



Stretched resonances in light nuclei studied experimentally at CCB IFJ PAN

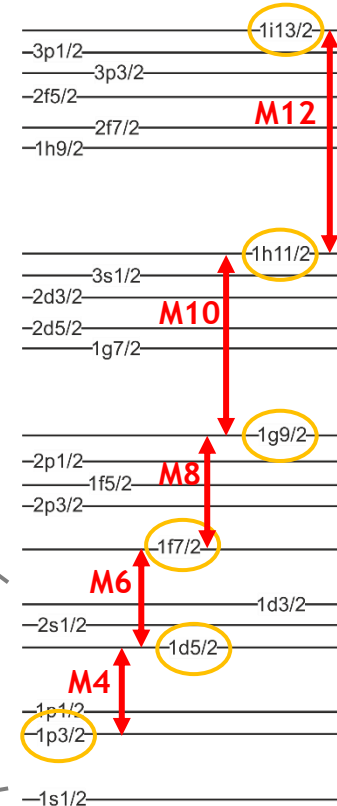
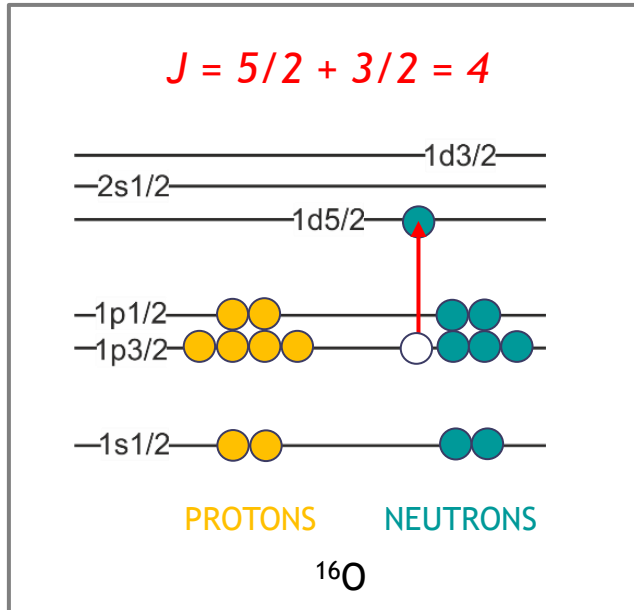
N.Cieplicka-Oryńczak¹, Y. Jaganathen⁹, B. Fornal¹, S. Leoni², M. Płoszajczak³, M. Ciemala¹, S. Ziliani², M. Kmiecik¹, A. Maj¹, J. Łukasik¹, P. Pawłowski¹, B. Sowicki¹, B. Wasilewska¹, M. Ziębliński¹, C. Boiano², S. Brambilla², P. Bednarczyk¹, S. Bottoni², A. Bracco², I. Burducea⁵, F. Camera², I. Ciepał¹, C. Clisu⁵, F.C.L. Crespi², K. Dhanmeher¹, N. Florea⁵, E. Gamba², J. Grębosz¹, M. N. Harakeh⁴, D. A. Iancu⁵, Ł.W. Iskra¹, M. Krzysiek¹, P. Kulesa¹, N. Marginean⁵, R. Marginean⁵, I. Matea⁷, M. Matejska-Minda¹, K. Mazurek¹, B. Million², W. Parol¹, M. Sferrazza⁸, L. Stan⁵, B. Włoch¹, C. Schmitt¹, D. Duda¹, K. Gajewska¹, O. Wieland², G. Corbari², A. Giaz², E. van Rompu⁶, P.-A. Söderström¹⁰, A. Kuşoğlu¹⁰, S. R. Ban¹⁰, D. Balabanski¹⁰, K. Hadyńska-Klęk¹¹, A. Špaček¹¹, P. Dey¹¹, A. Krzysiek¹¹, G. Szymanek¹¹

¹IFJ PAN Kraków, Poland, ²Università degli Studi di Milano and INFN Sezione di Milano, Italy, ³GANIL, Caen, France, ⁴University of Groningen, The Netherlands, ⁵IFIN-HH, Bucharest, Romania, ⁶KU Leuven, Belgium, ⁷Université Paris-Saclay, France, ⁸Université Libre de Bruxelles, Belgium, ⁹National Centre for Nuclear Research, Warsaw, Poland, ¹⁰ELI-NP, Bucharest, Romania, ¹¹Heavy Ion Laboratory, Warsaw, Poland

What is a „stretched” state?

Such states are dominated by a **single particle-hole component** for which the excited particle and the residual hole couple to the **maximal possible spin value**:

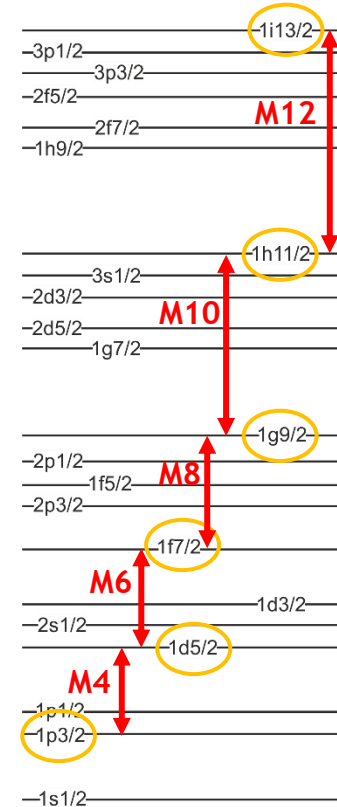
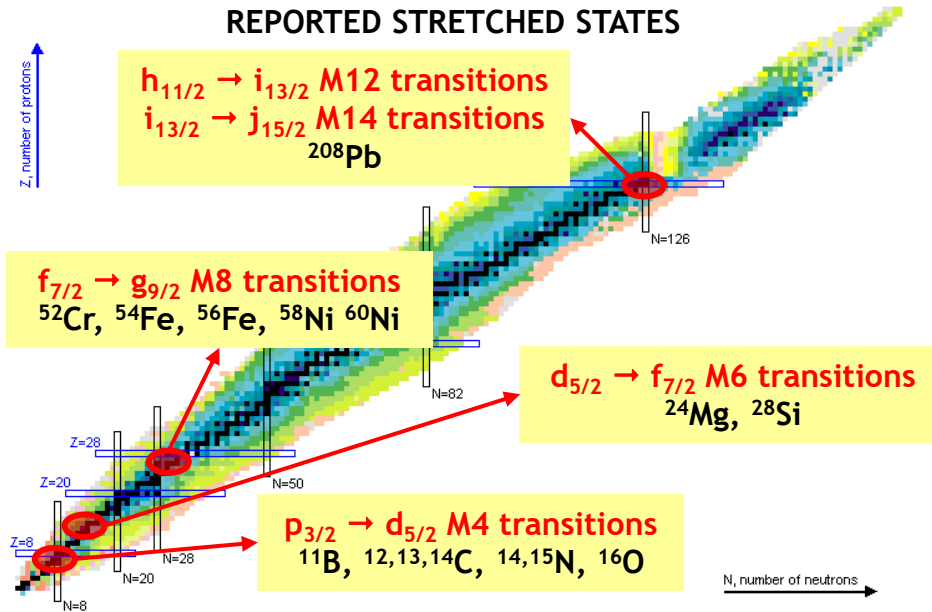
$$J_{\max} = j_p (\max) + j_h (\max)$$



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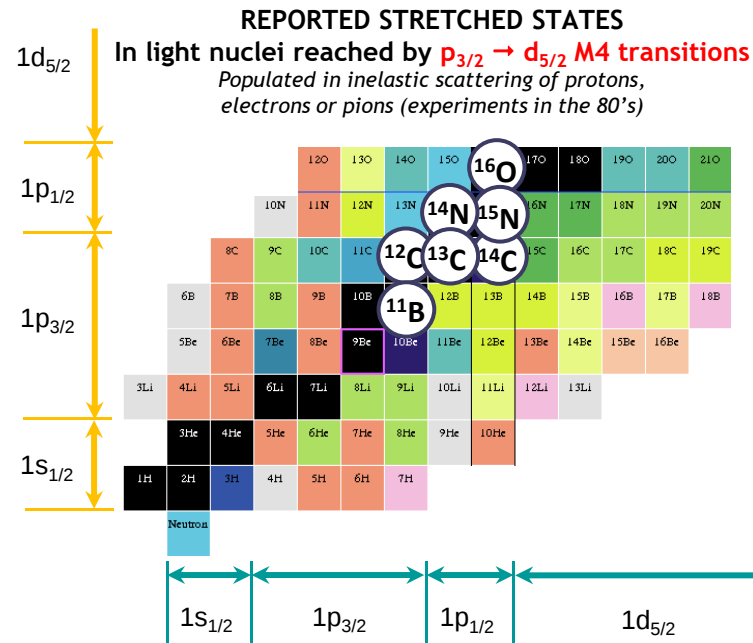
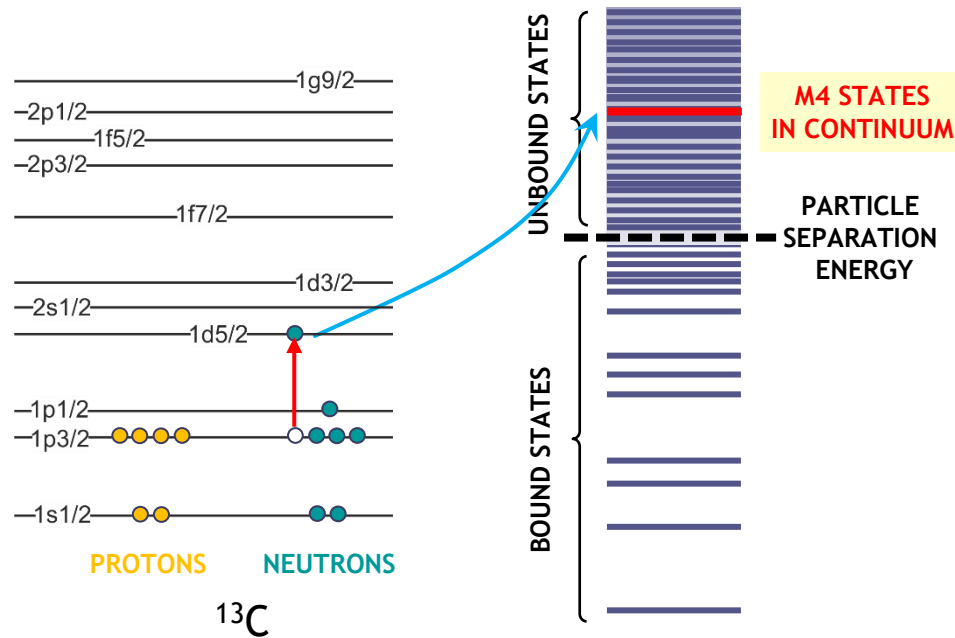


Stretched states in light nuclei - why are they interesting?

CONFIGURATIONAL PURITY

ones of the simplest known
nuclear excitations

TESTING GROUND FOR THEORETICAL CALCULATIONS
properties of stretched states (decay patterns e.g.) used as
demanding test of state-of-the-art theory approaches
(Gamow Shell Model e.g.)

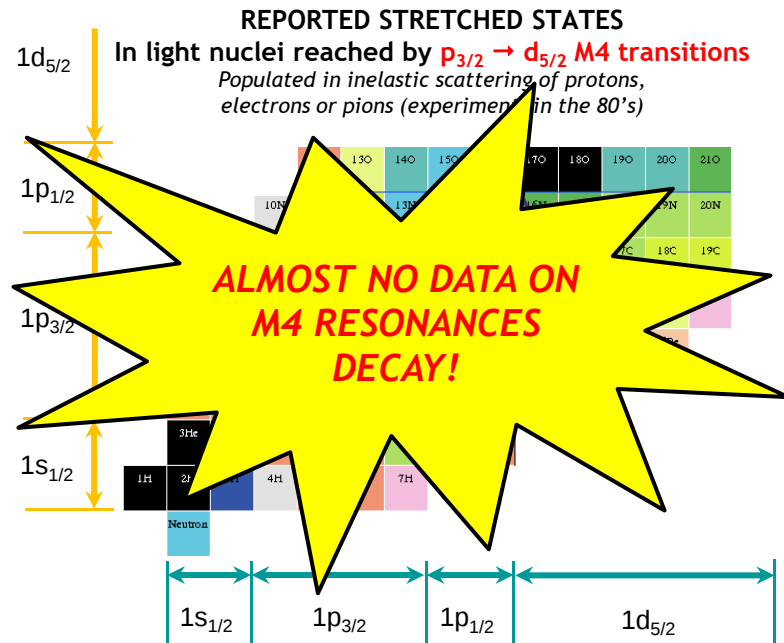
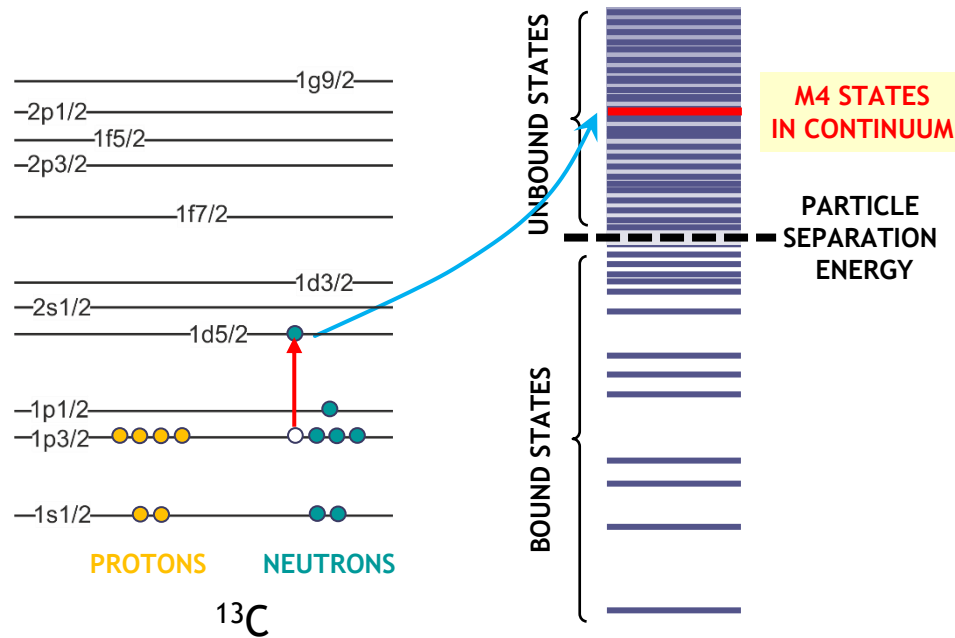


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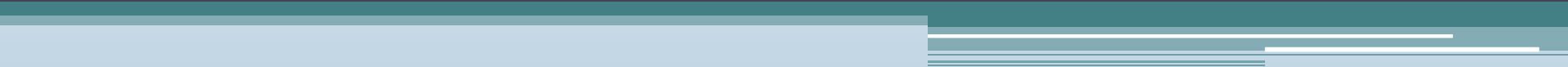
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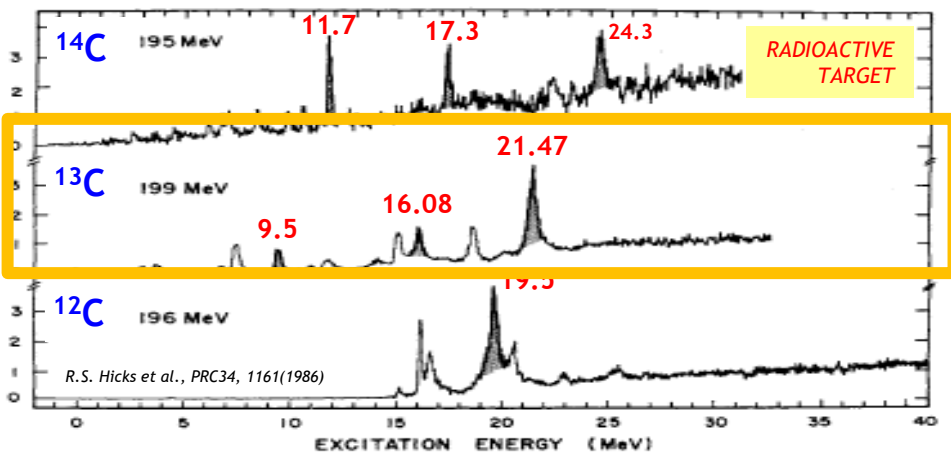


NUCLEI OF OUR INTEREST

A decorative graphic consisting of several horizontal lines of varying lengths and colors (teal, light blue, and white) extending from the left edge of the slide towards the right, positioned below the main title.

