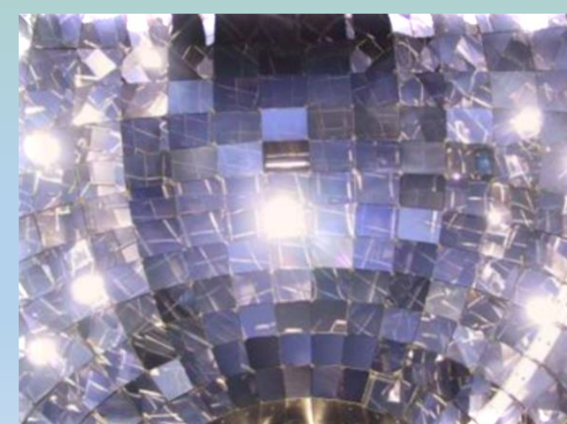
Population and decay of states of ^{12}C

G. Cardella

INFN **Sezione di Catania**

For Chirone collaboration

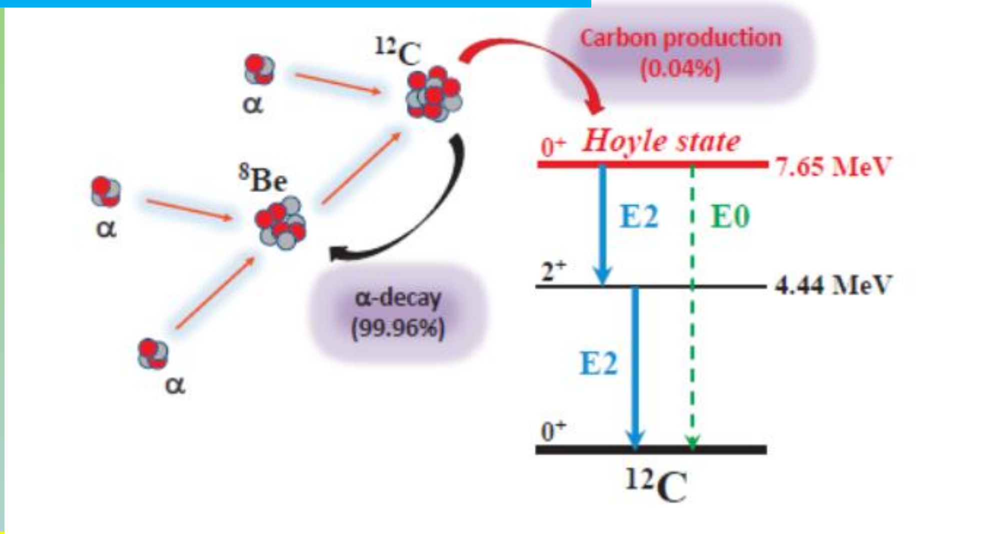
IWM-EC 2021 November 24^{th} CAEN



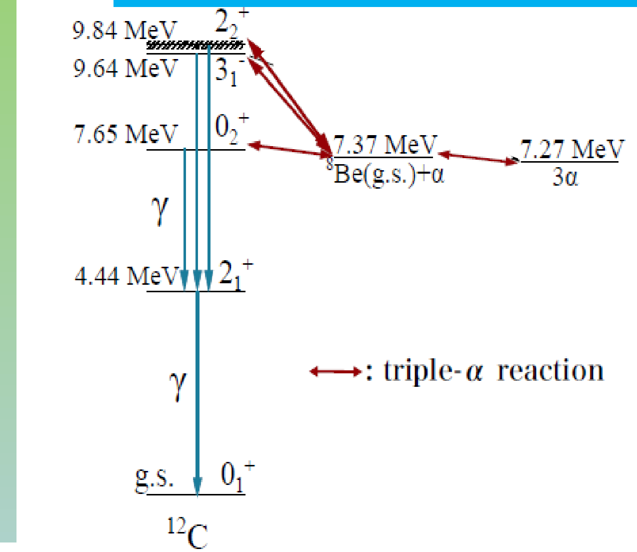
Istituto Nazionale di Fisica Nucleare

Production of Carbon in stars: The role of Hoyle and 9.64 MeV states γ-decay

T8 - 100 million of kelvin deg
The Hoyle state dance



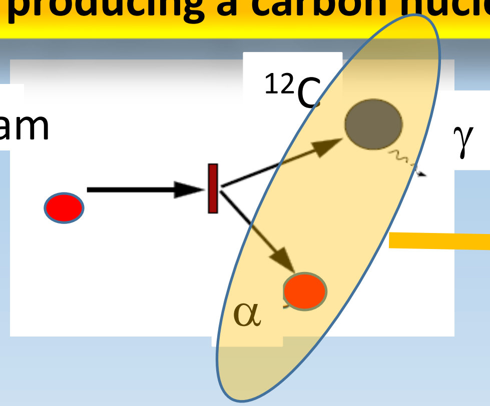
T9 - 1 Billion of kelvin deg
Other levels come into play

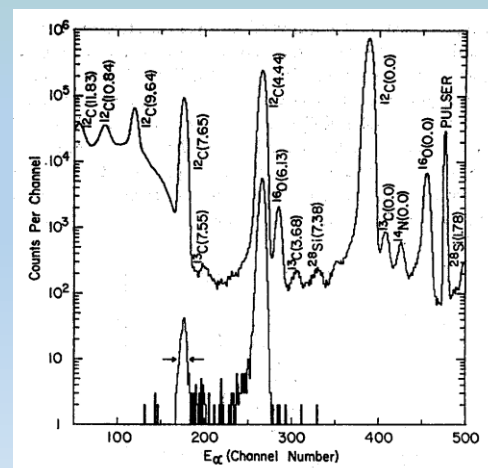


$$\Gamma_{rad}/\Gamma < 8.2 \times 10^{-7} (95\%\mathrm{C.L.})$$

Only about 4 times each 10000 events **(R.G.Markham et al Nucl.Phys.A270(1976)489)** **the Hoyle state decays trough the emission of two γ-rays so producing a carbon nucleus**

Chamberlin method





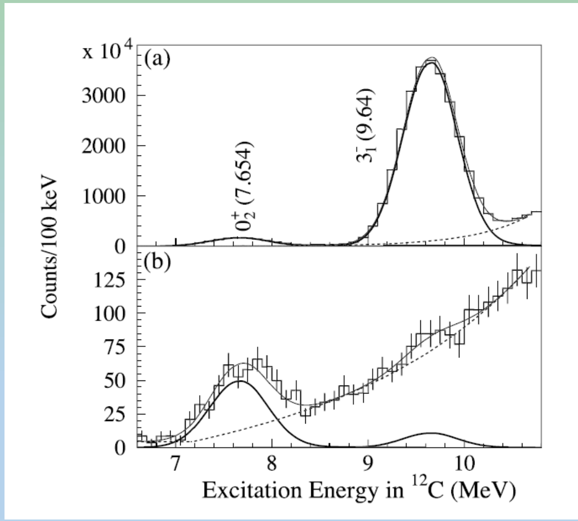
STATUS OF THE ART: recent attempts to improve results

