Fusion in massive stars: Pushing the $^{12}C+^{12}C$ cross-section to the limits with the STELLA experiment at IPN Orsay

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Outline

I. C burning, where, why, which reactions ?

II. Experimental efforts to measure $^{12}C+^{12}C$ /new technique

III. The STELLA – FATIMA experiment

IV. Results of the comissioning phase / $^{12}C+^{12}C$

V. Conclusions

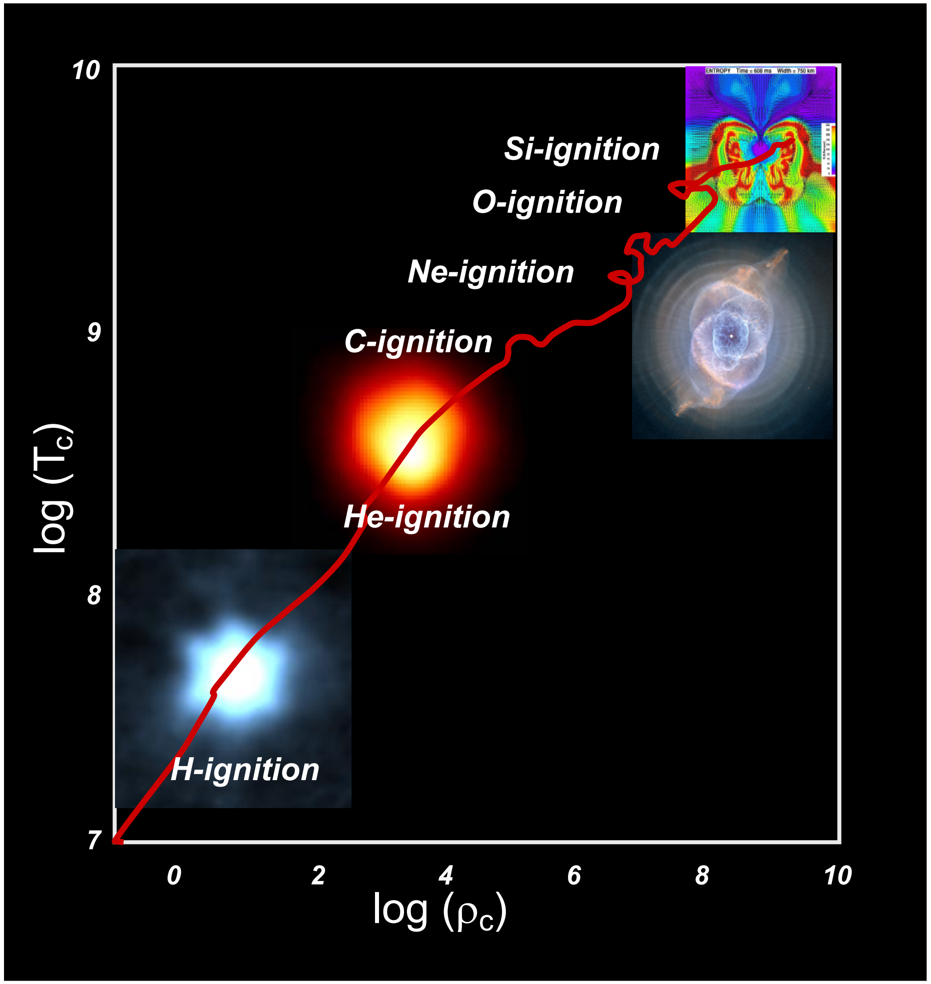
Burning phases in massive stars

different burning phases characterize the evolution of a „massive“ star

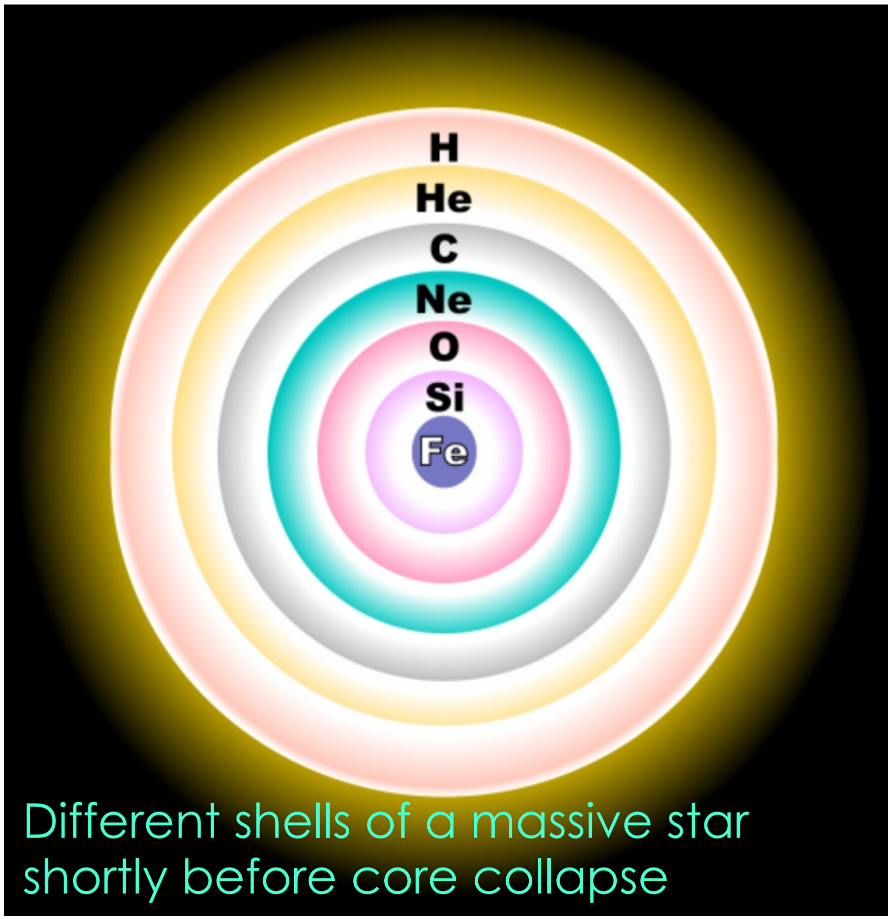
↓

each burning phase is controlled by different nuclear reactions, which govern the:

- energy production
- time scale
- nucleosynthesis



Carbon burning: a crucial phase in the stellar nucleosynthesis



Different shells of a massive star shortly before core collapse

- key reactions at each stage of stellar burning

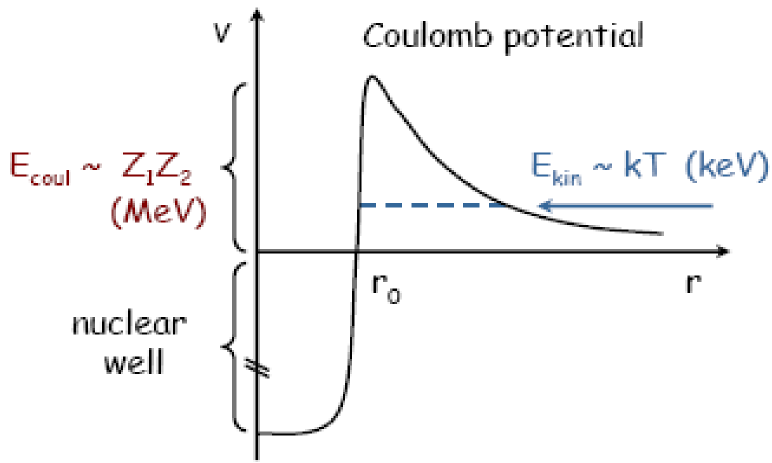
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$...

- In a star of 8-11 Solar masses, a carbon flash lasts just milliseconds.
- In a star of 25 Solar masses carbon burning lasts about 600 years.

Fusion reactions at thermonuclear energies

charged particles ➡ Coulomb barrier

energy available: from thermal motion

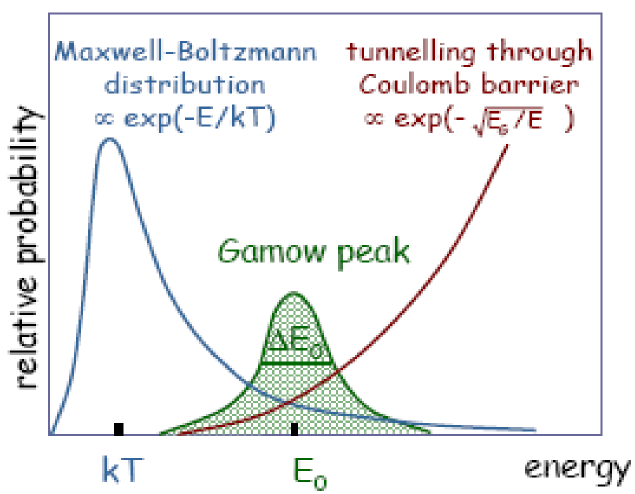


$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

during static burnings: $kT \ll E_{coul}$

reactions occur through TUNNEL EFFECT

➡ tunneling probability $P \propto \exp(-2\pi\eta)$



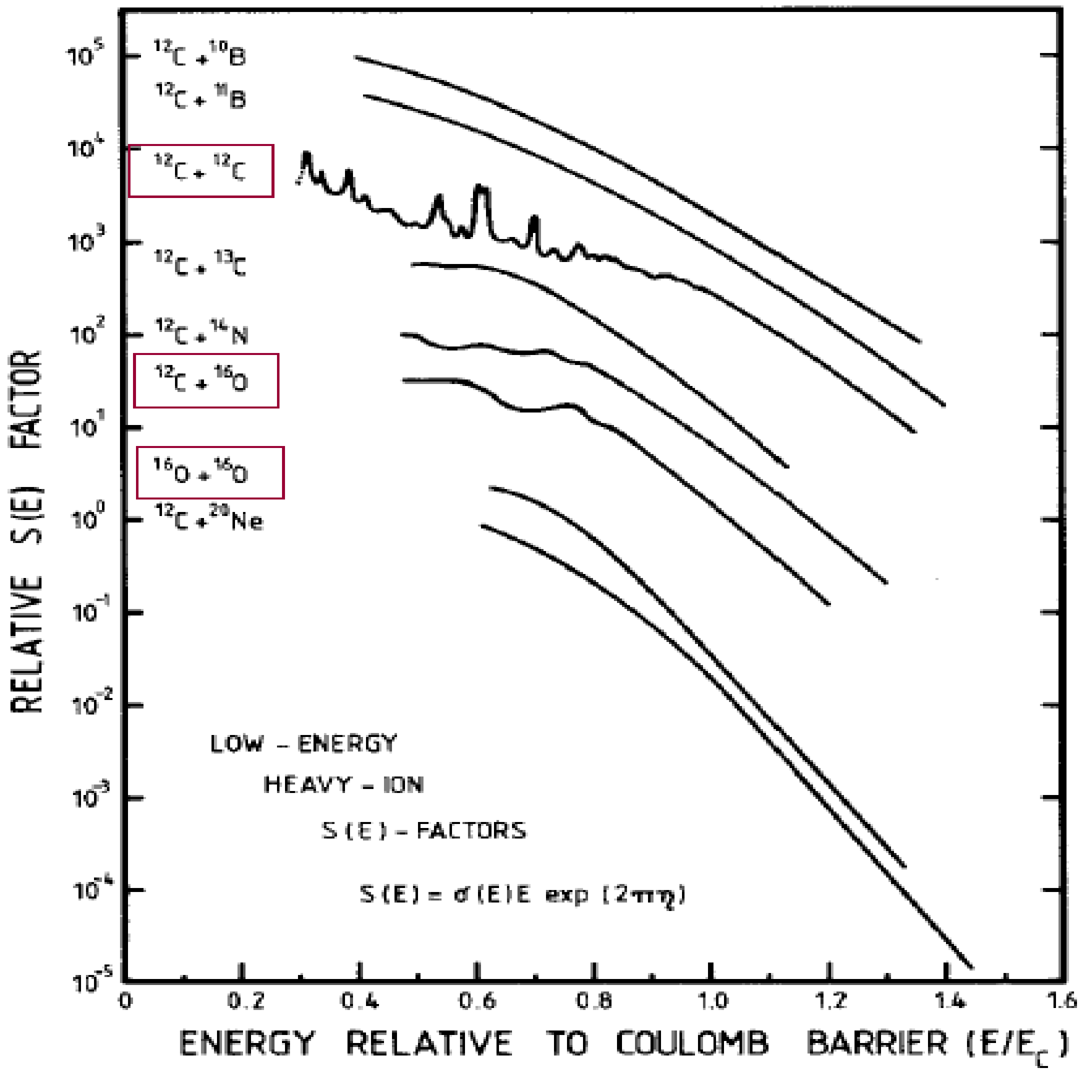
$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\,S(E)$$

