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

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Key Reactions in Nuclear Astrophysics (KRINA) 2025, Trento, 17-21 February 2025

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 mechanisms 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

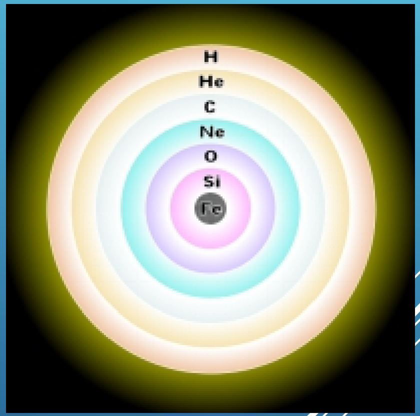
use the properties of the lab at the salt mine

(= long $T_{1/2}$ >1-2 hrs. activities)

  - Ni + α, Zn + α

Motivation

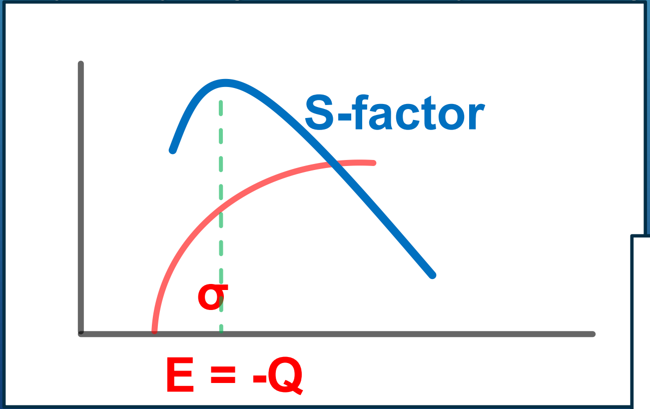
- In stellar nucleosynthesis, many of the important reactions involve the capture of very light particles: p, n, α.
- There are also a few crucial reactions between light ions
- heavier than ^{4}He, among them those involving ^{12}C and ^{16}O.
- Such reactions occur at very low energies, well below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

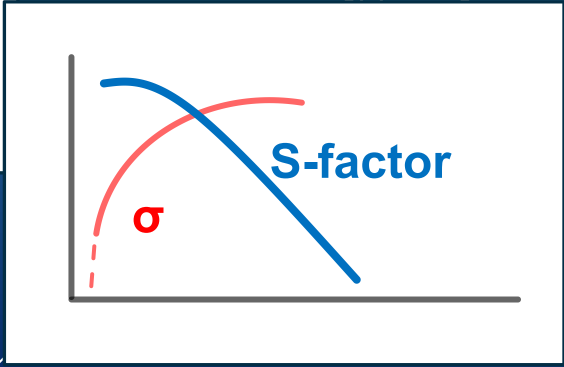


Ion-ion fusion near or below the Coulomb barrier

- 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, Akyüz-Winther, M3Y-Repulsion, 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, ...

The Hindrance Model - overview

- Hindrance effects first reported in (2002) by Jiang
- More experiments were done on fusion in medium-heavy systems
  - low-energy hindrance is a general phenomenon of heavy-ion fusion
  - but, shows up with varying intensities and distinct features in different systems
  - in most medium-heavy systems, the S-factor shows a clear maximum and then drops sharply at lower energies

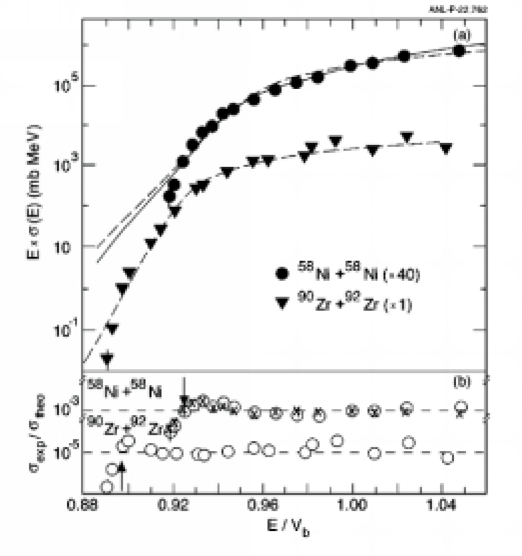
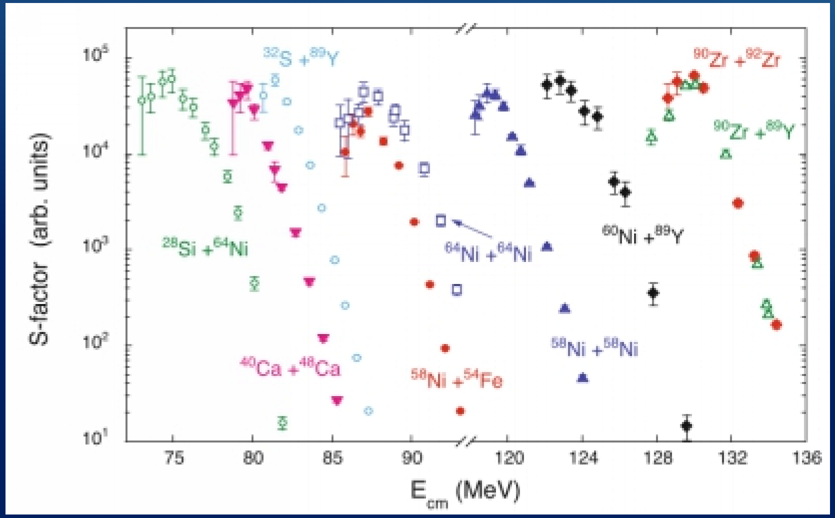
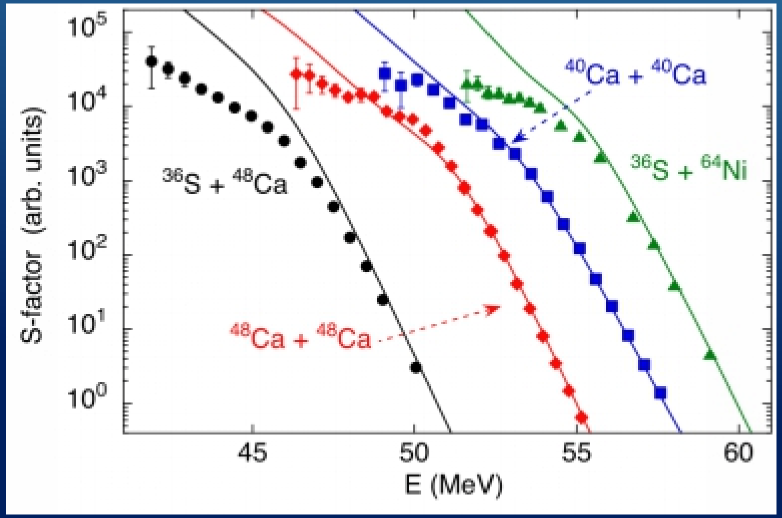
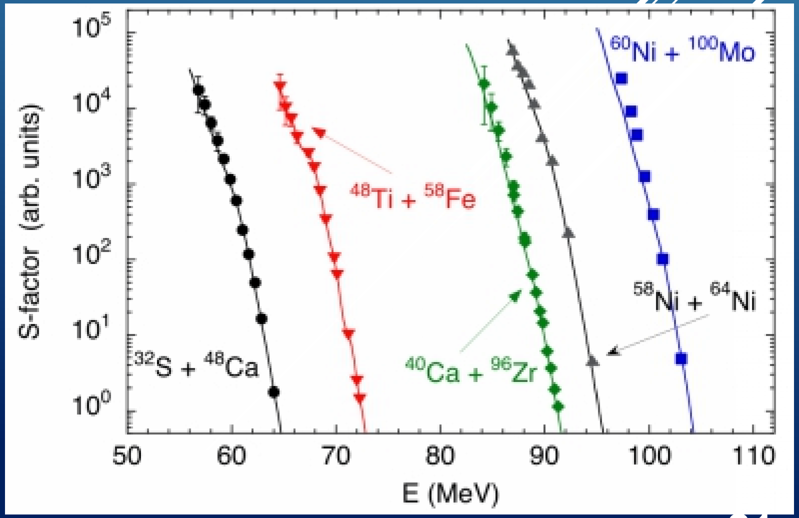


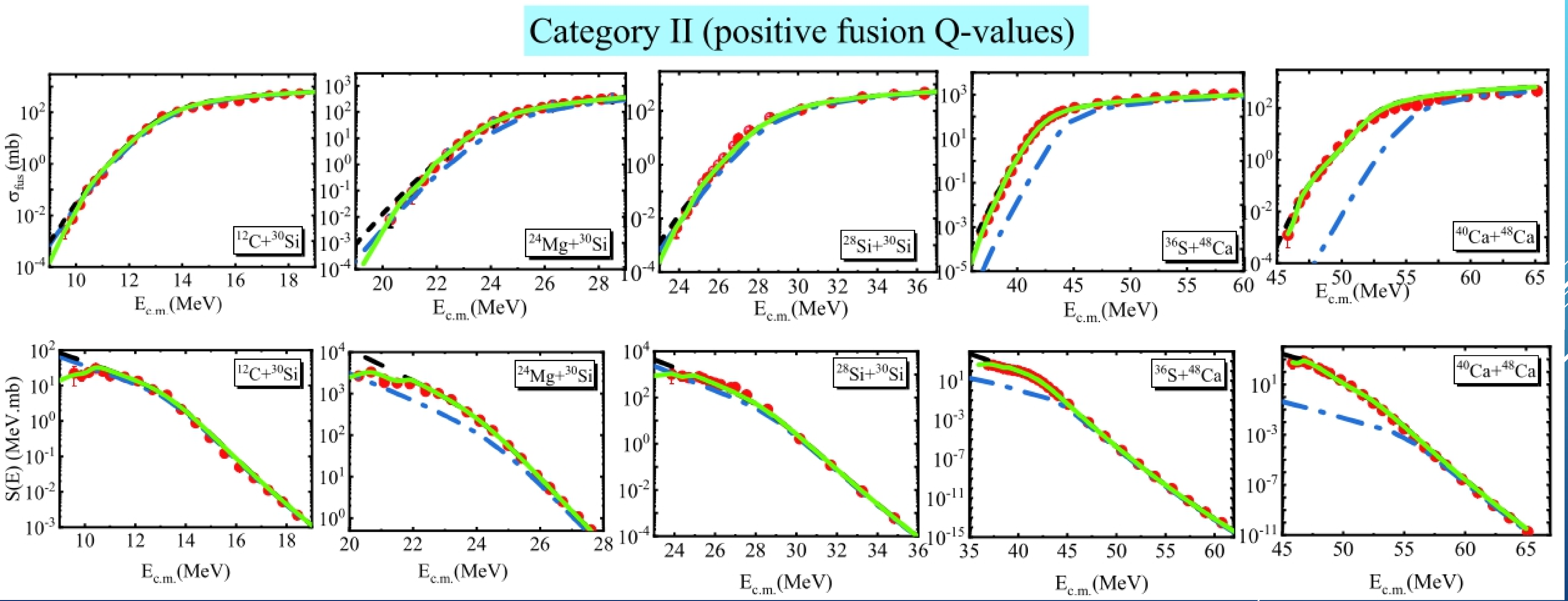
FIG. 1. (a) Plots of σE versus E/V_b for the systems $^{58}Ni + ^{58}Ni$ and $^{90}Zr + ^{92}Zr$. The lines are the results of either coupled-channels calculations (solid) or a phenomenological description with the Wong formula (dashed). See text for details. (b) $\sigma_{exp}/\sigma_{theo}$ vs E/V_b: circles: σ_{theo} calculated using the Wong formula; crosses: σ_{theo} calculated within the coupled-channels formalism.