Stretched resonances - from previous works

INELASTIC ELECTRON SCATTERING EXPERIMENTS



						12O	13O	14O	15O	16O	17O	18O	19O	20O	21O		
					10N	11N	12N	13N	14N	15N	16N	17N	18N	19N	20N		
						8C	9C	10C	11C	12C	13C	14C	15C	16C	17C	18C	19C

¹³C is a perfect case to start:

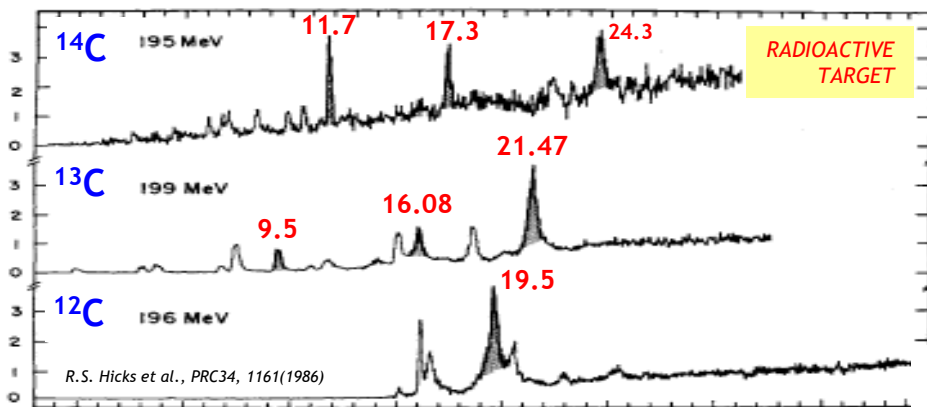
- ☑ strong M4 excitation
- ☑ well isolated peak
- ☑ quite easy preparation of target

1. **Introduction**
 2. **Background**
 3. **Methodology**
 4. **Results**
 5. **Conclusion**
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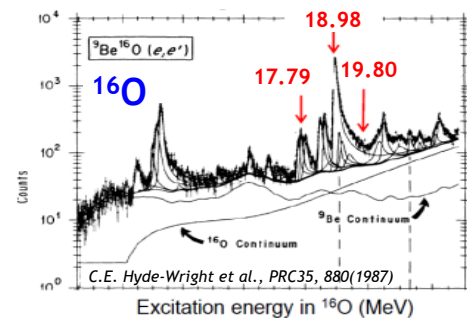
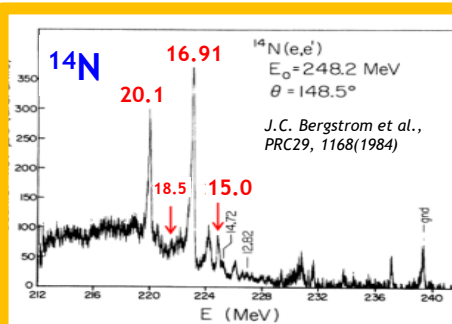
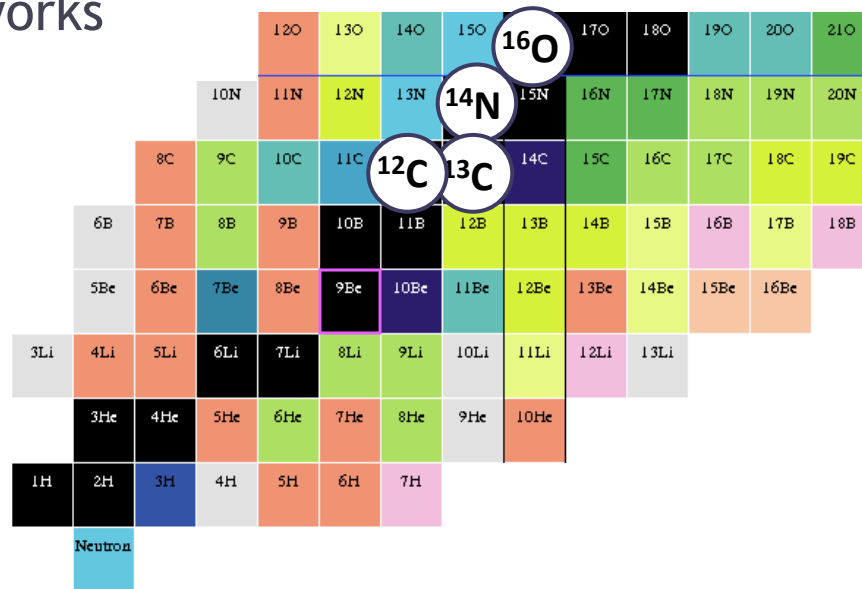
Stretched resonances - from previous works

INELASTIC ELECTRON SCATTERING EXPERIMENTS



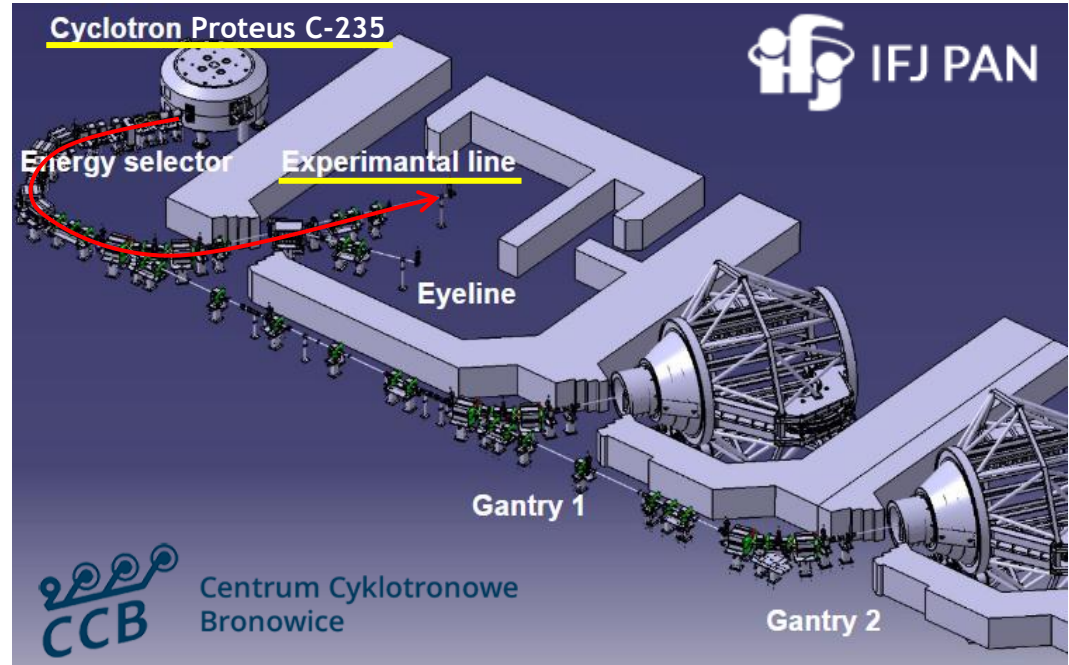
^{14}N has two strong M4 excitations, but the target is difficult to prepare...

Lithium amide: $^7\text{Li}-^{14}\text{N}-\text{H}_2 + (^{16}\text{O} \text{ contamination})$

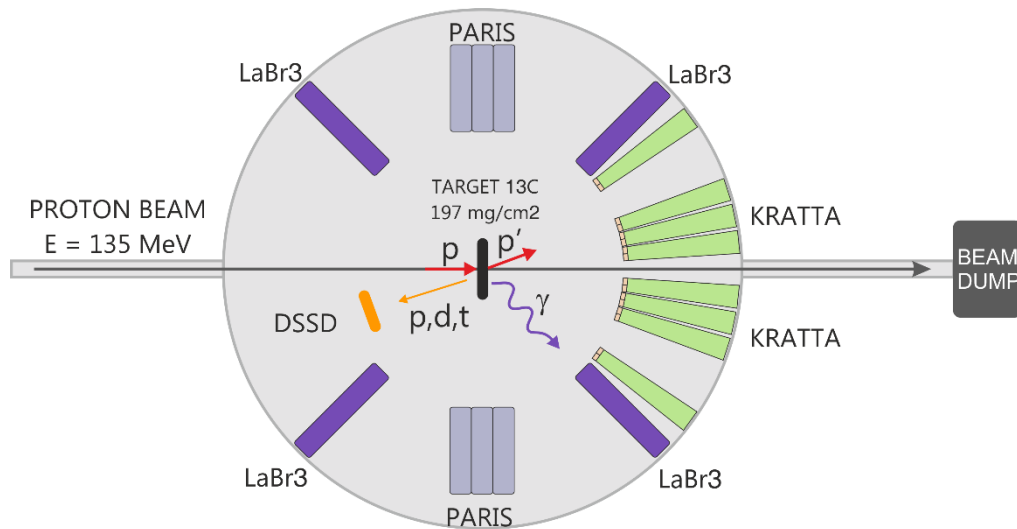


EXPERIMENTAL SETUP AT CCB IFJ

Experimental setup - Cyclotron Centre Bronowice (Kraków, Poland)



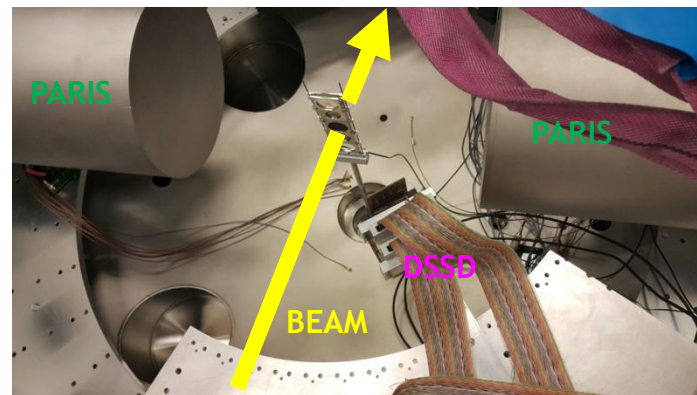
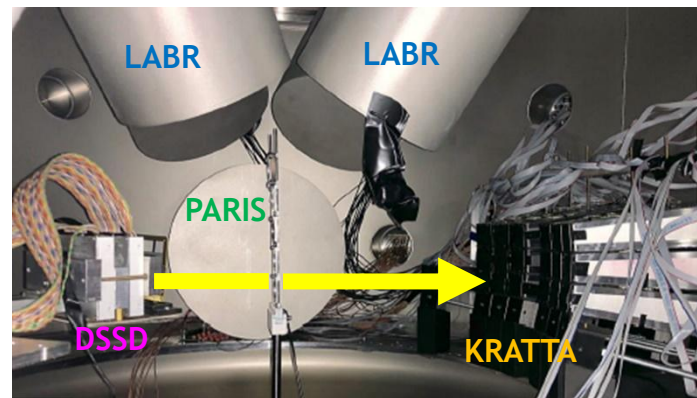
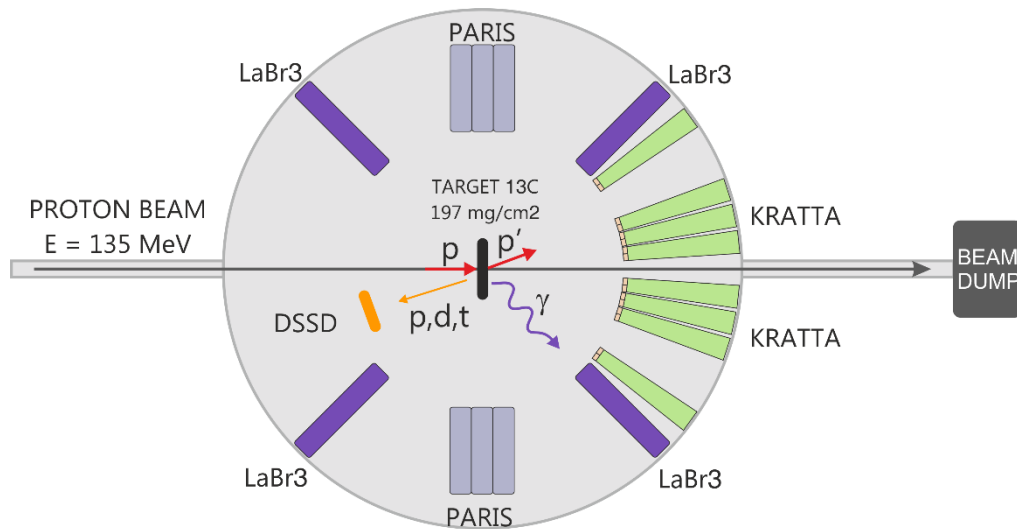
Experimental setup at CCB IFJ



Large vacuum scattering chamber at CCB

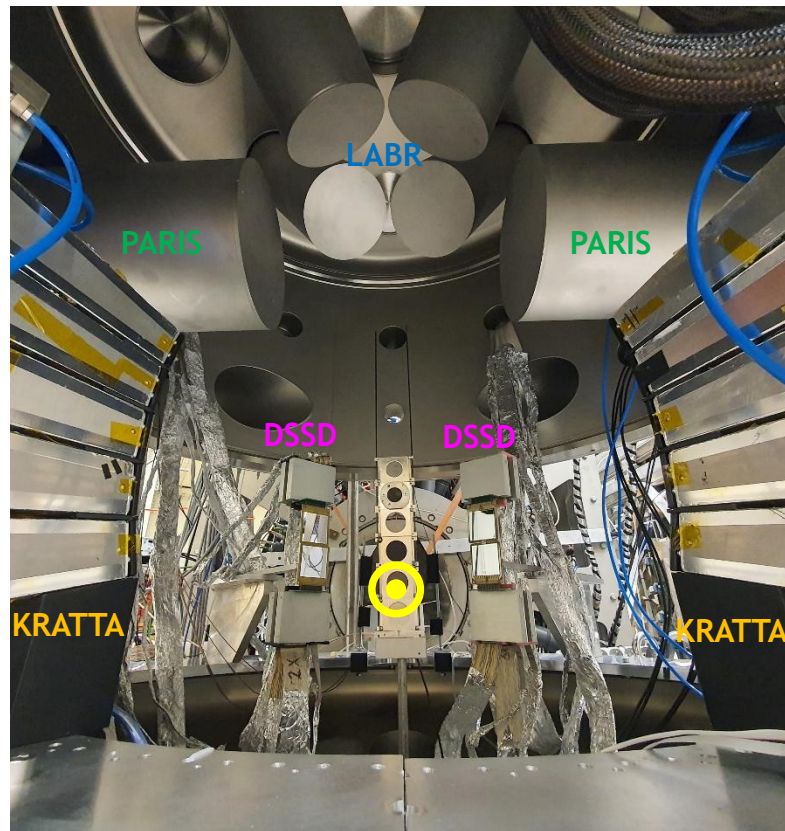
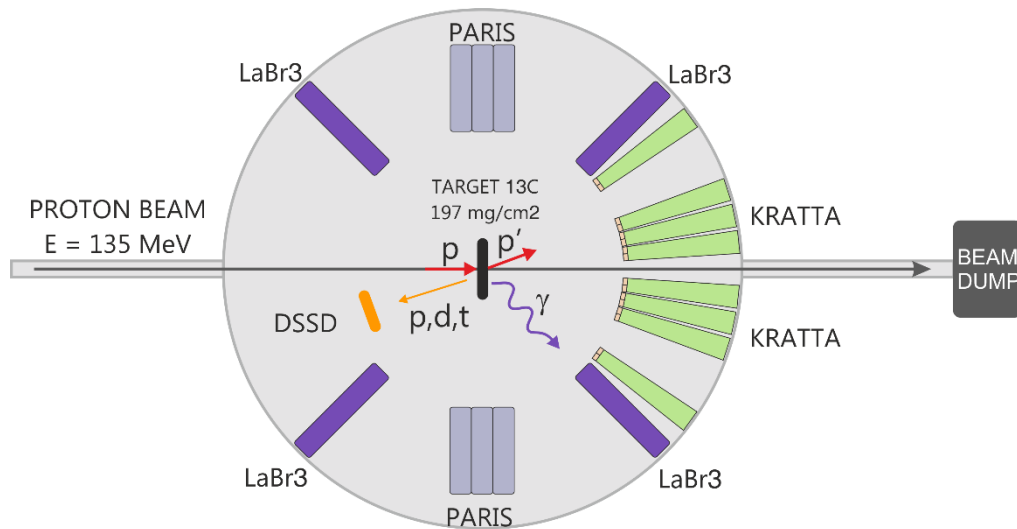
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- 2) γ -ray detection:
 - four **LaBr₃** detectors (3.5"x8")
 - two clusters of the **PARIS** scintillator array
- 3) Measurement of light charged particles produced in the reaction: a thick position-sensitive **Si detector**

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THE FIRST CASE: ^{13}C

May 2019 – June 2020

Spokepersons: S. Leoni (Univ. of Milan and INFN Milan), B. Fornal (IFJ PAN), M. Ciemała (IFJ PAN)

Previous studies of stretched states in ^{13}C

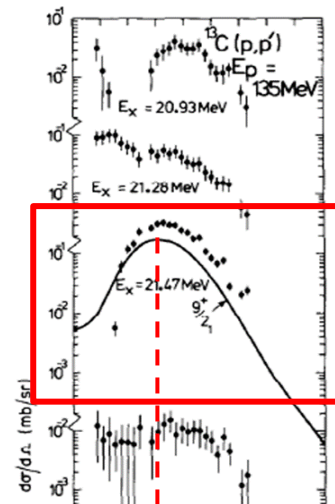
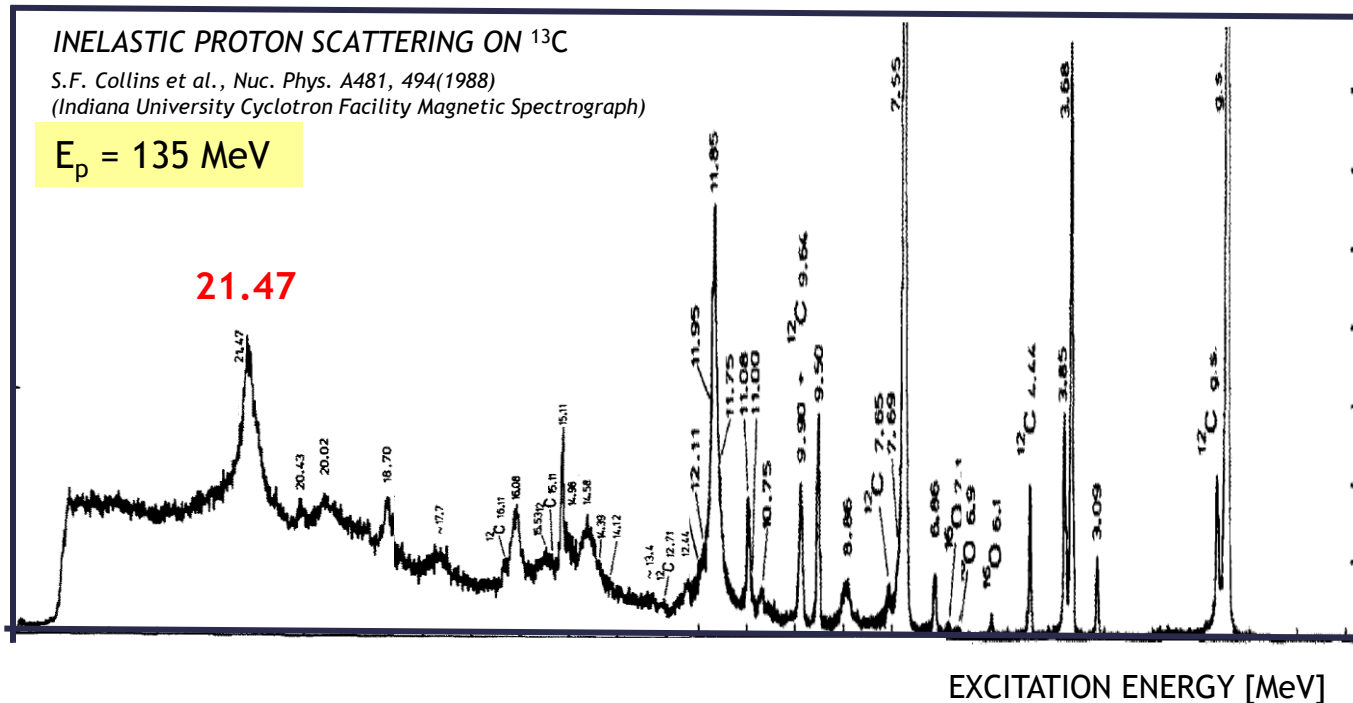
INELASTIC PROTON SCATTERING ON ^{13}C