T. Kib´edi et al PHYSICAL REVIEW LETTERS 125, 182701 (2020)

$p+^{12}C$ reaction at 10.7 MeV p-γ–γ coincidence at OSLO cyclotron
p measured with SIRI strip array – γ with CACTUS array of 26 NaI detectors

Hoyle status new surprising result

$$\Gamma_{\mathrm{rad}}/\Gamma = 6.2(6) \times 10^{-4}.$$

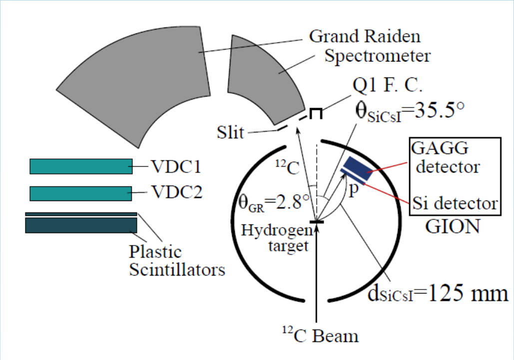


Tsumura at al Phys.Lett. B817(2021)136283

9.64 Yield larger than expectation also measured

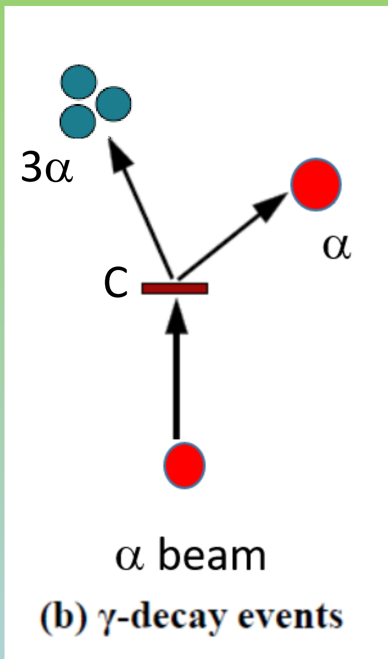
$$\Gamma_{\mathrm{rad}}/\Gamma_{\mathrm{tot}} = 1.3^{+1.2}_{-1.1} \times 10^{-6}$$

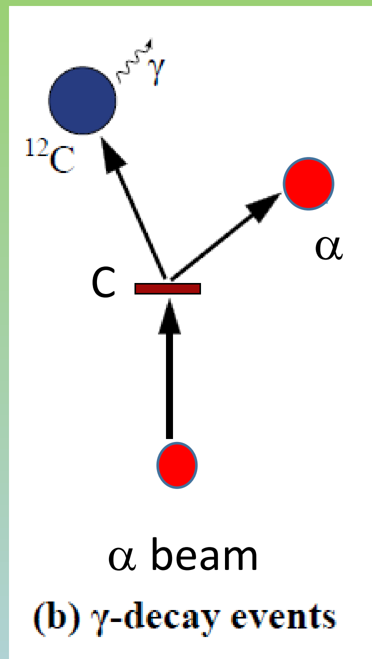
Very high background notwithstanding the big technological efforts



Solid hydrogen target

BACKGROUND REDUCTION : THE CRM method

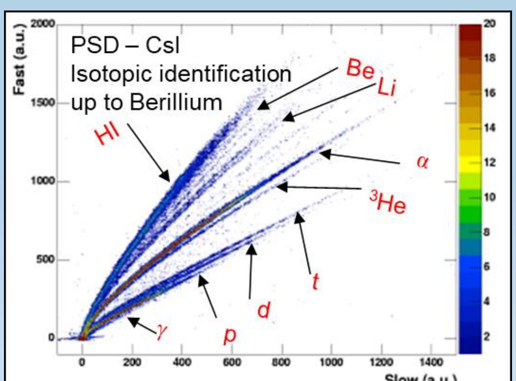


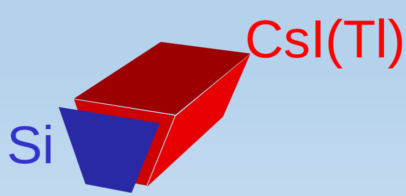


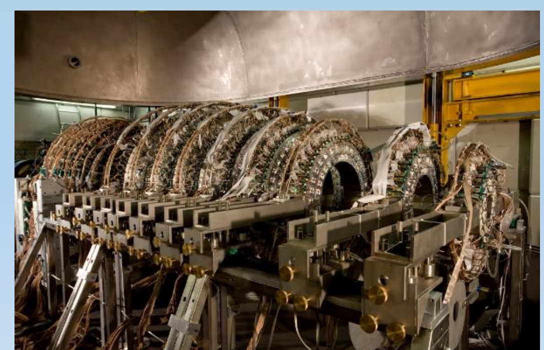
We can reduce the background using more constraints: measure all particles and γ – use energy and momentum conservation