The Hindrance Model - light-medium systems



Gharaei et al, Chin. Phys. C 45 (2021)

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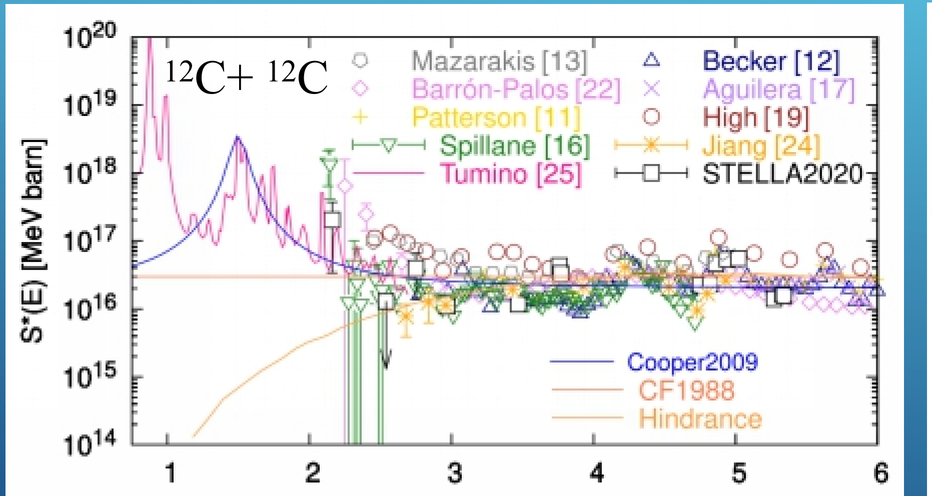
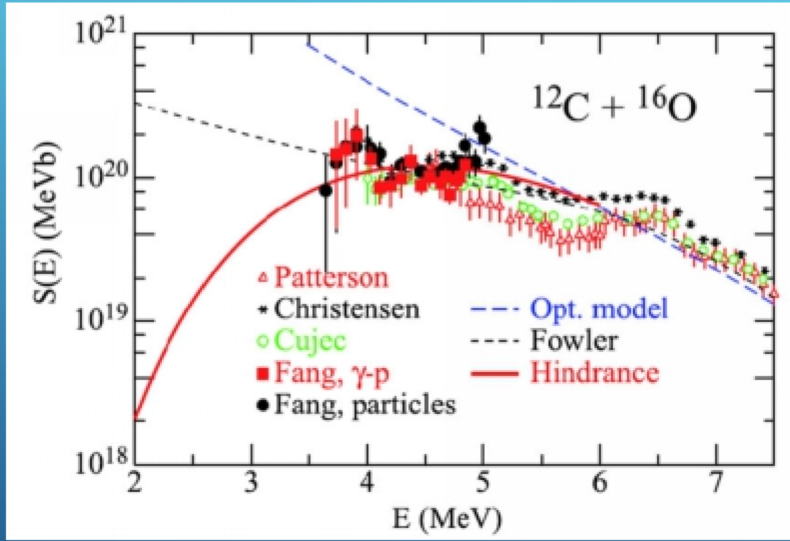
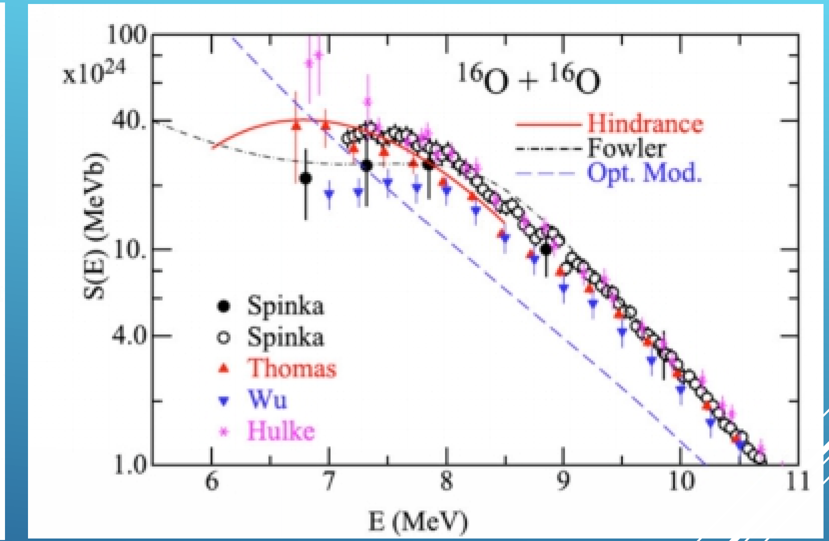
Fusion in light-light systems - current status

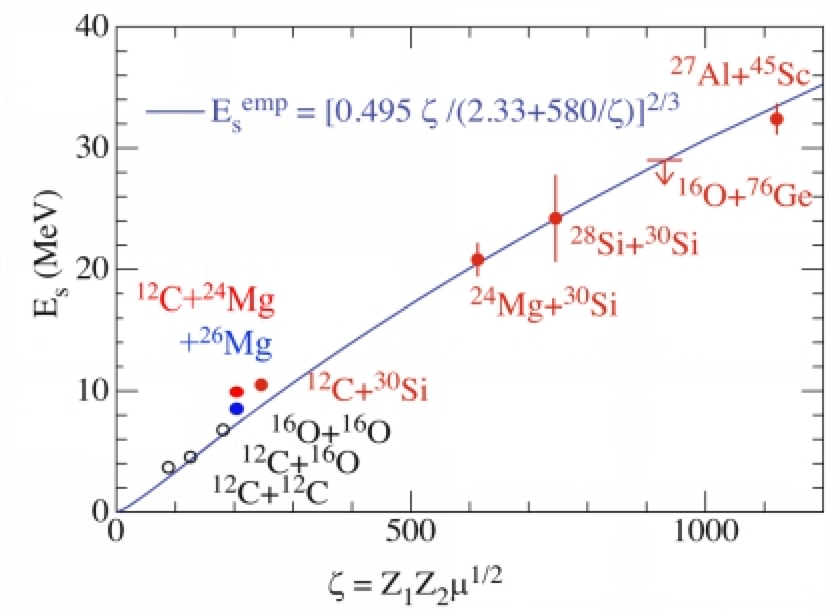


Tan et al, PRC 110 (2024)





Montagnoli et al, EPJA 59 (2023)



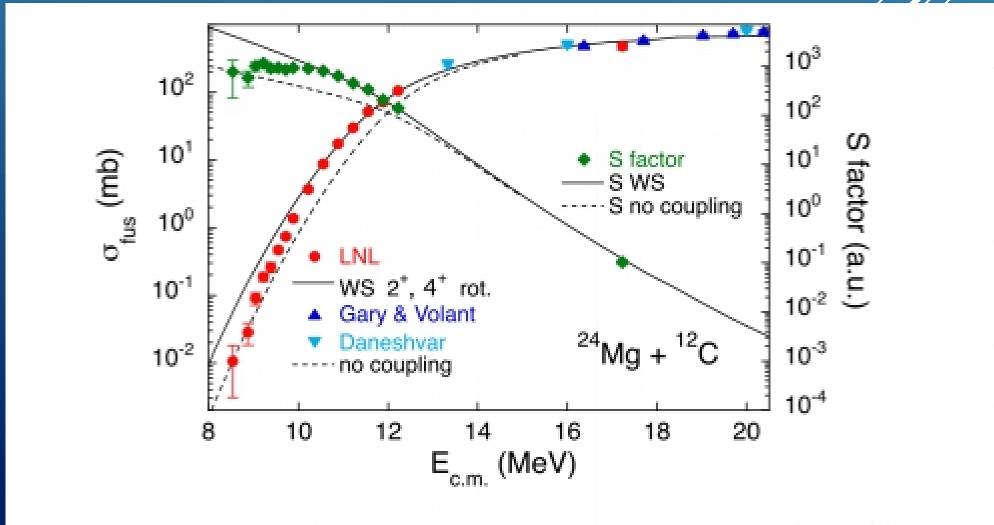


Fig. 46 Excitation function and *S*-factor for the system $^{12}C + ^{24}Mg$, compared with standard CC calculations. Figure taken from Ref.

The $^{12}C + ^{12}C$ debate

- The rate of the ^{12}C + ^{12}C fusion reaction is presently one of the most sought-after reaction rates in the study of nuclear astrophysics.
- Plays a very important role in many different stellar environments:
  - hydrostatic carbon burning in massive stars
  - type Ia thermonuclear supernovas driven by explosive fusion near the core of the white dwarf star in accreting or merging binary systems
  - x-ray superbursts thought to be ignited by the carbon fusion reactions in the burning ashes of accumulated hydrogen and helium on the surface of accreting neutron stars

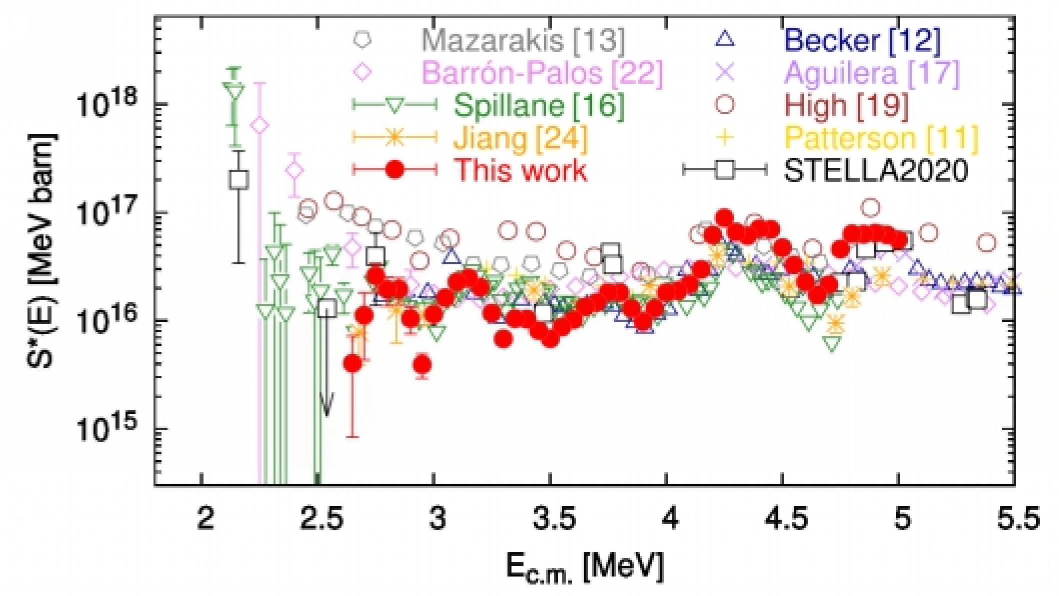


FIG. 10. The total $S^*(E)$ factor for this paper is shown and compared with previous direct measurement data [11–13,16,17,19,22,24,26].

Tan et al, PRC 110 (2024)