S.F. Collins et al., Nuc. Phys. A481, 494(1988)

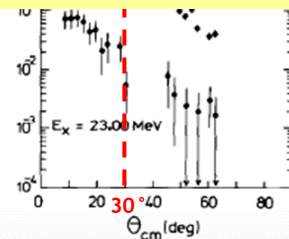
(Indiana University Cyclotron Facility Magnetic Spectrograph)

$E_p = 135 \text{ MeV}$

21.47



The M4 resonance at 21.47 MeV in ^{13}C is peaked at 30°



Previous studies of stretched states in ^{13}C

INELASTIC PROTON SCATTERING ON ^{13}C

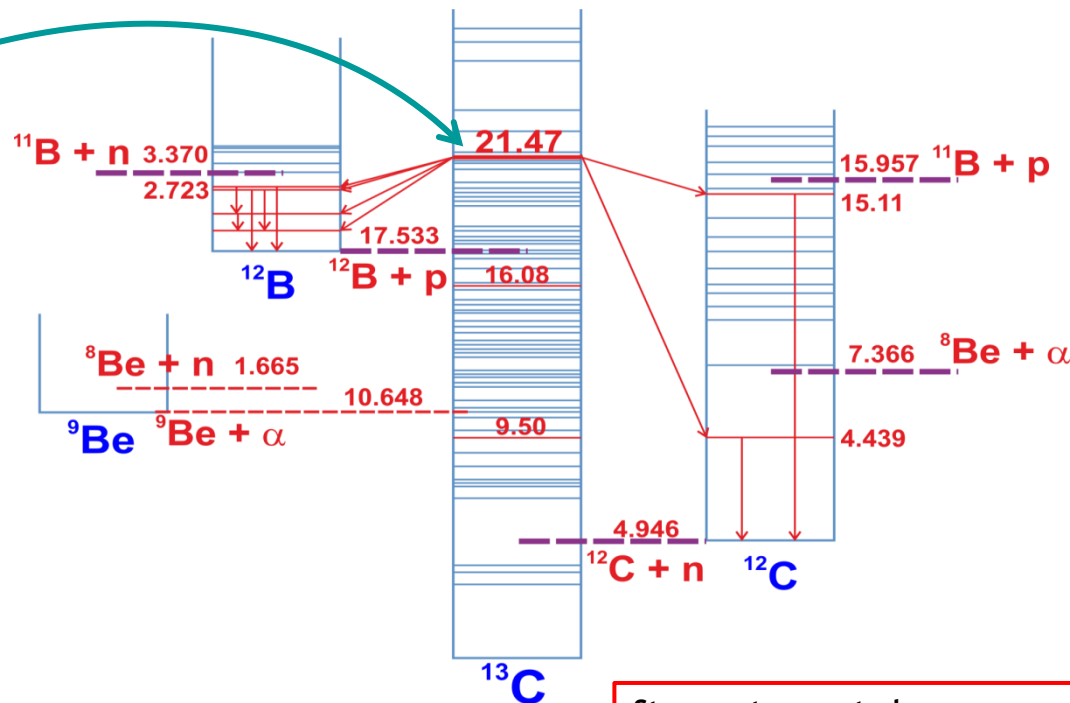
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GATE ON SCATTERED PROTONS

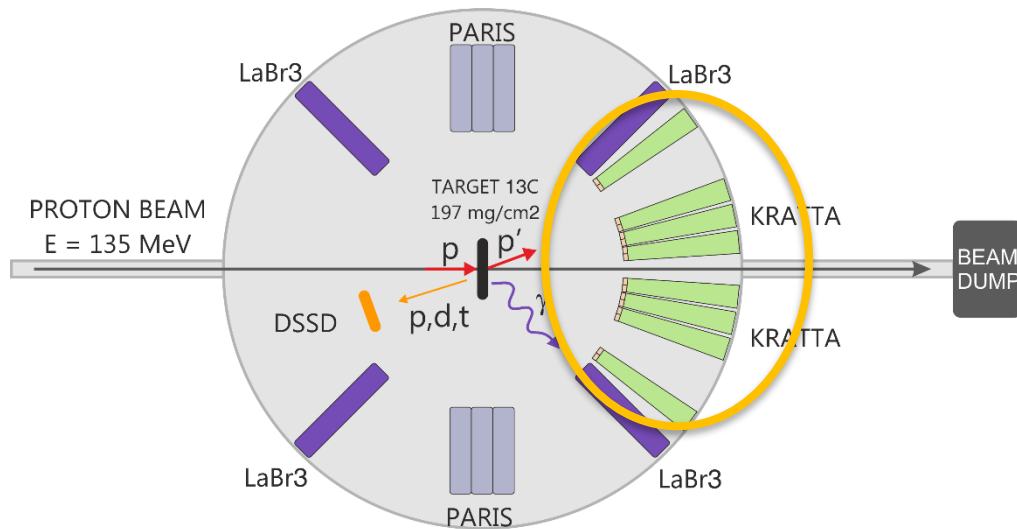


Strongest expected γ rays:

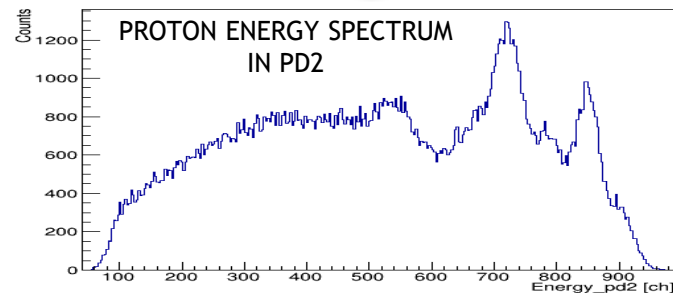
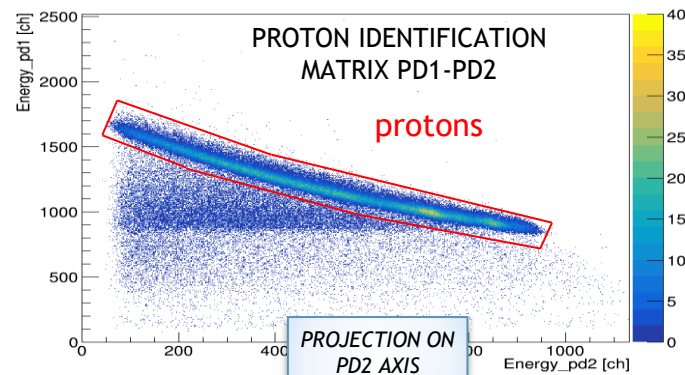
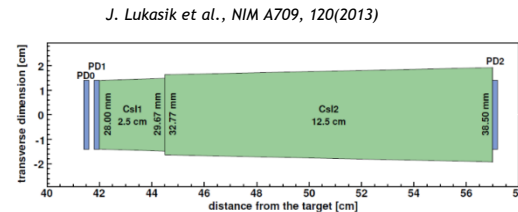
^{12}B : 953, 1668, 1674, 2723 keV

^{12}C : 4439, 15110 keV

Scattered protons measurement



scattered protons

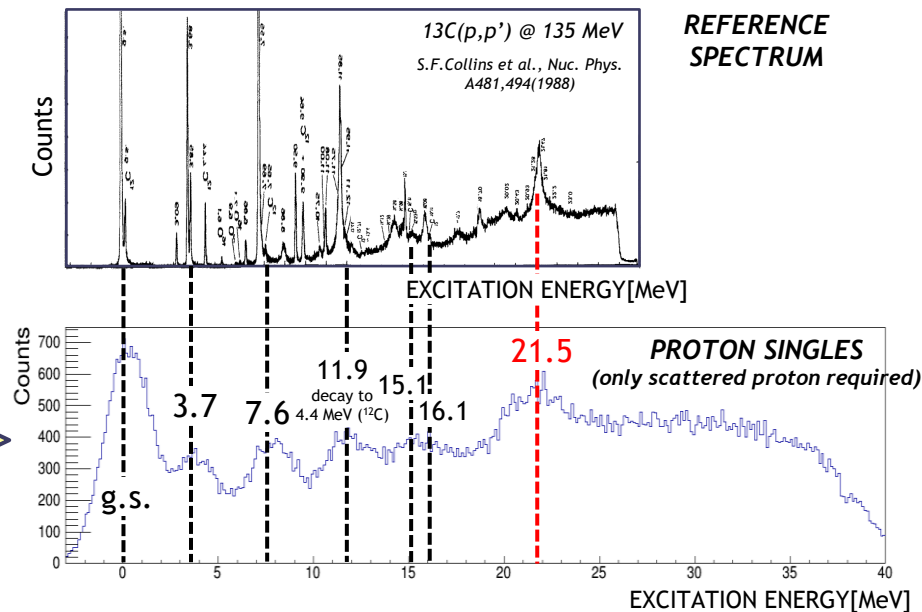


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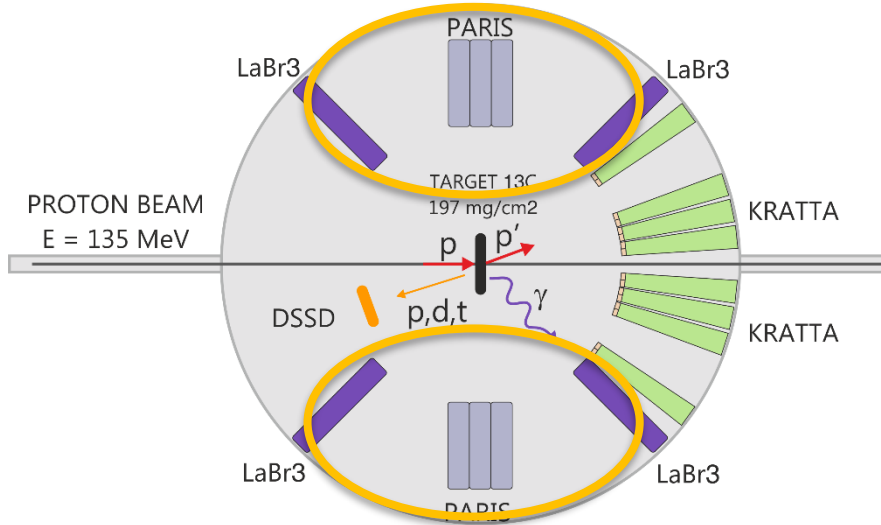
KRATTA - excitation energy spectra

Excitation energy spectra measured at $\sim 36^\circ$ corresponding to the excitations in the ^{13}C target nucleus measured as:

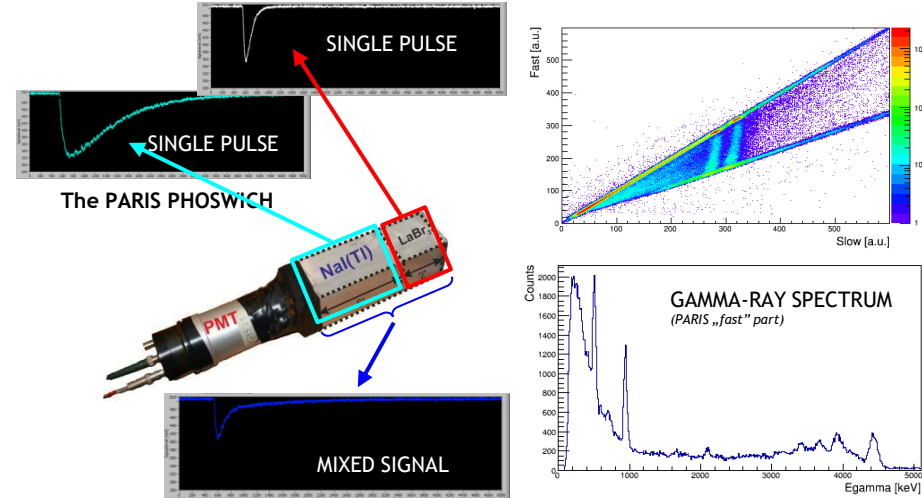
SINGLES (only scattered proton required)



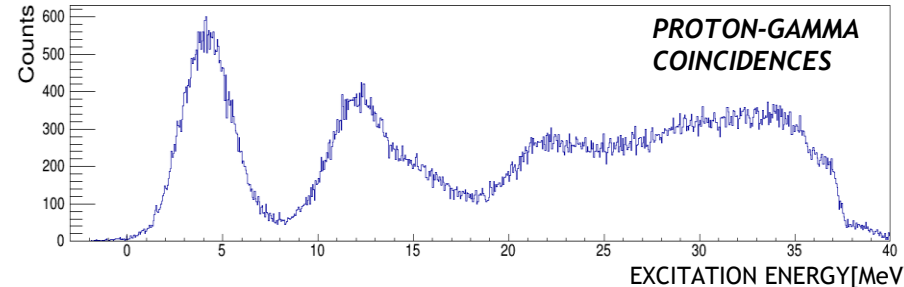
Gamma-ray measurement



IN COINCIDENCE WITH γ RAYS
(4 big LaBr₃ detectors + 18 modules of PARIS)



A. Maj et al., Acta Phys. Pol. B40, 565(2009) and <http://paris.ifj.edu.pl>



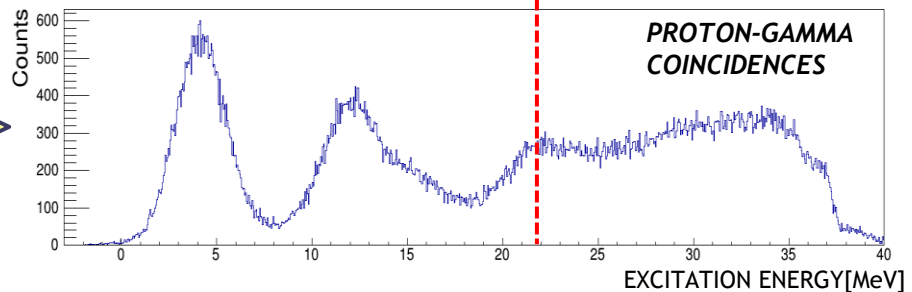
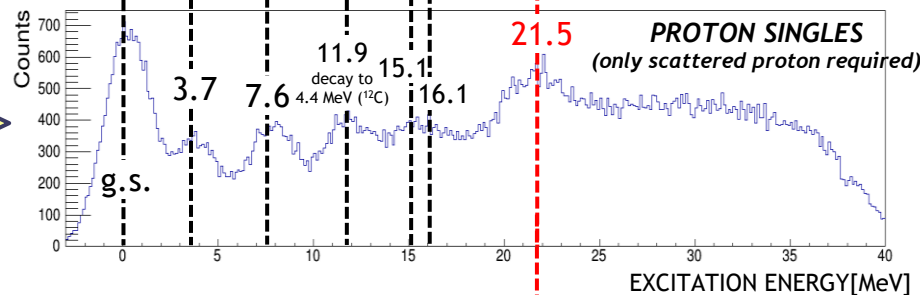
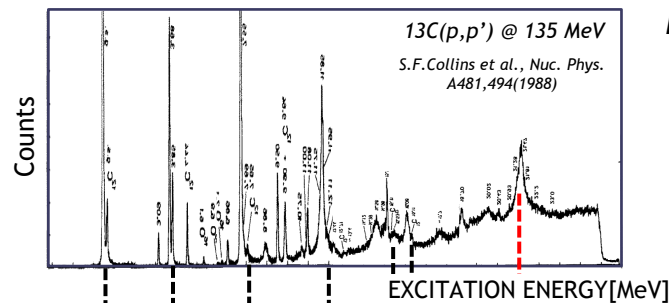
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KRATTA - excitation energy spectra

