THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

NARODOWE CENTRUM NAUKI
Project no. 2020/39/D/ST2/03443

Stretched resonances in light nuclei studied experimentally at CCB IFJ PAN

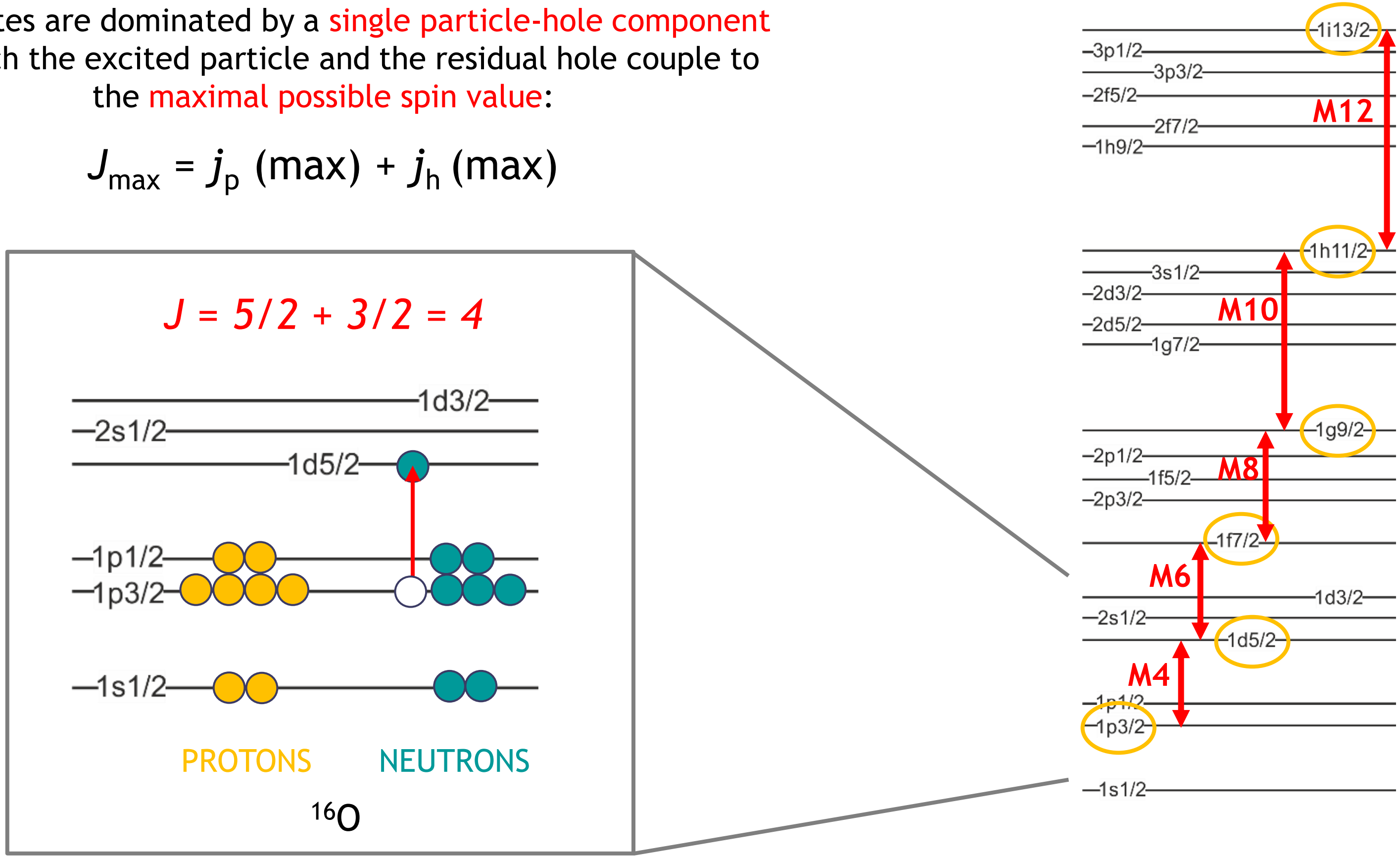
<u>N.Cieplicka-Oryńczak</u>[1], Y. Jaganathen[9], B. Fornal[1], S. Leoni[2], M. Płoszajczak[3], M. Ciemała[1], S. Ziliani[2], M. Kmiecik[1], A. Maj[1], J. Łukasik[1], P. Pawłowski[1], B. Sowicki[1], B. Wasilewska[1], M. Ziębliński[1], C. Boiano[2], S. Brambilla[2], P. Bednarczyk[1], S. Bottoni[2], A. Bracco[2], I. Burducea[5], F. Camera[2], I. Ciepał[1], C. Clisu[5], F.C.L. Crespi[2], K. Dhanmeher[1], N. Florea[5], E. Gamba[2], J. Grębosz[1], M. N. Harakeh[4], D. A. Iancu[5], Ł.W. Iskra[1], M. Krzysiek[1], P. Kulessa[1], N. Marginean[5], R. Marginean[5], I. Matea[7], M. Matejska-Minda[1], K. Mazurek[1], B. Million[2], W. Parol[1], M. Sferrazza[8], L. Stan[5], B. Włoch[1], C. Schmitt[1], D. Duda[1], K. Gajewska[1], O. Wieland[2], G. Corbari[2], A. Giaz[2], E. van Rompu[6], P.-A. Söderström[10], A. Kuşoğlu[10], S. R. Ban[10], D. Balabanski[10], K. Hadyńska-Klęk[11], A. Špaček[11], P. Dey[11], A. Krzysiek[11], G. Szymanek[11]