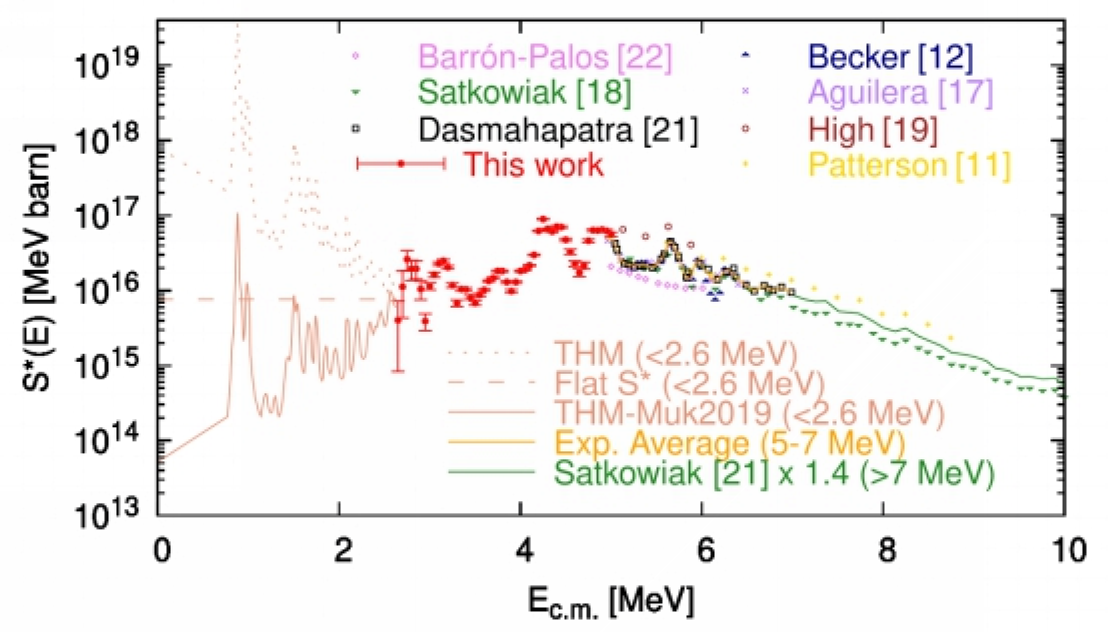
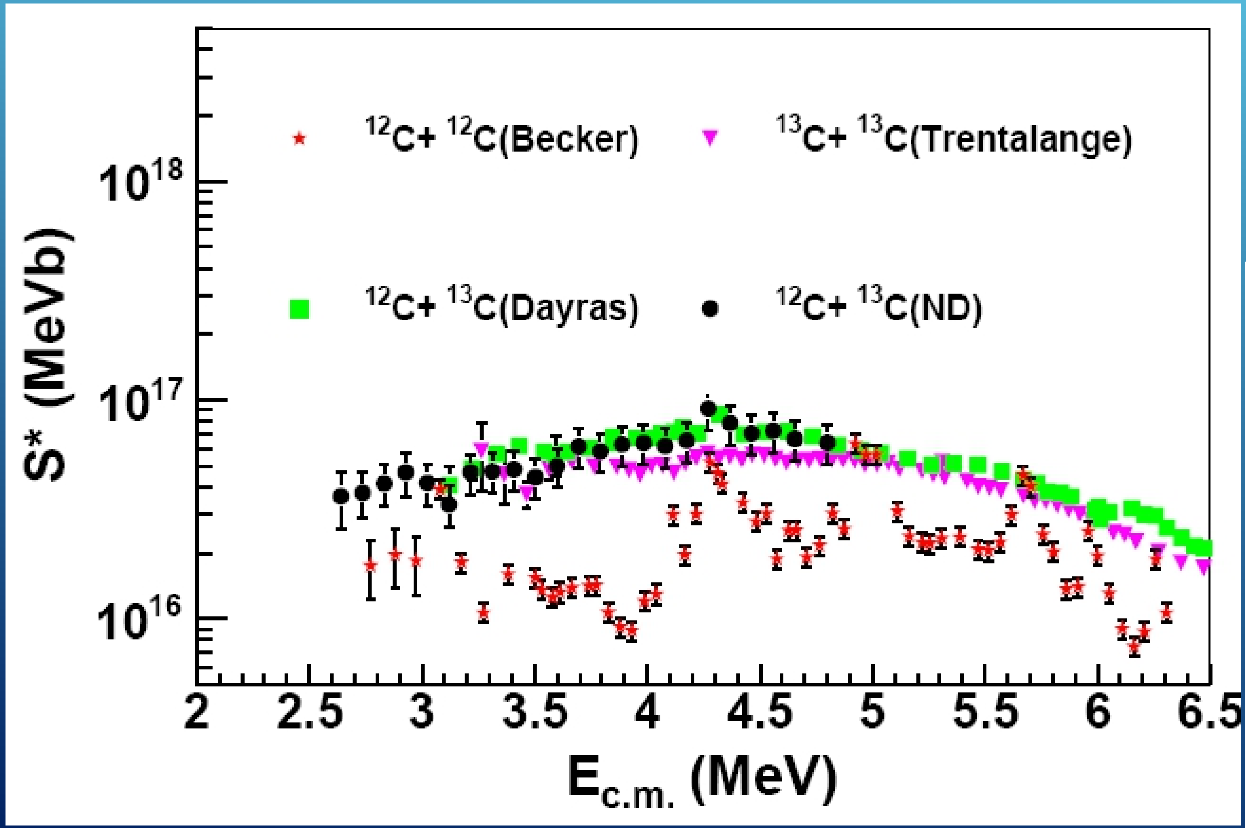
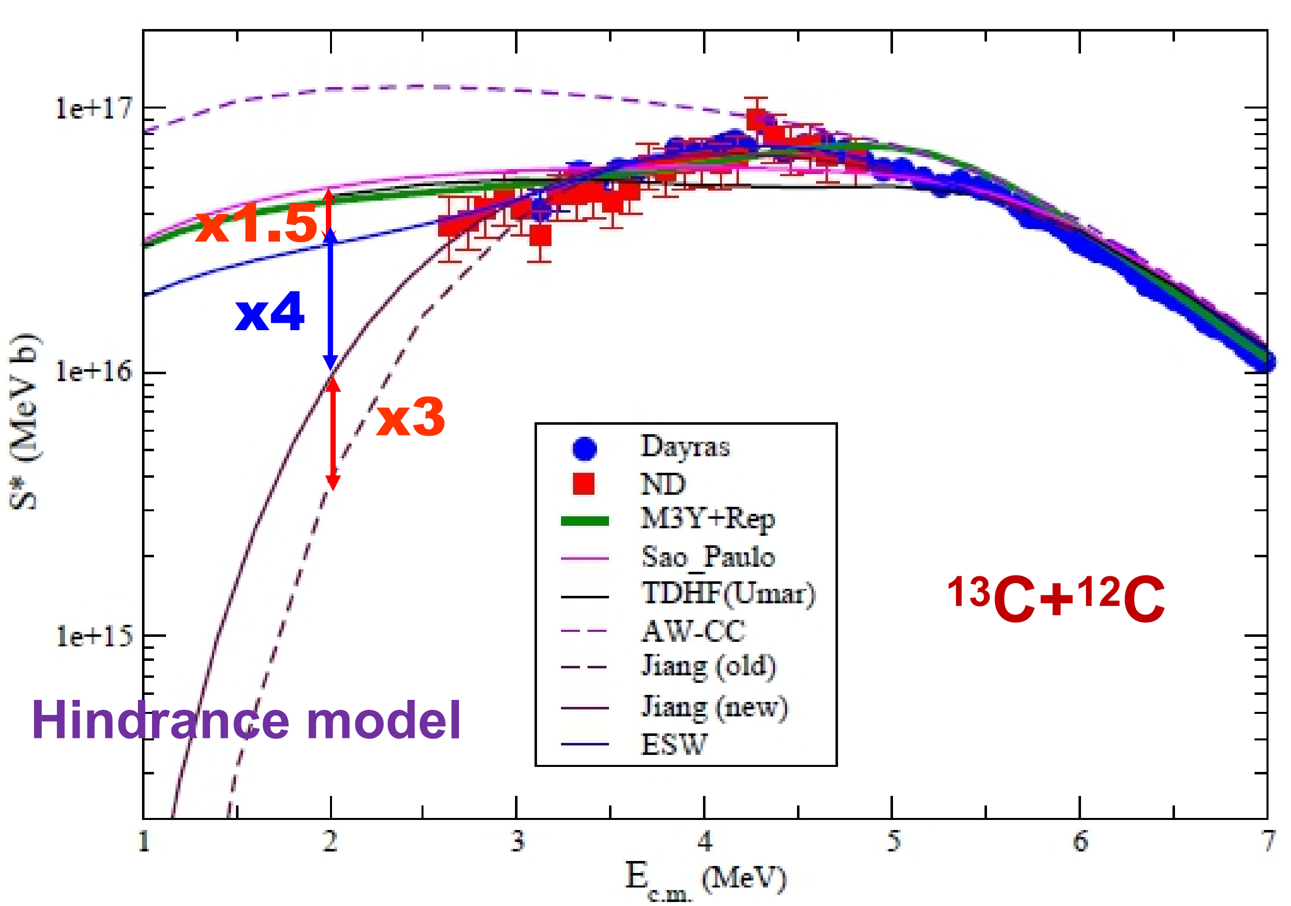


FIG. 11. The total $S^*(E)$ factor adopted for the reaction rate calculations is shown with three different options at lower energies.

$^{13}C + ^{12}C$ for $^{12}C + ^{12}C$



Test of extrapolating models

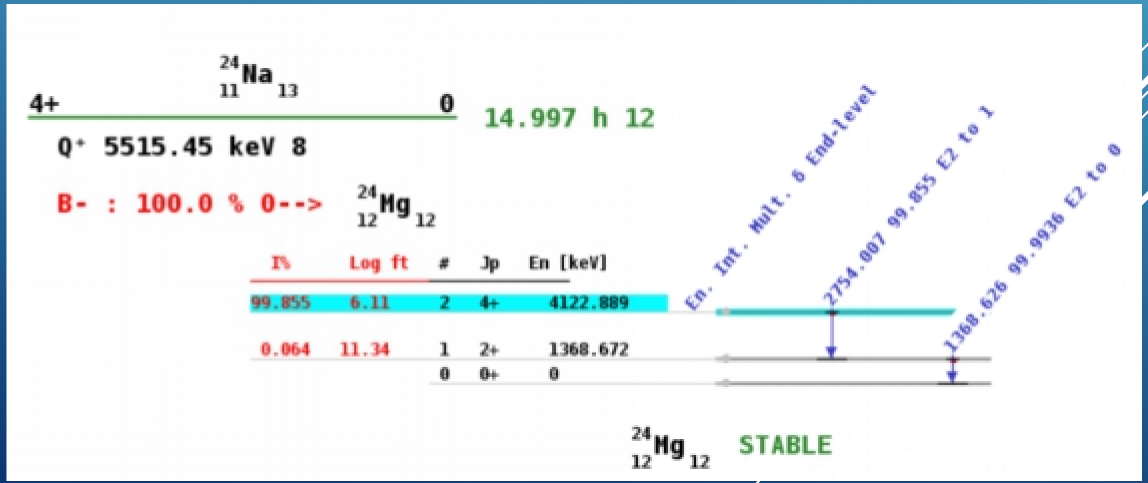


The $^{13}C + ^{12}C$ Experiment

- 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))

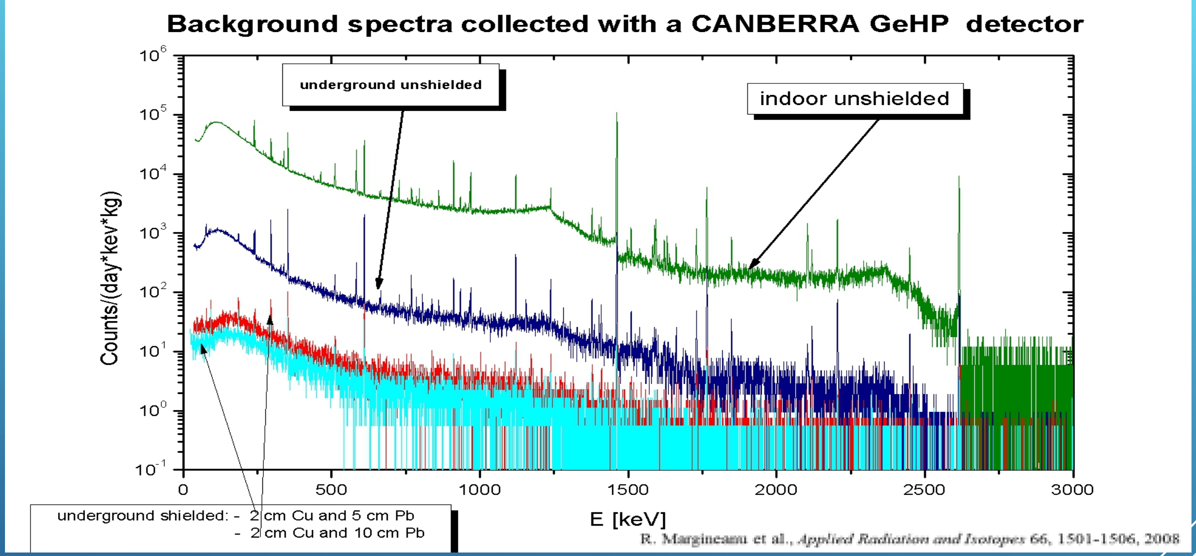
In beam irradiation, thick targets (Natural graphite disk ~ 1mm)

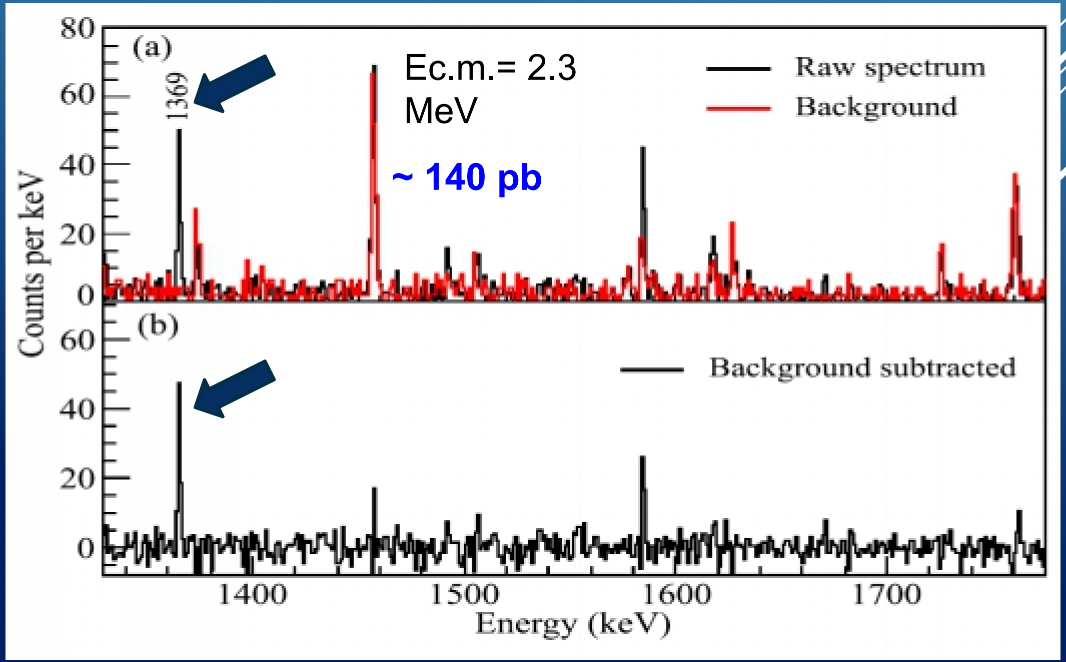
$^{12}C(^{13}C,p)\,^{24}Na$ - $T_{1/2}$ =15 h **E = 1369 keV**