Complete Redundant Measurement - CRM

Need a complete detector : CHIMERA



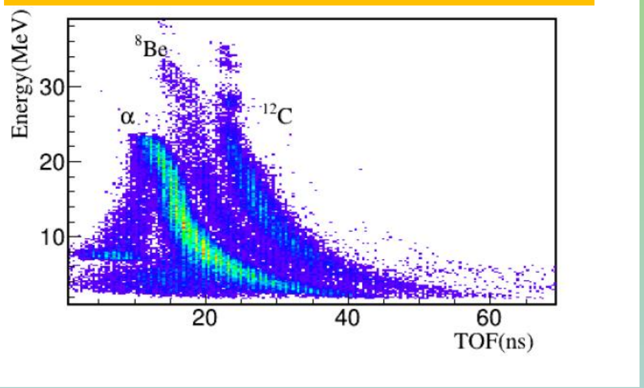


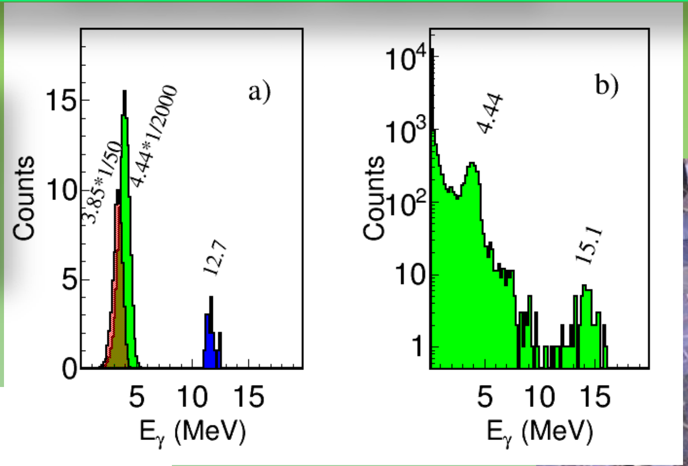


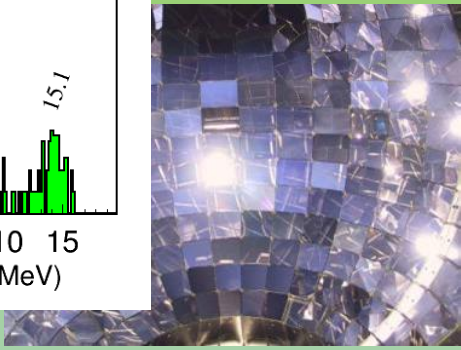
THE EXPERIMENT : detection method

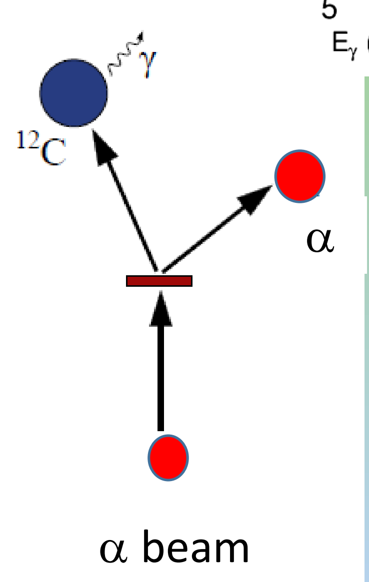
We performed the reaction α+^{12}C at 64 MeV at LNS

G.Cardella et al PRC in print

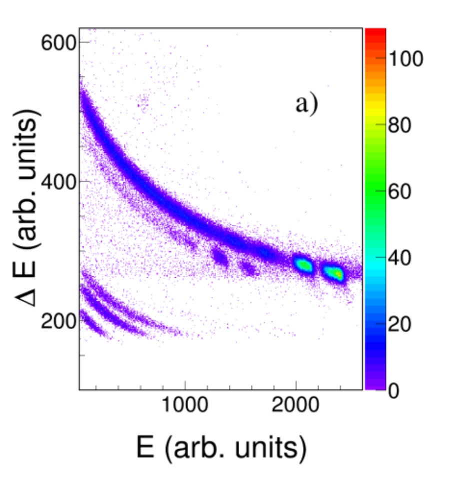






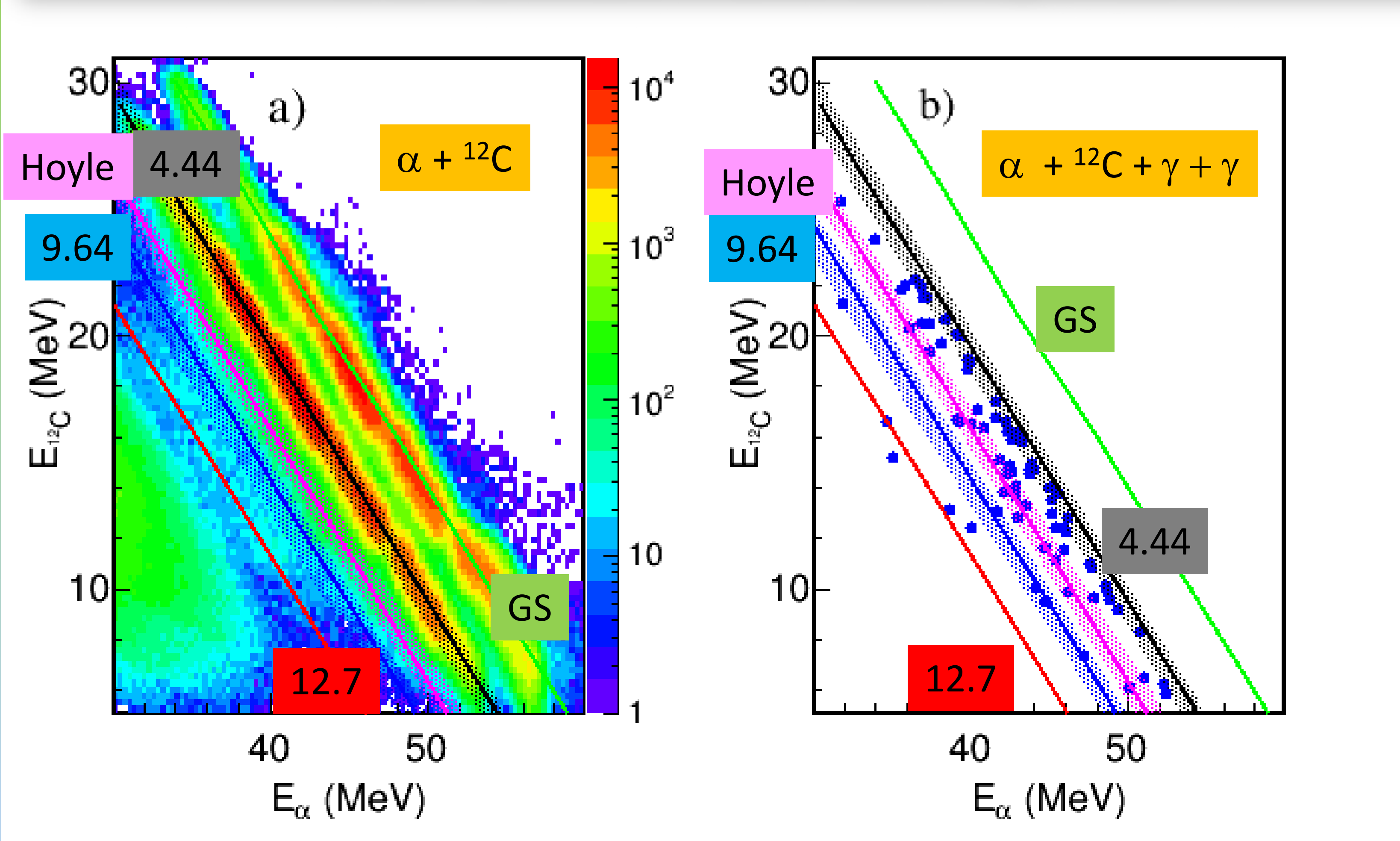


(b) γ-decay events



We detect and identify in energy both scattered α-particles(by ΔE-E) and carbon (by time of flight) – detection efficiency of kinematical coincidences is 100% in a 4π detector –γ rays in CsI(Tl)