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

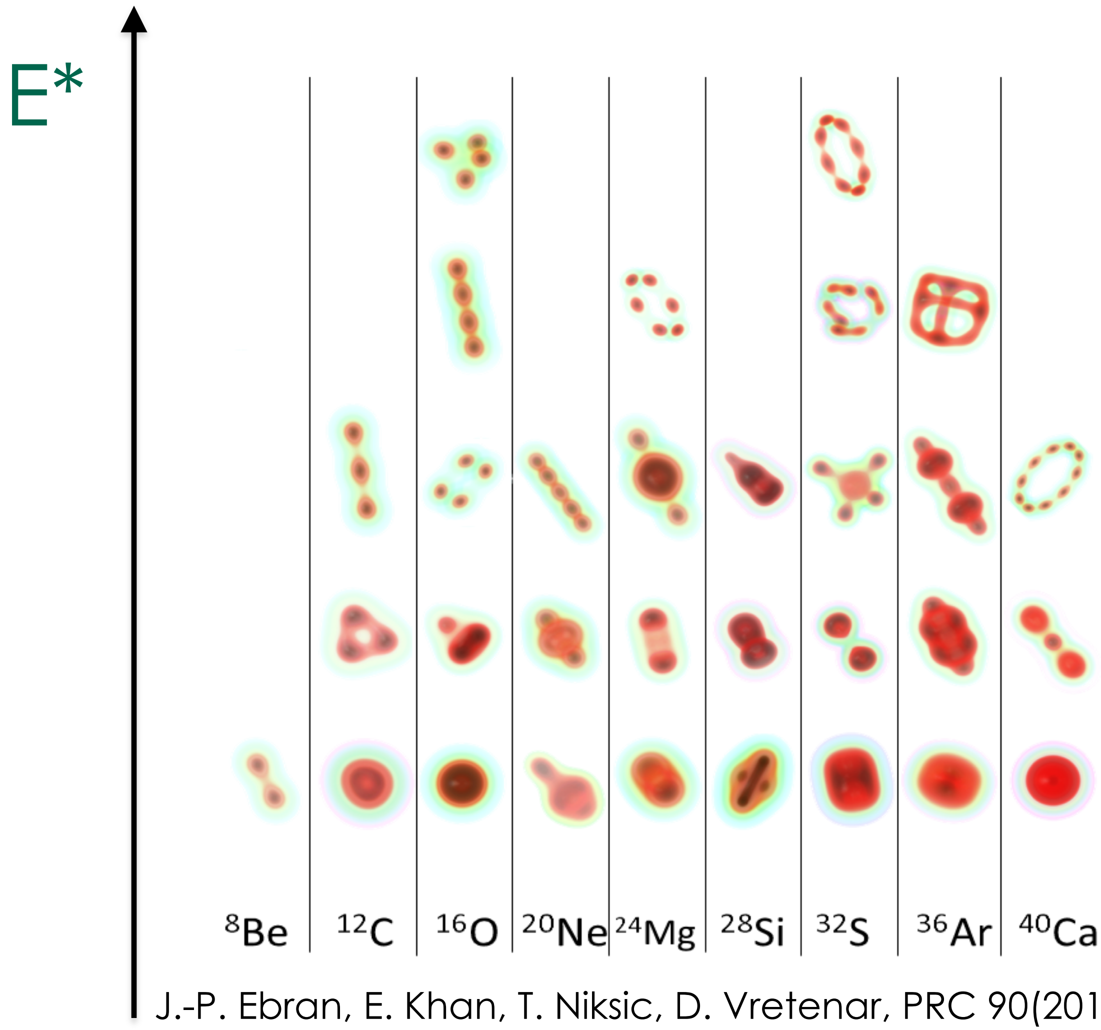
ASTROPHYSICAL S(E)-FACTOR

Cross-sections for some light systems at subcoulomb energies



R. Stokstad et al., Phys.Rev.Lett. 37 (1976)

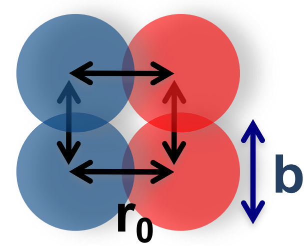
Ikeda diagram from microscopic calculations



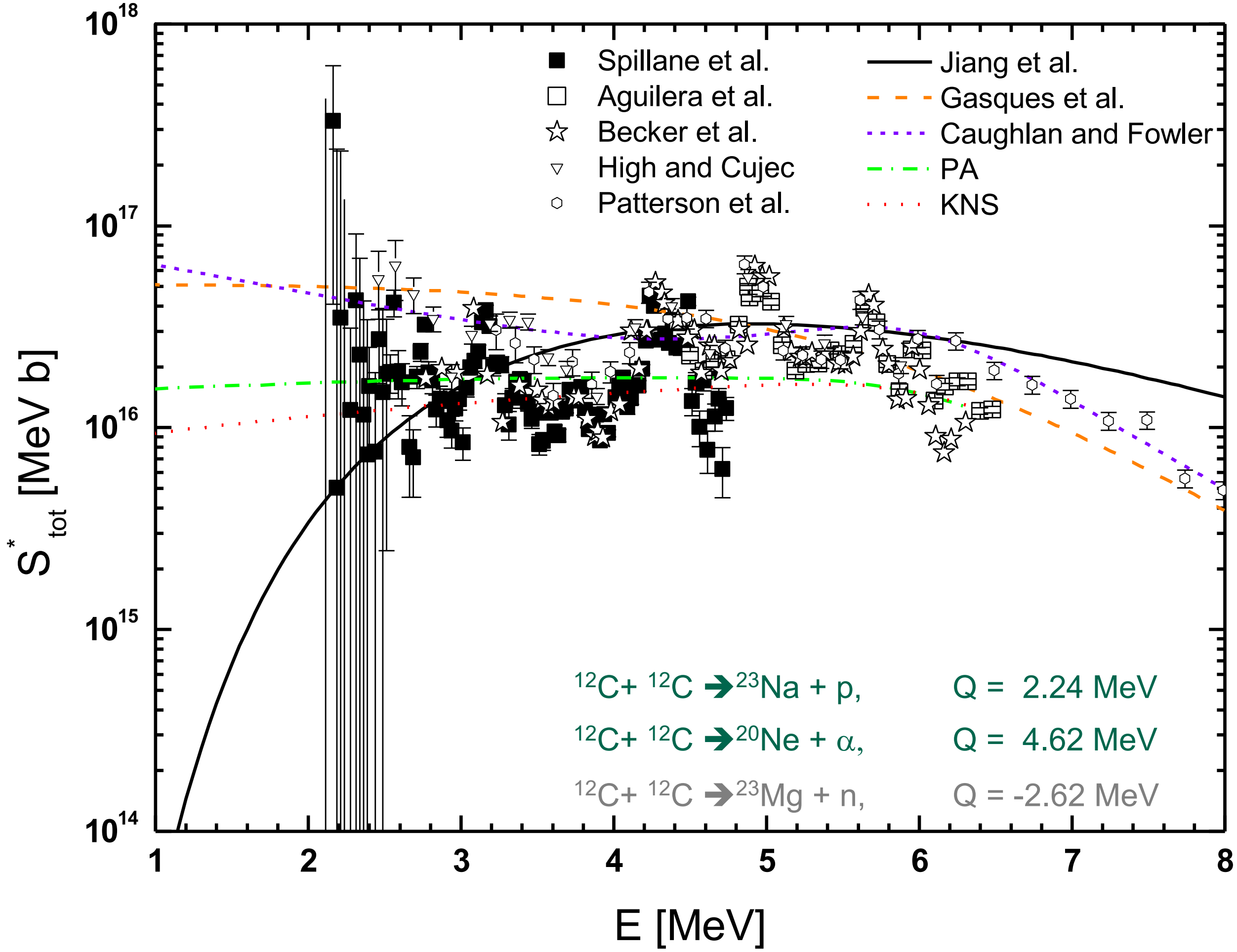
J.-P. Ebran, E. Khan, T. Niksic, D. Vretenar, PRC 90(2014)054329, Nature 487(2012)341

Emergence of clusters

- $\alpha_{loc} = b/r_0$
- energy



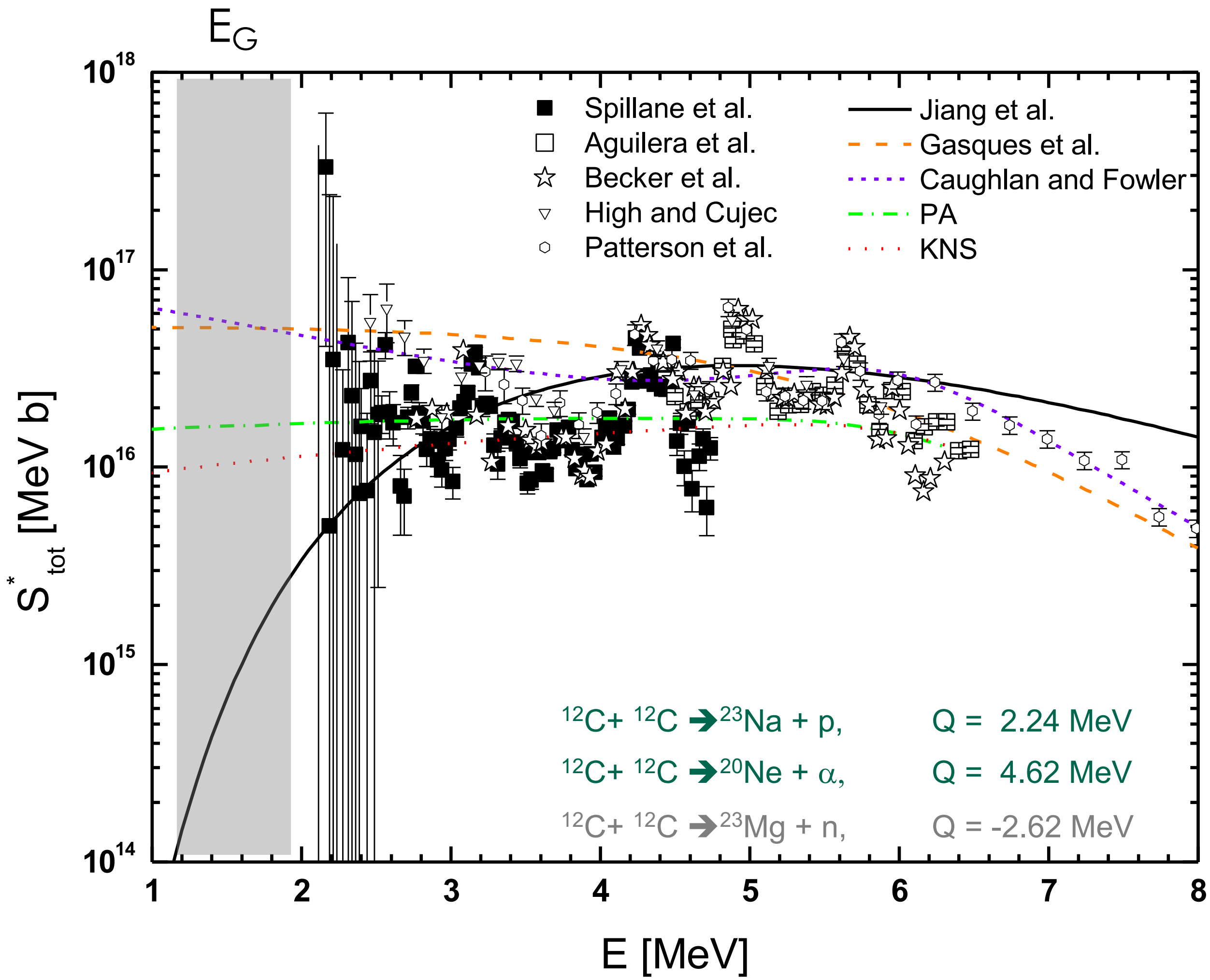
Carbon burning: $^{12}C + ^{12}C$, the main reaction

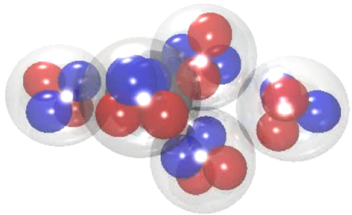


Experimental and theoretical efforts

- \+ J.R. Patterson *et al.*, APJ 157, 367, (1969)
- \- G.J. Michaud and E.W. Vogt, PRC 5, 350, (1972)
- \+ M.G. Mazarakis and W.E. Stephens, PRC 7, 1280, (1973)
- \- R.G. Stokstad *et al.*, PRL 37, 888, (1976)
- \+ P.R. Christensen *et al.*, Nucl. Phys. A 280, 189, (1977)
- \+ M.D. High and B. Čujec, NIM A 282, 181, (1977)
- \+ K.-U. Kettner *et al.*, PRL 38, 377, (1977)
- \+ K.A. Erb *et al.*, PRC 22, 507, (1980)
- \+ H.W. Becker *et al.*, Z. Phys. A 303, 305, (1981)
- \- Y. Suzuki and K.T. Hecht, Nucl. Phys. A 388, 102. (1982)
- \+ B. Čujec *et al.*, PRC 39, 1326, (1989)
- \- L.R. Gasques *et al.*, PRC 72, 025806, (2005)
- \+ E.F. Aguilera *et al.*, PRC 73, 064601, (2006)
- \+ L. Barrón-Palos *et al*, Nucl. Phys. A 779, 318, (2006)
- \+ D. Jenkins *et al.*, PRC 76, 044310, (2007)
- \+ C.L. Jiang *et al.*, PRC 75, 015803, (2007)
- \+ T. Spillane *et al.*, PRL 98, 122501, (2007)
- \+ J. Zickefoose, Ph.D. thesis, U. of Connecticut (2010)
- \+ C.L. Jiang *et al.*, NIM A 682, 12, (2012)
- \+ X. Fang *et al.*, Jour. Phys. 420, 012151, (2013)
- \+ C.L. Jiang *et al.*, PRL 110, 072701, (2013)
- \- A.A. Aziz *et al.*, PRC 91, 015811, (2015)
- \+ B. Bucher *et al.*, PRL 114, 251102, (2015)
- \+ A. Tumino *et al.*, EPJ Conf. 117, 09004, (2016)