^{13}C beam @ 5-25 μA, 4.6 – 11. MeV Lab (E_{cm}=2.3 – 5.4 MeV)

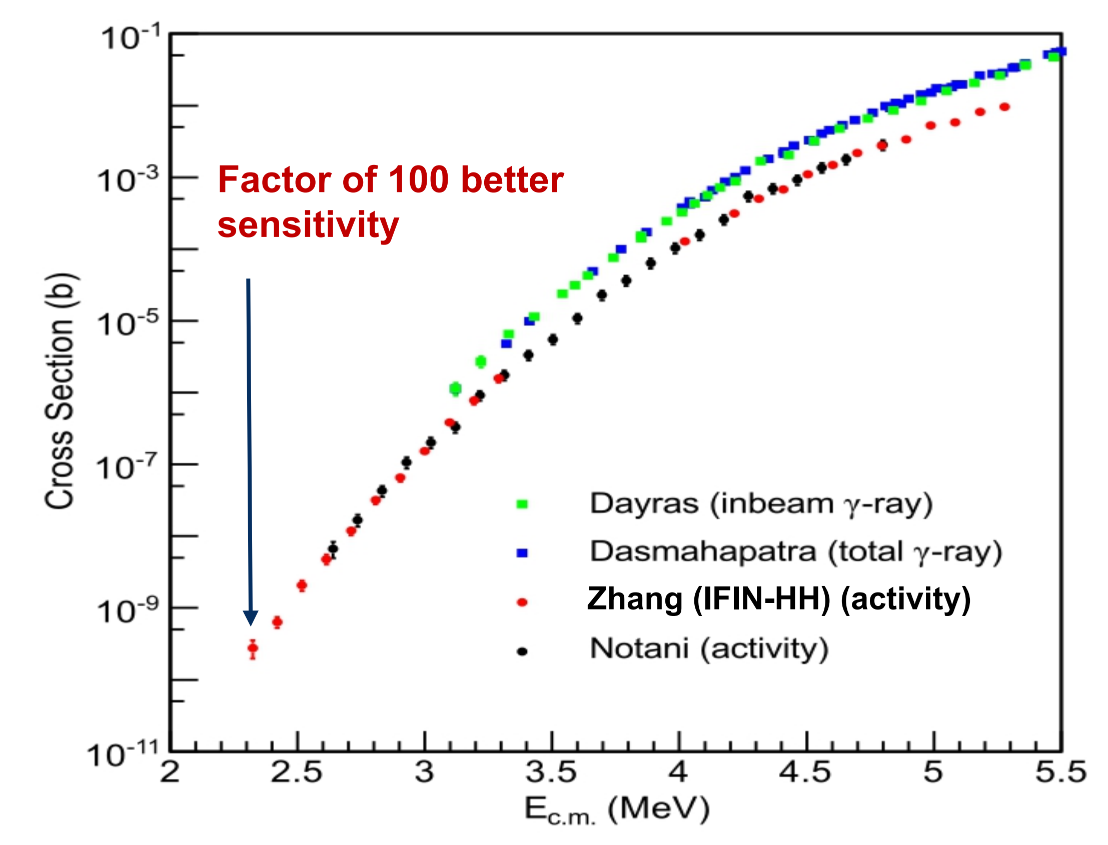
Ultra low background (µBq) laboratory at Slanic Salt Mine

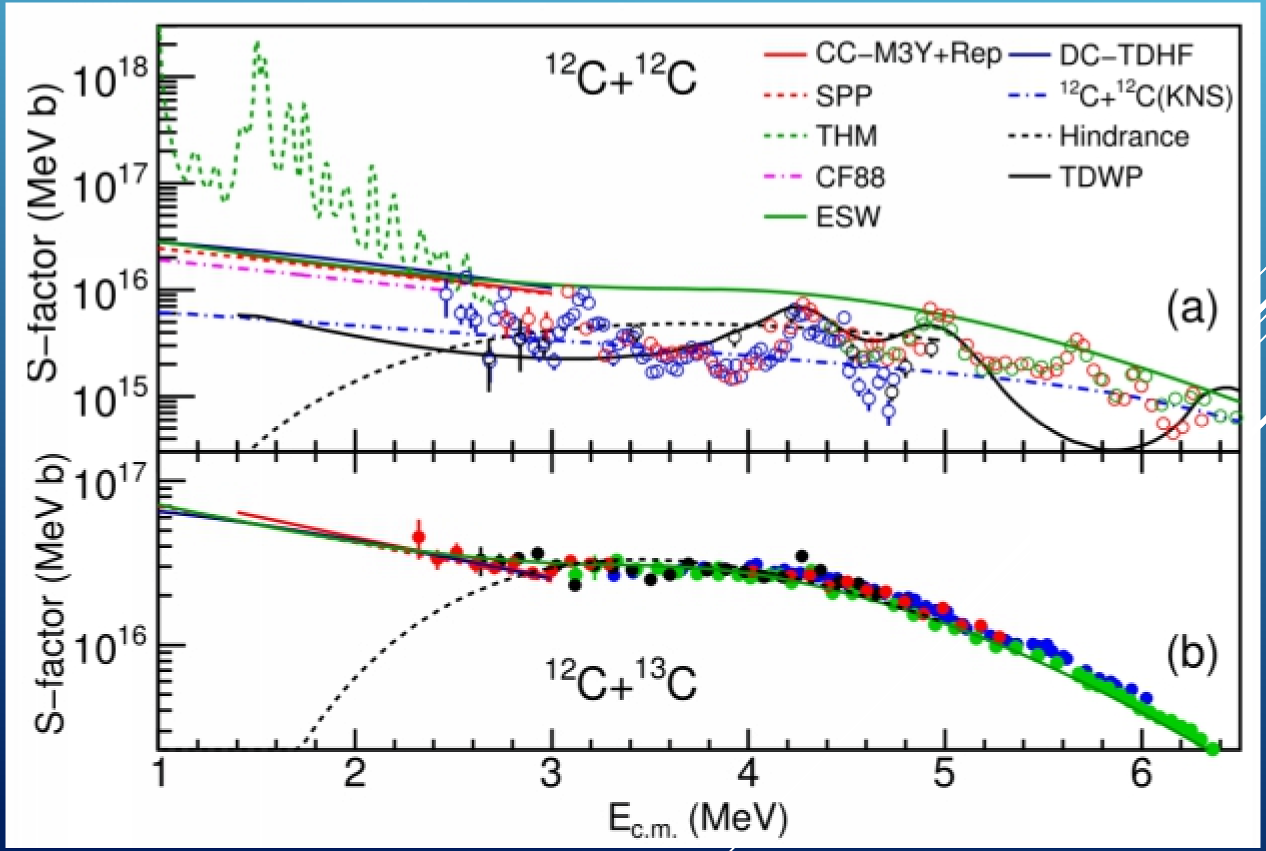




The $^{13}C + ^{12}C$ Experiment - Results

$$S^*(E_{C.M.}) = E_{C.M.}\sigma(E_{C.M.})e^{\xi/\sqrt{E_{C.M.}}+0.46E_{C.M.}} = S(E_{C.M.})e^{0.46E_{C.M.}},$$





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

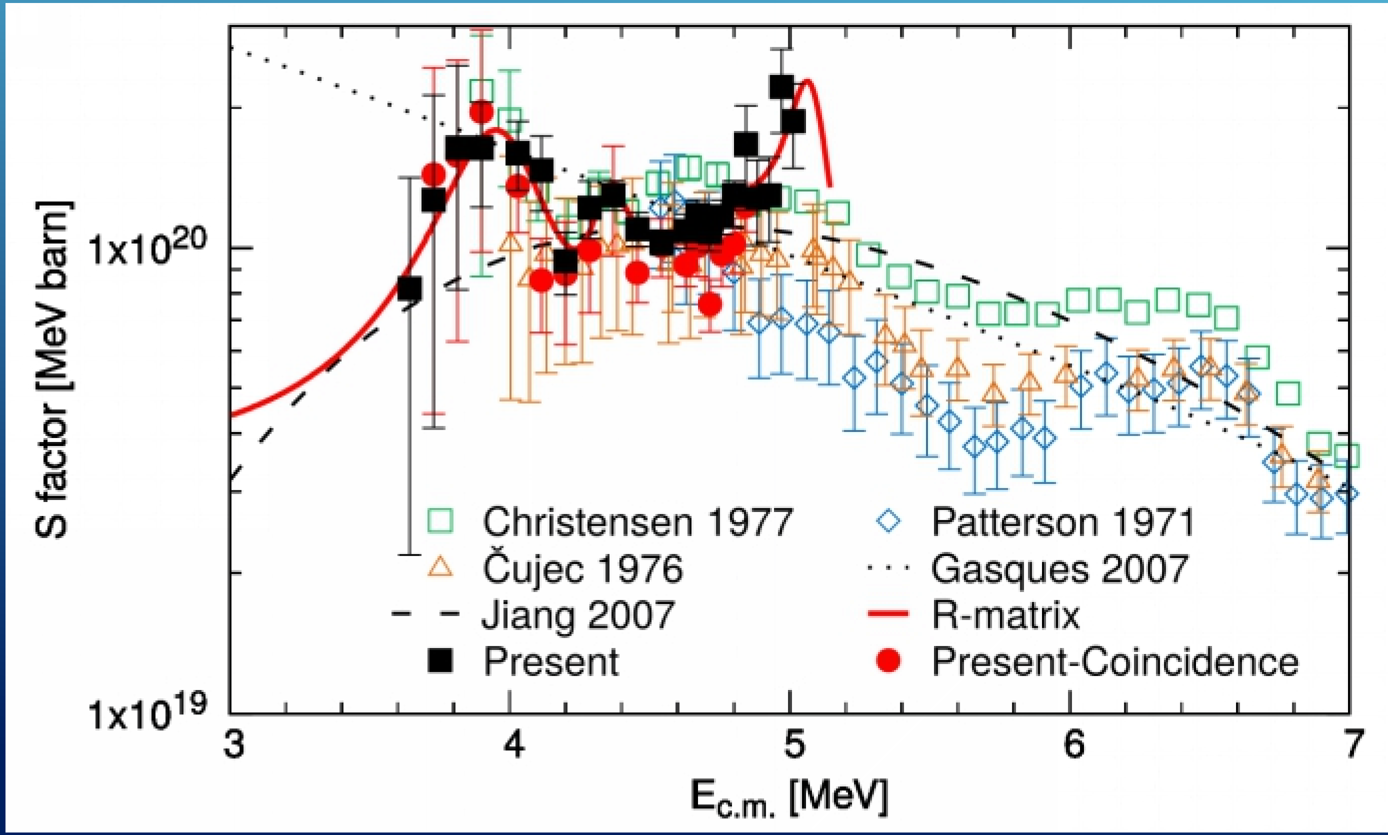
Extend study: approach used

- Direct measurements $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$ 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

- The ^{12}C + ^{16}O reaction plays a particularly important role in both the carbon and oxygen burning phases of stars.
- It also may play a role in the ignition of explosive burning processes.