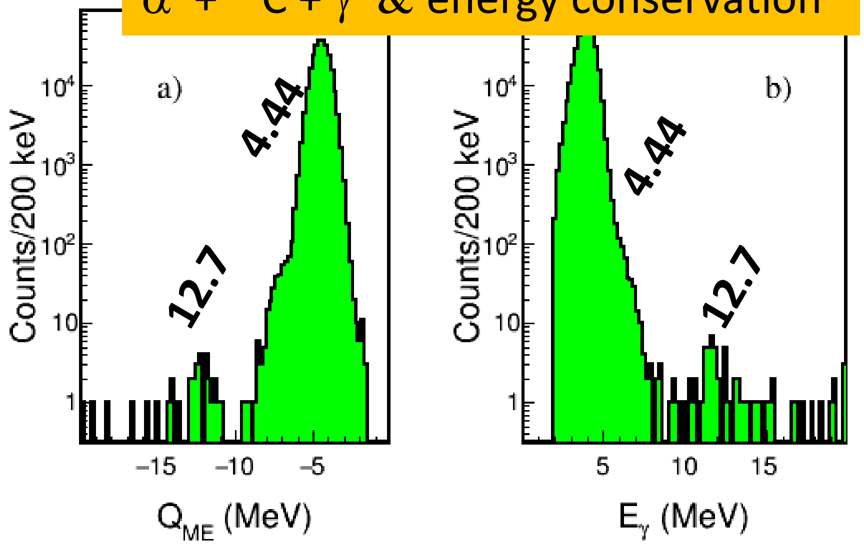
THE EXPERIMENT : CRM cleaning effect



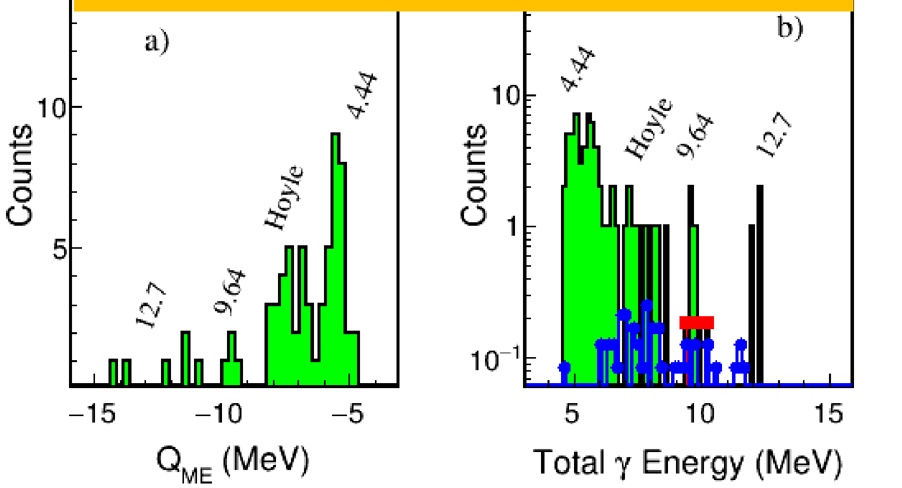
This plot shows how one can further clean Chamberlin method results imposing also the coincidence with 2-γ and all conservation rules even with a relatively scarce angular and energy resolution

THE EXPERIMENT : particle-gamma coincidences

$\alpha + {}^{12}C + \gamma$ & energy conservation

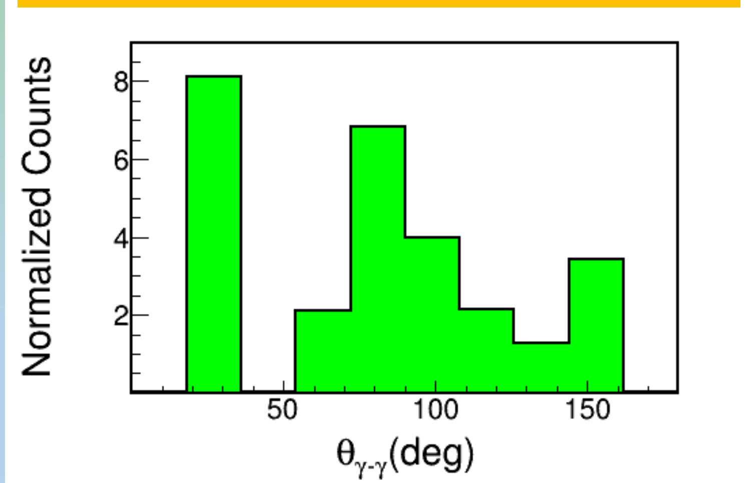


$\alpha + {}^{12}C + \gamma + \gamma$ & energy conservation



In coincidence with 1 γ we see only the 4.44 and the 12.7 MeV level both in Q-val and in γ-energy

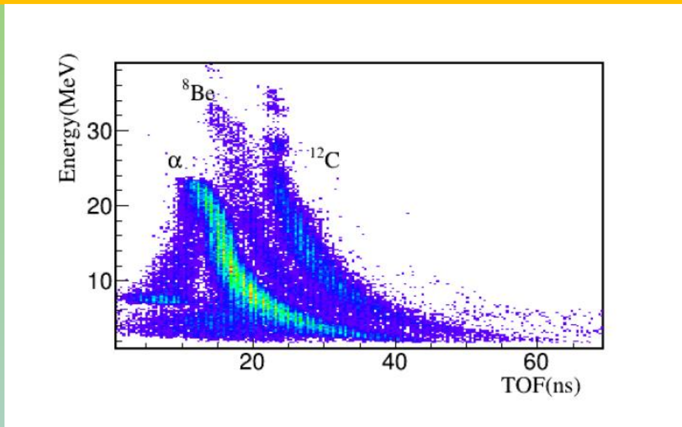
In coincidence with 2 γ we see a little residual background of the 4.44 the Hoyle, the 9.64 MeV and 12.7 MeV level both in Q-val and in γ-energy