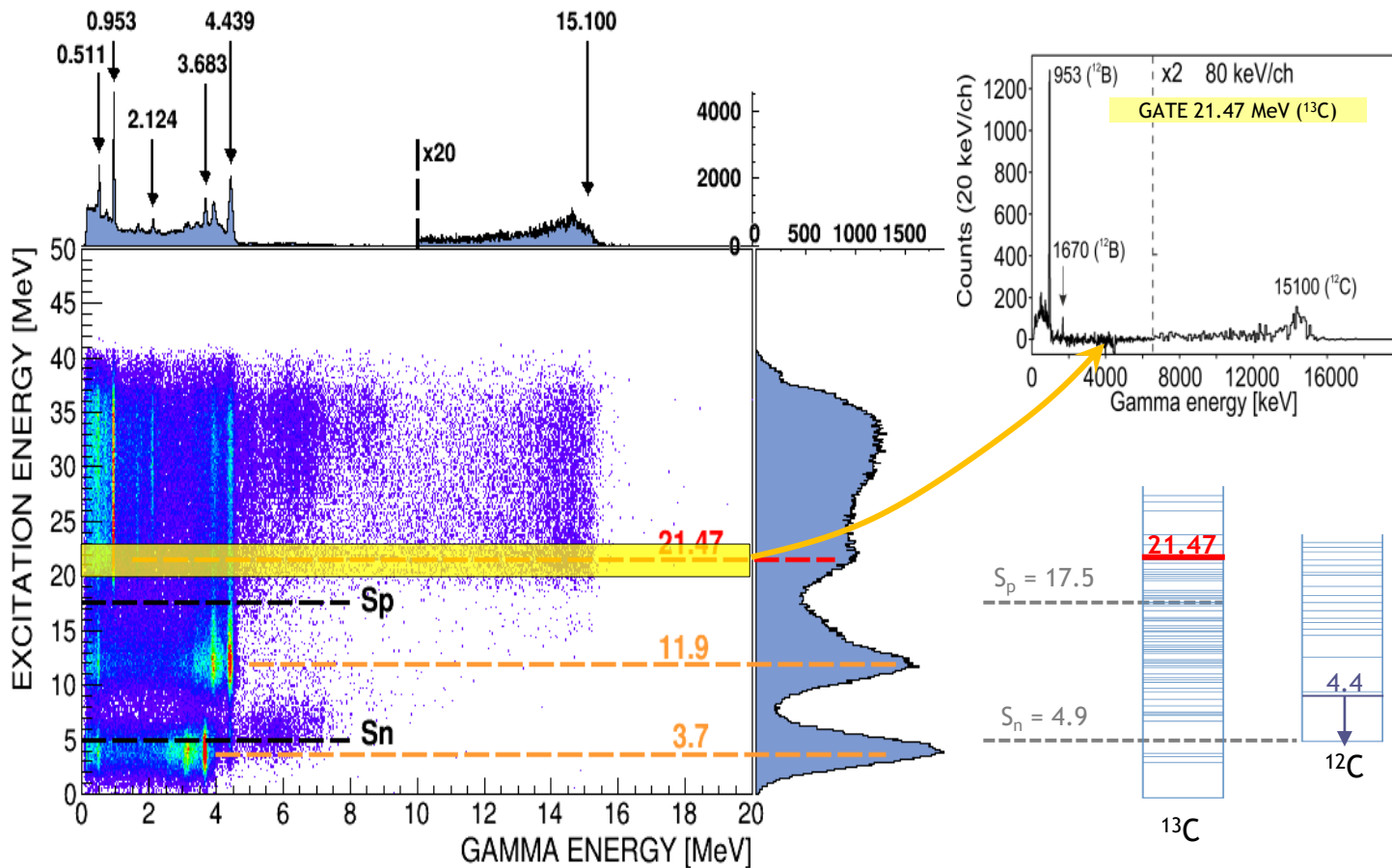
Excitation energy spectra measured at $\sim 36^\circ$ corresponding to the excitations in the ^{13}C target nucleus measured as:

SINGLES (only scattered proton required)

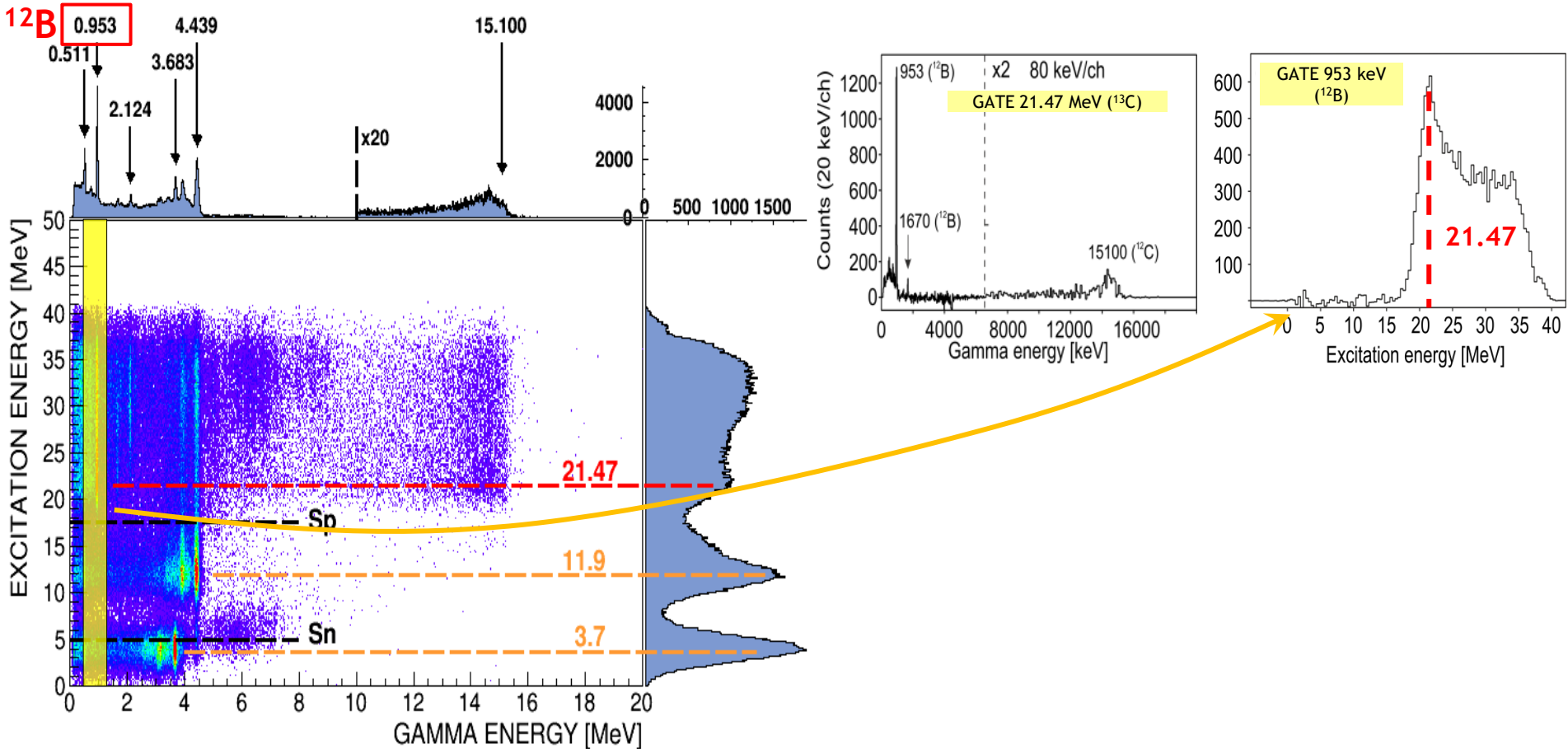
COINCIDENCES (scattered proton and gamma ray required)



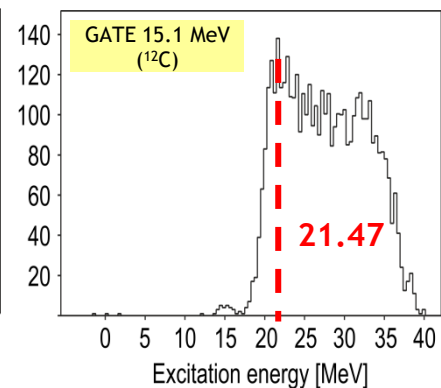
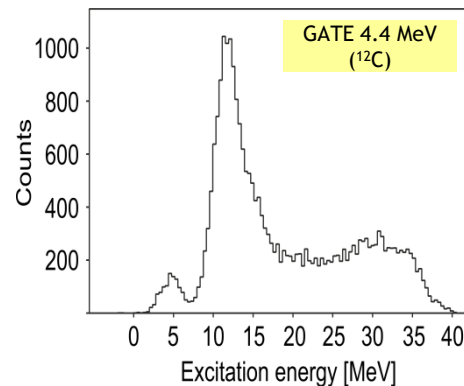
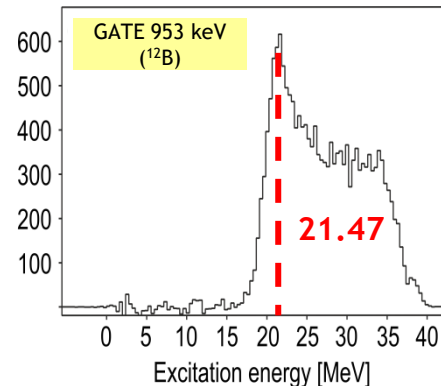
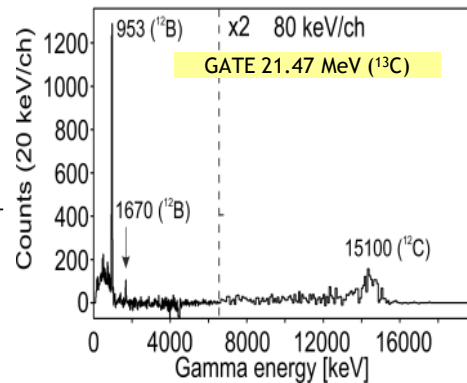
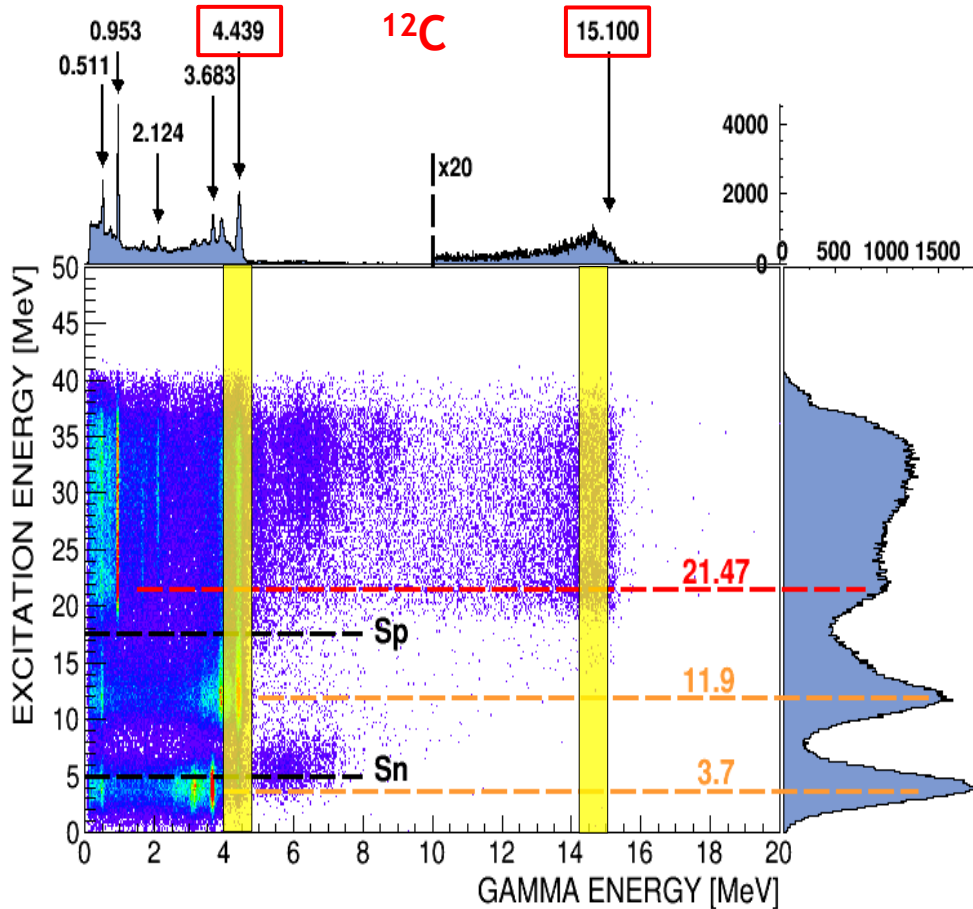
Experimental results: proton-gamma coincidence measurement



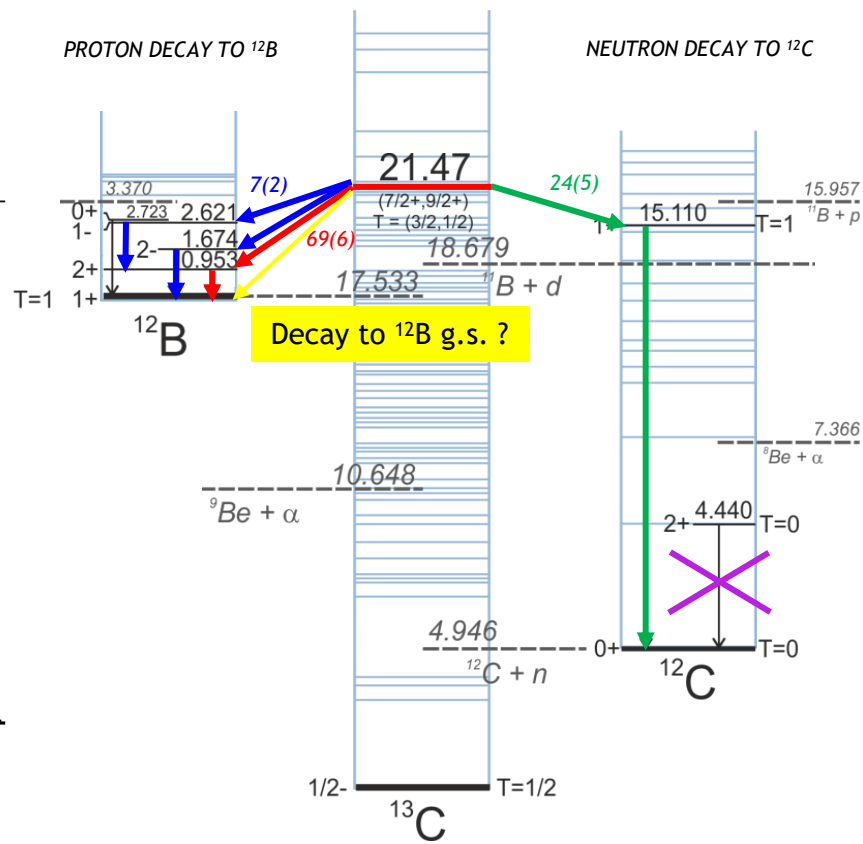
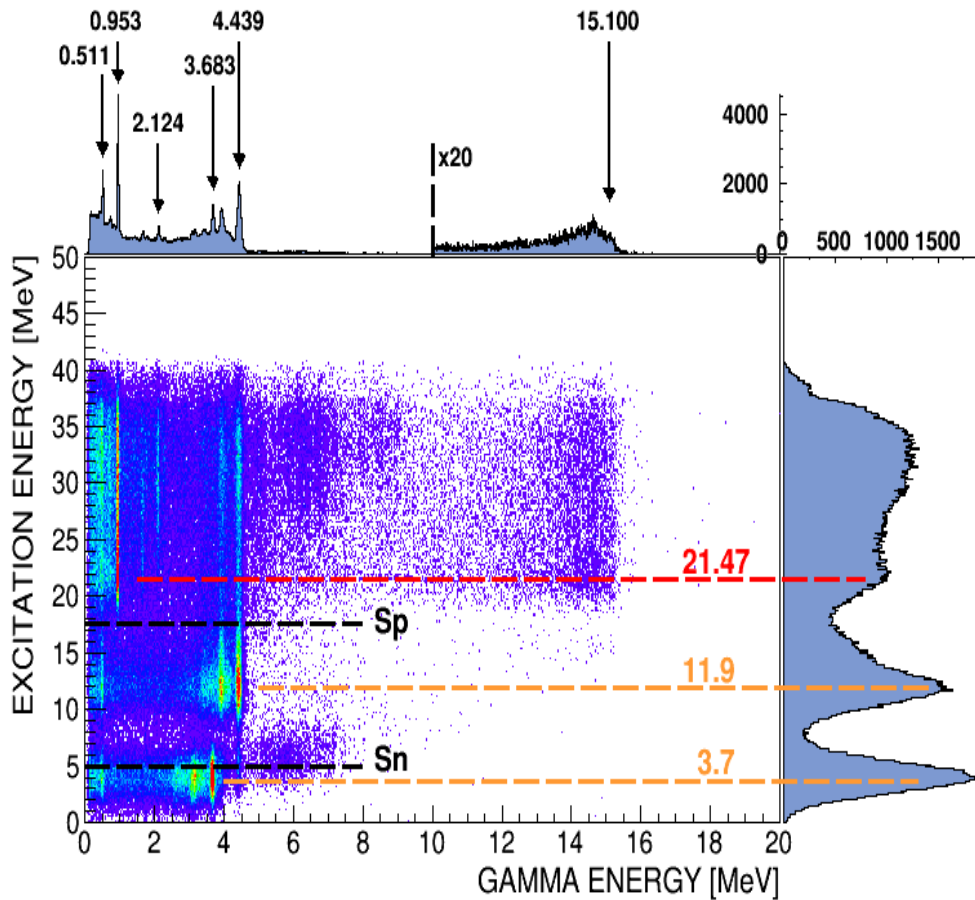
Experimental results: proton-gamma coincidence measurement



Experimental results: proton-gamma coincidence measurement



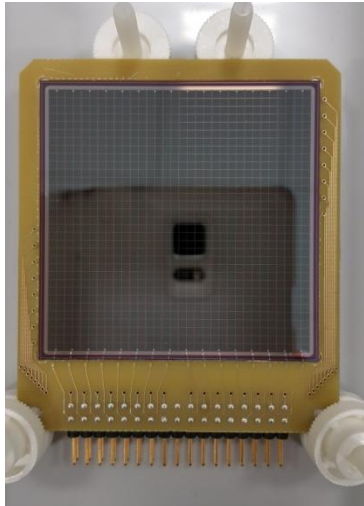
Experimental results: proton-gamma coincidence measurement



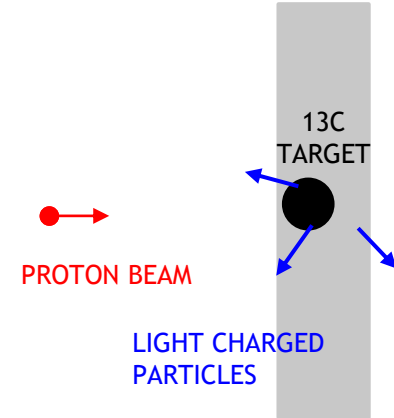
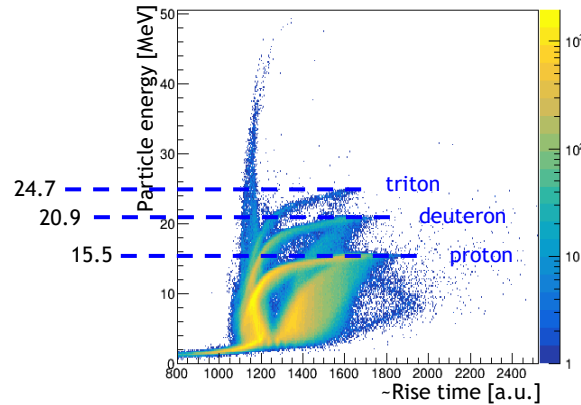
PERFORMANCE OF DSSSD (FROM THICK ^{13}C TARGET EXPERIMENT)