- More recently, a Trojan Horse Method study was performed to evaluate the $^{12}C(^{16}O, \alpha)^{24}Mg$ and $^{12}C(^{16}O, p)^{27}Al$ reactions at astrophysical energies by studying the $^{16}O(^{14}N, \alpha\ ^{24}Mg)^{2}H$ and $^{16}O(^{14}N, p\ ^{27}Al)^{2}H$ three-body reactions.
  - Analysis is ongoing



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

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Target testing - ^{13}C

CHETEC INFRA — Solid Targets for Astrophysics Research — Task 3.1

- Primarily targets were produced for an ongoing study on ion-ion fusion reactions at sub-Coulomb barrier energies
  - using **activation method** (preferrably thick targets, but thin were tested too)
- Goals: first and foremost, durable under beam currents > 1-5 pμA and irradiations longer than 1 hr and handling (transportation over large distances)

Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{16}O$	^{16}O beam on ^{13}C targets	^{13}C powder (on Ta backing 3mg/cm^2)	~130-150 nm* (~30μg/cm^2)	PVD	^{16}O beam [various intensities], RBS, SEM	Did not hold for irradiations with I > 1 pμA Complete deterioration in beam spot area

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Target testing - ^{16}O

CHETEC INFRA

Solid Targets for Astrophysics Research

Task 3.1

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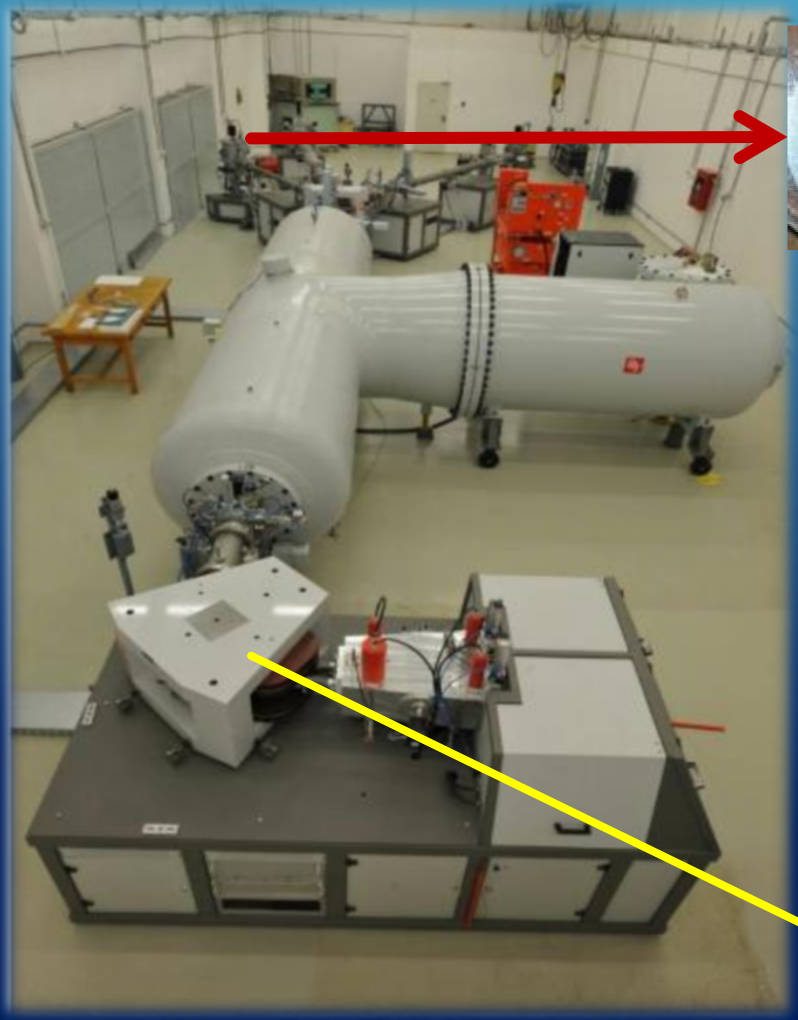
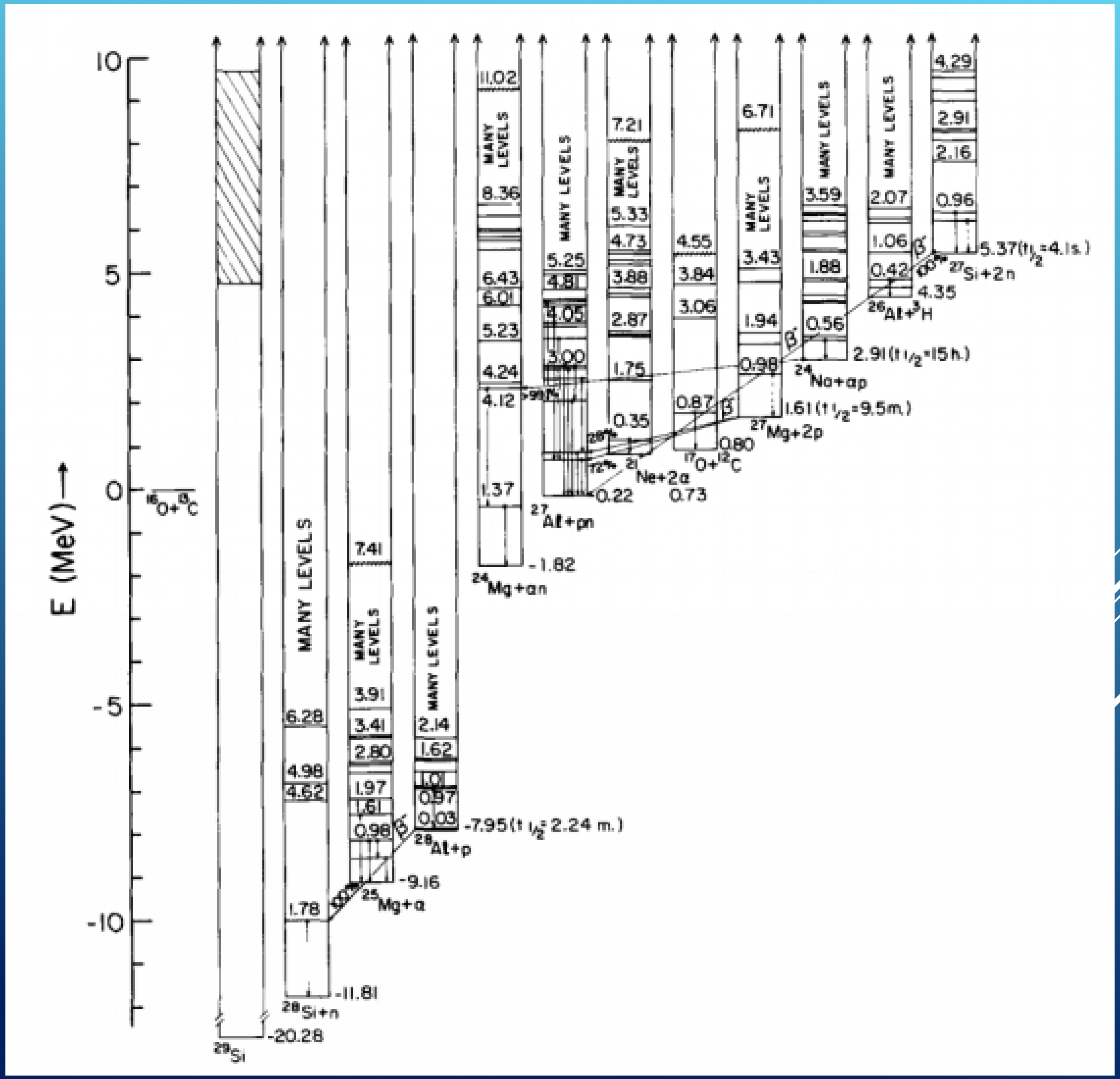
Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{16}O$	^{13}C beam on ^{16}O targets	CeO2 powder	1 mm (0.8-1 g/cm^2)	Tablet pressing*	^{13}C beam, SEM	Can hold for max 1 hr irradiations and I < 7 μA Crack under temperature changes even with target cooling

* fragile when handled

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

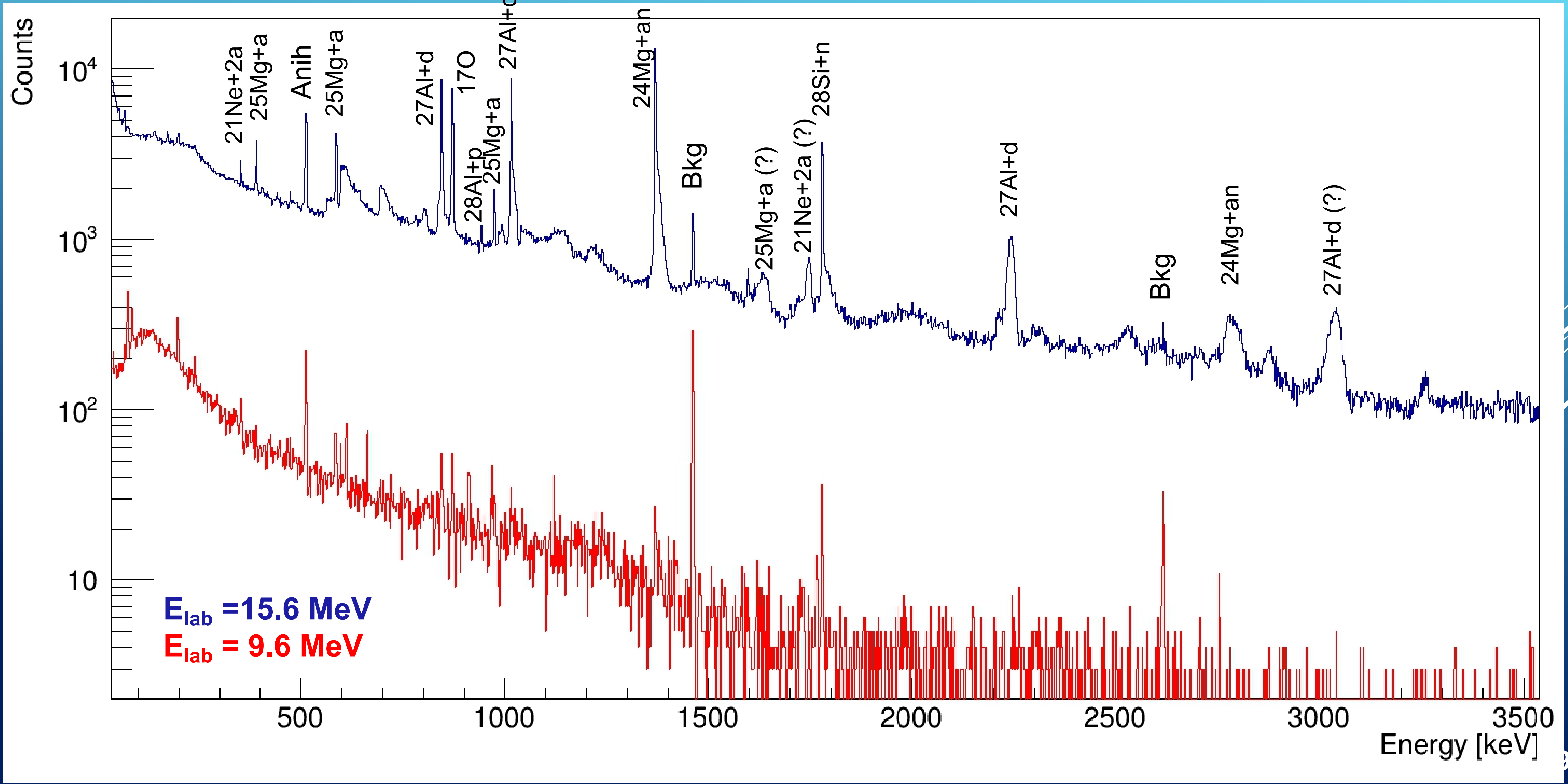
In beam irradiation, thick targets (CeO2 disk ~ 1 mm)