Carbon burning: $^{12}C + ^{12}C$, the main reaction





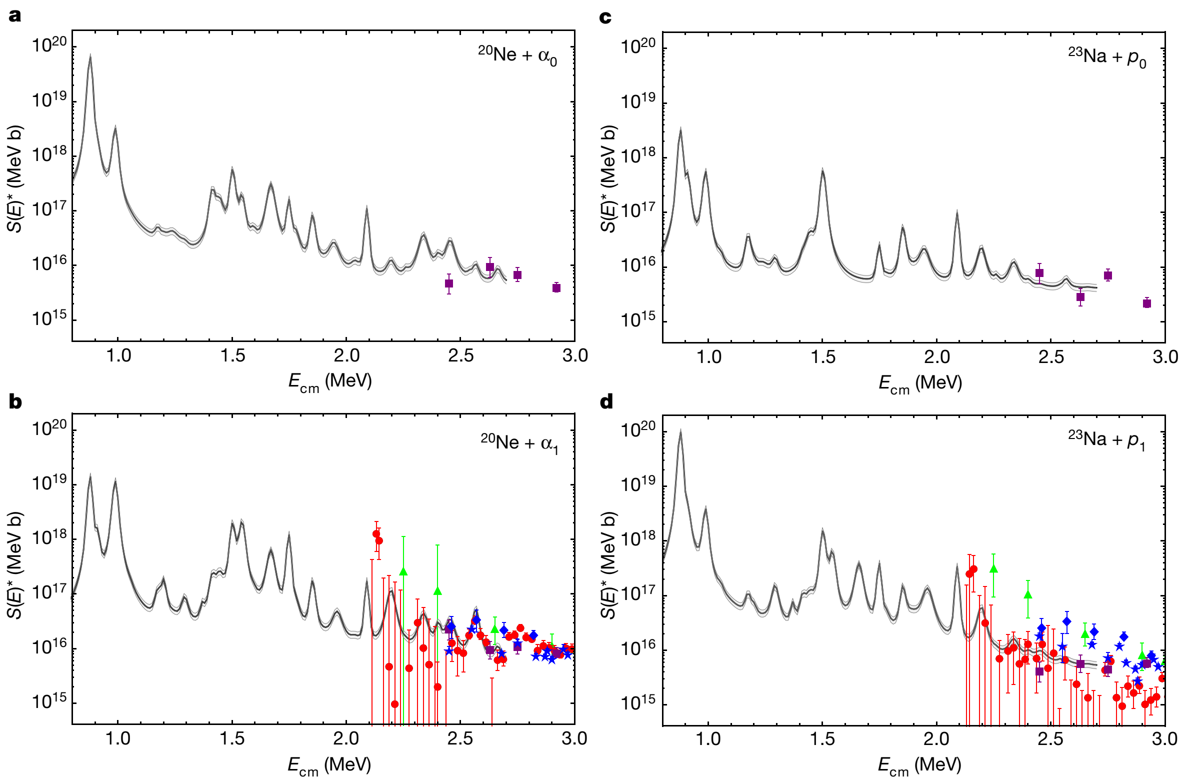
- Single particles or γ
- Extremely sensitive to background
- Extrapolations with very different trends
- Crucial role of resonances, impact on the reaction rate ?

LETTER

https://doi.org/10.1038/s41586-018-0149-4

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino[1,2]*, C. Spitaleri[2,3], M. La Cognata[2], S. Cherubini[2,3], G. L. Guardo[2,4], M. Gulino[1,2], S. Hayakawa[2,5], I. Indelicato[2], L. Lamia[2,3], H. Petrascu[4], R. G. Pizzone[2], S. M. R. Puglia[2], G. G. Rapisarda[2], S. Romano[2,3], M. L. Sergi[2], R. Spartá[2] & L. Trache[4]



$^{12}C+^{12}C$ cross-sections , sources of uncertainties

nb to pb range

1) Backgrounds:

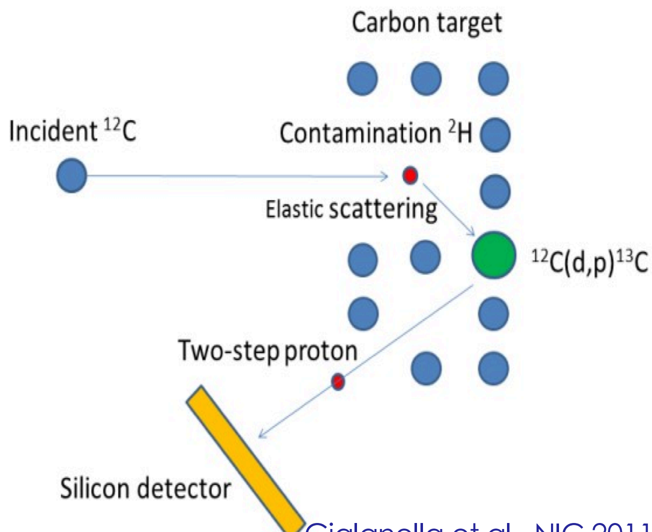
Detection of charged particles, p and α:

$^{12}C + H \longrightarrow$ p and $^{12}C + D \longrightarrow$ p or d

Detection of γ-rays:

$^{12}C + H \longrightarrow \gamma$ and $^{12}C + D \longrightarrow \gamma$;

cosmic rays and room backgrounds



Gialanella et al., NIC 2011

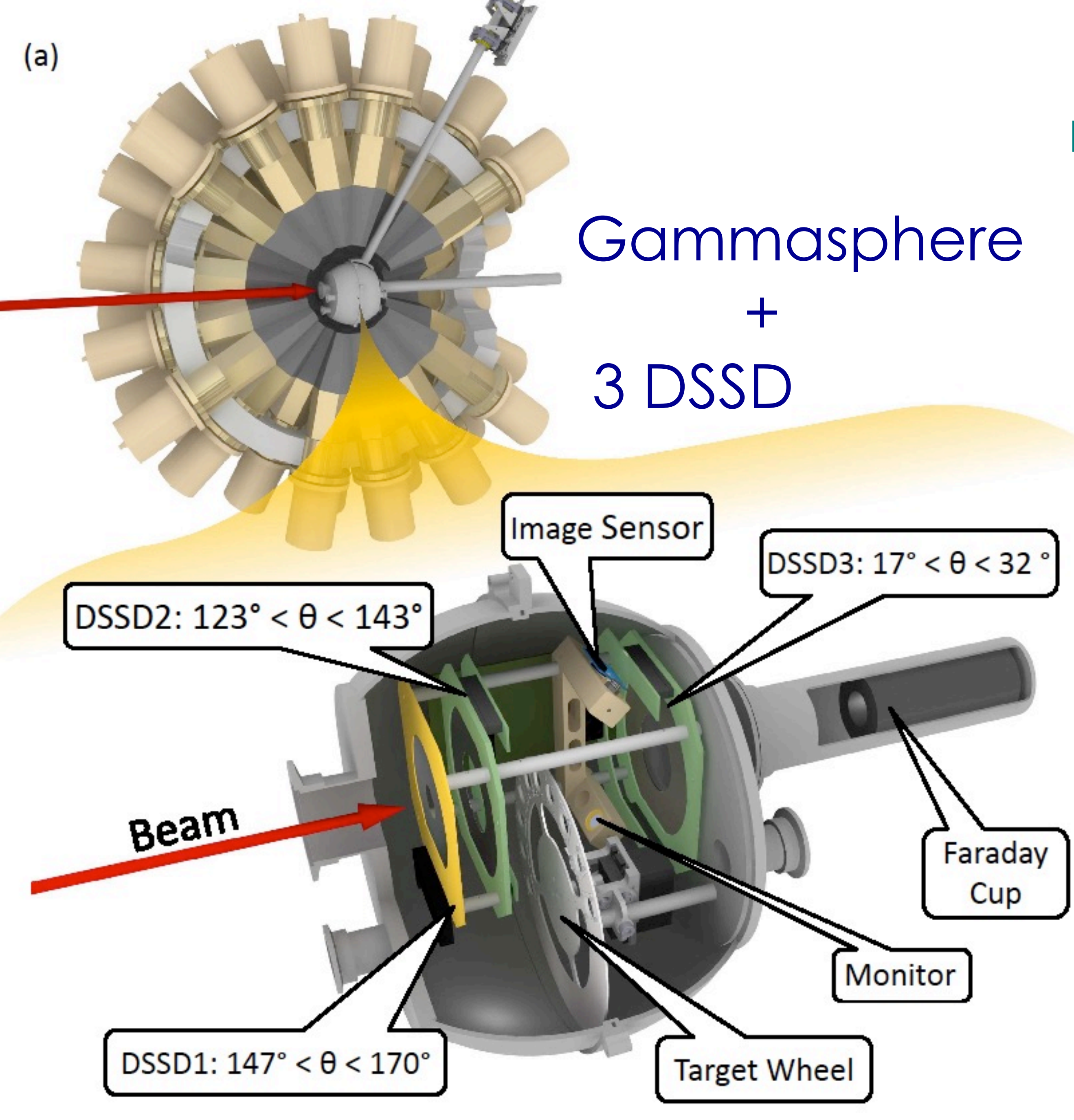
2) Thick targets measurements:

Taking the difference of two measurements at different energies.