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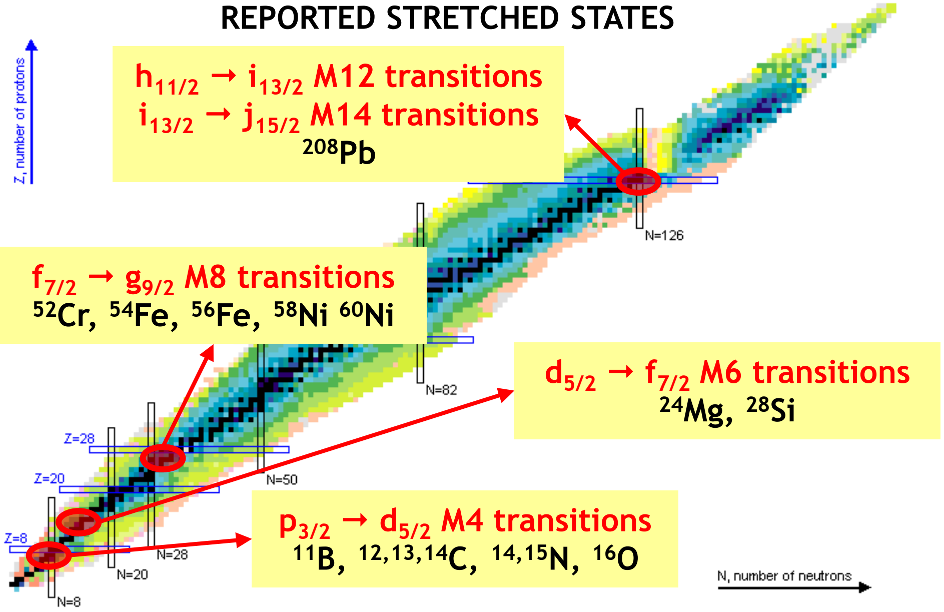
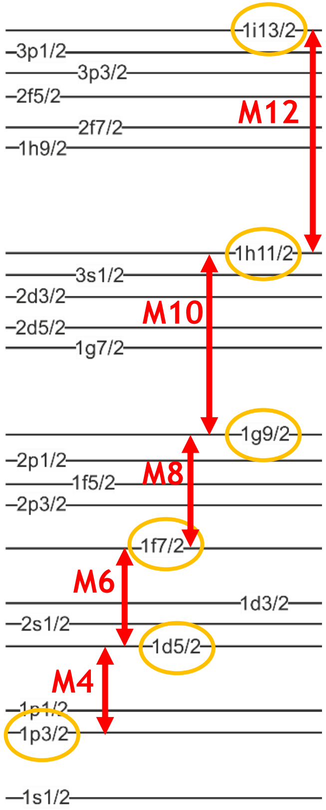
REPORTED STRETCHED STATES

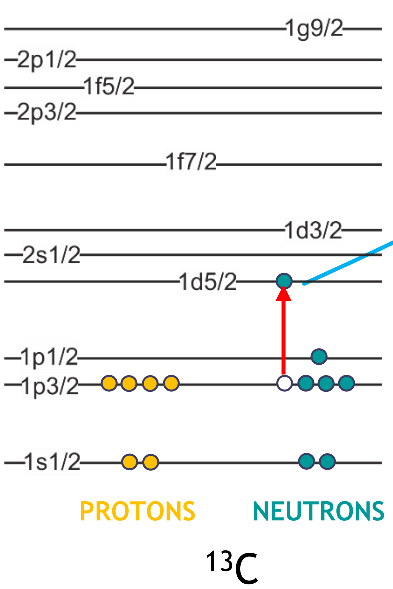


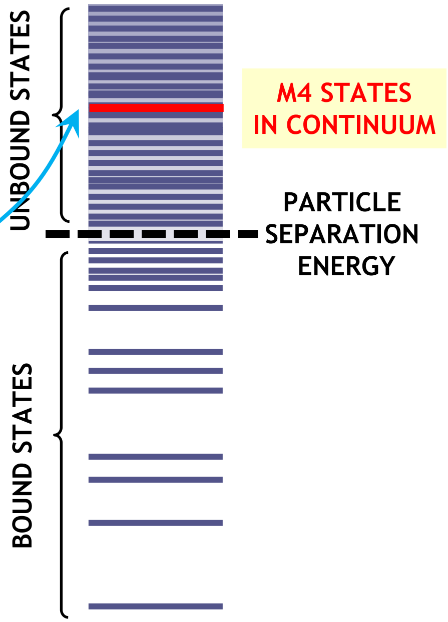


Stretched states in light nuclei – why are they interesting?

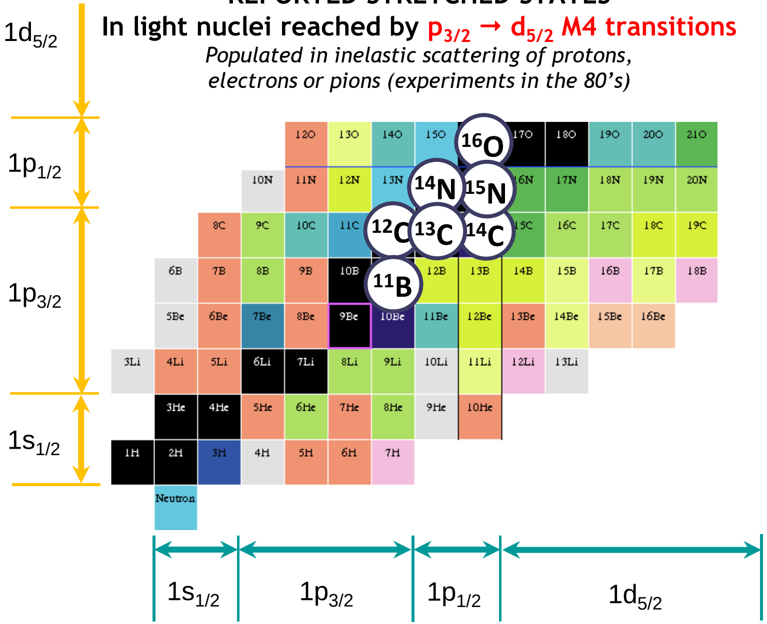
CONFIGURATIONAL PURITY
ones of the simplest known nuclear excitations

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.)