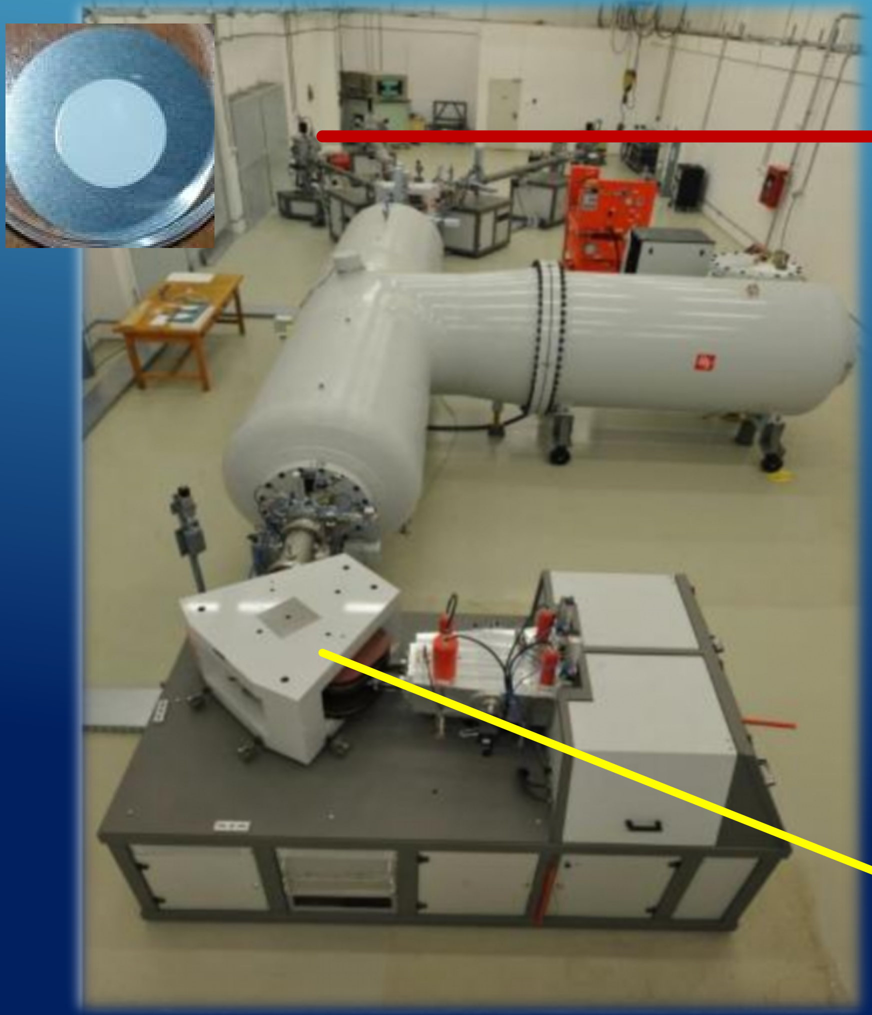
^{13}C beam @ 0.2 - 6 pμA and energy @ 7.6 – 15.6 MeV (Lab)

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

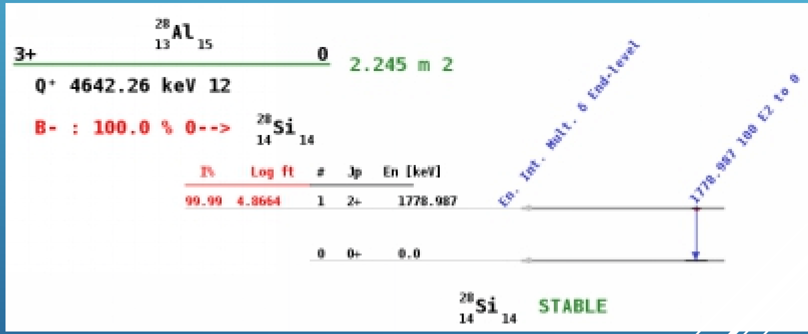


The $^{13}C+^{16}O$ Reaction - Activation

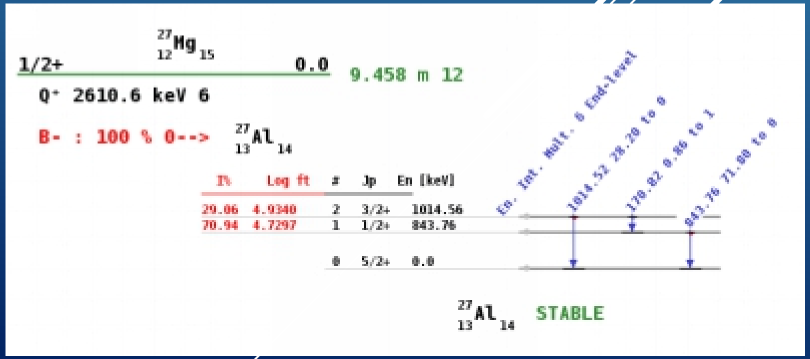
In beam irradiation, thick targets (CeO_2 disk ~ 1 mm)



$^{16}O(^{13}C,p)\ ^{28}Al$ ($T_{1/2}$ = 2.25 min)

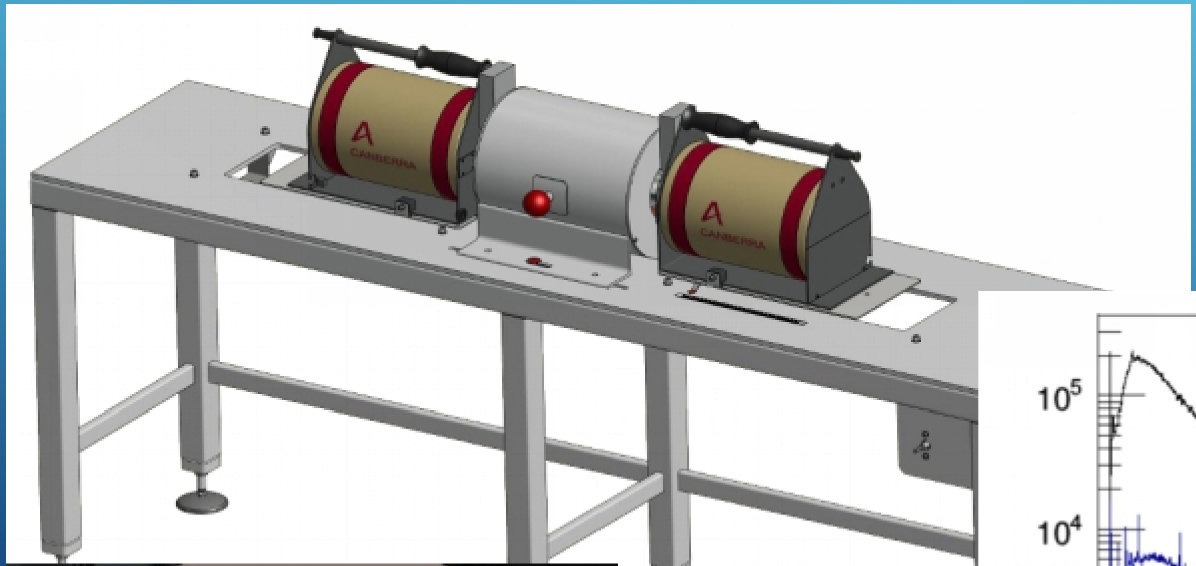


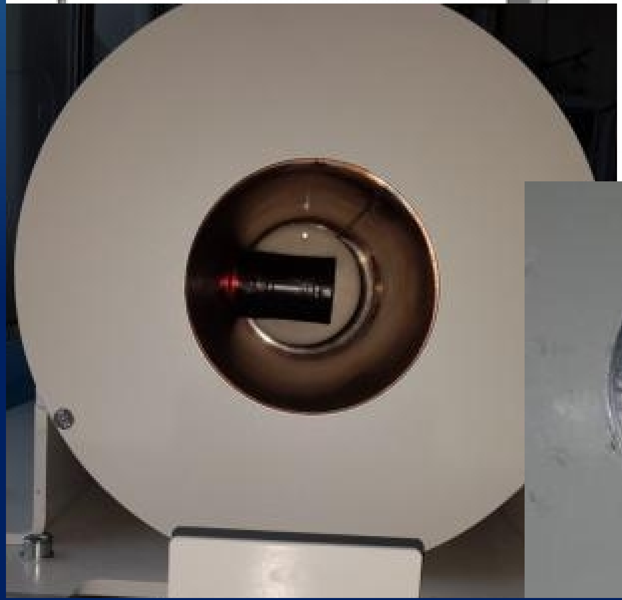
$^{16}O(^{13}C,2p)\ ^{27}Mg$ ($T_{1/2}$ =9.5 min)



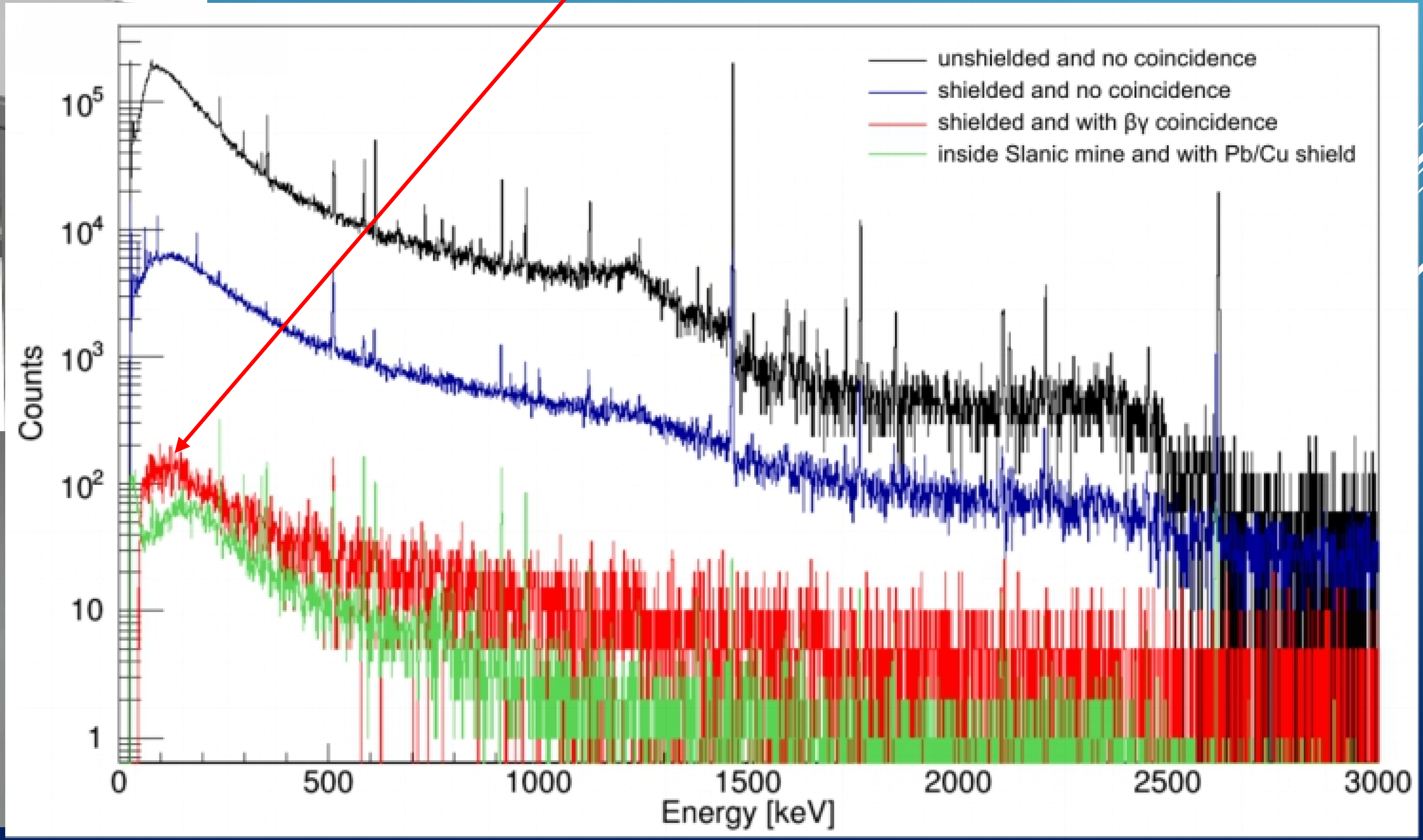
^{13}C beam @ 0.2 - 6 pμA and energy @ 7.6 – 15.6 MeV (Lab)