Double Sided Silicon Strip Detector (Micron Semiconductor Ltd)

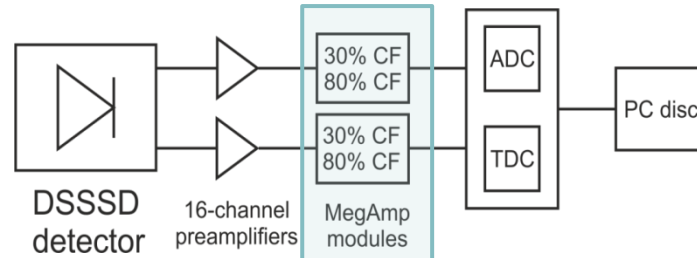
Active area: 50mm x 50mm
No. of strips: 32 (16 per side)
Thickness: 1.5 mm



PARTICLE IDENTIFICATION MATRIX (for one strip, representative example)



SCHEME OF ACQUISITION LINE



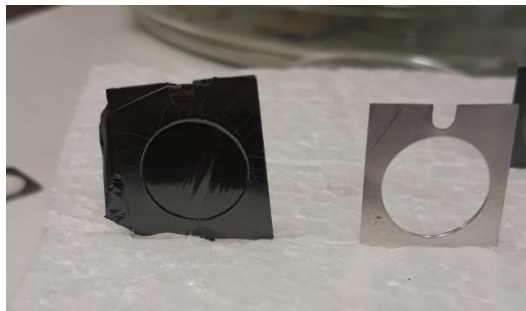
MegAmp Pulse Shape Amplifier
(C. Boiano, S. Brambilla, INFN Milano)

Information on the energy
and rise time allowing for
light particle identification

Thin 1 mg/cm² ¹³C target experiment

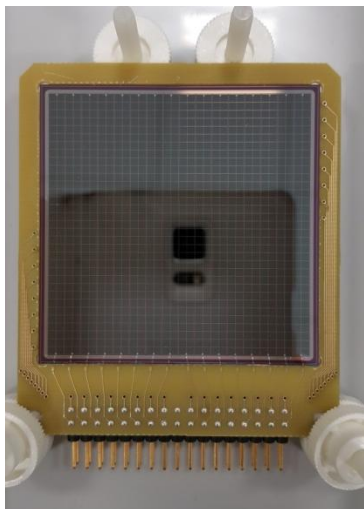
Double Sided Silicon Strip Detector (Micron Semiconductor Ltd)

Active area: 50mm x 50mm
No. of strips: 32 (16 per side)
Thickness: 1.5 mm



**¹³C target made of 10 foils in separate frames,
total thickness 1 mg/cm²**

(Nicoleta Florea, Nicu Marginean IFIN-HH, Bucharest, Romania)



Why another experiment?

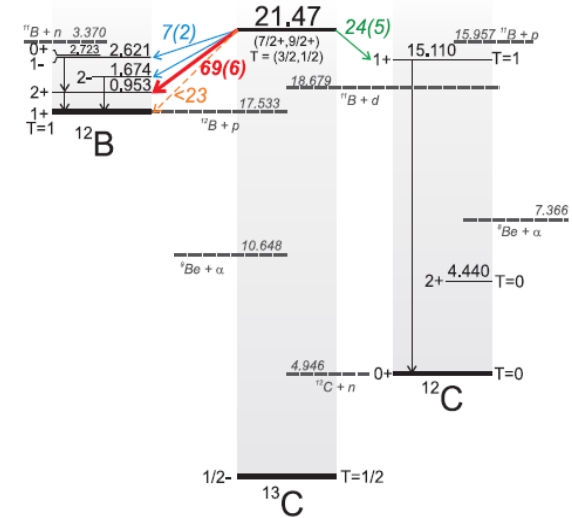
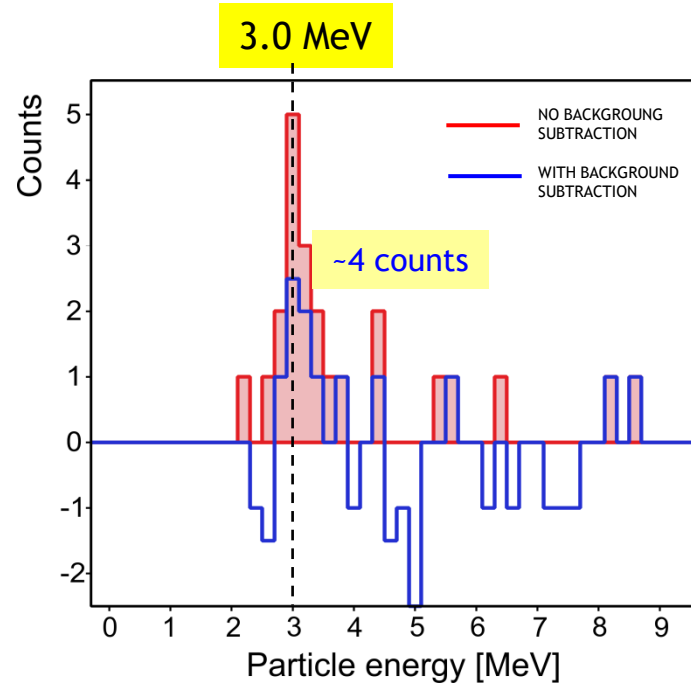
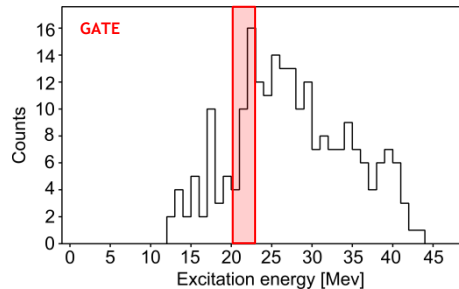
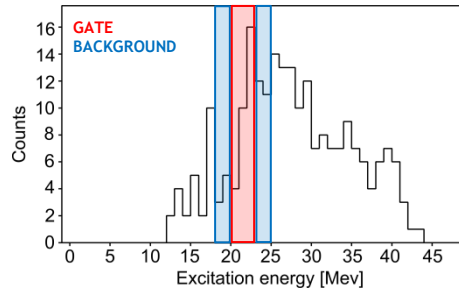
Expected energies of emitted protons are below 4 MeV so protons will stuck in the thick target

**THIN TARGET NEEDED
FOR LOW-ENERGY PROTONS!**

Excit. Energy in ¹² B [MeV]	E _{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

Scattered proton - light charged particle coincidences

Projection of the excitation energy vs. particle energy matrix

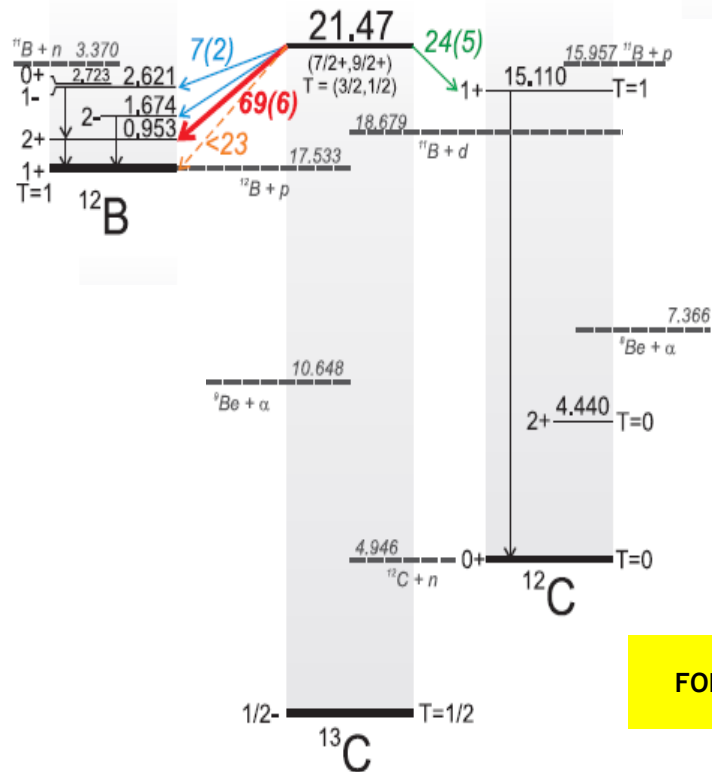


Excit. Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

Experimental results:

Decay of the 21.47-MeV stretched state in ^{13}C

Fraction of the decay with gamma-ray emission from daughter nucleus: 46(10)%



Gamow Shell Model calculations

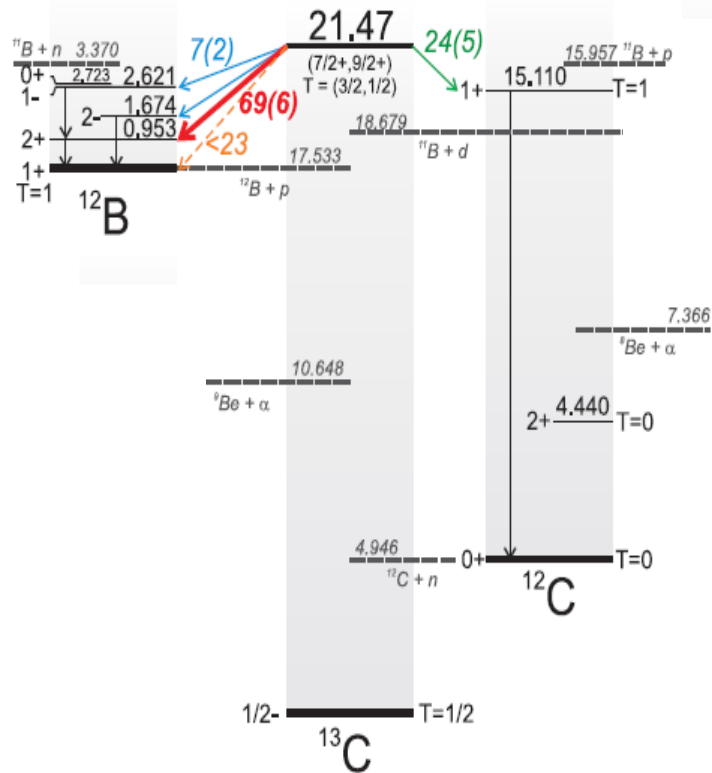
(by Y. Jaganathen (IFJ PAN) and M. Płoszajczak (GANIL))

The Gamow Shell Model is an open-quantum system extension of the traditional Shell Model, which provides:

- a rigorous treatment of **bound and unbound nuclear excitations**, including coupling to a continuum of non-resonant particles
- a fully **consistent calculation of the resonance energy and width** and their mutual relation

FOR THE FIRST TIME GSM CALCULATIONS WERE PERFORMED FOR SUCH „HEAVY” SYSTEM

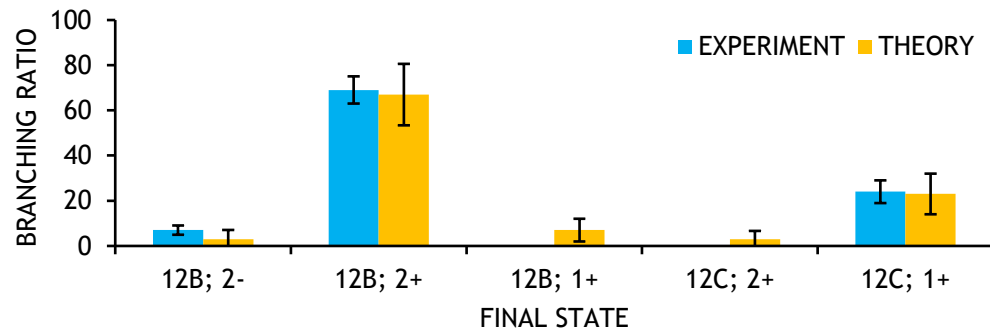
Experimental results:
Decay of the 21.47-MeV stretched state in ^{13}C



Gamow Shell Model calculations

(by Y. Jaganathen (IFJ PAN) and M. Płoszajczak (GANIL))

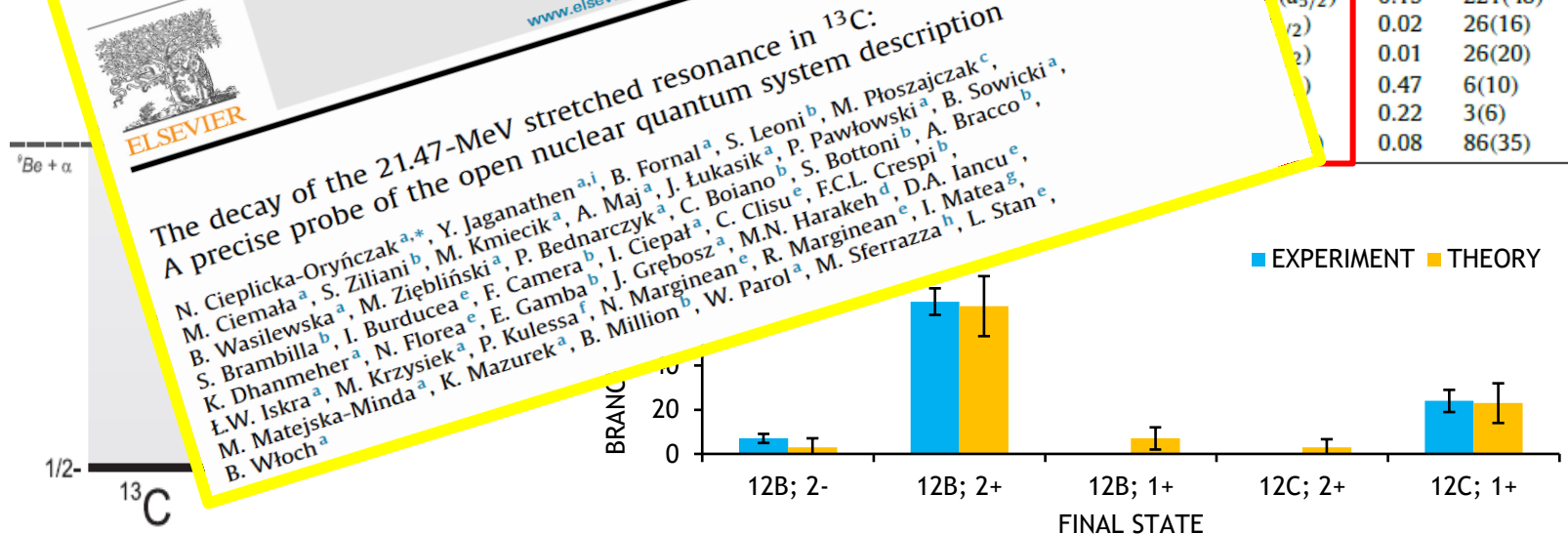
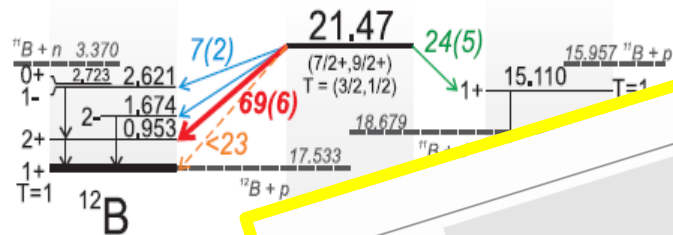
$J^\pi = (7/2^+, 9/2^+), T = (1/2, 3/2)$			$J^\pi = 7/2_7^+, T = 1.36$				
$E_{\text{exp}} = 21.47 \text{ MeV}$			$E_{\text{th}} = 20.9(5) \text{ MeV}$				
$\Gamma_{\text{exp}} = 270(20) \text{ keV}$			$\Gamma_{\text{th}} = 400(300) \text{ keV}$				
A, Z	$J^\pi; T$	$E_{\text{exp}} [\text{MeV}]$	BR_{exp}	$E_{\text{th}} [\text{MeV}]$	BR_{th}	S_f	$\Gamma_p [\text{keV}]$
^{12}B	$1^-; 1$	2.621		2.810	$0(f_{7/2})$	0	0
	$2^-; 1$	1.674	7(2)	1.979	$3(4)(p_{3/2})$	0.01	13(6)
	$2^+; 1$	0.953	69(6)	0.867	$0(f_{7/2})$	0	0
^{12}C	$1^+; 1$	0.0	<23	-0.030	$60(13)(d_{5/2})$	0.19	221(48)
	$2^+; 1$	16.106		15.7	$7(4)(d_{3/2})$	0.02	26(16)
					$7(5)(d_{5/2})$	0.01	26(20)
					$2(3)(d_{5/2})$	0.47	6(10)
					$1(2)(d_{3/2})$	0.22	3(6)
	$1^+; 1$	15.110	24(5)	14.8	$23(9)(d_{5/2})$	0.08	86(35)



Experimental results:
Decay of the 21.47-MeV stretched state in ^{13}C

Gamow Shell Model calculations

(by Y. Jaganathan and M. Płoszajczak (GANIL))



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ELSEVIER

The decay of the 21.47-MeV stretched resonance in ^{13}C :
A precise probe of the open nuclear quantum system description

N. Cieplicka-Oryńczak^{a,*}, Y. Jaganathan^{a,i}, B. Fornal^a, S. Leoni^b, M. Płoszajczak^c,
M. Ciemala^a, S. Ziliani^b, M. Kmiecik^a, A. Maj^a, J. Łukasik^a, P. Pawłowski^a, B. Sowicki^a,
B. Wasilewska^a, M. Ziębliński^a, P. Bednarczyk^a, C. Boiano^b, S. Bottoni^b, A. Bracco^b,
S. Brambilla^b, I. Burducea^e, F. Camera^b, I. Ciepał^a, C. Clisu^e, F.C.L. Crespi^b,
K. Dhanmeher^a, N. Florea^e, E. Gamba^b, J. Grębosz^a, M.N. Harakeh^d, D.A. Iancu^e,
Ł.W. Iskra^a, M. Krzysiek^a, P. Kulesza^f, N. Marginean^e, R. Marginean^e, I. Matea^g,
M. Matejska-Minda^a, K. Mazurek^a, B. Million^b, W. Parol^a, M. Sferazza^h, L. Stan^e,
B. Włoch^a