REPORTED STRETCHED STATES
In light nuclei reached by $p_{3/2} \rightarrow d_{5/2}$ M4 transitions
Populated in inelastic scattering of protons, electrons or pions (experiments in the 80's)



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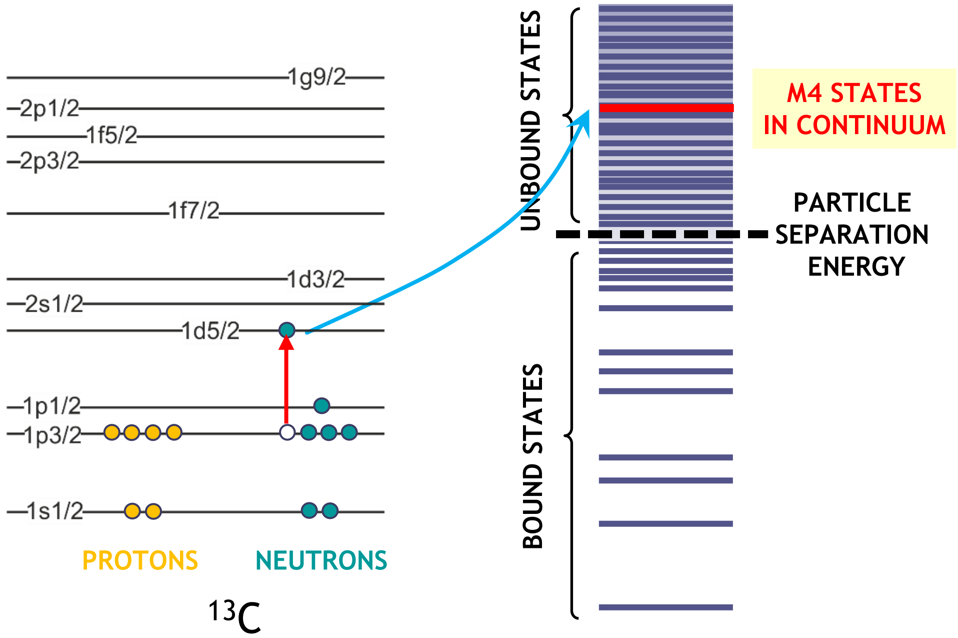

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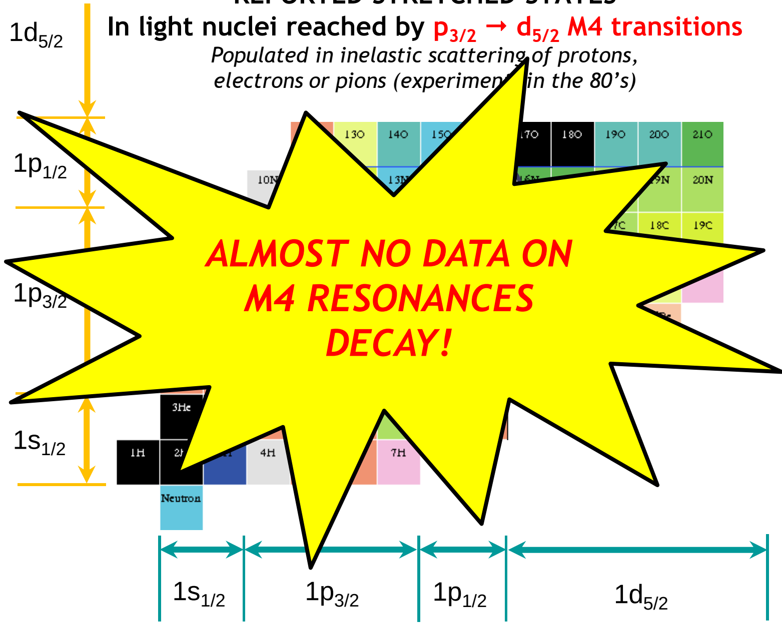
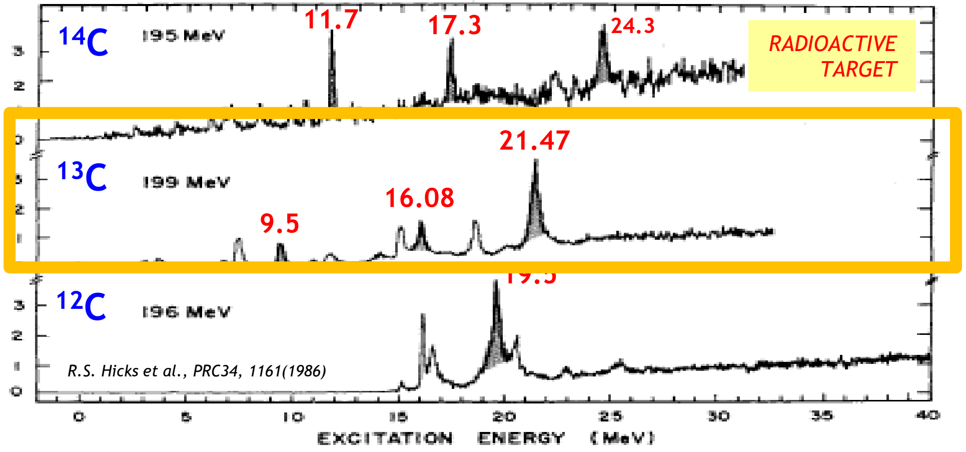
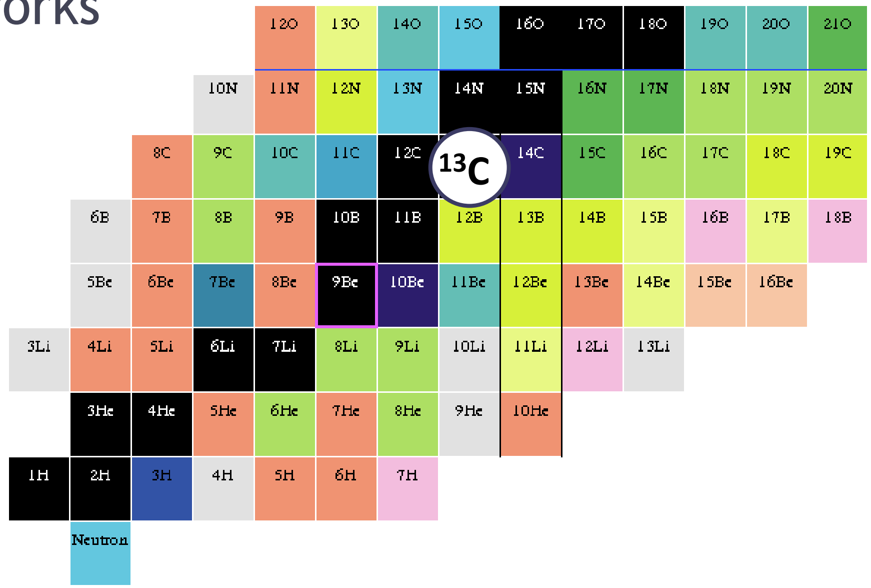


