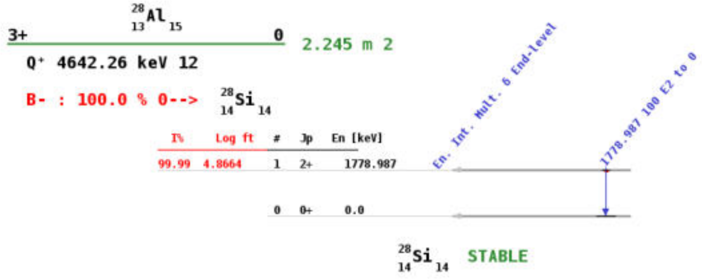
The $^{13}C+^{16}O$ Reaction - Activation

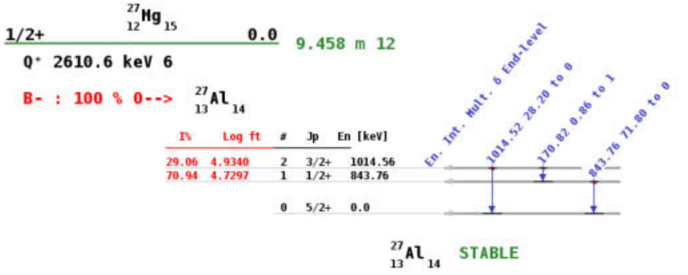
In beam irradiation, thick targets (CeO_2 disk ~ 1 mm)



$T_{1/2}$ = 2.25 min



$T_{1/2}$ =9.5 min

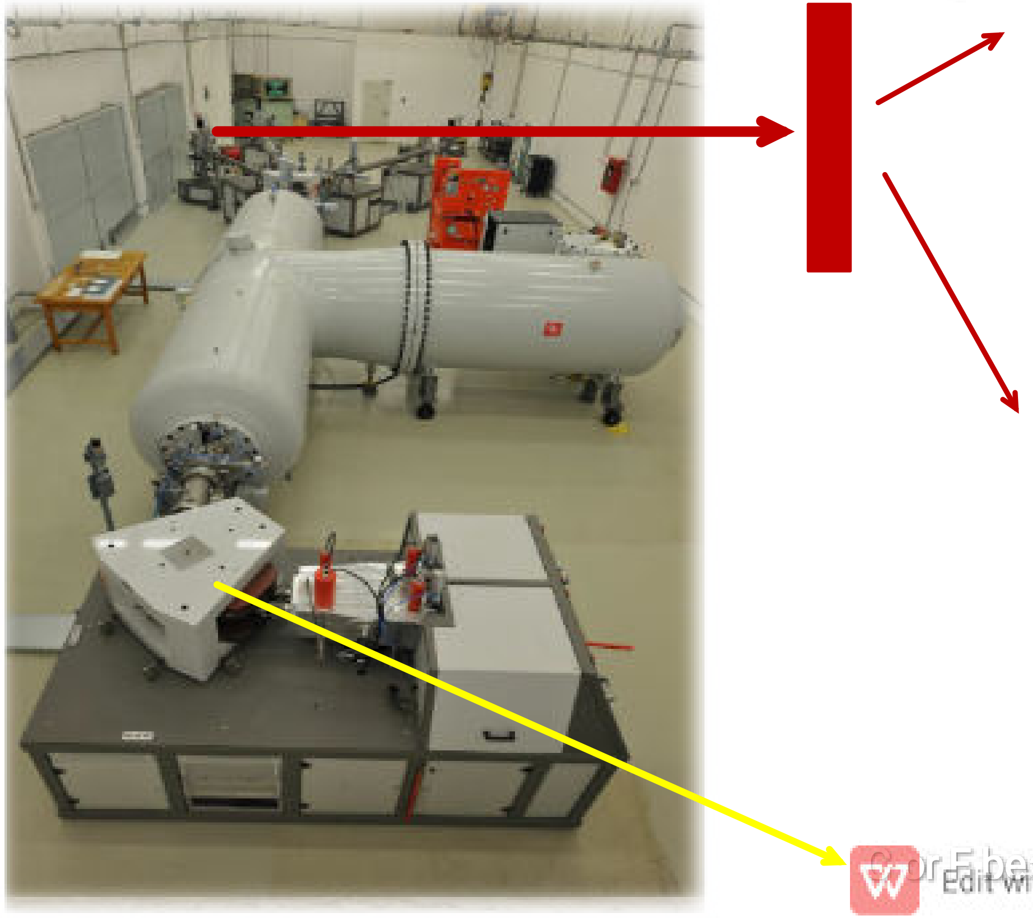


^{13}C beam @ 0.2 - 6 pμA and energy @ 7.6 – 15.6 MeV (Lab)

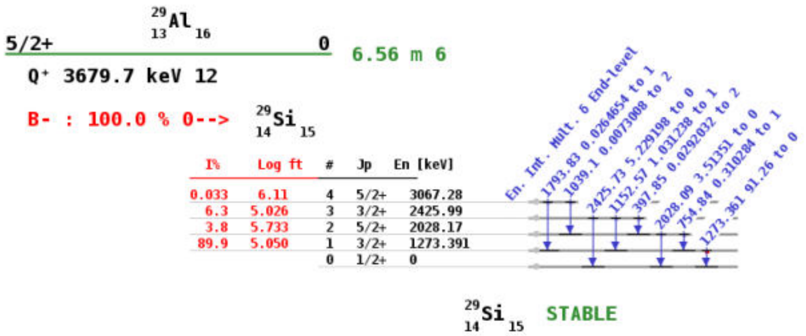
The $^{19}F+^{12,13}C$ Reaction

*Collaboration with L. Guardo, R. Sparta et al @ INFN-LNS, through ChETEC-INFRA TNA

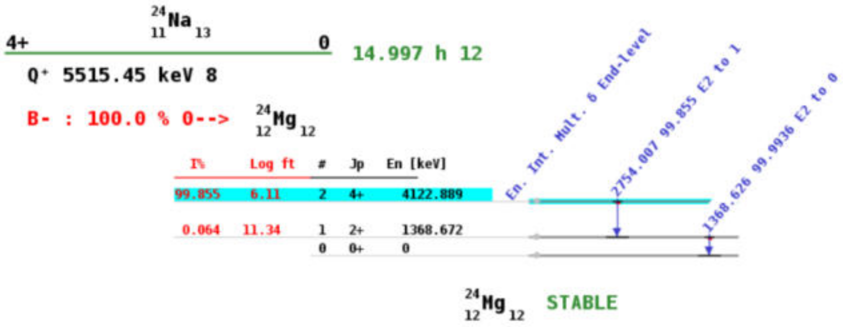
In beam irradiation of thick targets followed by deactivation measurements



$T_{1/2}$ = 6.5 min



$T_{1/2}$ = 15 hrs



C or F beam @ 12 - 25 MeV and 0.2 – 20 µA

FUTURE PLANS

Thick target activation method + Salt mine/BEGA can be used to reach the Gamow window

ACKNOWLEDGMENTS AND THANKS

THANK YOU!