$E_x = 1.36$ MeV

Final State	S_f	Γ_p [keV]
$7/2^-$	0	0
$3/2^-$	0.01	13(6)
$1/2^-$	0	0
$5/2^-$	0.19	221(48)
$3/2^-$	0.02	26(16)
$1/2^-$	0.01	26(20)
$5/2^-$	0.47	6(10)
$3/2^-$	0.22	3(6)
$1/2^-$	0.08	86(35)

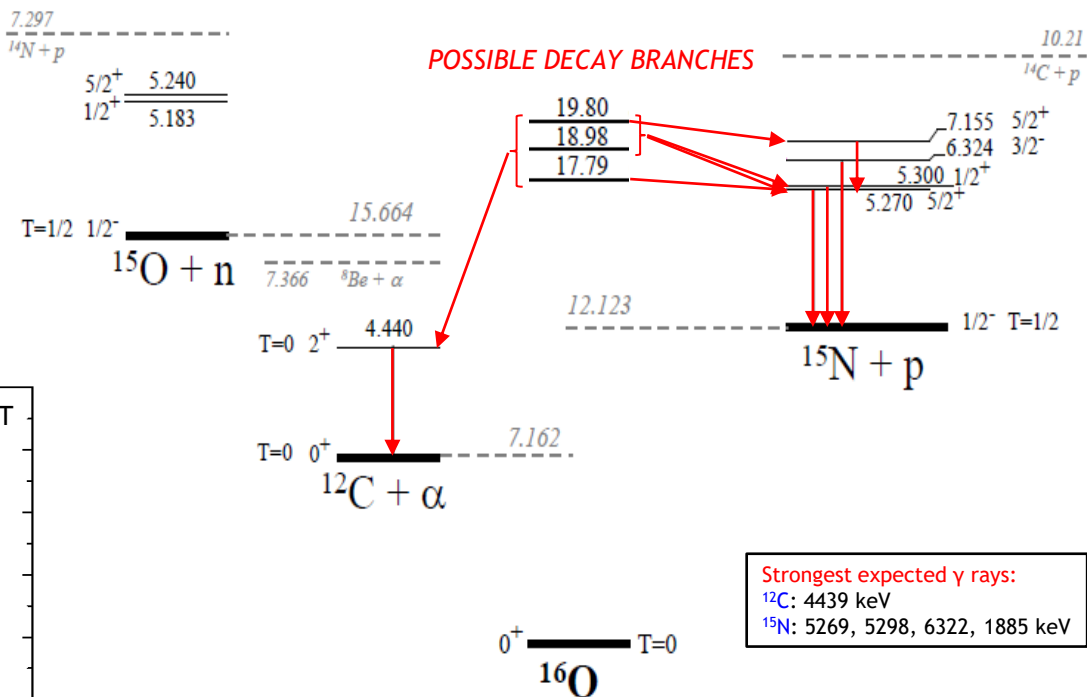
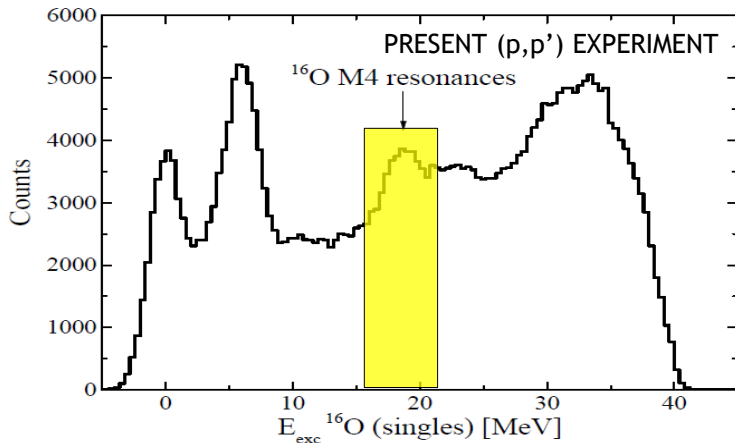
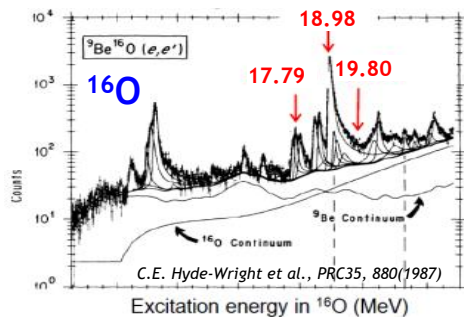
^{14}N AND ^{16}O

December 2019 – March 2020

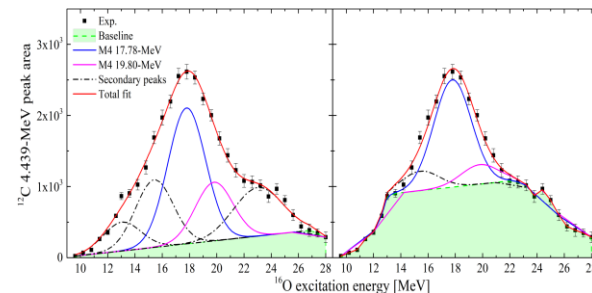
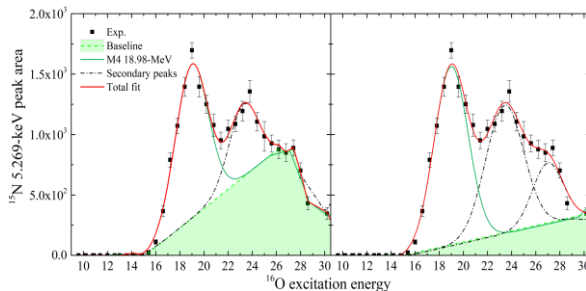
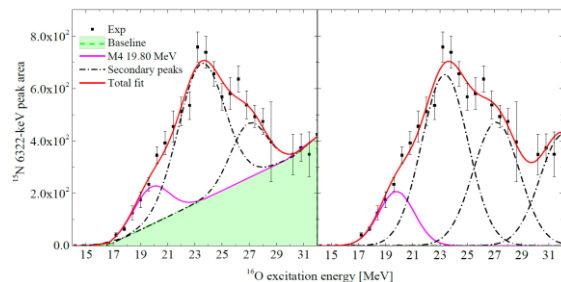
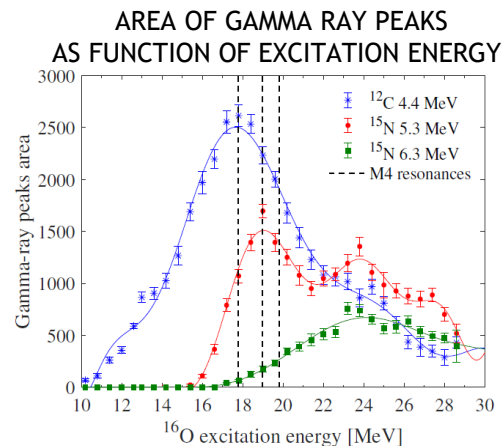
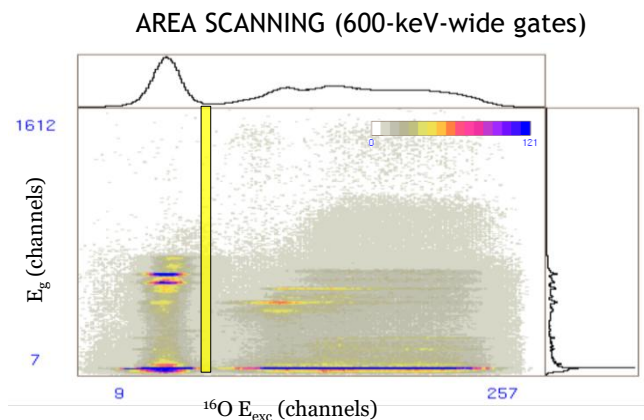
Spokepersons: S. Ziliani (Univ. of Milan and INFN Milan), N. Cieplicka-Oryńczak (IFJ PAN)

Stretched resonances in ^{16}O

$^7\text{Li}-^{14}\text{N}-\text{H}_2 + (^{16}\text{O} \text{ contamination})$ target 160 mg/cm²



Stretched resonances in ^{16}O



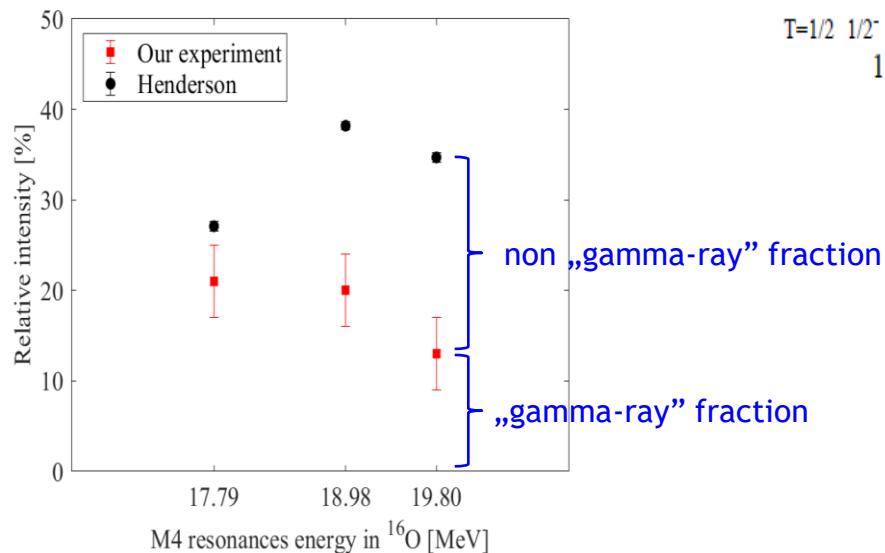
EXTRACTION OF DECAY BRANCHINGS ASSOCIATED TO GAMMA EMISSION

S.Ziliani, PhD thesis, University of Milan (2021)

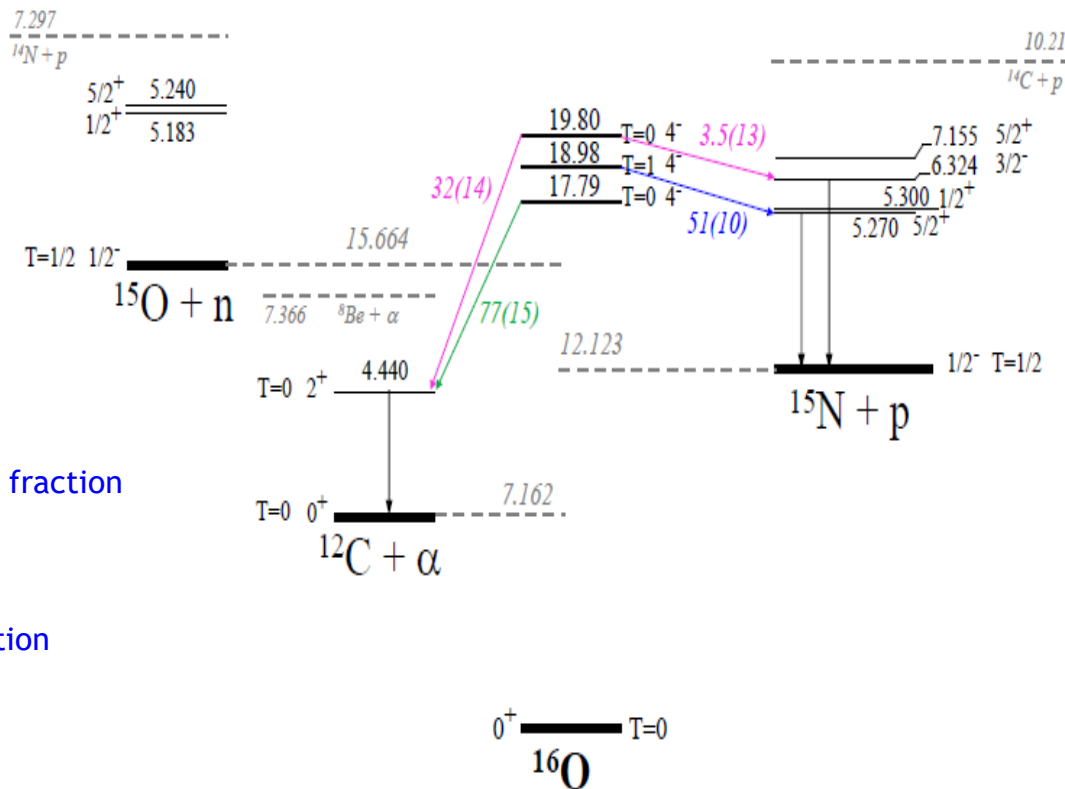
Branching ratios in ^{16}O

COMPARISON OF RELATIVE POPULATION WITH PREVIOUS (p,p') EXPERIMENT

R.S. Henderson et al., Aust.J.Phys.32,411(1979)



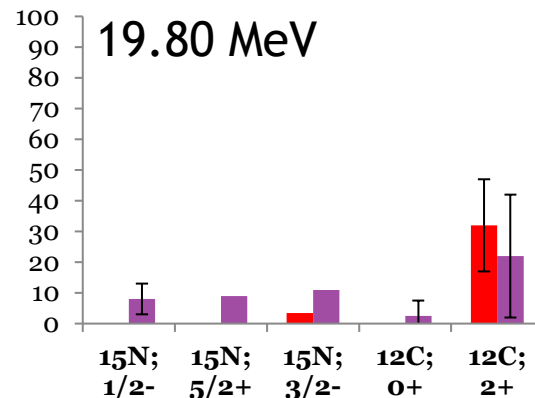
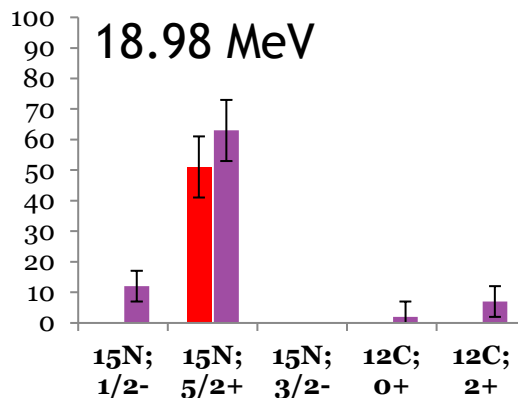
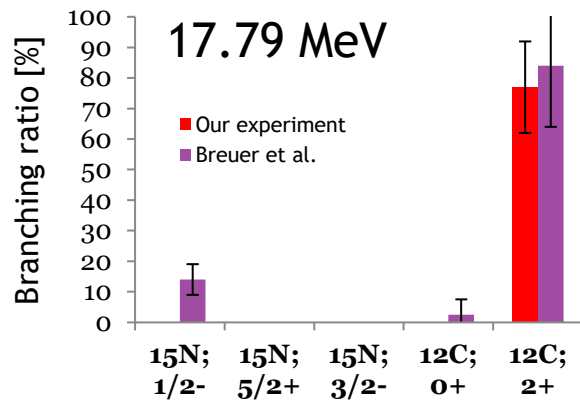
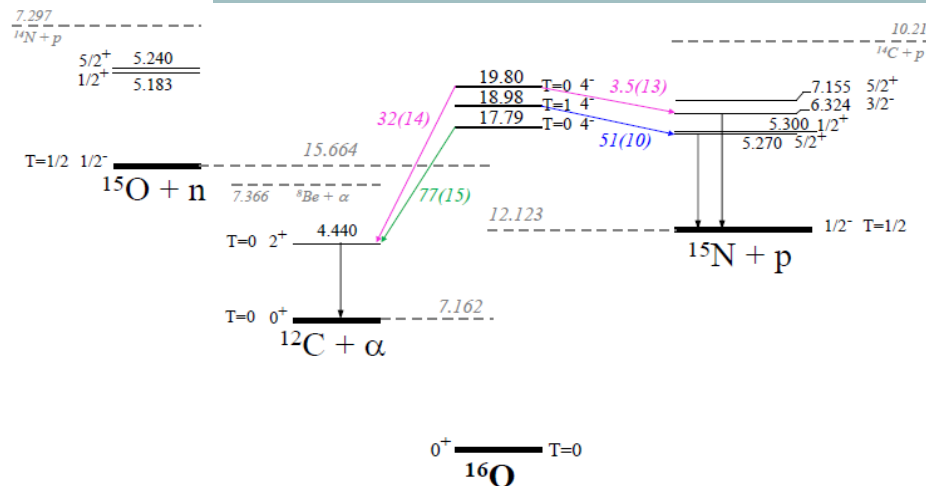
RESULTS FROM PRESENT (p,p') EXPERIMENT



Branching ratios in ^{16}O

COMPARISON OF BR WITH PREVIOUS
 $^{17}\text{O}(d,t)$ AND $^{17}\text{O}(^3\text{He},\alpha)$ EXPERIMENTS

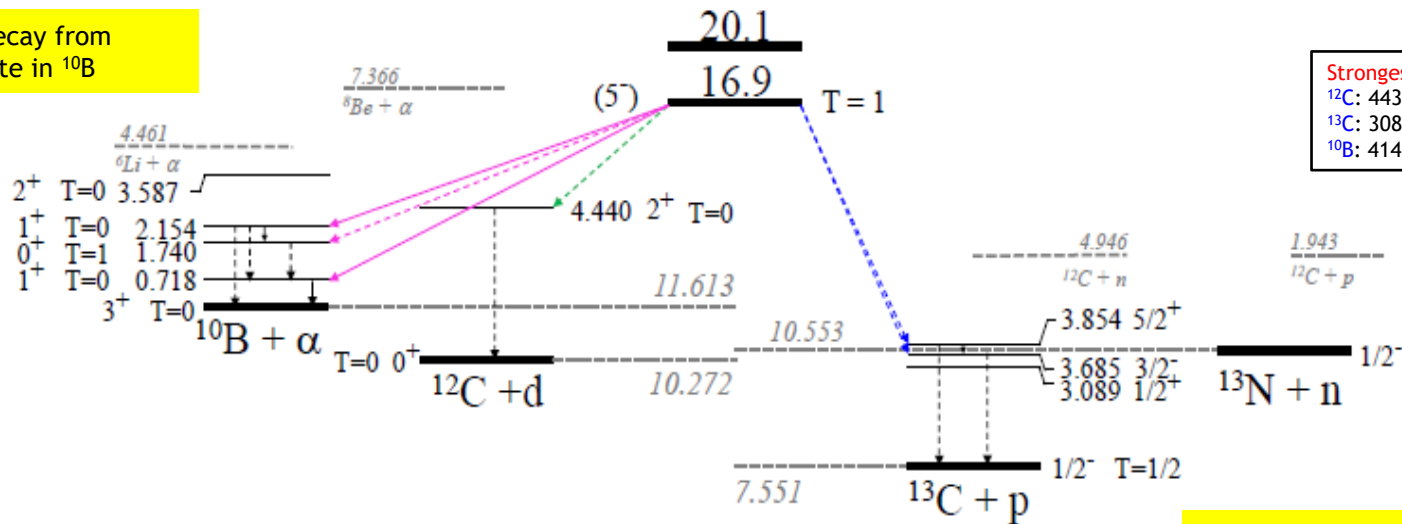
H. Breuer et al., Phys.Lett. 96B, 35 (1980)