NUCLEI OF OUR INTEREST

Stretched resonances – from prevoius works

INELASTIC ELECTRON SCATTERING EXPERIMENTS



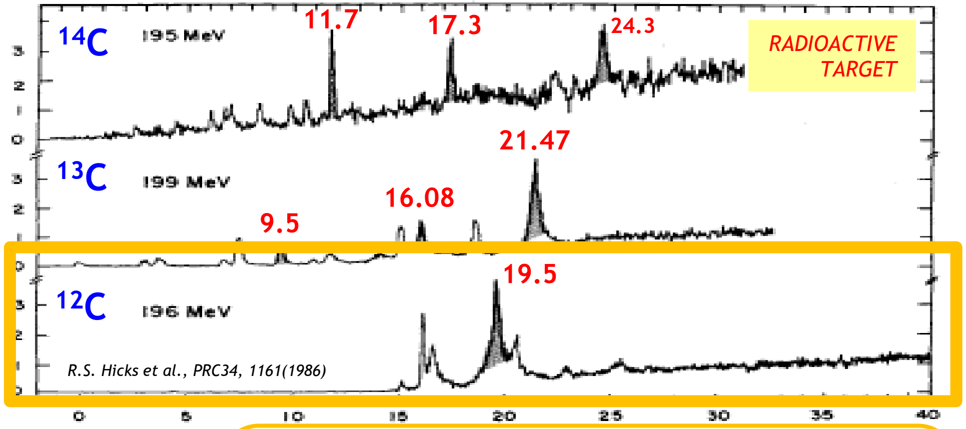


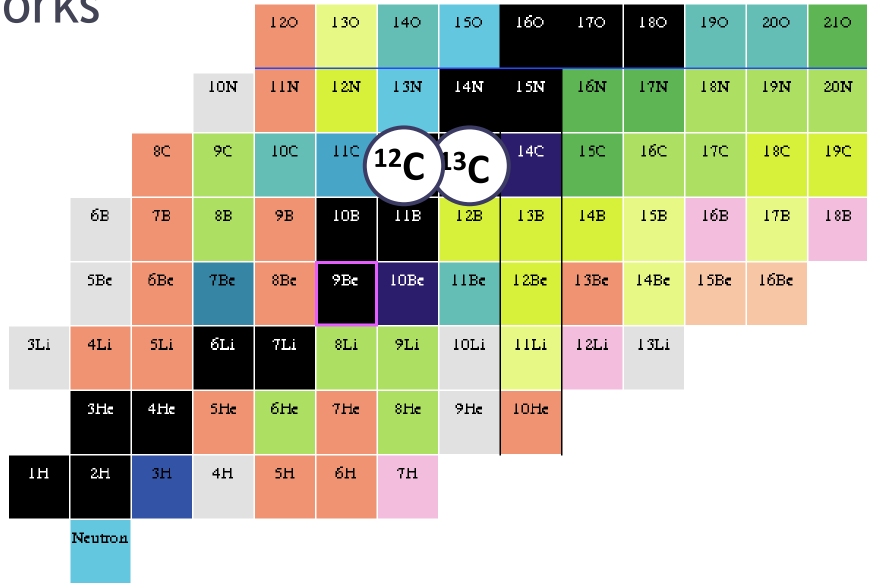
^{13}C is a perfect case to start:

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

Stretched resonances – from prevoius works

INELASTIC ELECTRON SCATTERING EXPERIMENTS

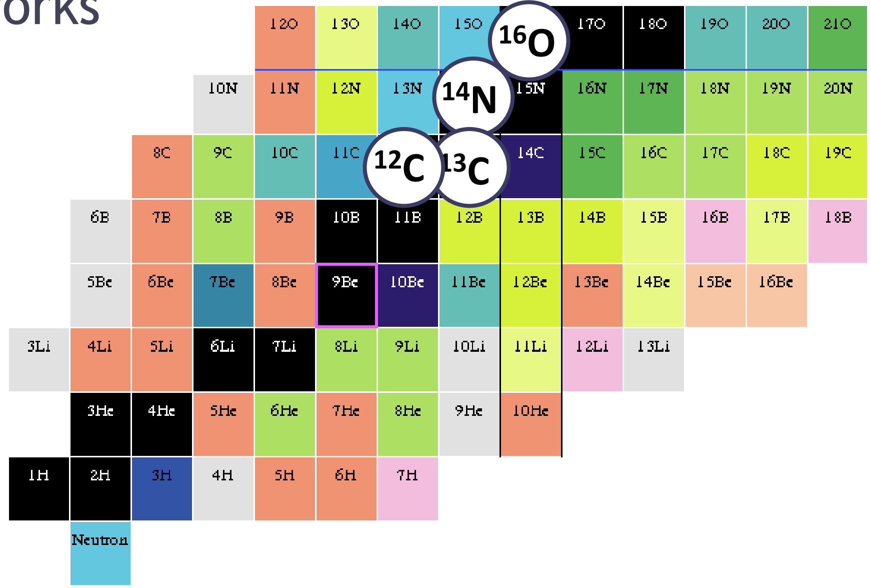




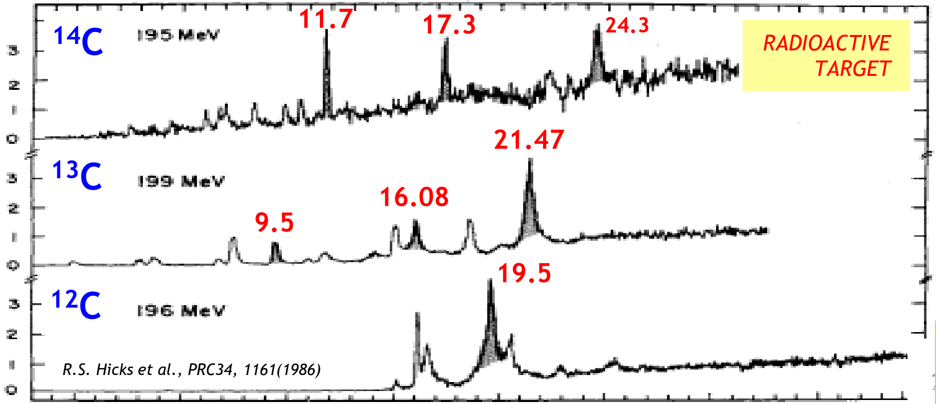
^{12}C: the 19.5-MeV stretched M4 excitation is mixed with other multipolarities