BEGA STATION

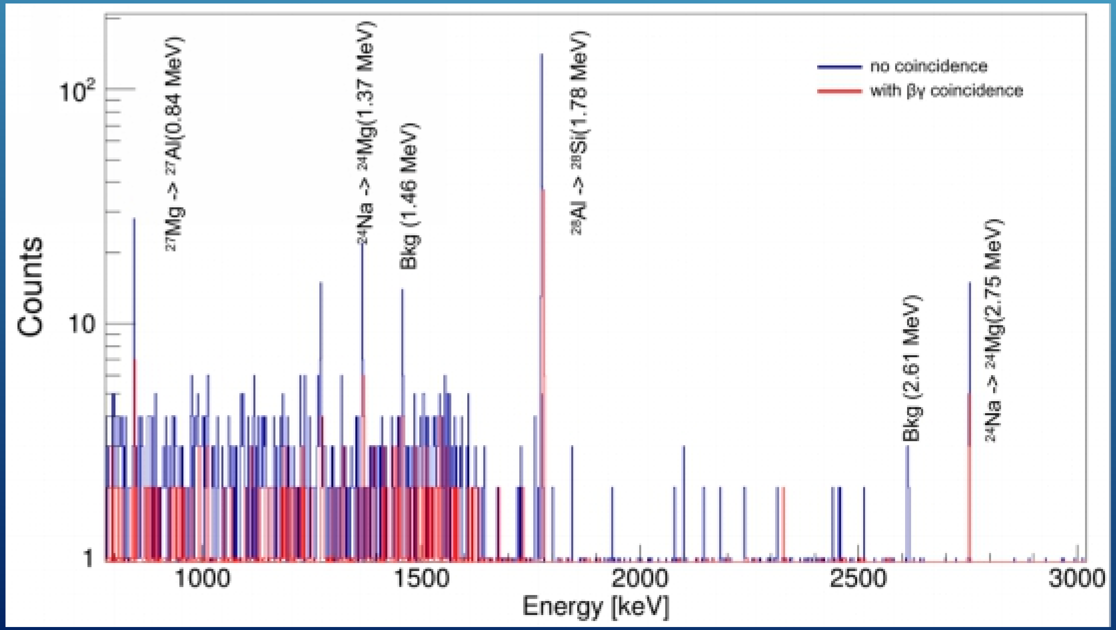


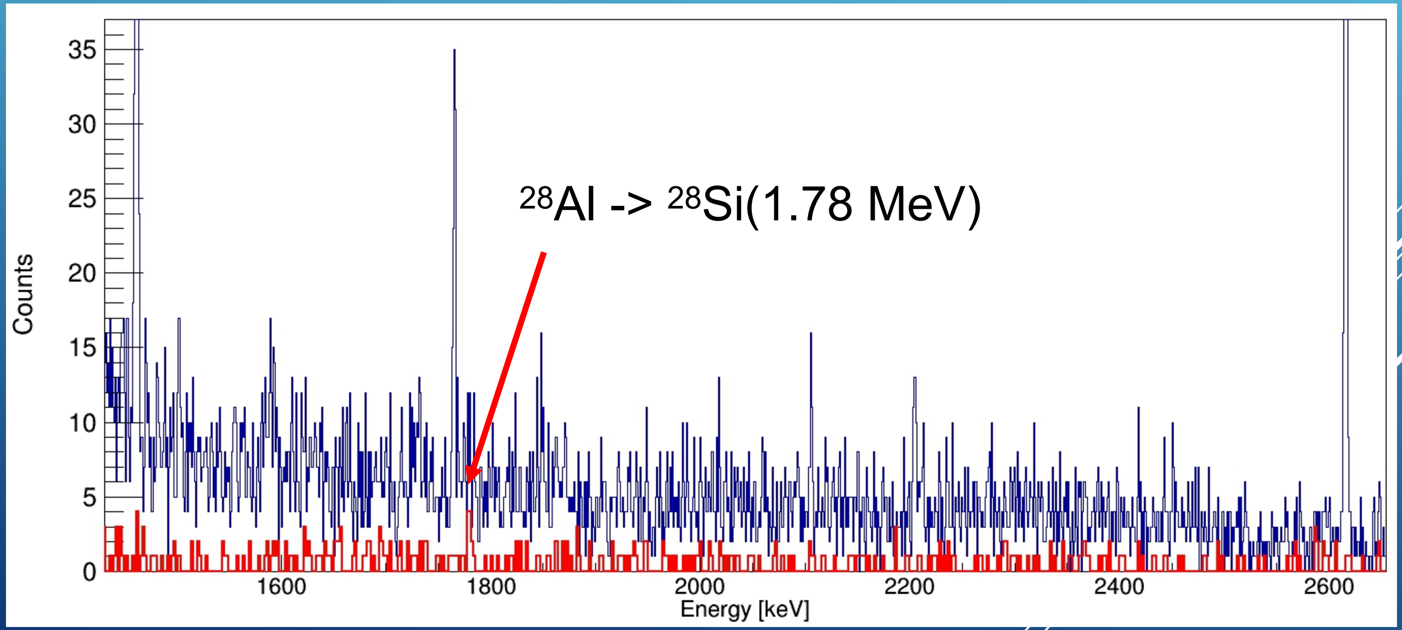


~ factor of 1000 background reduction



^{13}C +^{16}O – Preliminary results - Activation spectra





E_{Lab} = 11 MeV
t_{irr} = 1 hr and t_{decay} = 25 min

E_{Lab} = 8.4 MeV
t_{irr} = 1 hr and t_{decay} = 10 min
3 measurements

Target testing - ^{16}O

- Primarily targets were produced for an ongoing study on ion-ion fusion reactions at sub-Coulomb barrier energies

  - using **activation method** (preferrably thick targets, but thin were tested too)

- Goals: first and foremost, durable under beam currents > 1-5 pμA and irradiations longer than 1 hr and handling (transportation over large distances)

Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{16}O$	^{13}C beam on ^{16}O targets	Ta_2O_5	Several (< 0.5 mg/cm^2)	Anodization of Ta foil in water	^{13}C beam, RBS	Good uniformity, large number of O atoms, easy handling Did not hold for irradiations with I > 1 pμA

Target testing - ^{16}O

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ChETEC INFRA — Solid Targets for Astrophysics Research — Task 3.1

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  - using **activation method** (preferrably thick targets, but thin were tested too)
- Goals: first and foremost, durable under beam currents > 1-5 pμA and irradiations longer than 1 hr and handling (transportation over large distances)

Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{16}O$	^{13}C beam on ^{16}O targets	WO_3 (on Ta backing)*	~ 240 nm (~200 μg/cm^2)	PVD	^{13}C beam, RBS	Good uniformity, large number of O atoms, easy handling Did not hold for irradiations with I > 1 pμA

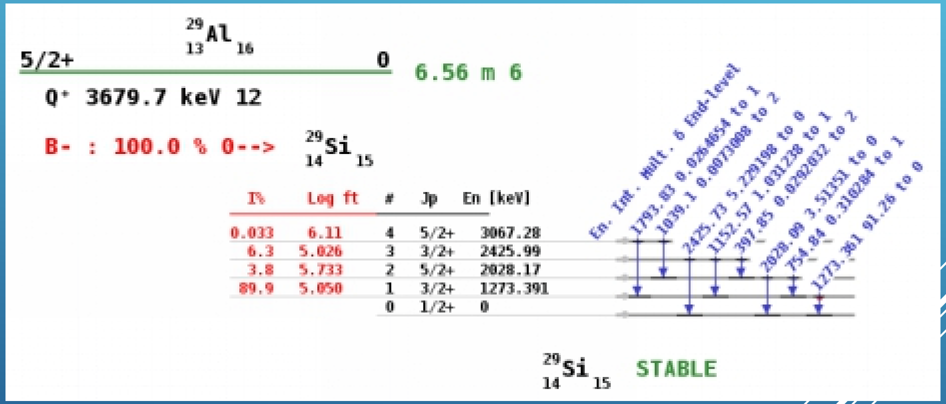
* targets tested as part of TNA experiment (proposal 23203309-ST for Dec 2023)

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

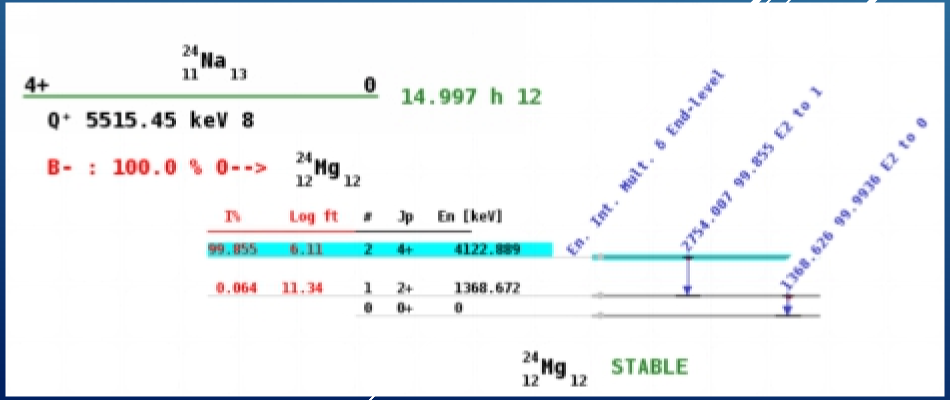
*Collaboration with L. Guardo, R. Sparta et al @ INFN-LNS, through ChETEC-INFRA TNA

In beam irradiation of thick targets followed by deactivation measurements

$^{19}F(^{12}C,2p)\,^{29}Al$ - $T_{1/2}$ = 6.5 min



$^{19}F(^{13}C,2\alpha)\,^{24}Na$ - $T_{1/2}$ = 15 hrs



19F beam @ 12 - 25 MeV and 0.2 – 20 µA

Target testing - ^{19}F

Task 3.1

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- Goals: first and foremost, durable under beam currents > 1-5 pμA and irradiations longer than 1 hr and handling (transportation over large distances)

Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{19}F$	^{13}C beam on ^{19}F targets	LiF powder	1 mm	Tablet pressing*	^{13}C beam	Overwhelming contamination in prompt spectra from reactions on Li (that also produced dangerous rates in the detector) Did not hold for irradiations with I > 1 μA and longer than 1 hr

* fragile when handled

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Target testing - ^{19}F

CHETEC INFRA

Solid Targets for Astrophysics Research

Task 3.1

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- Goals: first and foremost, durable under beam currents > 1-5 pμA and irradiations longer than 1 hr and handling (transportation over large distances)

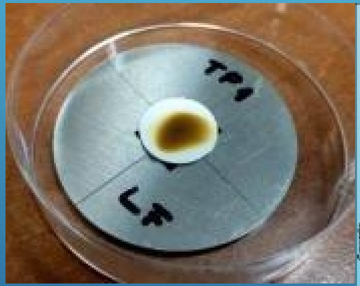
Reaction to study	Method	Target material	Thickness	Production method	Tested with	Result
$^{13}C + ^{19}F$	^{13}C beam on ^{19}F targets	BaF_2 powder	1 mm	Tablet pressing*	^{13}C beam	Did not hold for irradiations with I > 1 μA and longer than 1 hr