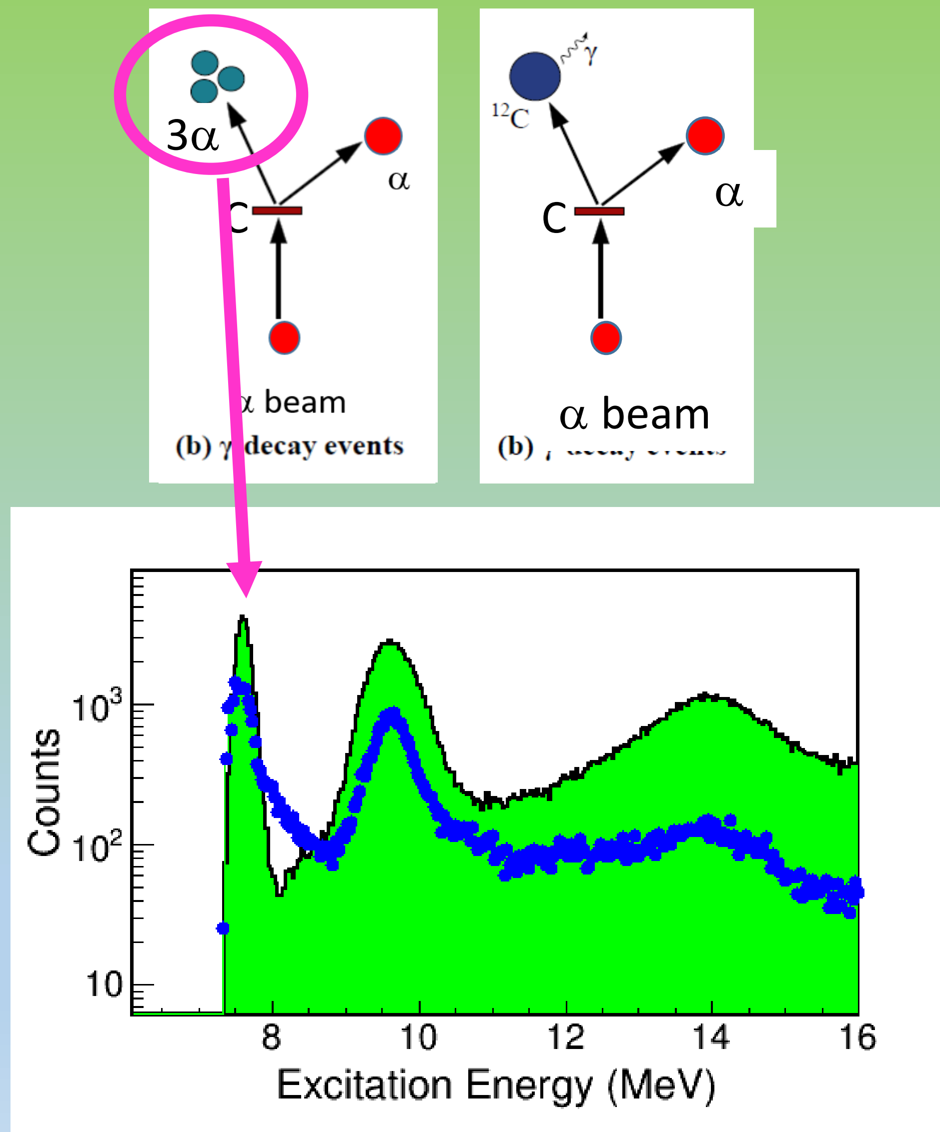
γ rays angular correlation for the Hoyle state similar to M.Munch et al PRC 93, 065803(2016)

THE EXPERIMENT : YIELD EVALUATION

How to extract the yield of Hoyle and 9.64 Mev Level?



We detect and identify α particles from the decay of ^{12}C so we can evaluate the excitation energy in the 3-α CM and produce the excitation energy spectrum giving the yields



THE EXPERIMENT : evaluated yields

level	singles (counts/ 1000)	two γ counts	efficiency 2 γ %	yield 2γ
12.7	7±1.4	1±1	5.1	0.0028±0.0028
9.64	778.2	2±1.6	4.0	6.4±5.1 x10^{-5}
7.65	199.8	12±3.8	3.3	1.8± 0.6 x10^{-3}

9.64 Tsumura

$$\Gamma_{\text{rad}}/\Gamma_{\text{tot}} = 1.3^{+1.2}_{-1.1} \times 10^{-6}$$

Hoyle - kibedi

$$\Gamma_{\text{rad}}/\Gamma = 6.2(6) \times 10^{-4}.$$

Very large error bars the two results are compatible

Hoyle decay too large WHY?

THE EXTRA-YIELD : efimov state?

Look to some old paper

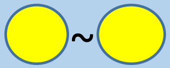
Volume 33B, number 8 PHYSICS LETTERS 21 December 1970

ENERGY LEVELS ARISING FROM RESONANT TWO-BODY FORCES IN A THREE-BODY SYSTEM

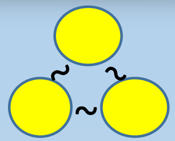
V. EFIMOV
A.F.Ioffe Physico-Technical Institute, Leningrad, USSR

Received 20 October 1970

Again in the 70s of last century Efimov suggested that when two bodies have a resonance, in the system formed by 3 bodies, one will observe a bound status and in principle also an infinite number of excited levels over it. Its goal was to demonstrate that the Hoyle level could be explained by this quantum effect but he failed



2 α resonance
92 keV (^{8}Be)



3 α bound level

THE EXTRA-YIELD : Efimov state?

On 2006 these quantum levels were observed in atomic physics

Vol 440|16 March 2006|doi:10.1038/nature04626 nature

LETTERS

Evidence for Efimov quantum states in an ultracold gas of caesium atoms

T. Kraemer[1], M. Mark[1], P. Waldburger[1], J. G. Danzl[1], C. Chin[1,2], B. Engeser[1], A. D. Lange[1], K. Pilch[1], A. Jaakkola[1], H.-C. Nägerl[1] & R. Grimm[1,3]