New technique

Particle-γ coincidences

Argonne NATIONAL LABORATORY



Gammasphere
+
3 DSSD

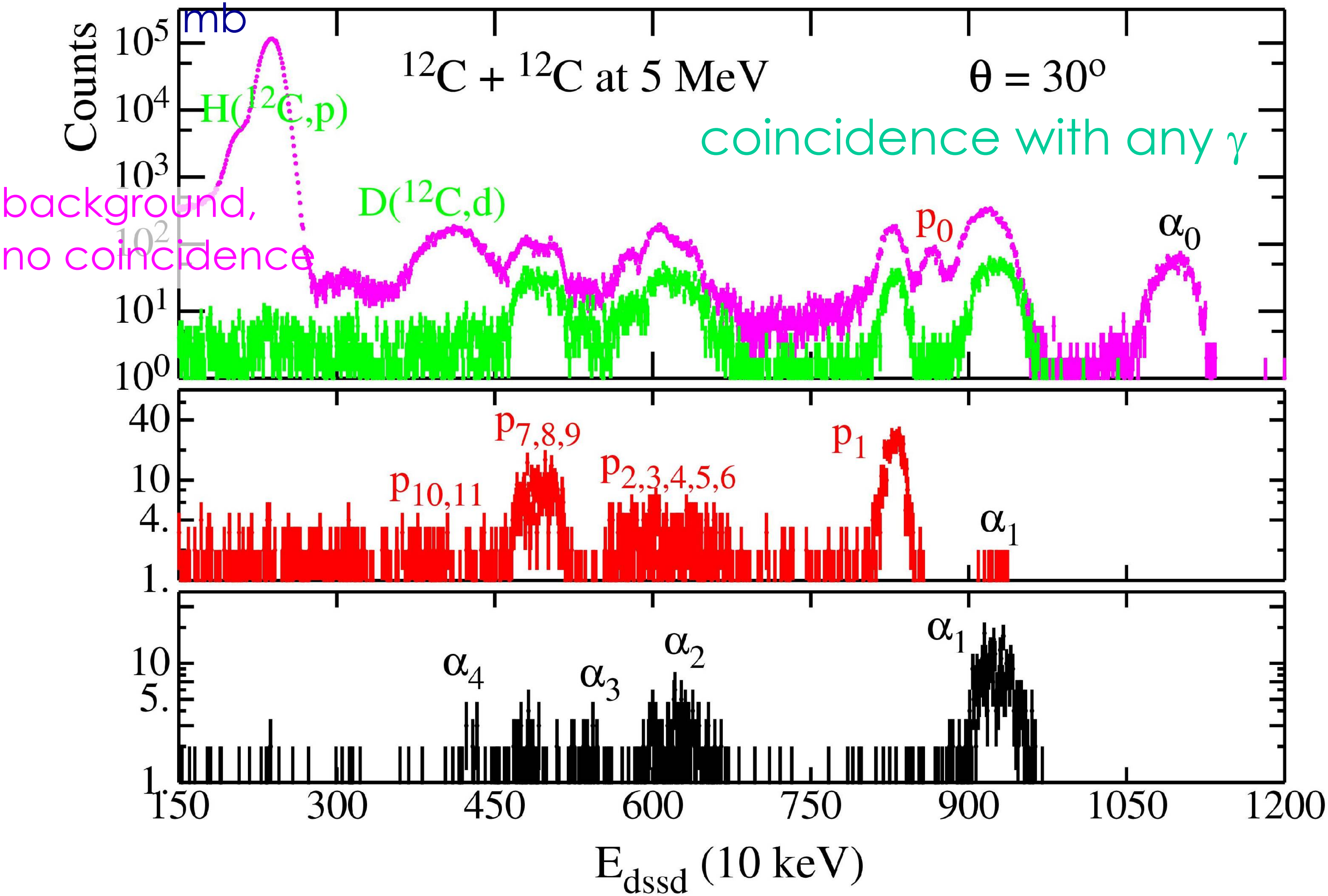
1) Reduction of the backgrounds

2) Using thin target

$I_{Max\text{-}12C} = 600$ pnA

New technique

Particle spectra, E_{lab} = 10 MeV, σ ~5 mb



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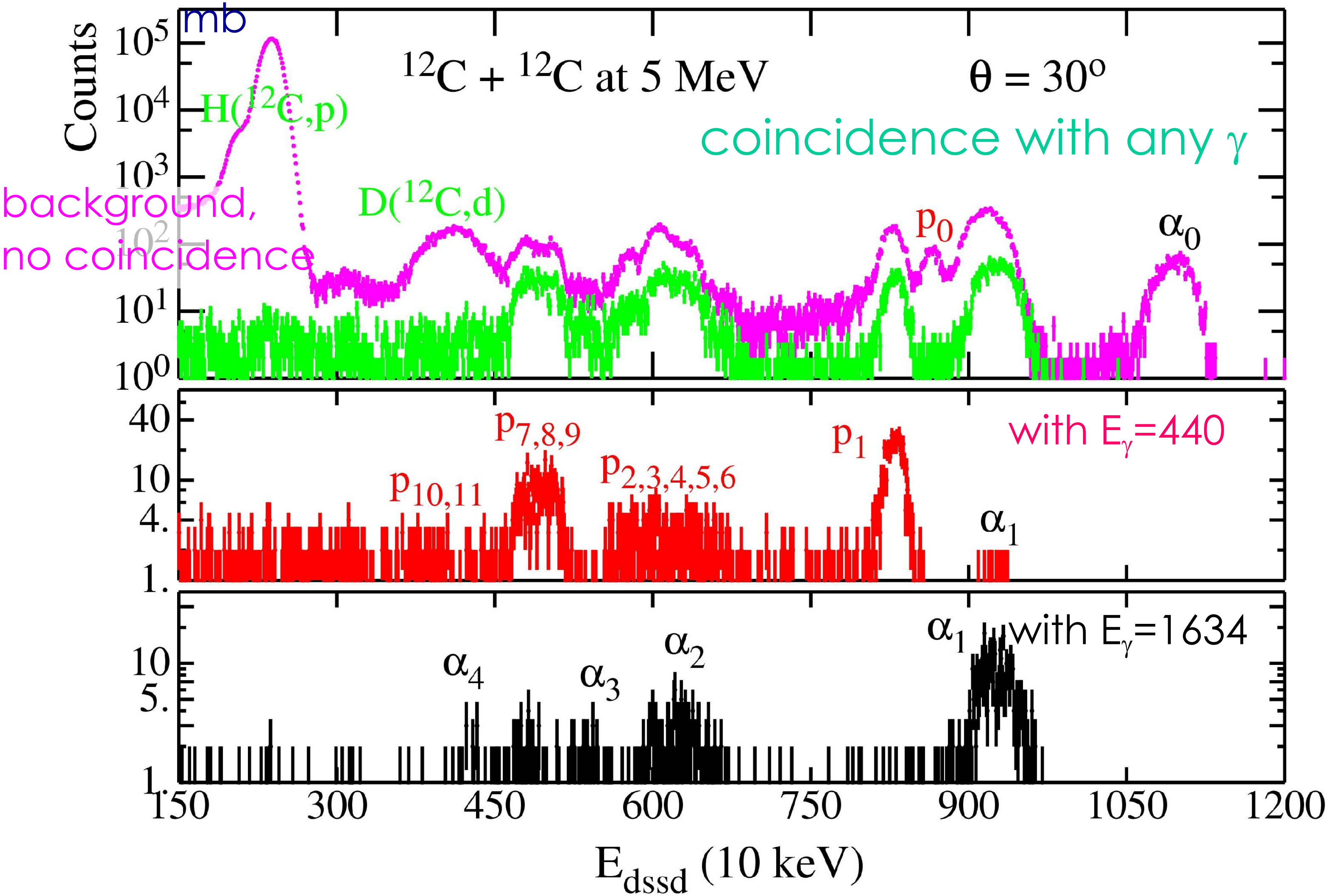

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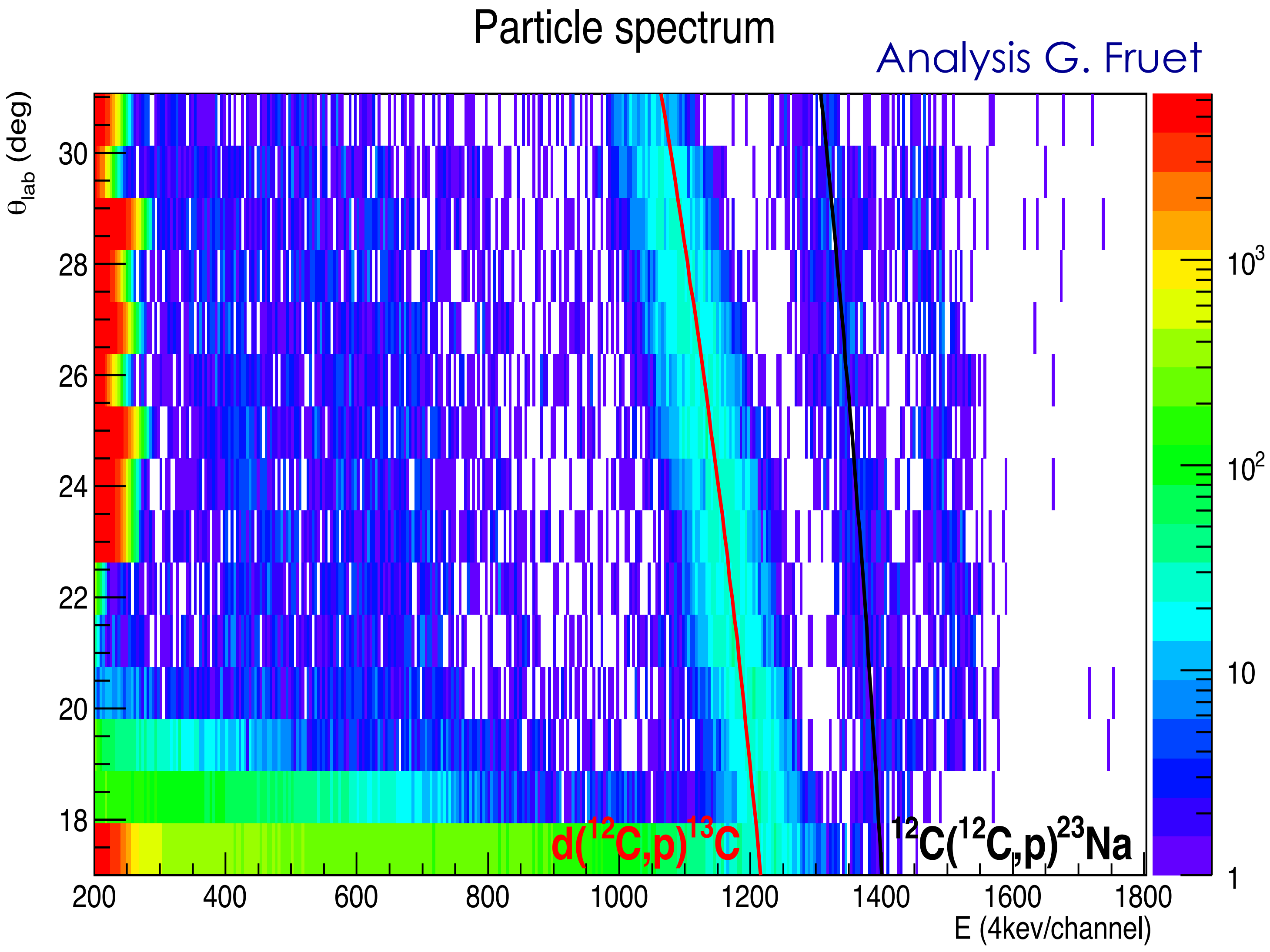
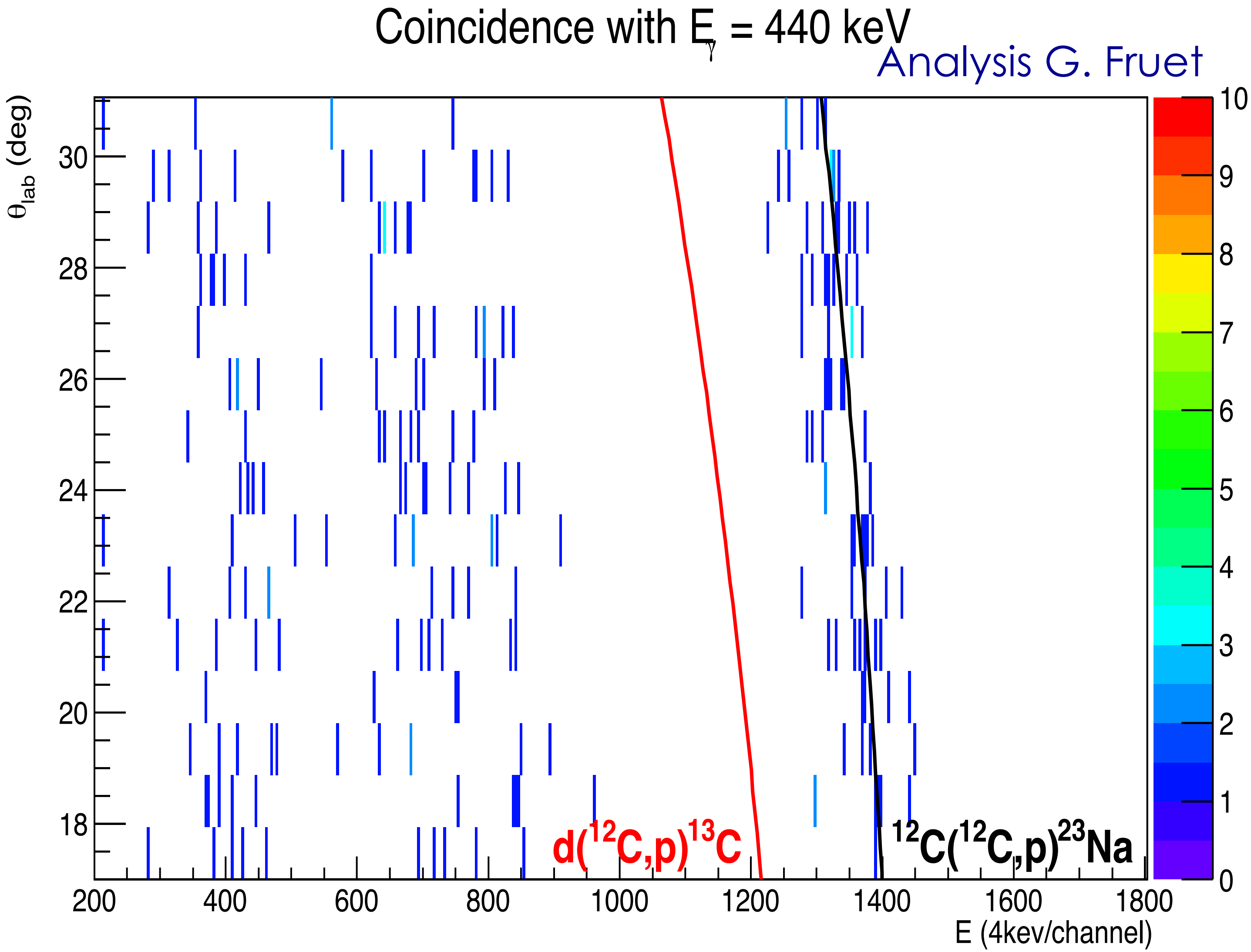
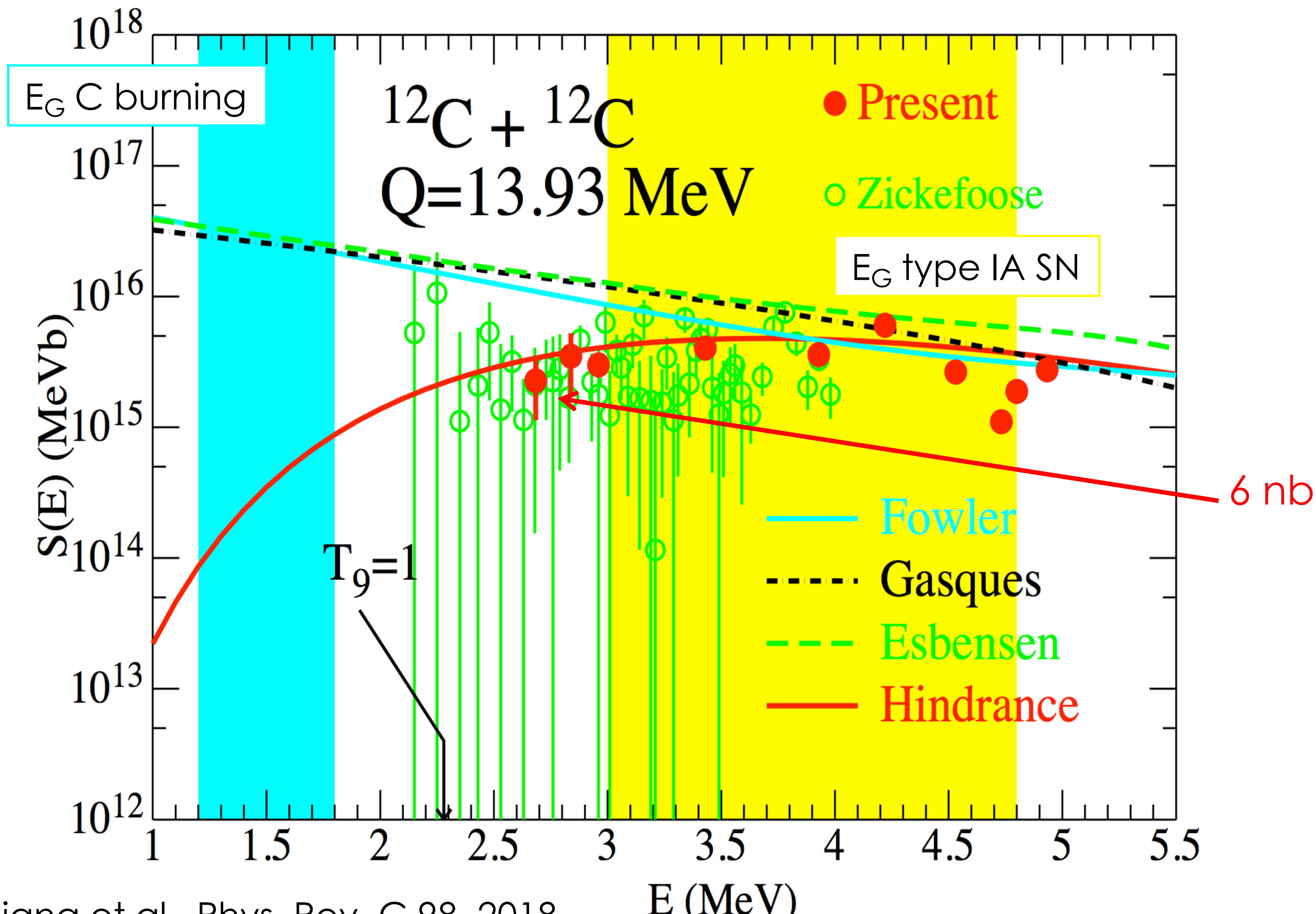