Stretched M4 resonances in ^{14}N

$^7\text{Li}-^{14}\text{N}-\text{H}_2$ + (^{16}O contamination) target 160 mg/cm²

No γ decay from
2⁺ state in ^{10}B



Strongest expected γ rays:

^{12}C : 4439 keV

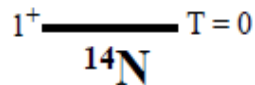
^{13}C : 3089, 3684, 3853 keV

^{10}B : 414, 718, 1021, 2868 keV

No γ decay from first
excited state in ^{13}C

PERSPECTIVES

- ❑ New thick target of $^7\text{Li}-^{14}\text{N}-\text{H}_2$ (about 160 mg/cm²) without oxygen contamination
- ❑ Similar experimental setup



QUALITATIVE INFORMATION ON DECAY
BRANCHINGS ASSOCIATED TO GAMMA EMISSION

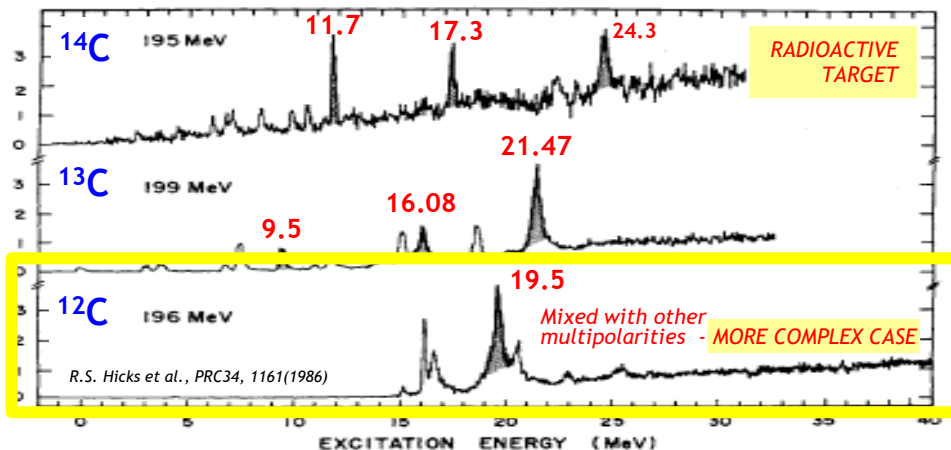
Very recent experiment: ^{12}C

October 2024 – January 2025

Spokepersons: N. Cieplicka-Oryńczak (IFJ PAN), G. Corbari (Univ. of Milan and INFN Milan)

Study of M4 stretched configuration decay in ^{12}C

INELASTIC ELECTRON SCATTERING EXPERIMENTS

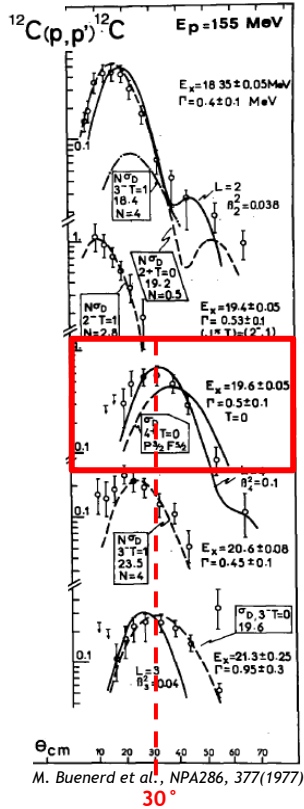


- comparison of cross sections measured in (π^+, π'^+) and (π^-, π'^-) experiments was interpreted as due to isospin mixing between two or more 4^- levels of $T = 1$ and $T = 0$ character
- a significant 2^- strength was found for the 19.4-MeV peak identified in the inelastic scattering of 398-MeV protons on the ^{12}C target

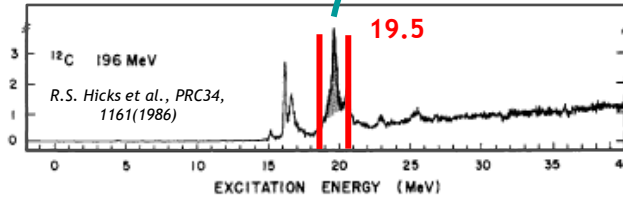
The 19.5-MeV state in ^{12}C having strong single-particle-hole component partially overlaps with other states...

Decay data can help to resolve the complicated energy spectrum in ^{12}C at high excitation energies!

Expected decay scheme of the 19.5-MeV state in ^{12}C



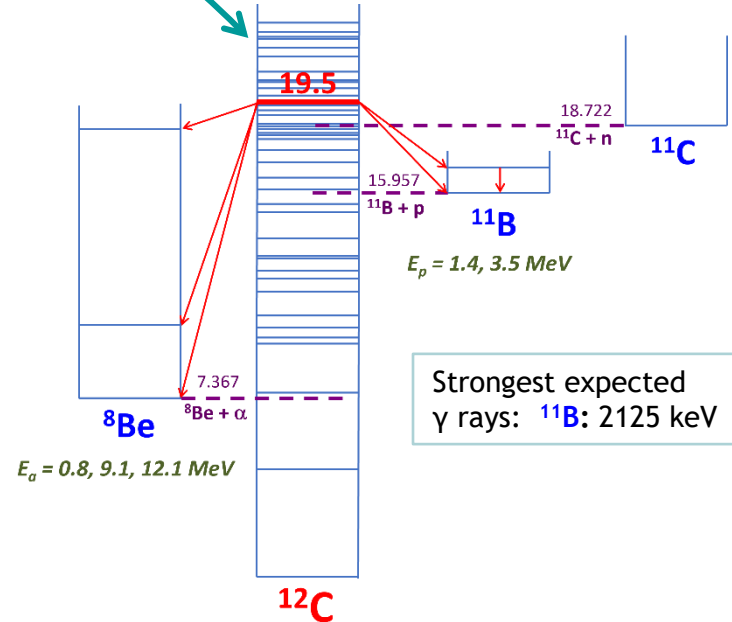
INELASTIC ELECTRON SCATTERING EXPERIMENTS



GATE ON THE SCATTERED PROTONS

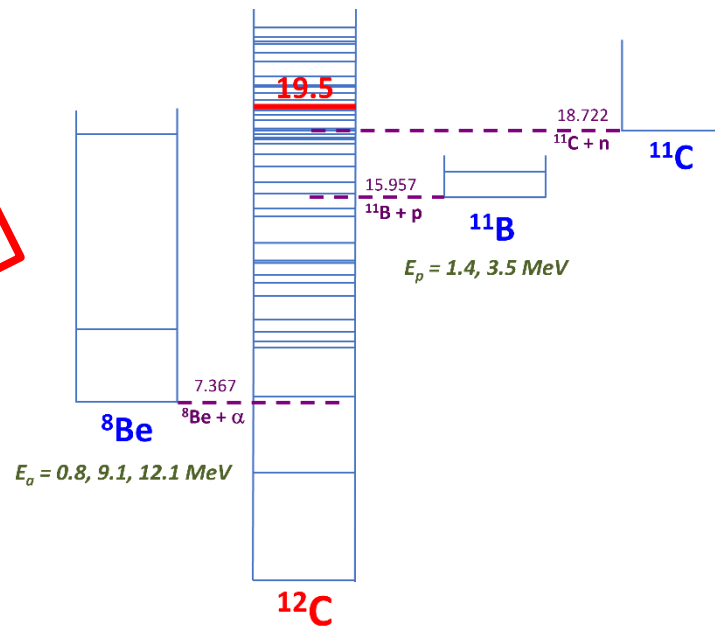
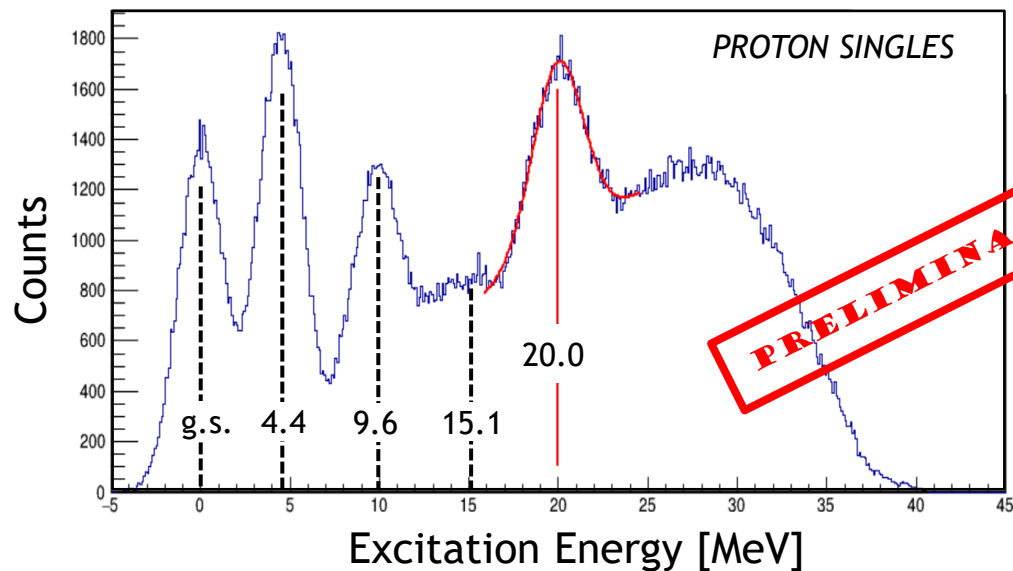
The population of the M4 resonance at 19.5 MeV in ^{12}C is peaked at 30°

The aim of the proposed experiment is to **identify the decay of the 19.5-MeV** $1p_{3/2} \rightarrow 1d_{5/2}$ resonance in ^{12}C

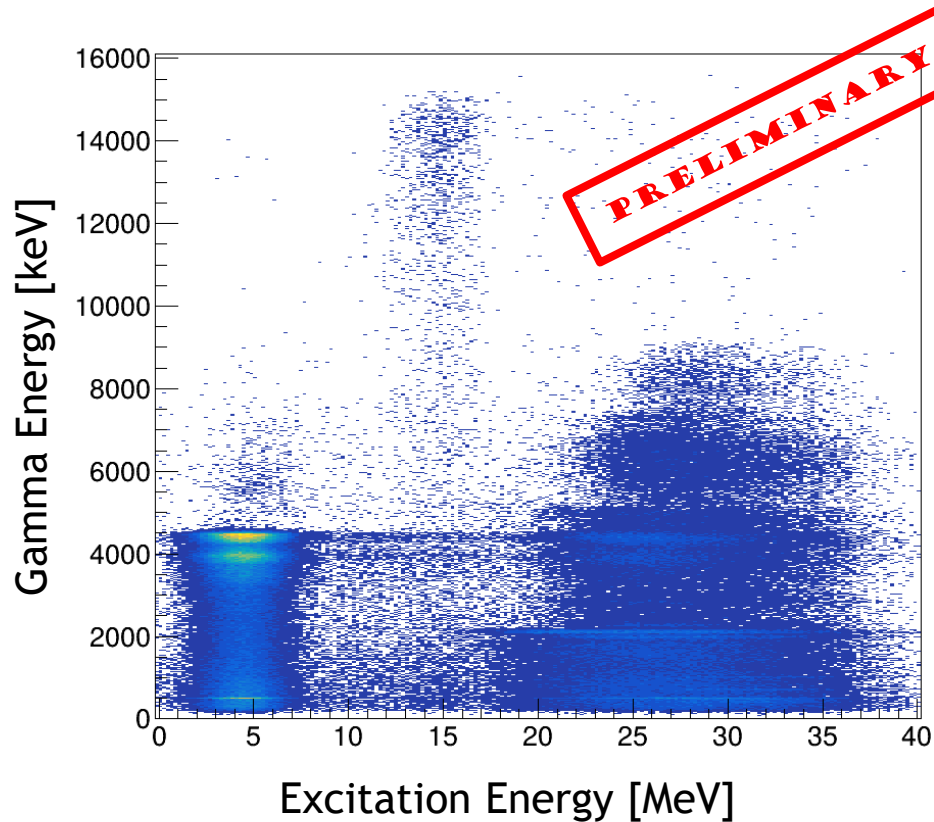


Experimental results: ^{12}C population in (p,p') at 135 MeV reaction

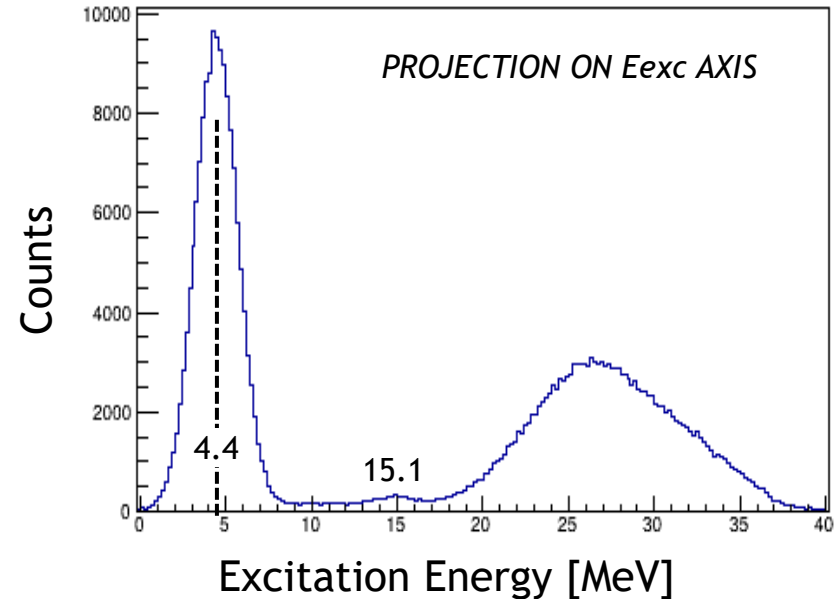
- Excitation Energy from proton measurement (150 mg/cm² target)
- No gamma ray detection required („proton singles”)



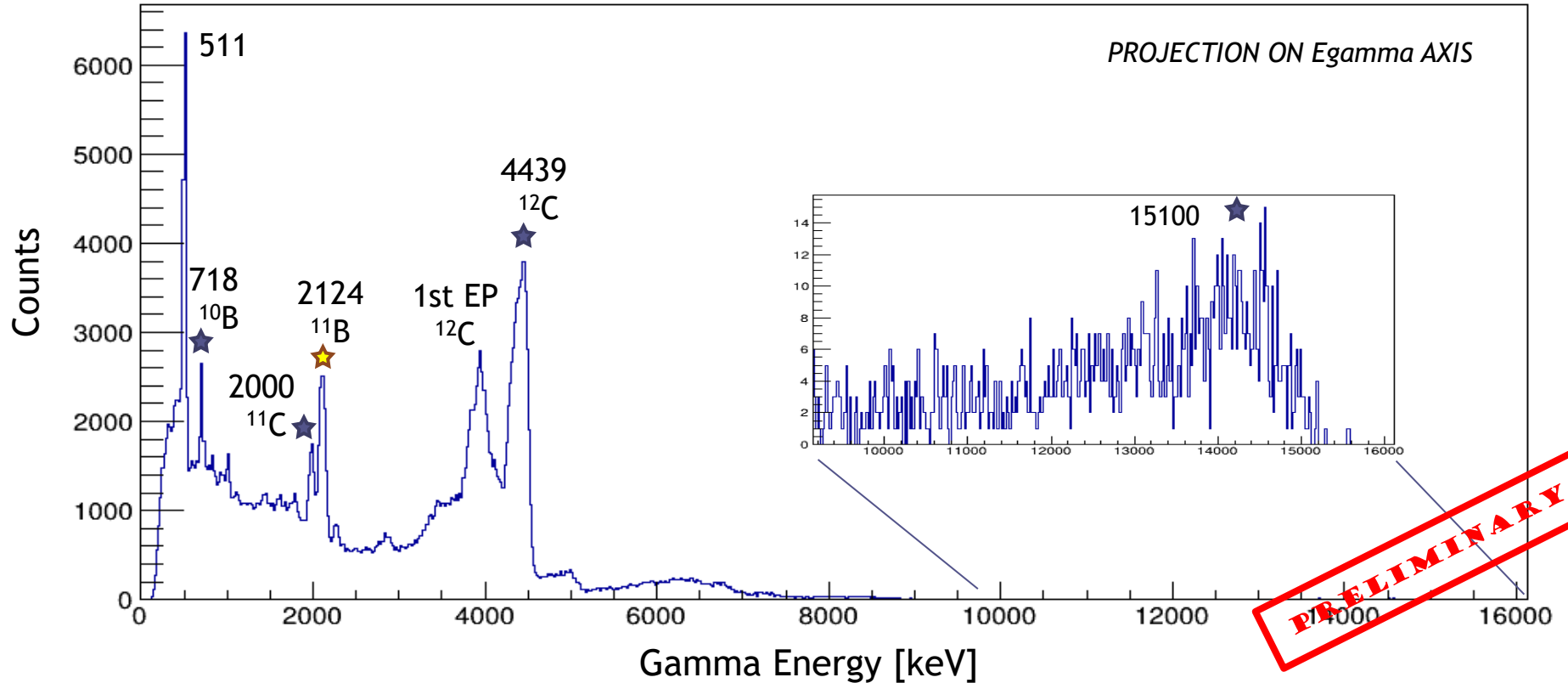
Experimental results: proton-gamma coincidence measurement