Physics Letters B 779 (2018) 460–463

Contents lists available at ScienceDirect

Physics Letters B

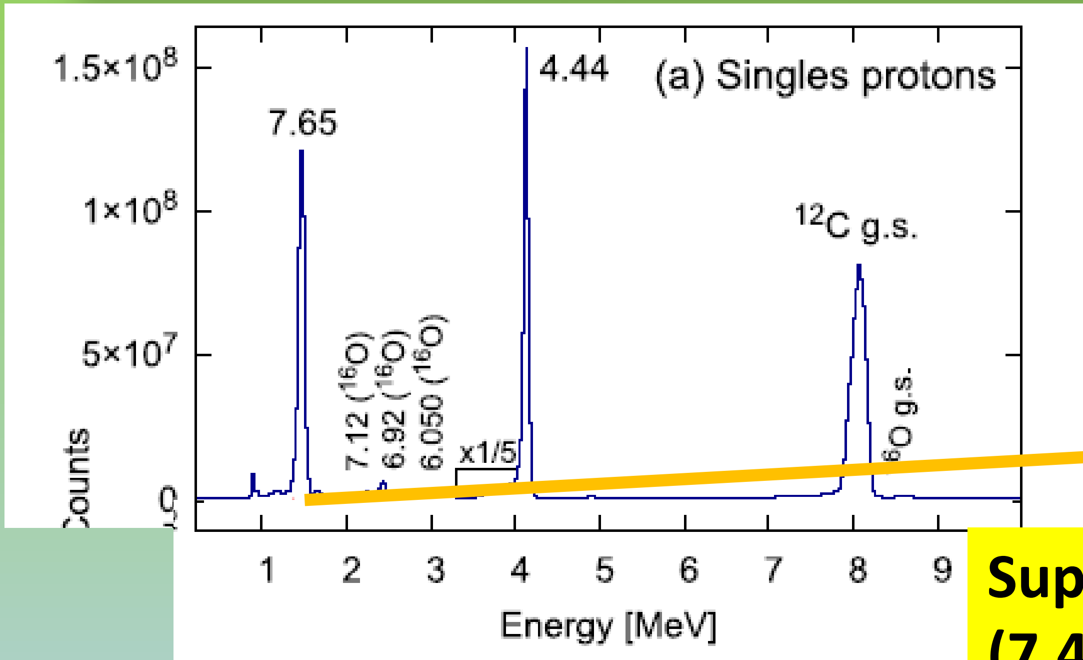
www.elsevier.com/locate/physletb

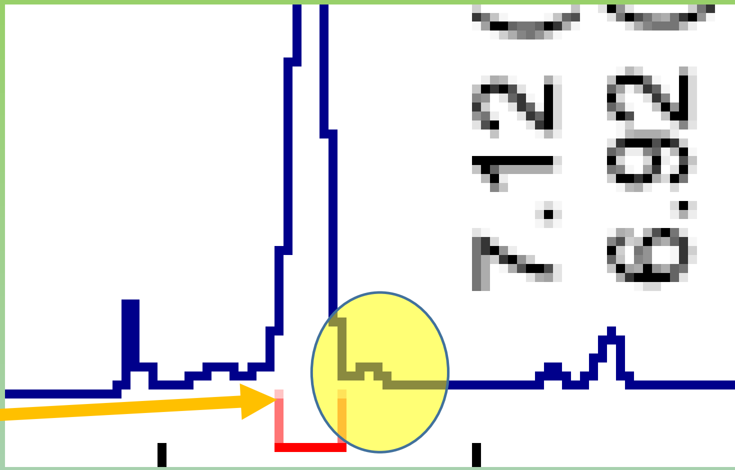
Decay modes of the Hoyle state in ^{12}C

H. Zheng [a], A. Bonasera [a,b], M. Huang [c], S. Zhang [c]

We discuss a hypothetical 'Efimov state' at $E^*(^{12}\mathrm{C}) = 7.458$ MeV,

THE EXTRA-YIELD : Efimov state?





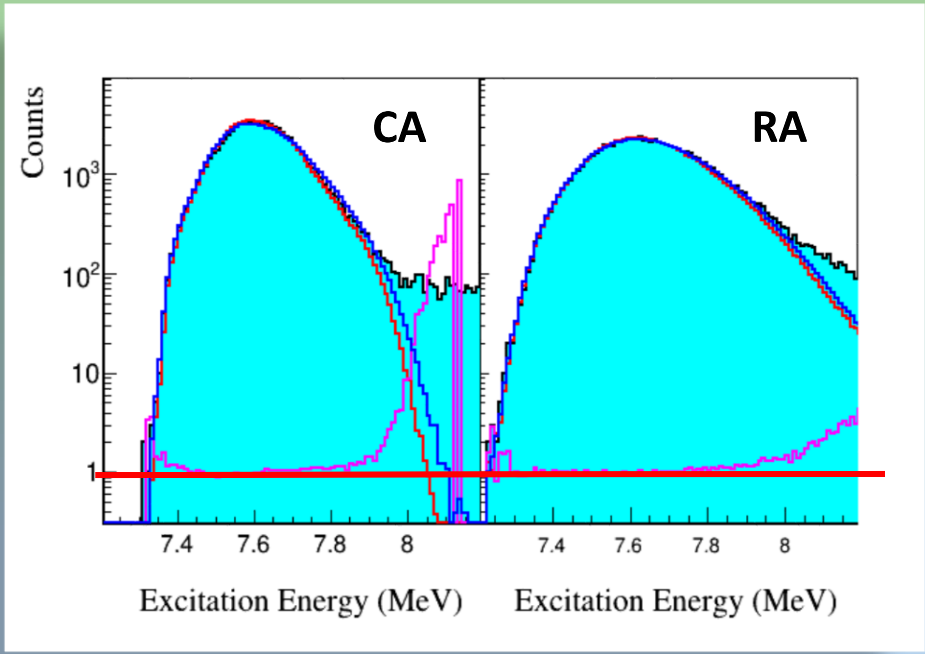
Suppose the Efimov level (7.458MeV) is populated near the Hoyle state (7.64MeV)

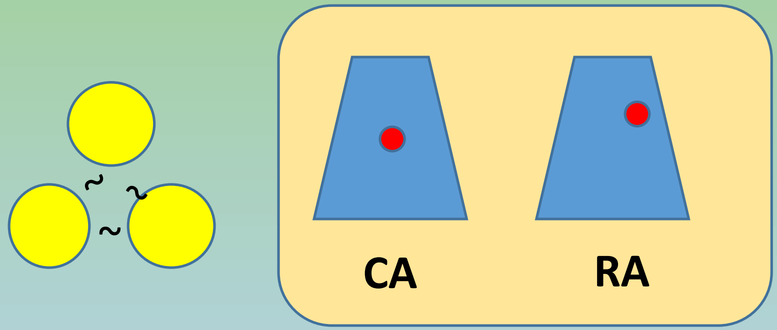
Efimov state should have near 100% γ decay width against the 4 10^{-4} of the Hoyle state due to large barrier for α decay

It is enough a very low population probability to explain our yield enhancement

THE EXTRA-YIELD : looking for Efimov state in 3-α data?

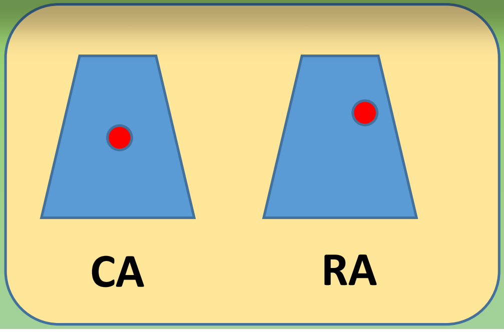
In order to search for events different from the Hoyle state decay we simulate the response of our detection system