New technique



Results

Gammasphere runs E_{Lab} = 5.5 – 10 MeV, $I_{Max\text{-}12C}$ = 600 pnA



CL Jiang et al., Phys. Rev. C 98, 2018

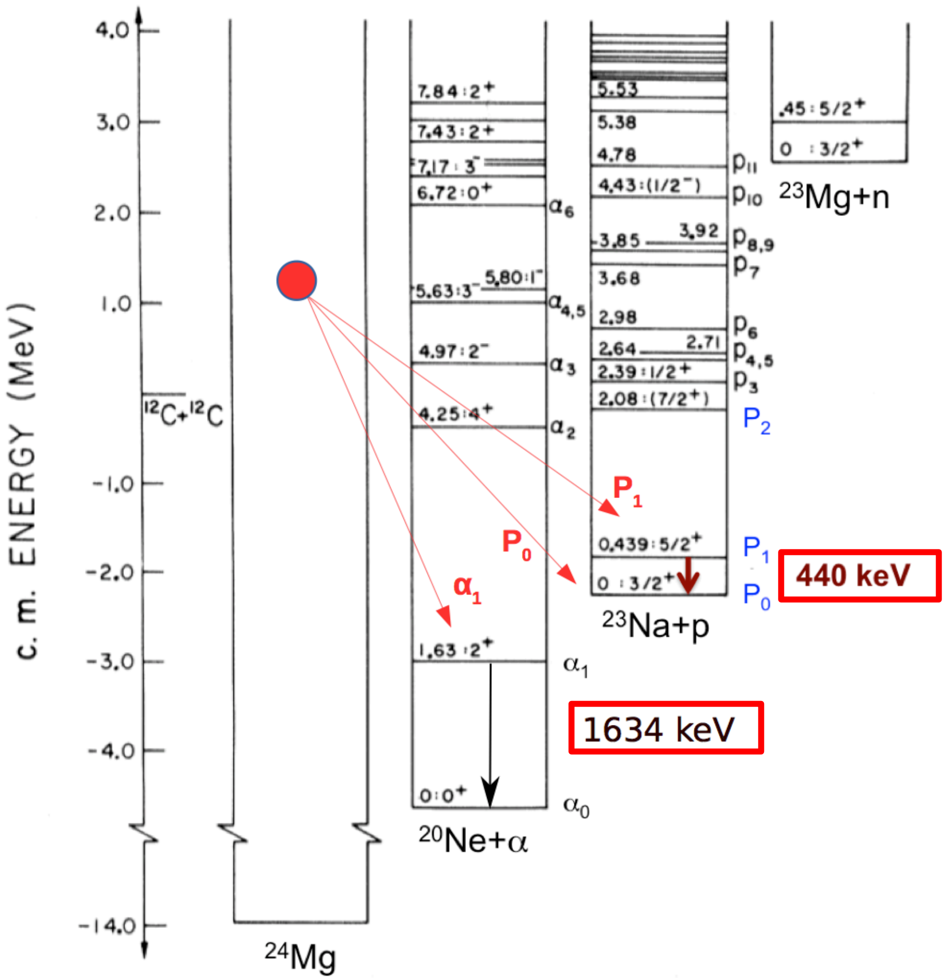
New challenges

Increase beam intensity

Adapt target system

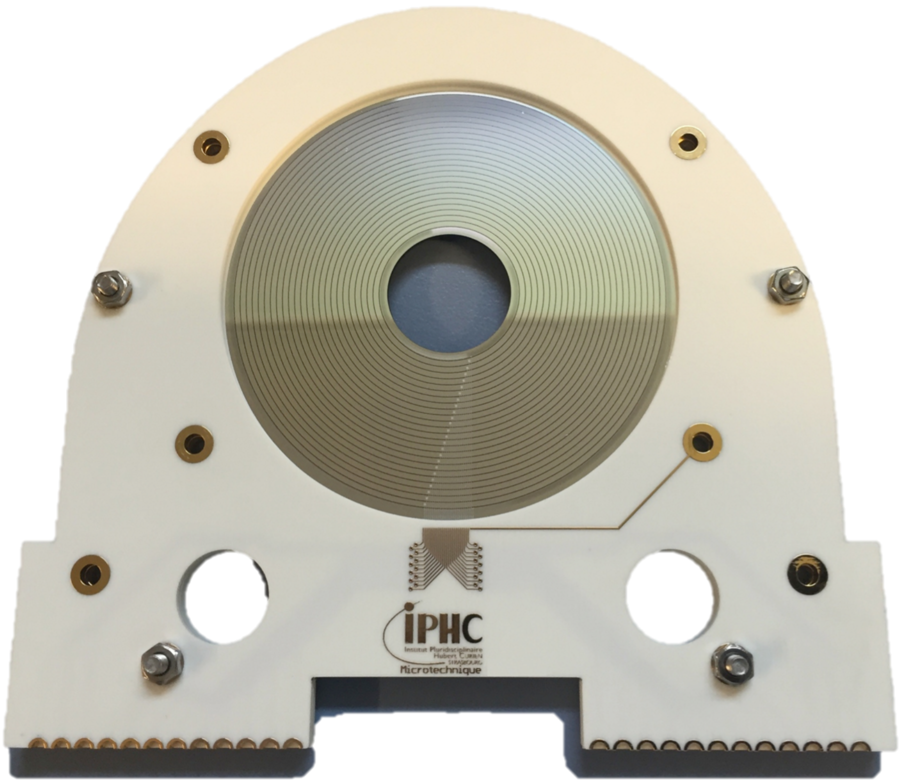
Use of the γ-particle coincidence technique with better gamma efficiency

Challenges for the STELLA + FATIMA project



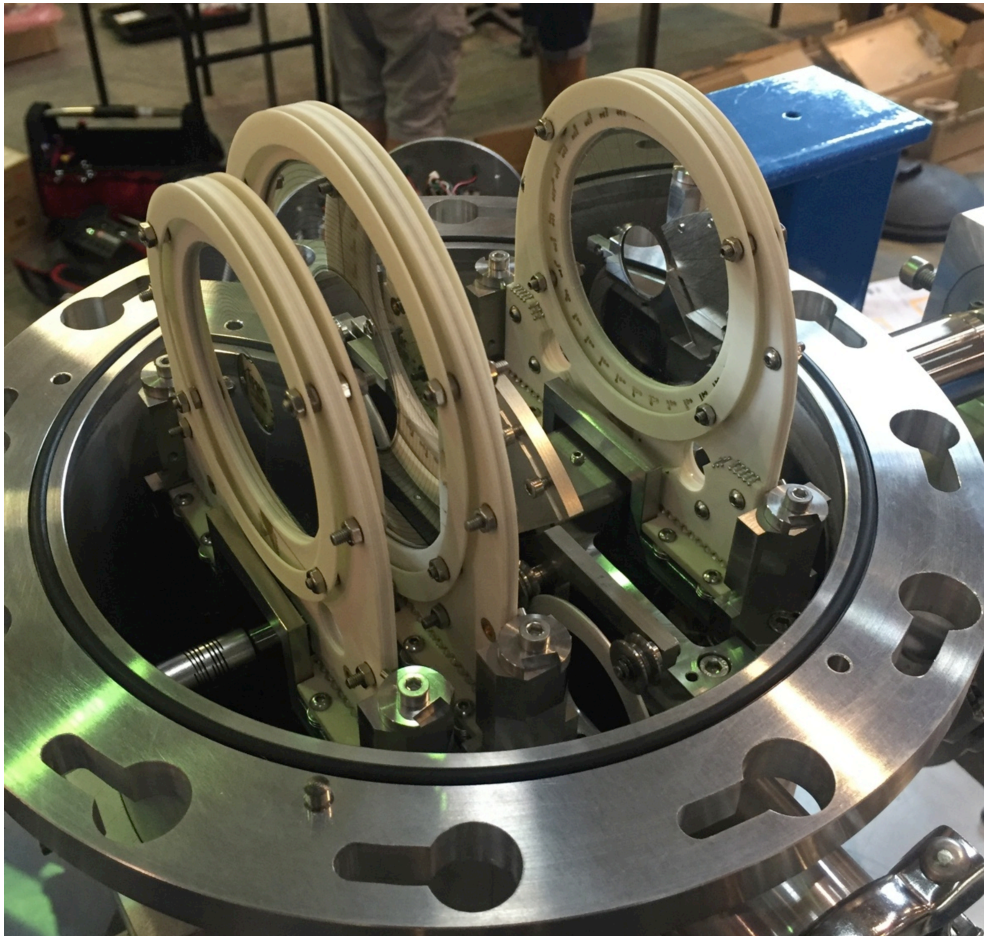
- γ-particle coincidences : $\text{Efficiency}_{Tot} = \varepsilon_\gamma \times \varepsilon_{part}$
- Contamination
- Carbon build-up
- Thin target under high intensity beam
- ‘Long’ beamtime

Particle detection



- Annular DSSD, MICRON chip Collab. York
- New PCB design / ceramics
- New pin connectors
- $\Delta\Omega \sim 24\ \%$ of 4π.

Particle detection



- Annular DSSD, MICRON chip
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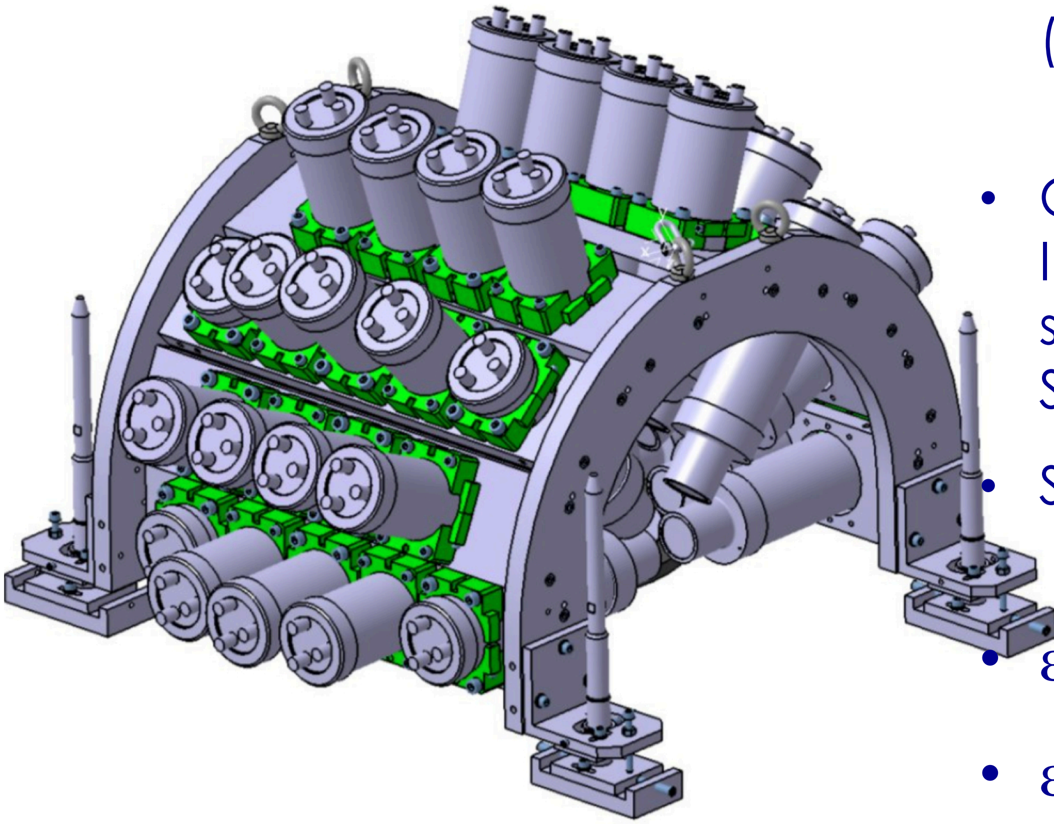
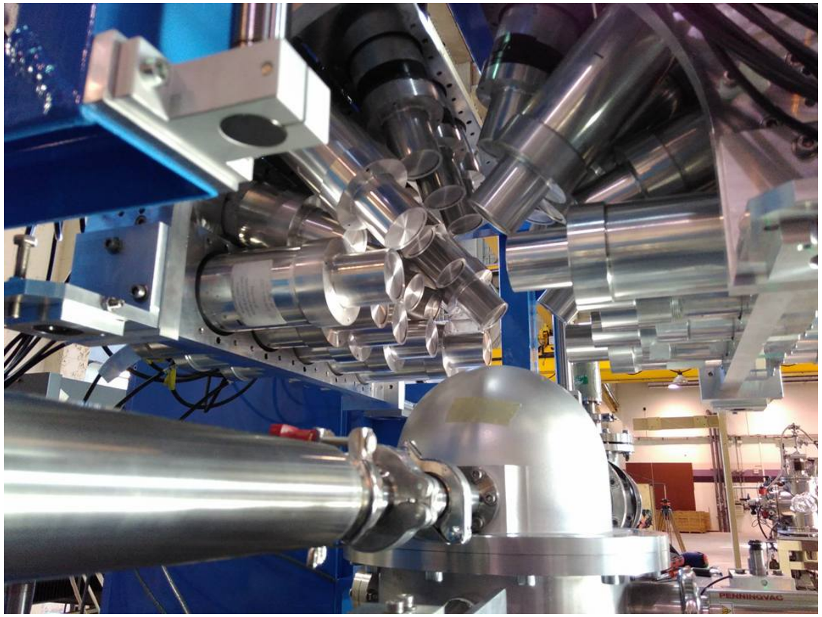
Gamma detection