- ☐ One weekend only
- ☐ Coincidences with 4 big LaBr only

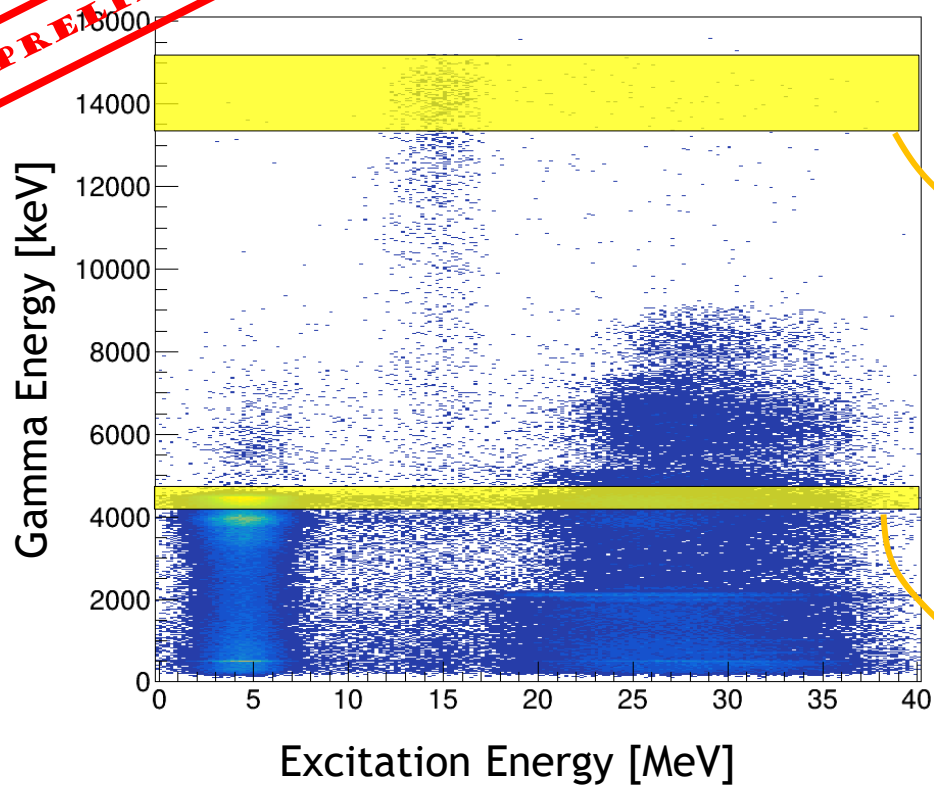


Experimental results: proton-gamma coincidence measurement

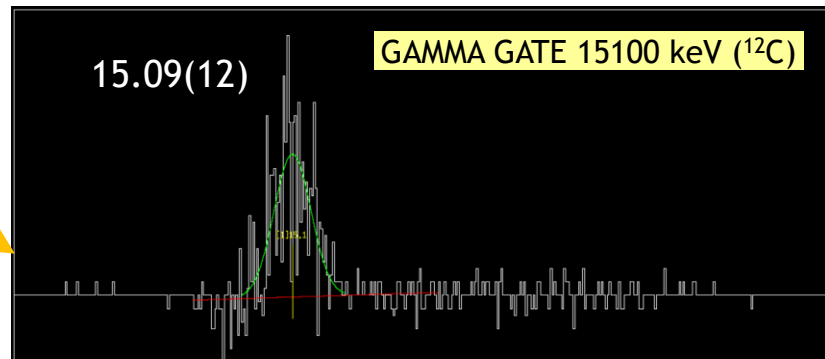


Experimental results: proton-gamma coincidence measurement

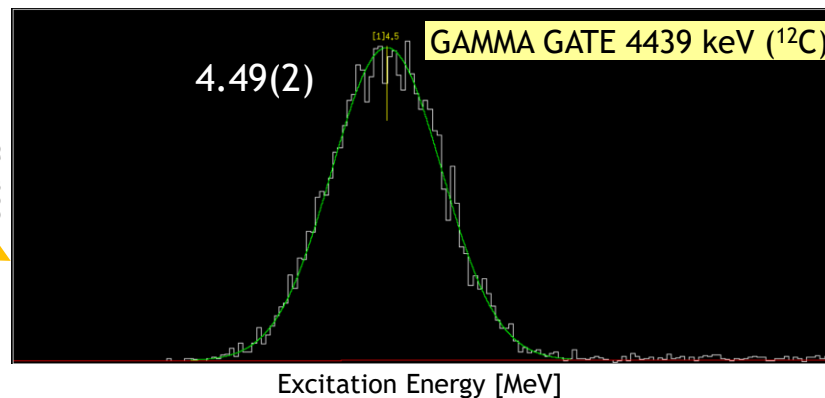
PRELIMINARY



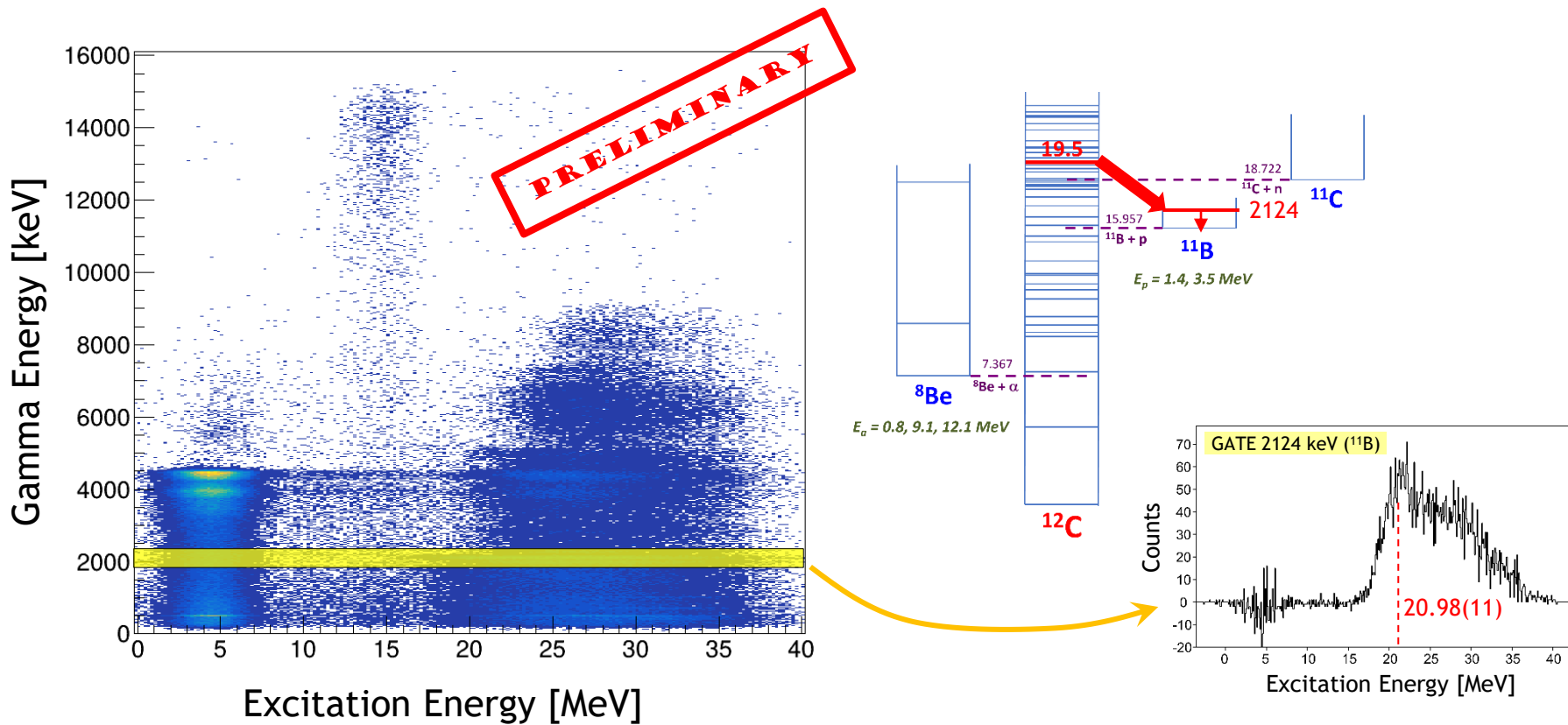
Counts



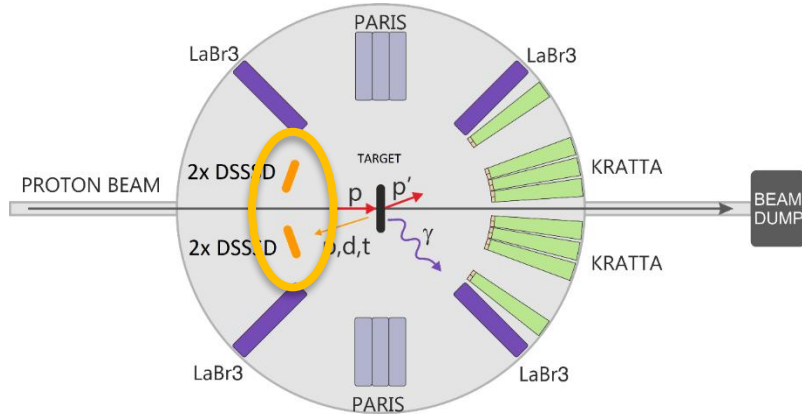
Counts



Experimental results: proton-gamma coincidence measurement

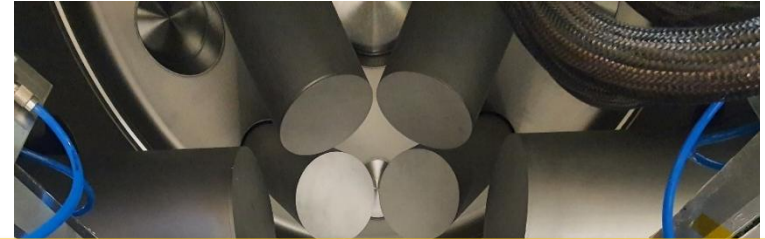


Light charged particles measurements: 4 DSSD detectors



SETUP

- 1) Scattered protons measurement: **KRATTA** telescope array
- 2) γ -ray detection:
 - four **LaBr_3** detectors (3.5"x8")
 - two clusters of the **PARIS** scintillator array
- 3) Measurement of light charged particles produced in the reaction: four thick position-sensitive **Si detectors**



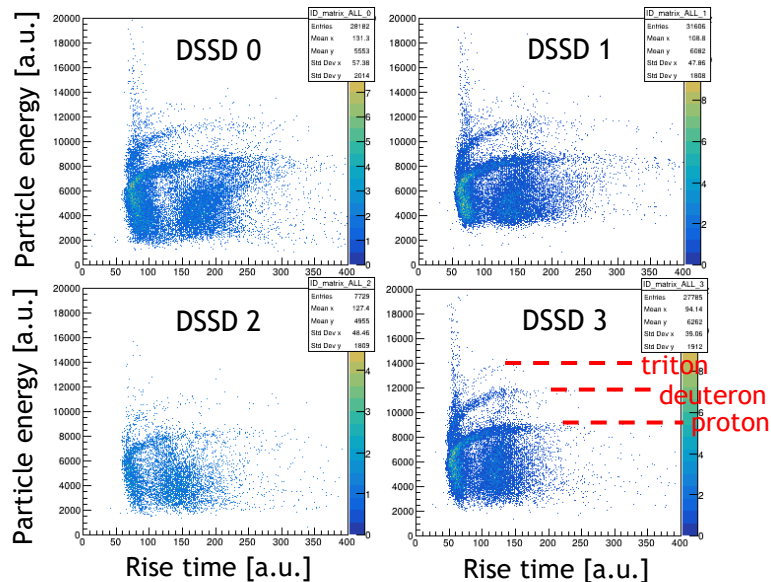
Scattered proton - light charged particle coincidences

- ❑ Excitation Energy from proton measurement (150 mg/cm² target)
- ❑ Statistics from one weekend only

PRELIMINARY

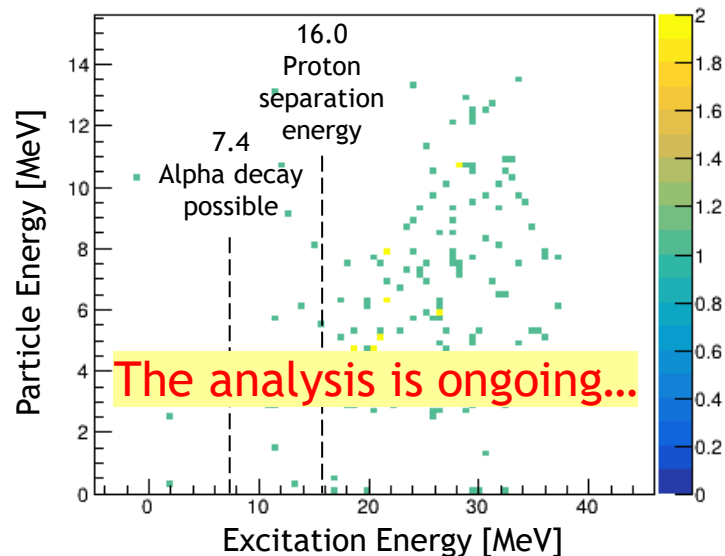
PARTICLE IDENTIFICATION MATRICES

from $^{12}\text{C}(p,p')$ reaction (1 mg/cm² target)



EXCITATION ENERGY - PARTICLE ENERGY MATRIX

from $^{12}\text{C}(p,p')$ reaction (1 mg/cm² target)



Summary

- ✓ The first information on the **decay branching of the 21.47-MeV stretched state in ^{13}C** nucleus was obtained from proton-gamma coincidence measurements.
- ✓ Successful comparison with experiment in terms of **state energy, width and decay branchings** proves the high quality and precision of the GSM wave-function calculations.
- ✓ Qualitative information on branching ratios from the 16.9-MeV stretched state in ^{14}N was obtained
- ✓ Information on the branching ratios from the 17.8-, 19.0-, and 19.8-MeV stretched states in ^{16}O was obtained.

This newly developed theoretical approach will be crucial in predicting structures in the continuum in other nuclei in this key region of nuclear chart.

The preliminary results of the ^{12}C experiment provided information on the proton-decay branch of the 19.5-MeV stretched resonance

... analysis will be continued!

Thank you for your attention!

Stretched states in the continuum - Gamow Shell Model calculations

Calculations by Y. Jaganathen (IFJ PAN) and M. Płoszajczak (GANIL)

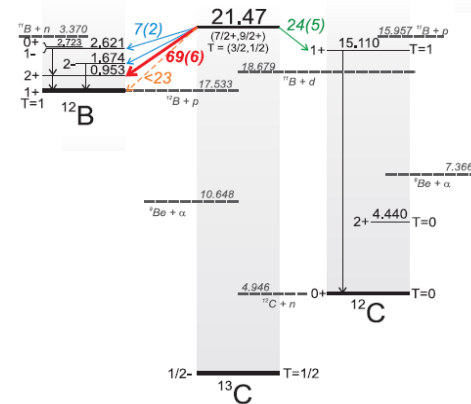
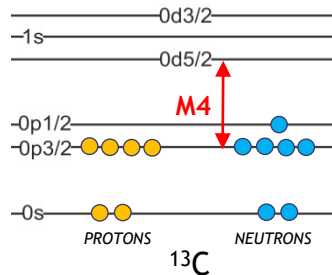
Mostly decays to the 1^+ states of ^{12}B and ^{12}C

Small percentage of a particle-hole excitation between the $p_{3/2}$ and the $d_{5/2}$ orbitals

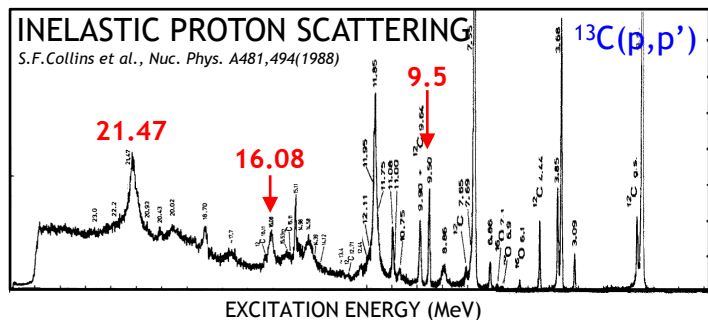
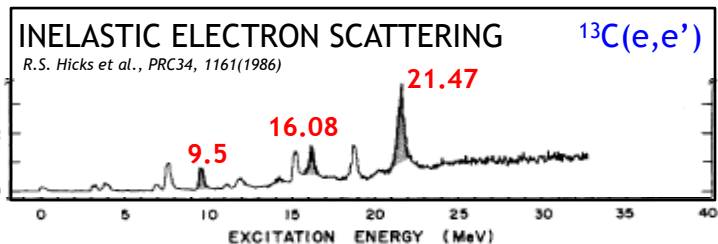
Does not decay to the 1^+ state at 15.11 MeV in ^{12}C or to the negative parity states in ^{12}B

CANDIDATES FOR THE 21.5-MeV M4 RESONANCE IN ^{13}C :

State	T	E	Γ	%M4(n)	%M4(p)
$7/2_6^+$	1.44	19.9(5)	1500(200)	32%	22%
$7/2_7^+$	1.36	20.9(5)	400(300)	32%	19%
$7/2_8^+$	0.90	22.1(8)	2500(1000)	8%	9%
$9/2_3^+$	1.49	21.8(7)	150(300)	38%	27%



Previous studies of M4 resonances in ^{13}C



From $^{13}\text{C}(\pi,\pi')$ scattering:

- 9.5 MeV is $9/2^+$: pure neutron excitation
- 16.08 MeV is $7/2^+$: mainly proton excitation
- 21.47 MeV is $(7/2^+, 9/2^+)$ proton and neutron excitations

INELASTIC PION SCATTERING