→ *MORE COMPLEX CASE*

Stretched resonances – from prevoius works

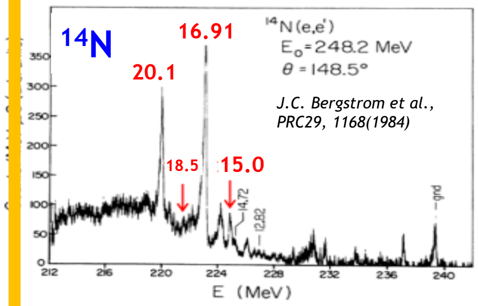


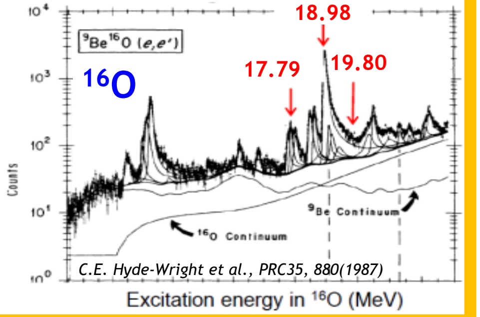
INELASTIC ELECTRON SCATTERING EXPERIMENTS



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

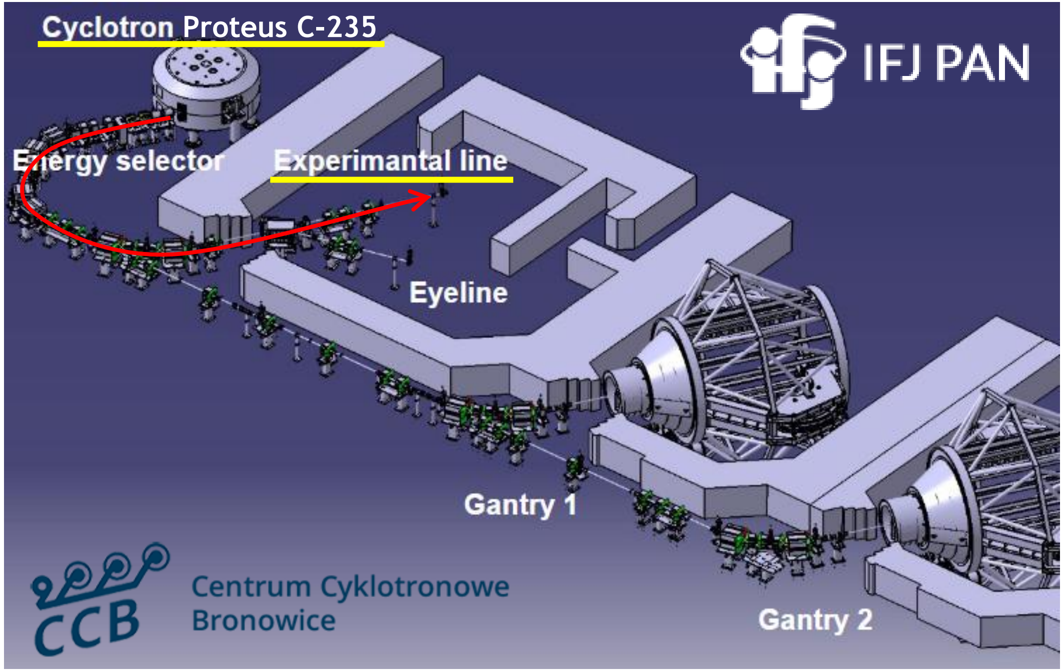
Lithium amide: ^{7}Li-^{14}N-H$_2$ + (^{16}O contamination)



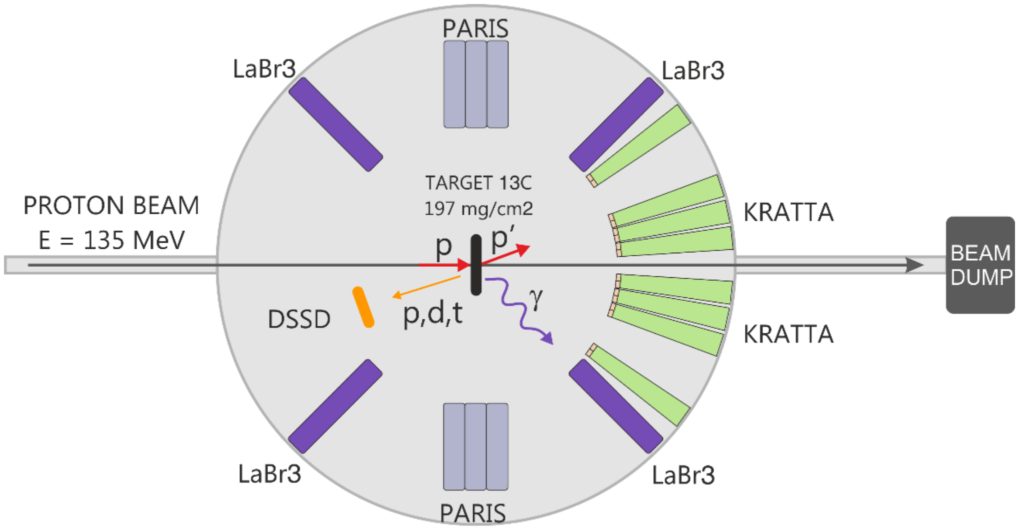


EXPERIMENTAL SETUP AT CCB IFJ

Experimental setup – Cyclotron Centre Bronowice (Kraków, Poland)