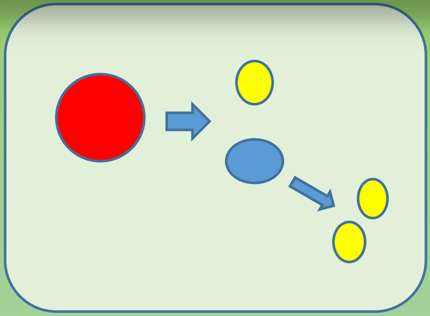


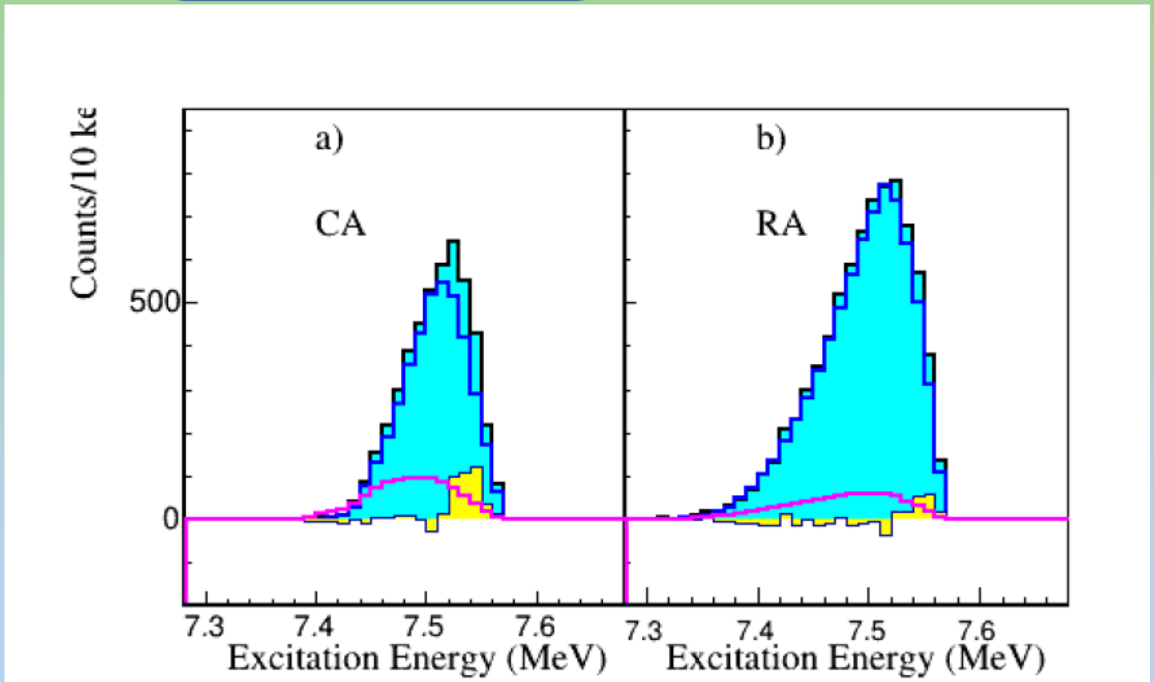
To get the 3-α CM energy we must assign an angle to each event the center of the detector CA or a random angle RA

THE EXTRA-YIELD : looking for Efimov state in 3-α data – sequential decay



SD –Sequential Decay





Experimental data selected with cuts (cyan filled)

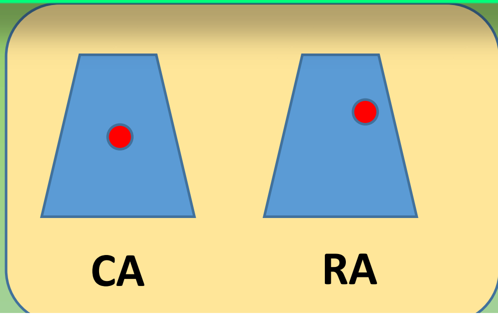
simulations of hoyle decay wrongly measured.

experimental data minus wrong simulated events and random coincidences

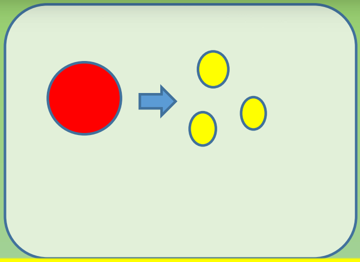
Violet is expected EFIMOV spectrum

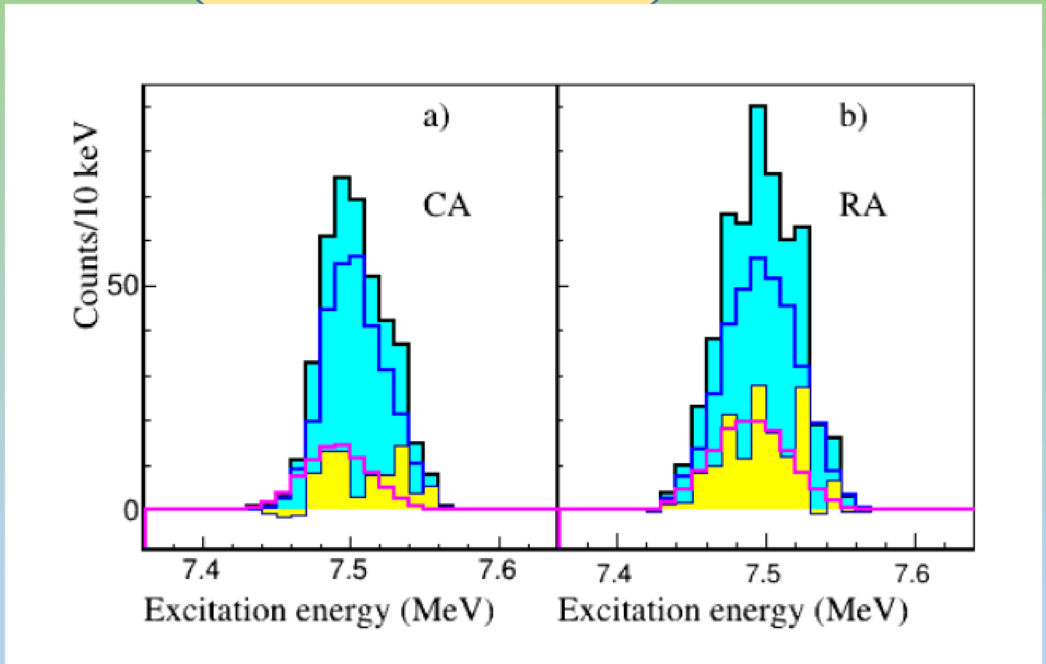
No evidence for EFIMOV sequential decay

THE EXTRA-YIELD : looking for efimov state in 3-α data – direct decay



DD - Direct Decay





The shape of the spectra is similar to expectation
The yield is too large in the case of RA
While for the detection efficiency we expect the contrary

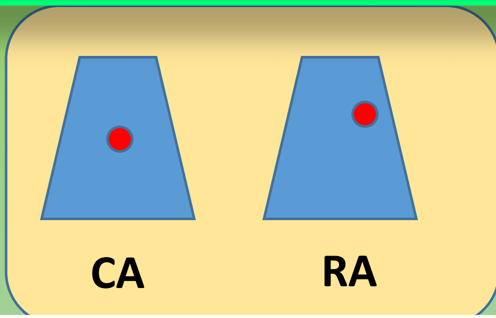
Experimental data selected with cuts (cyan filled)

simulations of hoyle decay wrongly measured.

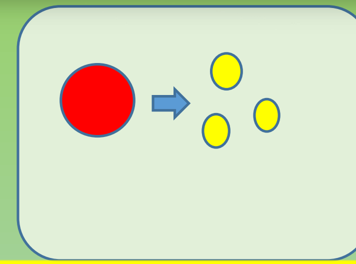
experimental data minus wrong simulated events and random coincidences