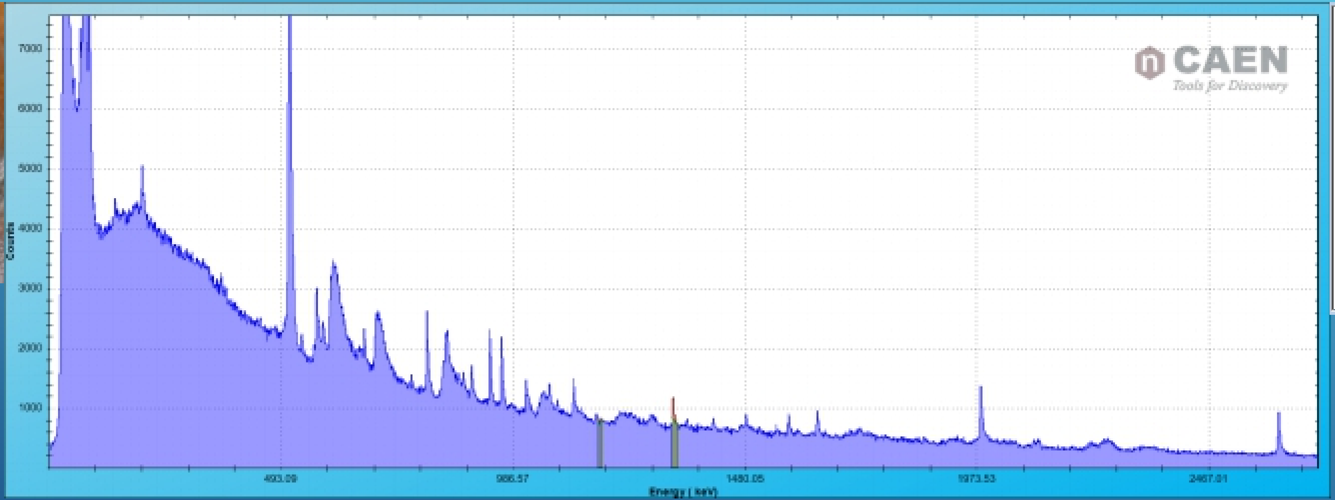
* very fragile when handled

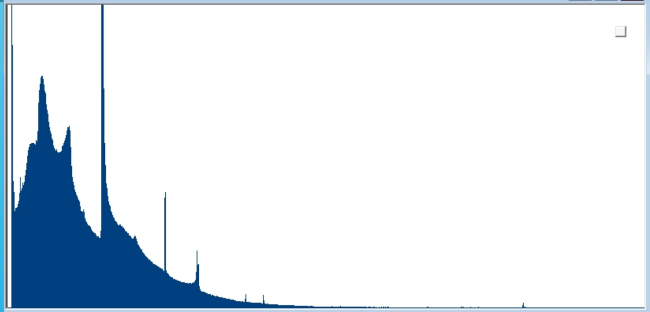
Target testing - ^{19}F

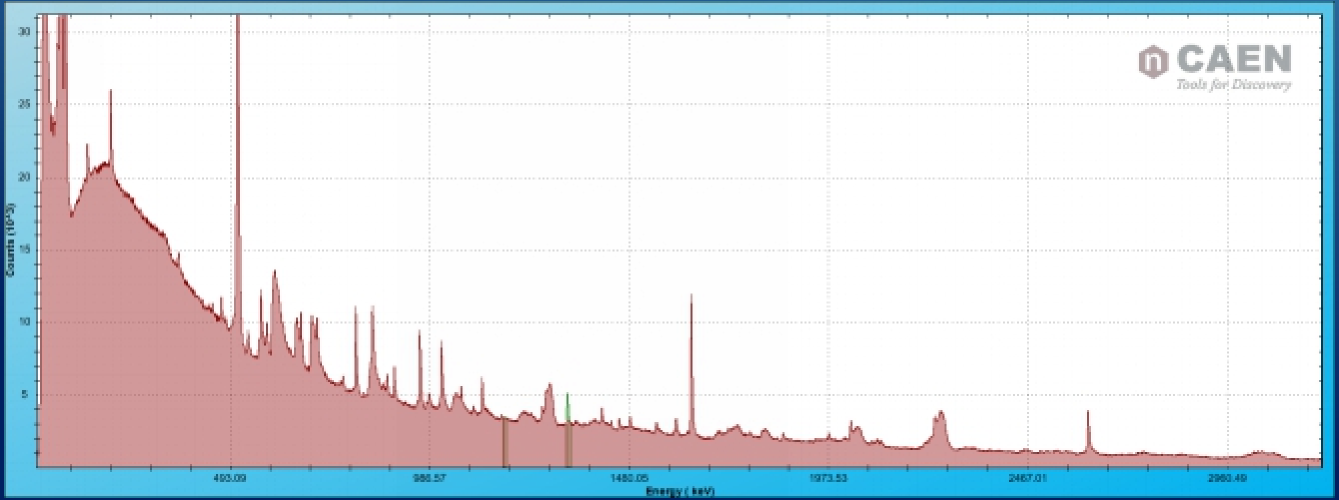
Solid
Targets for
Astrophysics
Research

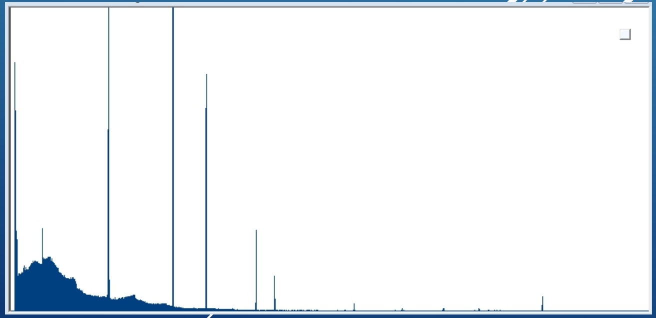
Task 3.1









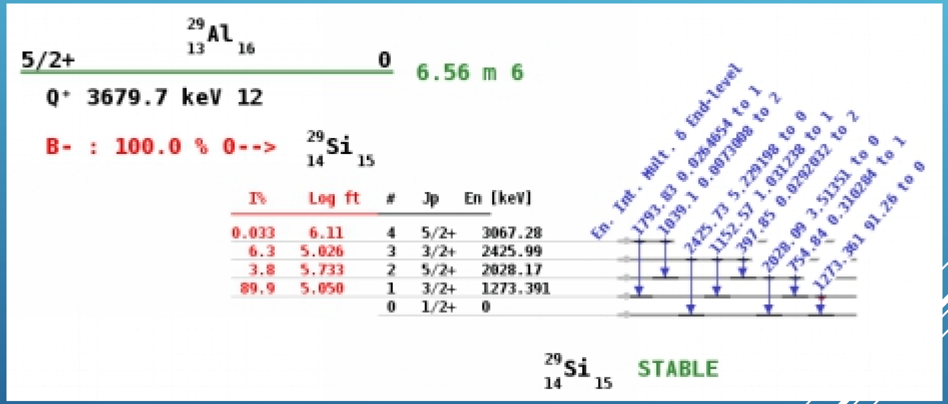


The $^{19}F+^{12,13}C$ Reaction

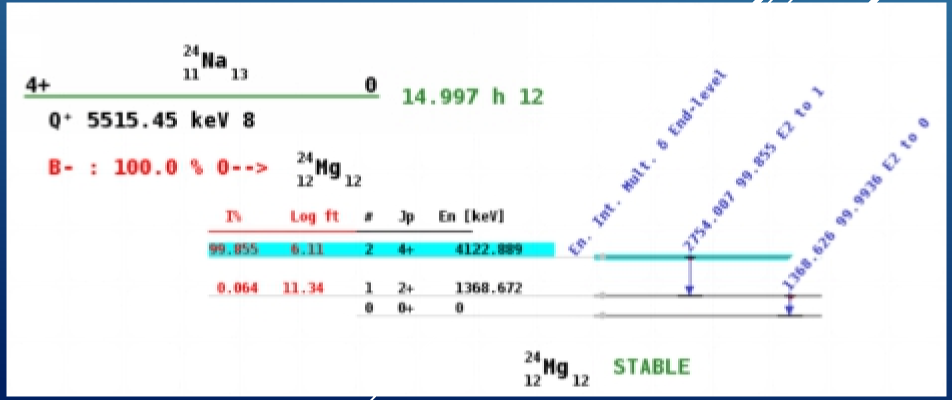
*Collaboration with L. Guardo, R. Sparta et al @ INFN-LNS, through ChETEC-INFRA TNA

In beam irradiation of thick targets followed by deactivation measurements

$^{19}F(^{12}C,2p)\ ^{29}Al$ - $T_{1/2}$ = 6.5 min

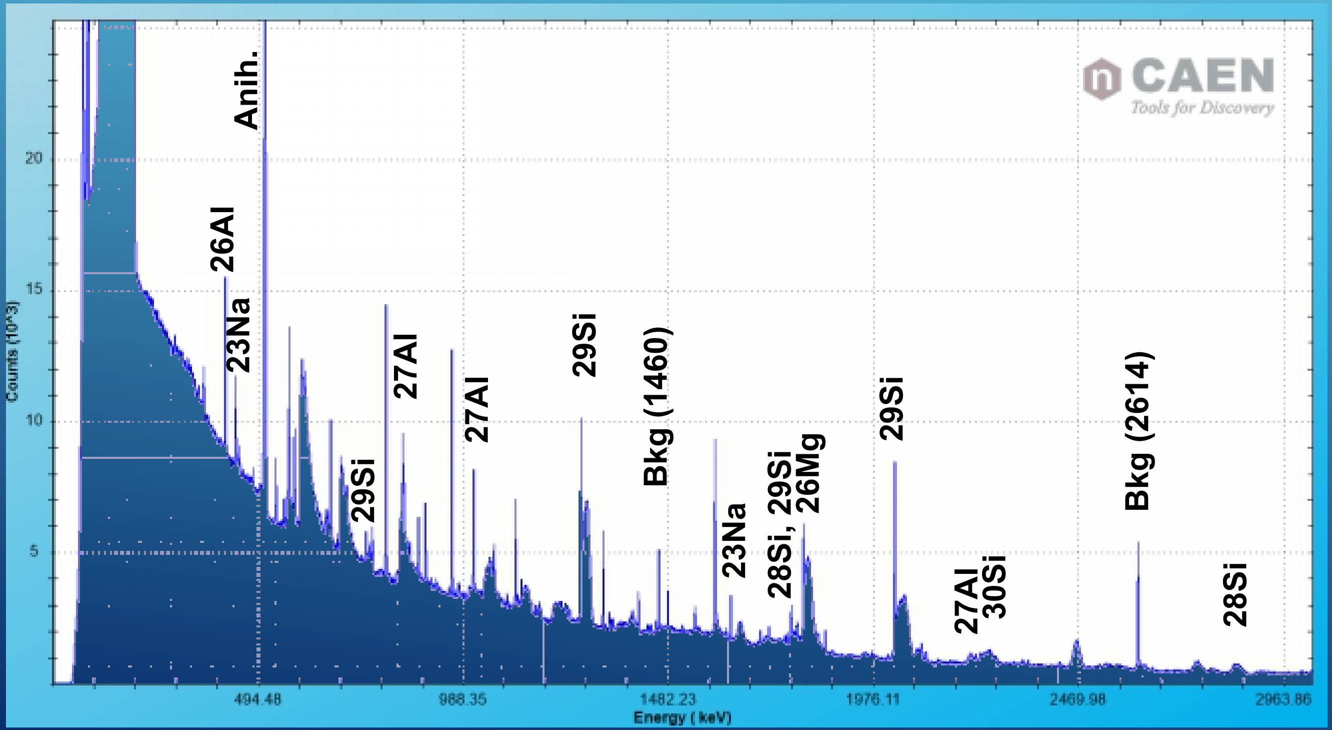


$^{19}F(^{13}C,2\alpha)\ ^{24}Na$ - $T_{1/2}$ = 15 hrs



19F beam @ 12 - 25 MeV and 0.2 – 20 μA

$^{19}F+^{12,13}C$ – Preliminary Results - Prompt Measurements



	Contributing Reaction
^{30}Si	$^{19}F + ^{12}C \rightarrow ^{29}Si + p$ $^{19}F + ^{13}C \rightarrow ^{29}Si + d$
^{29}Si	$^{19}F + ^{12}C \rightarrow ^{29}Si + d$ $^{19}F + ^{13}C \rightarrow ^{29}Si + t$
^{28}Si	$^{19}F + ^{12}C \rightarrow ^{28}Si + t$ $^{19}F + ^{13}C \rightarrow ^{28}Si + nt$
^{27}Al	$^{19}F + ^{12}C \rightarrow ^{27}Al + \alpha$ $^{19}F + ^{13}C \rightarrow ^{27}Al + n\alpha$
^{26}Al	$^{19}F + ^{12}C \rightarrow ^{26}Al + n\alpha$ $^{19}F + ^{13}C \rightarrow ^{26}Al + 2n\alpha$
^{26}Mg	$^{19}F + ^{12}C \rightarrow ^{26}Mg + p\alpha$ $^{19}F + ^{13}C \rightarrow ^{26}Mg + d\alpha$
^{23}Na	$^{19}F + ^{12}C \rightarrow ^{23}Na + 2\alpha$ $^{19}F + ^{13}C \rightarrow ^{23}Na + n2\alpha$

- In order to obtain the total fusion cross-section and perform fusion model calculations, we need channel branching factors
- We have received beamtime from Chetec-INFRA TNA through proposal by X.D. Tang that will focus on prompt measurements at higher energies with the goal of disentangling the reactions channels from the separate isotopes ^{12}C and ^{13}C.

FUTURE PLANS

- Thick target activation method + Salt mine/BEGA can be used to reach the Gamow window
  - finalize analysis of data for both $^{13}C+^{16}O$ and $^{13}C+^{19}F$
  - statistical model calculations to determine the contribution of each reaction channel to the total fusion cross-section
  - perform measurements in the Salt mine for the ^{24}Na channel to reach the Gamow window
  - target testing and characterization for use in this and other studies
    - collab with X.D. Tang (IMP Lanzhou) through Chetec-INFRA - 13C-enriched targets
- The overall 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

ACKNOWLEDGMENTS AND THANKS

- This study of ion-ion fusion reactions has received funding from the Romanian government through a Post-Doctoral grant (PN-III-P1-1.1-PD-2019-0234). All experiments performed at the 3 MV Tandetron™ are funded through the Romanian Government Programme for Infrastructure of National Interest (IOSIN) program.
- This work also received support from Chetec-INFRA through the task group 3.1 (Solid Targets for Astrophysics Research) and the TNA (Trans-National Access) program.
- Local support:
  - L. Trache, D. State, A. Stefanescu, I. Stefanescu, N. Florea, D. Iancu, R. Andrei, D. Filipescu, I. Burducea, M. Straticiuc
- Collaborators from INFN-LNS Catania:
  - G.L. Guardo, R. Sparta, M. La Cognata, A. Tumino, M.L. Sergi, A. Di Pietro, T.N. Szegedi

THANK YOU!