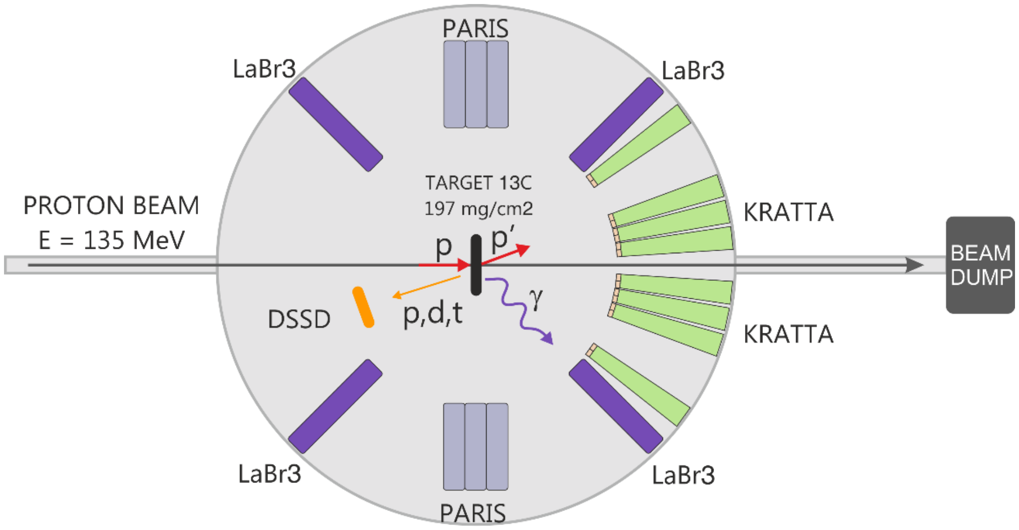
Experimental setup at CCB IFJ

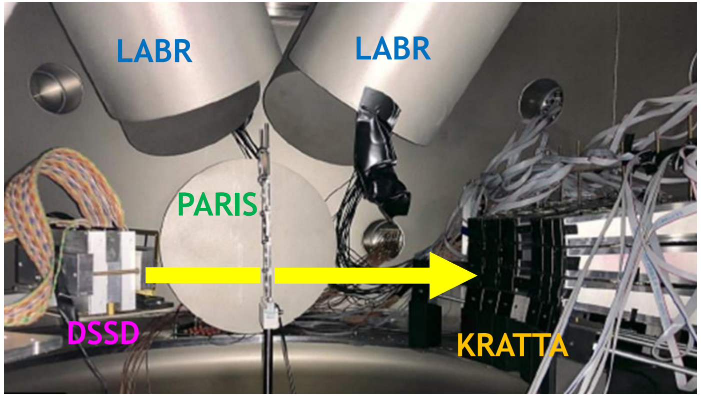


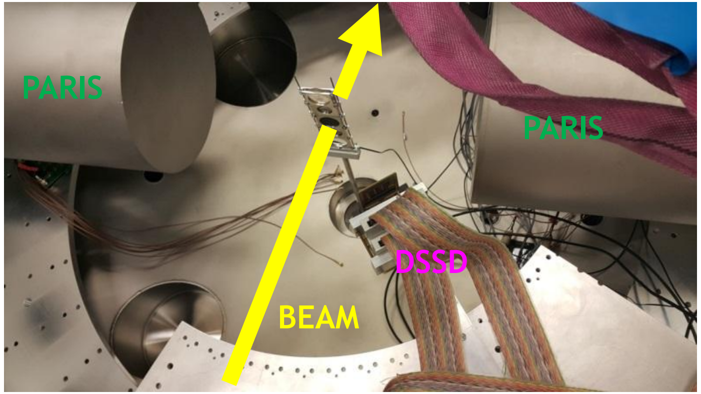
Large vacuum scattering chamber at CCB

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: a thick position-sensitive Si detector

Experimental setup at CCB IFJ







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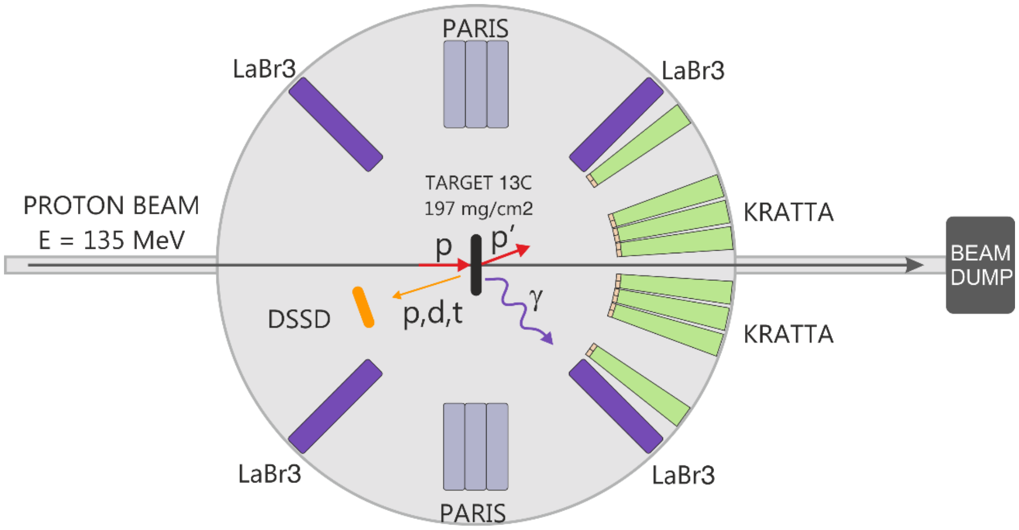