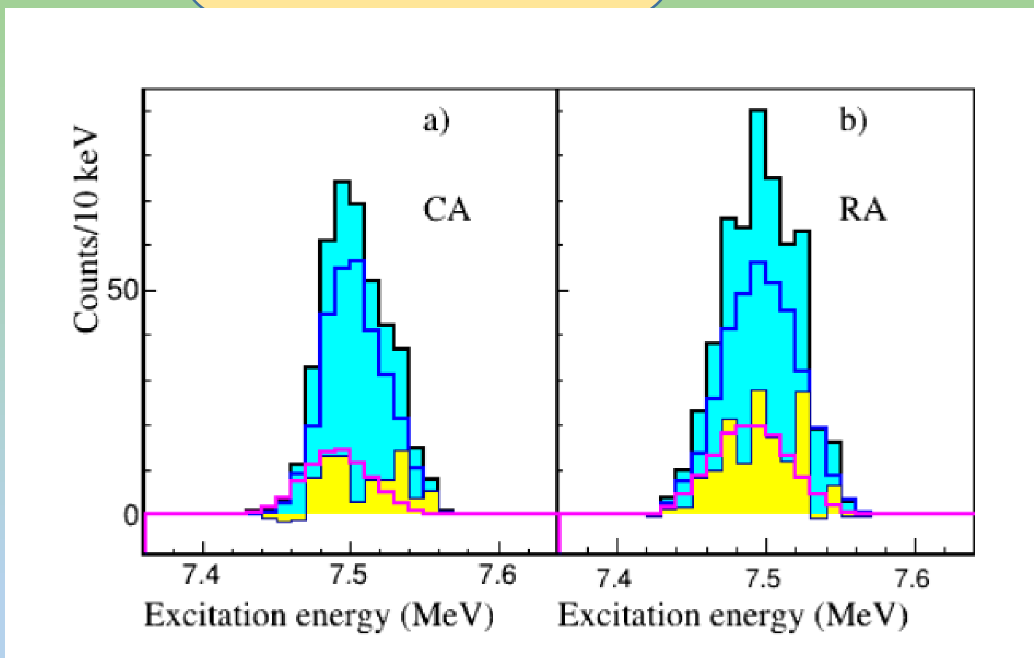
Violet is expected EFIMOV spectrum

THE EXTRA-YIELD : looking for efimov state in 3-α data – direct decay



DD - Direct Decay





The shape of the spectra is similar to expectation
The yield is too large in the case of RA
While for the detection efficiency we expect the contrary

108 events RA efficiency 8% means 1350 events against 85000 Hoyle events

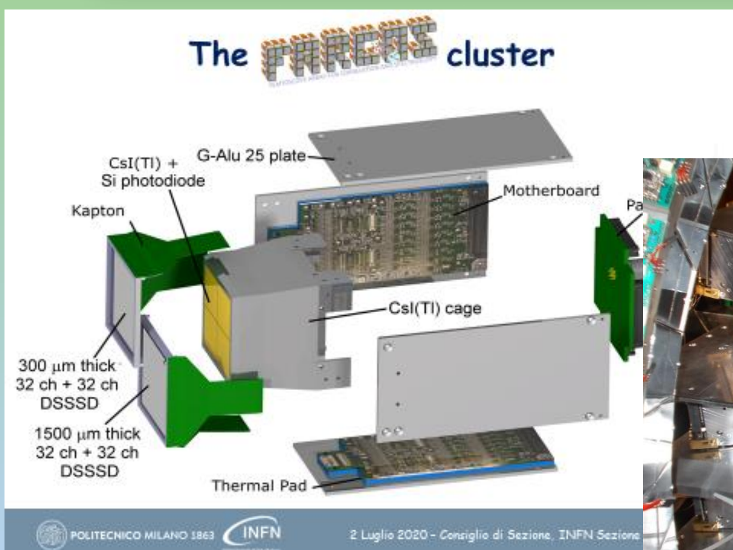
47 events CA efficiency 24% -> 195 events over 85000

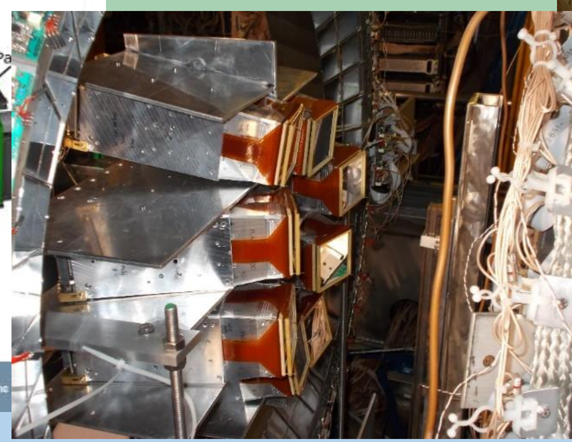
For the gamma experiment we required also the coincidence with high energy alpha scattered having only 28500 events this means around 65 events compatible with Efimov what expected if we have 80% γ decay probability of the Efimov state.

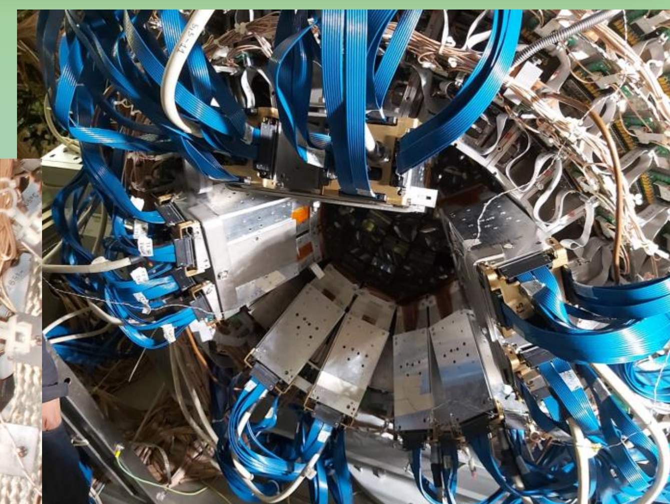
THE EXTRA-YIELD : new measurement?

I have not conclusive convincing data we must perform new measurements able to evidence the presence of 100 Efimov events near to 100000 Hoyle events we need much more precise measurements

We will improve the experiment using the new FARCOS telescopes to measure better q-values







Hope to do the new experiment beginning 2023

γ decay of Hoyle and 9.64 MeV levels

FIRST DIRECT OBSERVATION OF γ-DECAY of 9.64 MeV LEVEL

TOO LARGE γ-DECAY WIDTH OF THE HOYLE STATE

EFIMOV STATE?

NO EVIDENCE OF SEQUENTIAL DECAY OF EFIMOV STATE

POSSIBLE PRESENCE OF DIRECT DECAY OF SUCH A STATE

HOYLE EXTRA-YIELD COMPATIBLE WITH CONTAMINATION FROM EFIMOV DECAY ASSUMING $\Gamma\gamma/\Gamma$~80%

Future opportunities

NEW MEASUREMENTS WITH BETTER RESOLUTION ON Q-VALUE MEASUREMENT USING FARCOS

The collaboration

G. Cardella(1), A. Bonasera(2)(3), N.S. Martorana(2)(4), L. Acosta(1)(5), E. De Filippo(1), E. Geraci(1)(4), B. Gnoffo(1)(4), C. Guazzoni(6), L.Lo Monaco(4), C. Maiolino(2), A. Pagano(1), E.V. Pagano(2), M. Papa(1), S. Pirrone(1), G. Politi(1)(4), F. Rizzo(2)(4), P. Russotto(2), D. V. Sicari(6), and M. Trimarchi(1)(7)

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