Design IPHC : G. Heitz / M. Heine

- Up to 36 $LaBr_3$ detectors from the FATIMA collaboration (P. Regan et al.)
- Cylindrical geometry IPHC designed mechanical support, Strabourg + York construction
- Self activity
- ε = 8% @ 440 keV
- ε = 5% @ 1634 keV

Gamma detection



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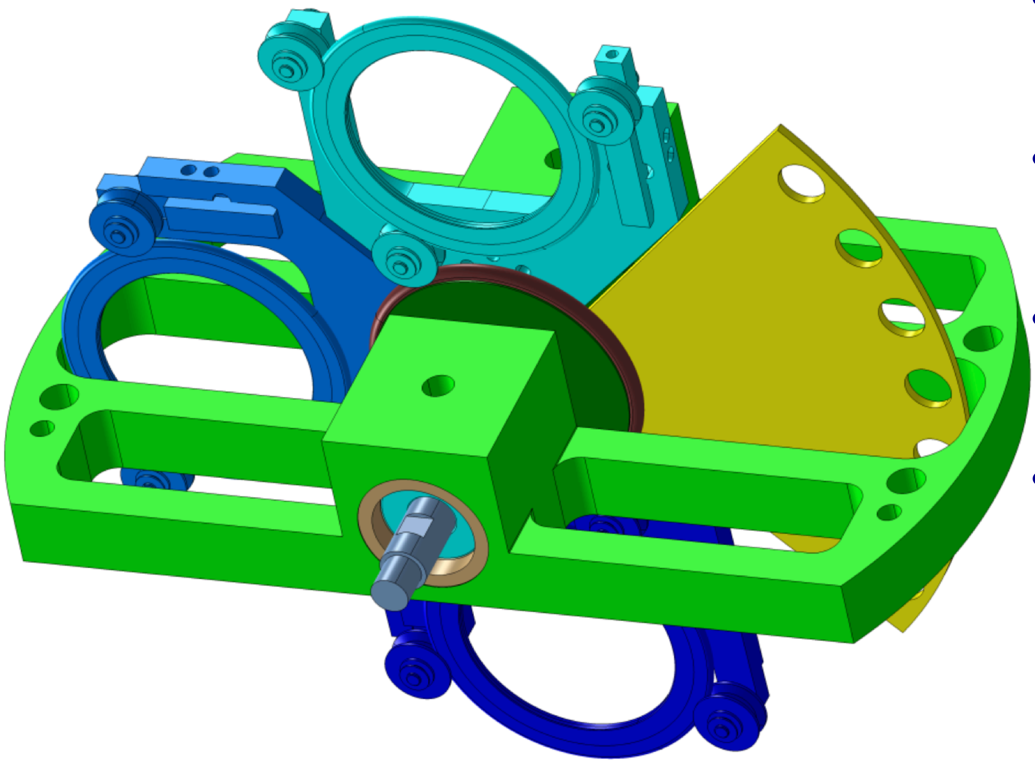
Targets

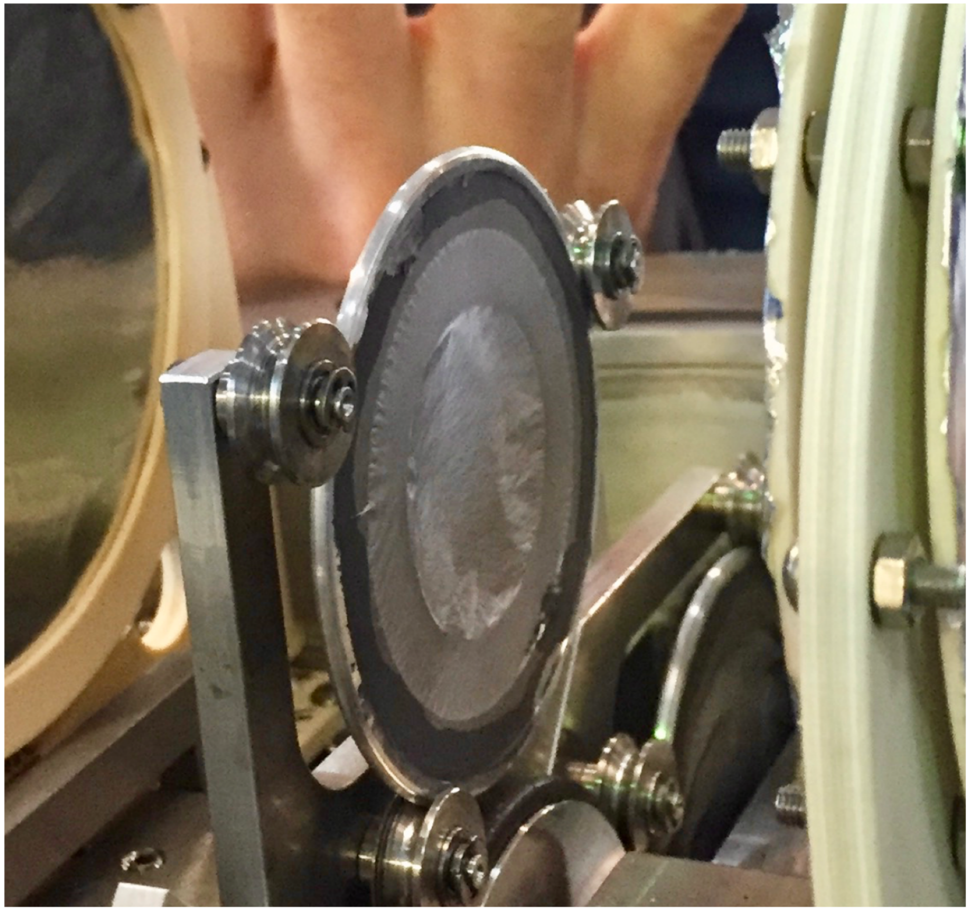
- Cryogenic pumping
- Fixed target system
- Rotating target (> 1000 rpm)
- I > 1 pμA



Collaboration : IPHC and GANIL

M. Heine et al., submitted to NIMA

Targets



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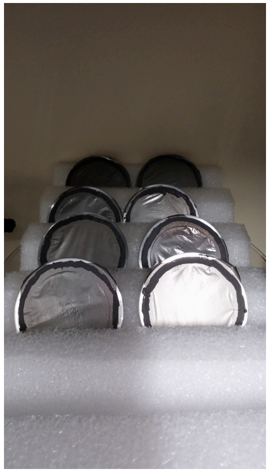
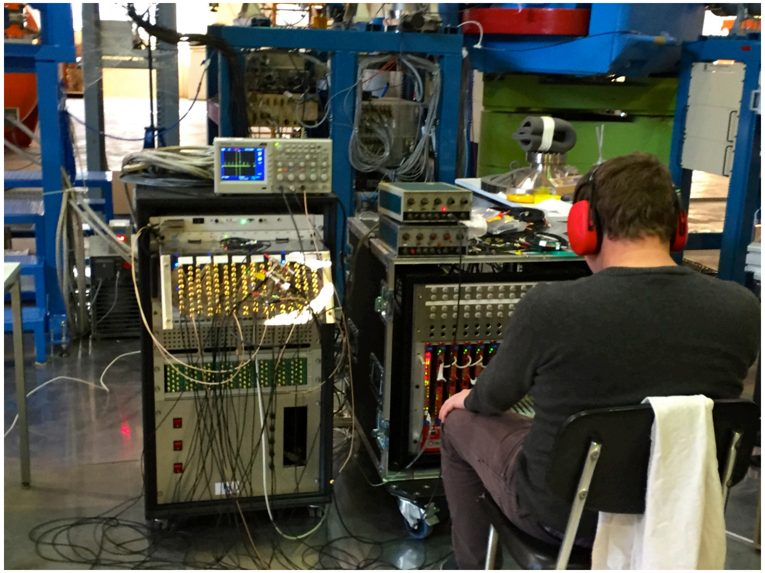


M. Heine et al., submitted to NIMA

DAQ



M. Heine, M. Rudigier

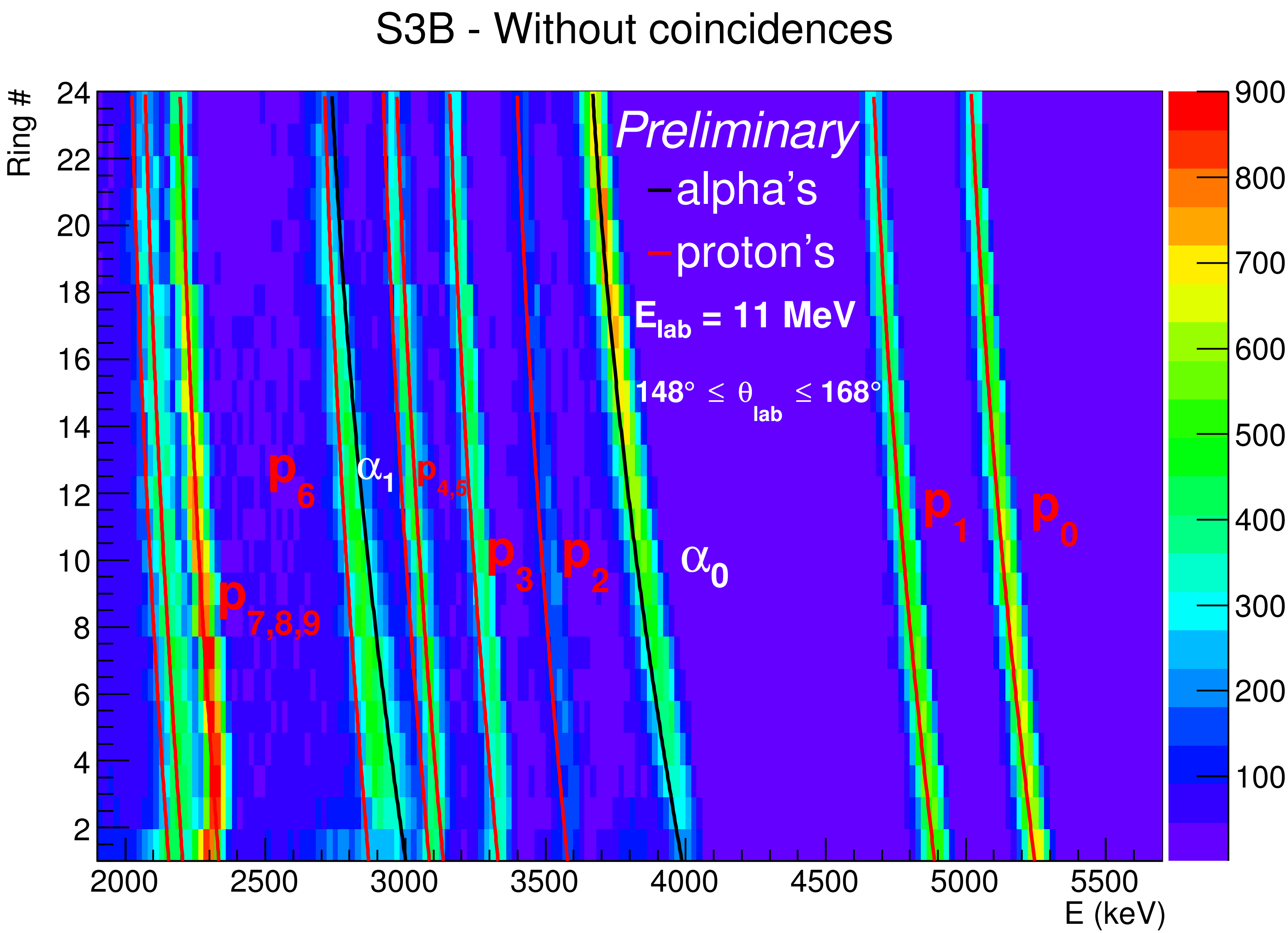
- µTCA system (CERN)
- 96 channels
- 125 MHz clock
- Synchronized with the FATIMA DAQ.