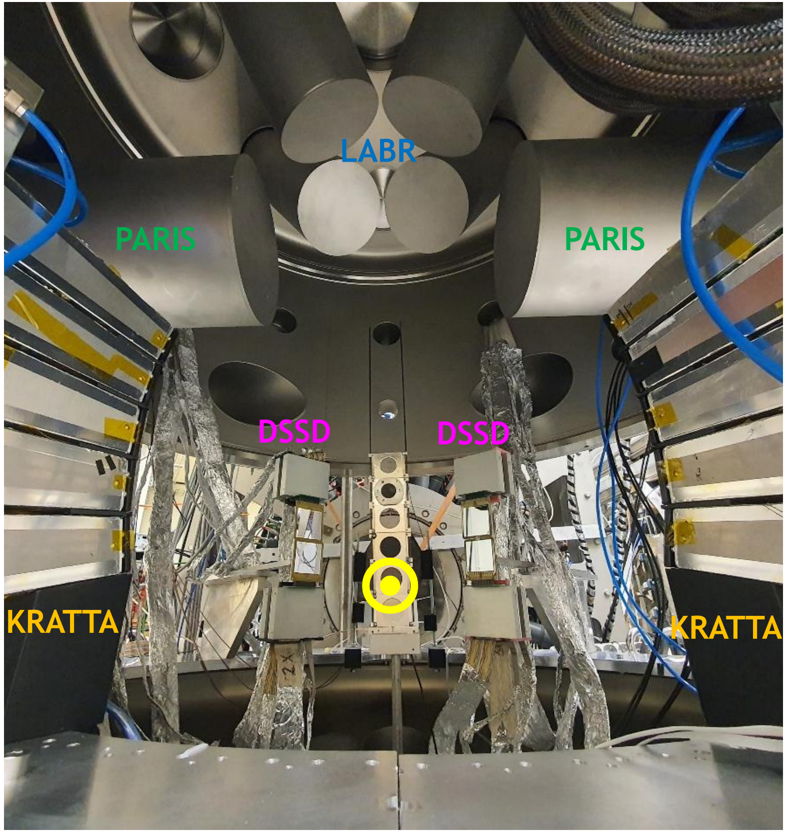

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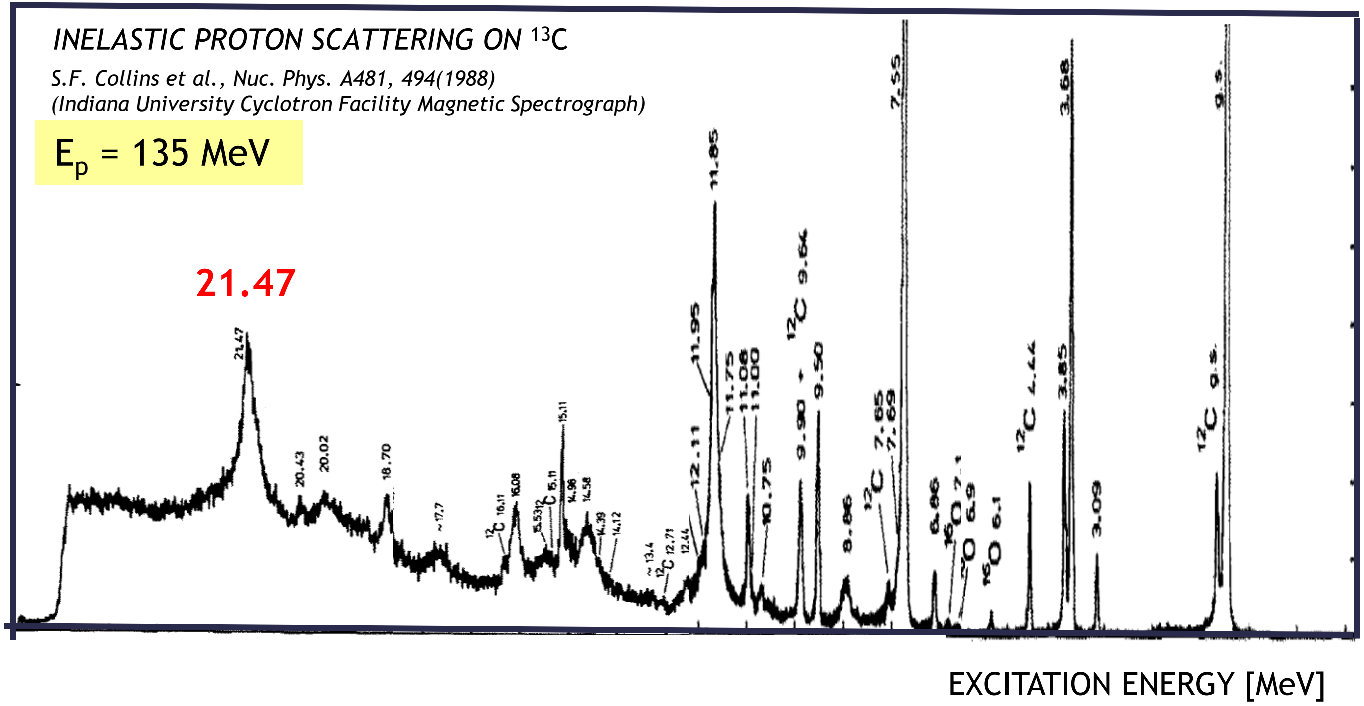
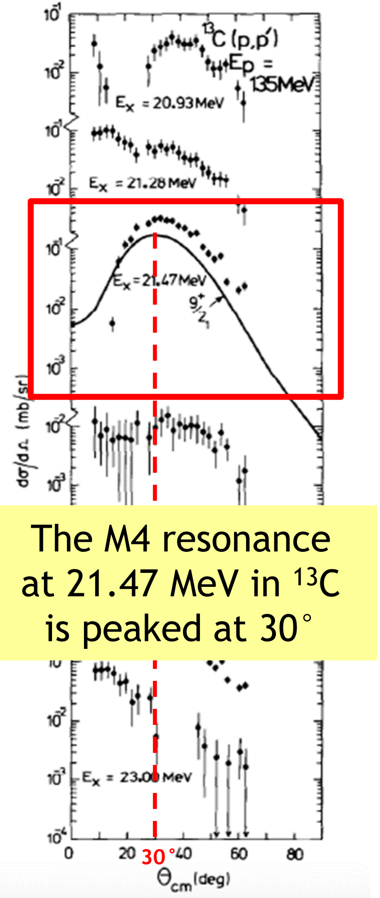
THE FIRST CASE: ^{13}C

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





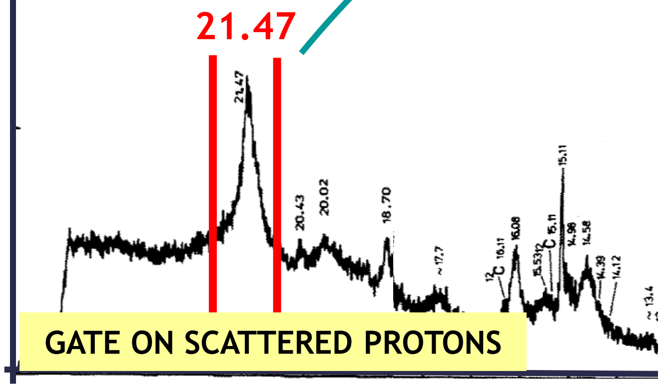
The M4 resonance at 21.47 MeV in ^{13}C is peaked at 30°