M. Heine et al., submitted to NIMA

Beam

- Andromede facility, University of Paris-Sud - Orsay
- 4 MV Pelletron
- ECR Source
- ^{12}C up to 10 μA

Results of the 1st run



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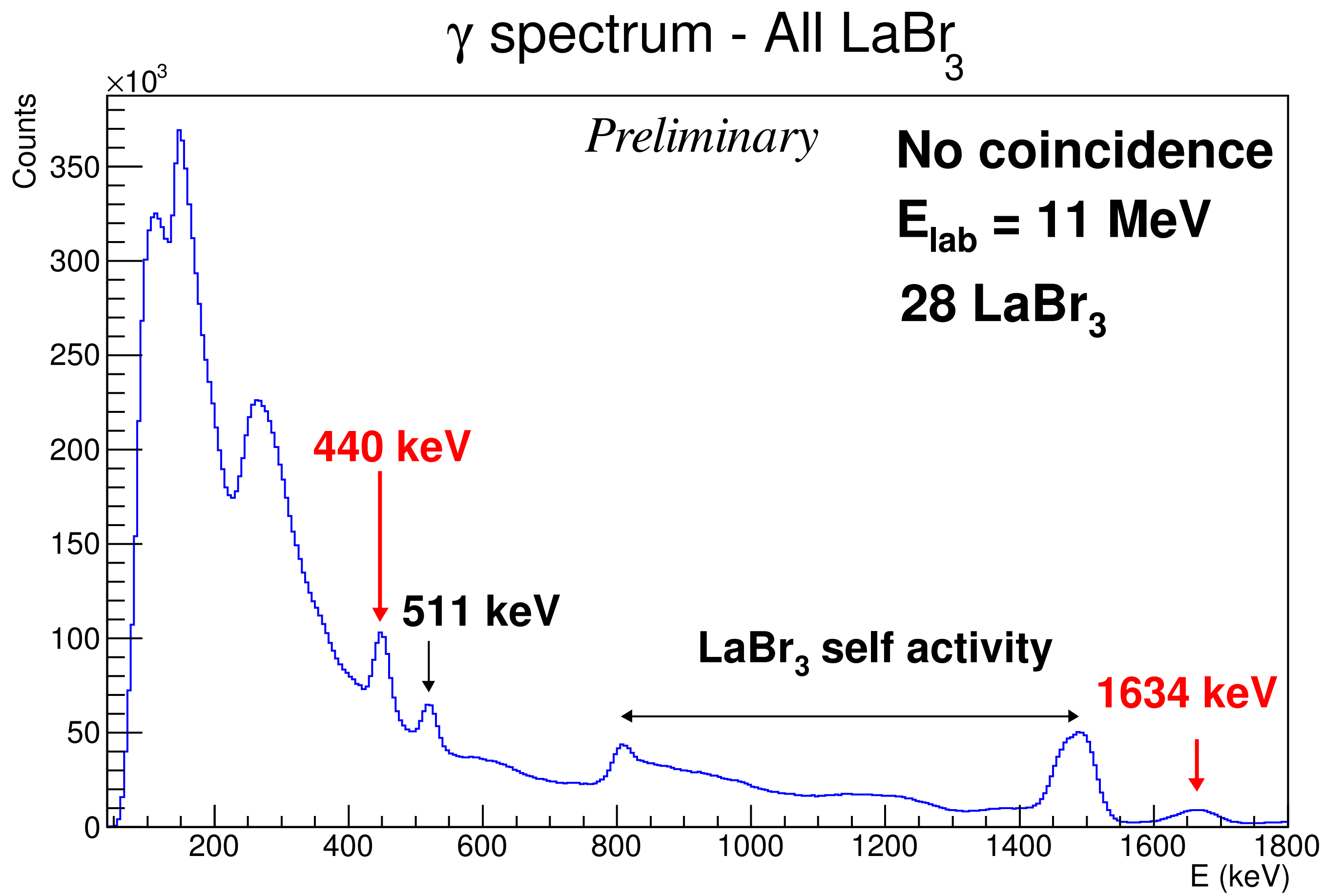
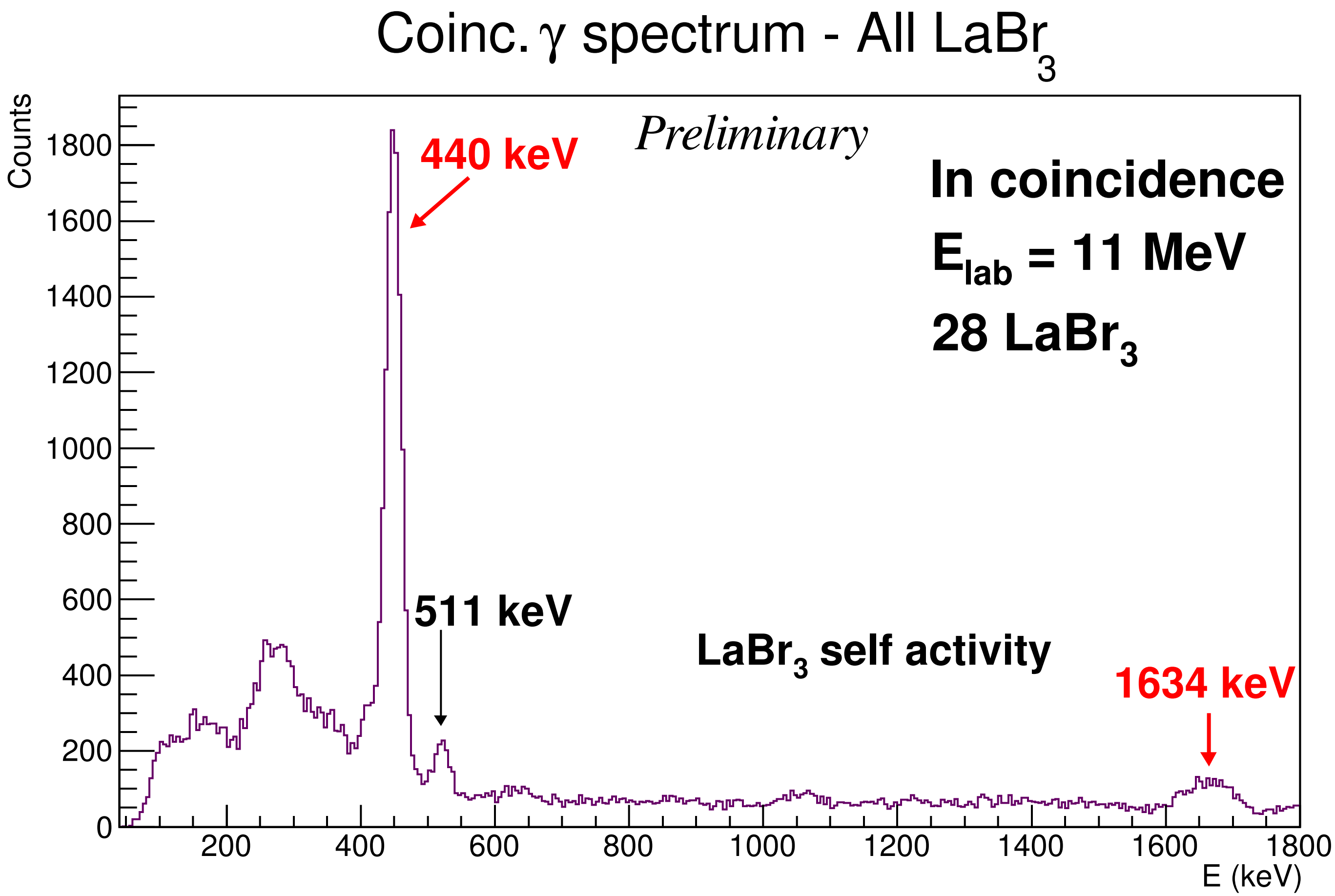


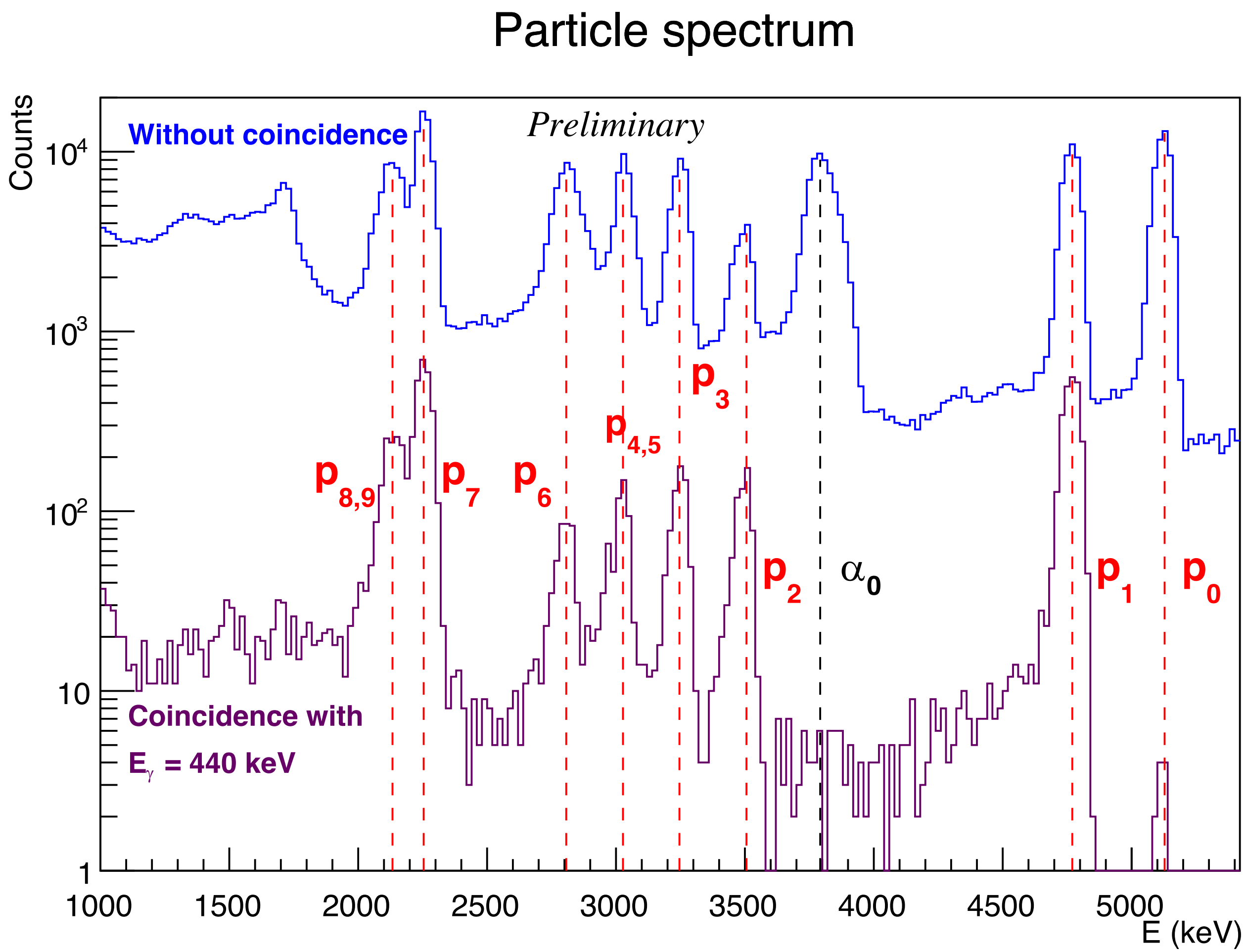
Self activity & γ of interest from $^{12}C+^{12}C$ fusion

Results of the 1st run



Coincidence with 1 particle : γ from fusion

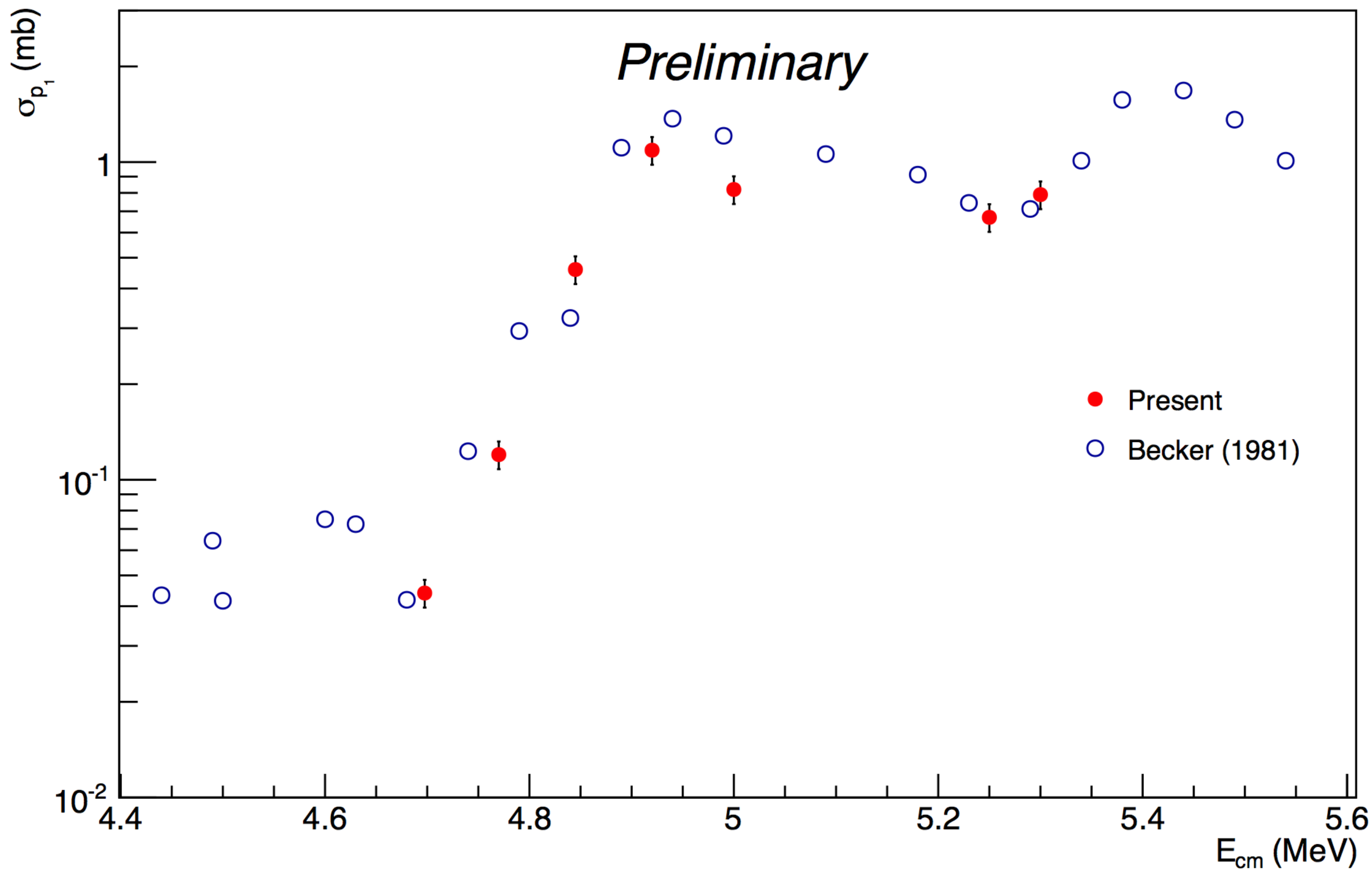
Results of the 1st run



Gate on E_γ = 440 keV

Suppression of α_0 and p_0 / $\varepsilon_{440\ keV}$ = 6%

Results of the 1st run

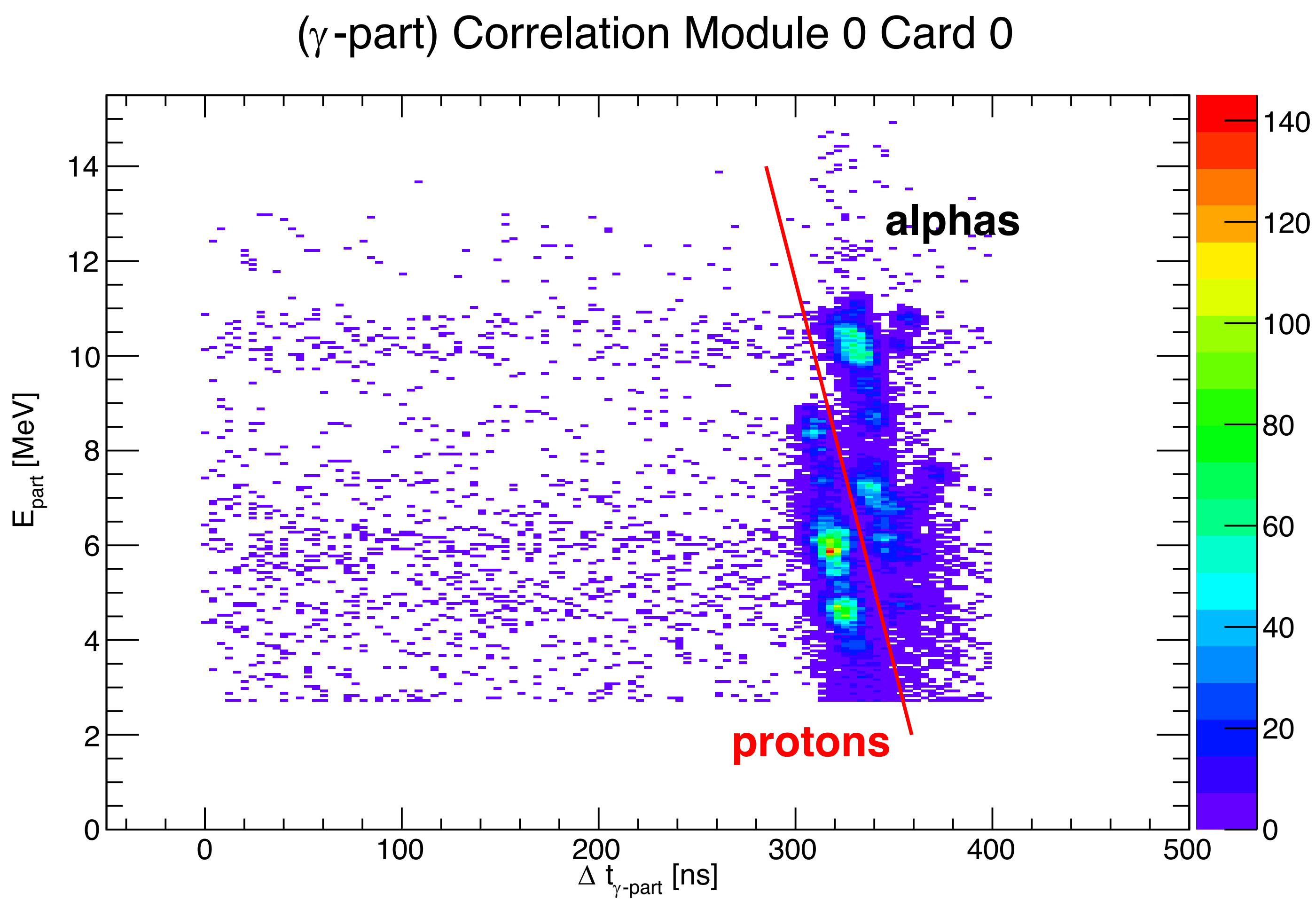


p_1 cross section vs center of mass energy

Cross section consistent with previous experiments

Analysis performed by G. Fruet and M. Heine

Timing and background ...



M. Heine et al., submitted to NIMA

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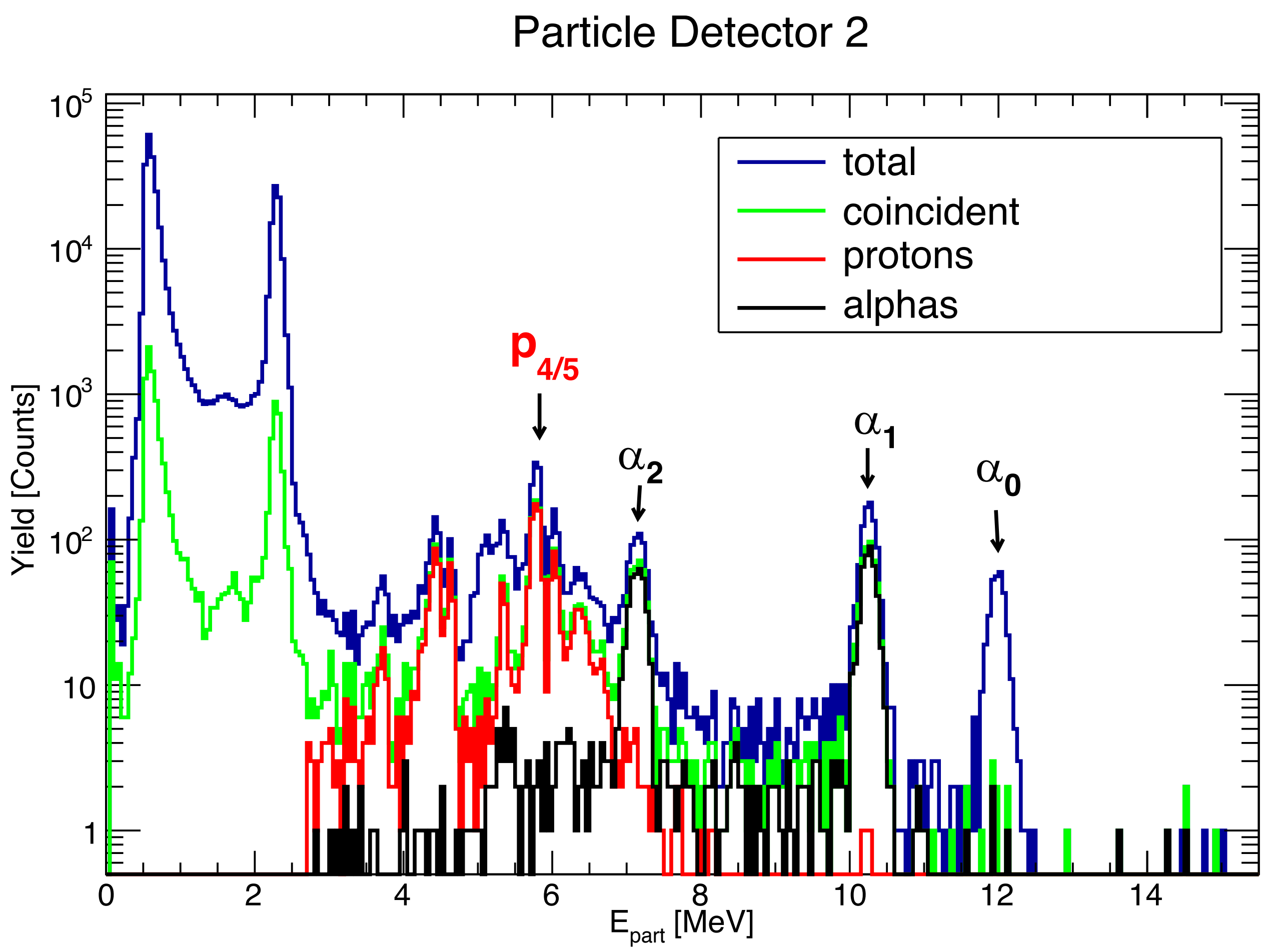
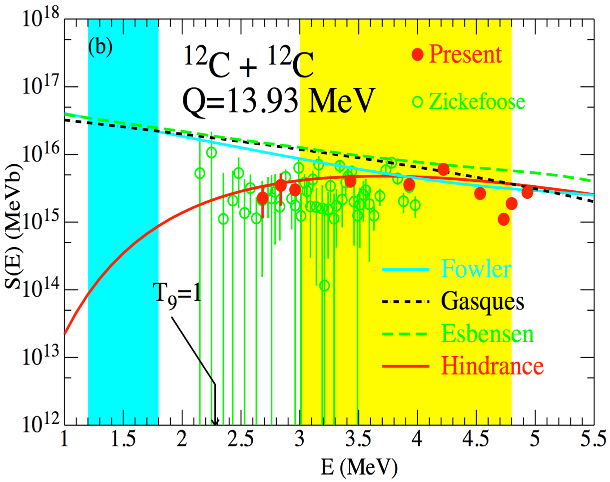


Conclusions

- Succesfull comissioning of the STELLA + FATIMA experiment
- 12 energy points explored E_{Lab} = 11 to 5.6 MeV consistent with previous work
- Succesful test of the rotating target system
- Data under analysis
- High intensity phase (^{12}C+^{12}C, I > 1 μA): Sept. – Dec. 2017
- Other systems in the coming phases

Conclusions

… astrophysics ?



Results from the Gammasphere run

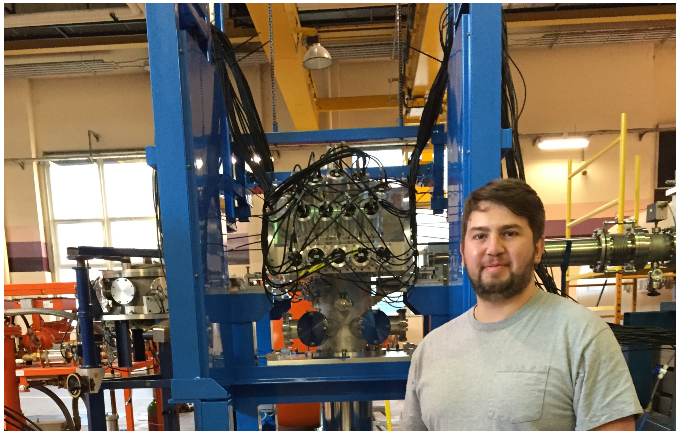
- Reduced reaction rates match the observed ^{26}Al abundance in the Galaxy.
- And, it also leads to a further enhancement of the ^{60}Fe production in the Galaxy

K. Knie et al., Phys. Rev. Lett. 83 (1999) & 93 (2004)

A. Wallner et al., Nature 532, 69 (2016)

L.R. Gasques et al., Phys. Rev. C76, 035802 (2007)

Thanks !



University of Strasbourg and IPHC (France):

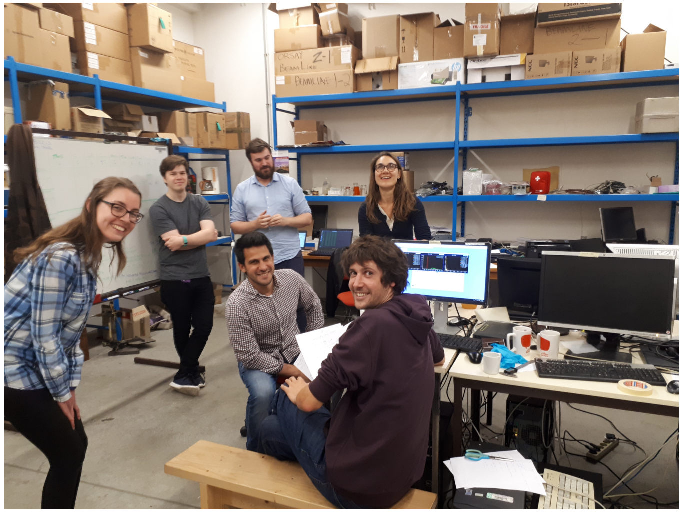
S.C, G. Fruet, F.Haas, M.Heine et al.

University of York (UK): *D.Jenkins , L.Morris*

IPN Orsay : *S. Della Negra, F. Hammache, N. de Séreville, P. Adsley, A. Meyer et al.*

Argonne National Laboratory (USA):

C.L.Jiang, D.Santiago-Gonzalez, K.E.Rehm, B.B.Back et al.



University of Surrey (UK):

P.H. Regan, M. Rudigier

GANIL (Caen, France):

C. Stodel et al.

University of Aarhus (Denmark):

O. Kirsebom