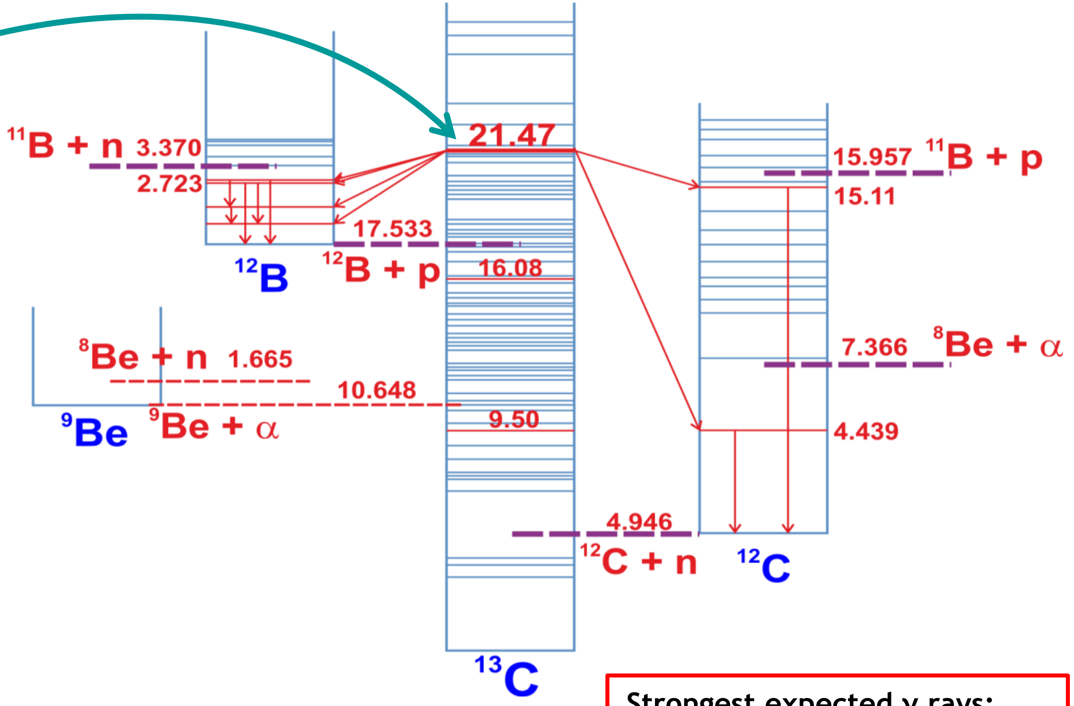
Previous studies of stretched states in ^{13}C

INELASTIC PROTON SCATTERING ON ^{13}C

S.F. Collins et al., Nuc. Phys. A481, 494(1988)
(Indiana University Cyclotron Facility Magnetic Spectrograph)

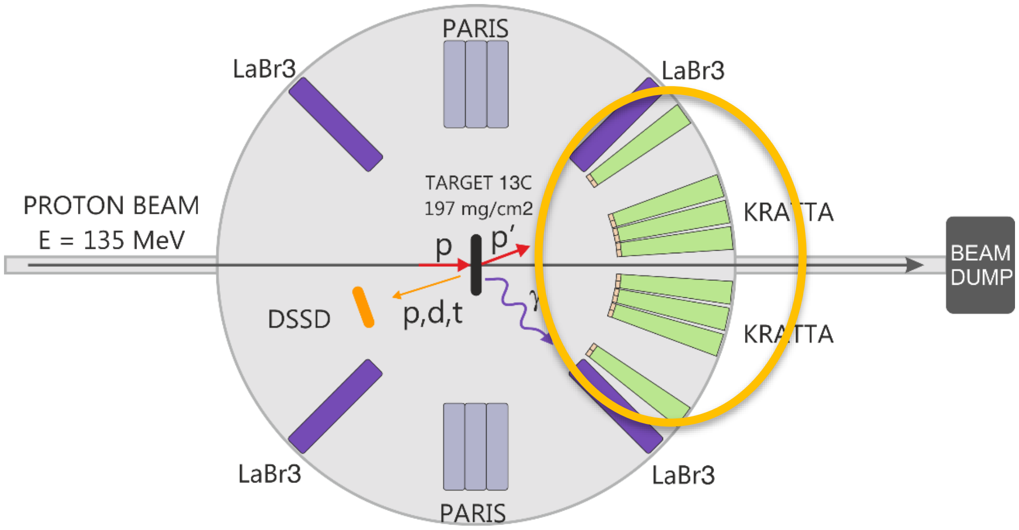
E_p = 135 MeV



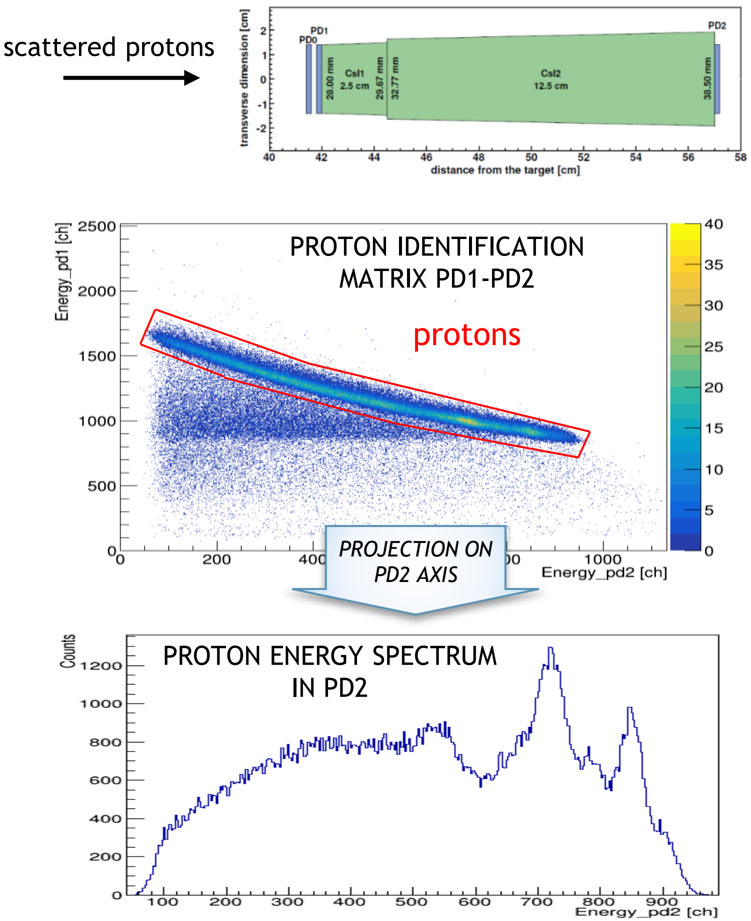


Strongest expected γ rays:
^{12}B: 953, 1668, 1674, 2723 keV
^{12}C: 4439, 15110 keV

Scattered protons measurement



J. Lukasik et al., NIM A709, 120(2013)



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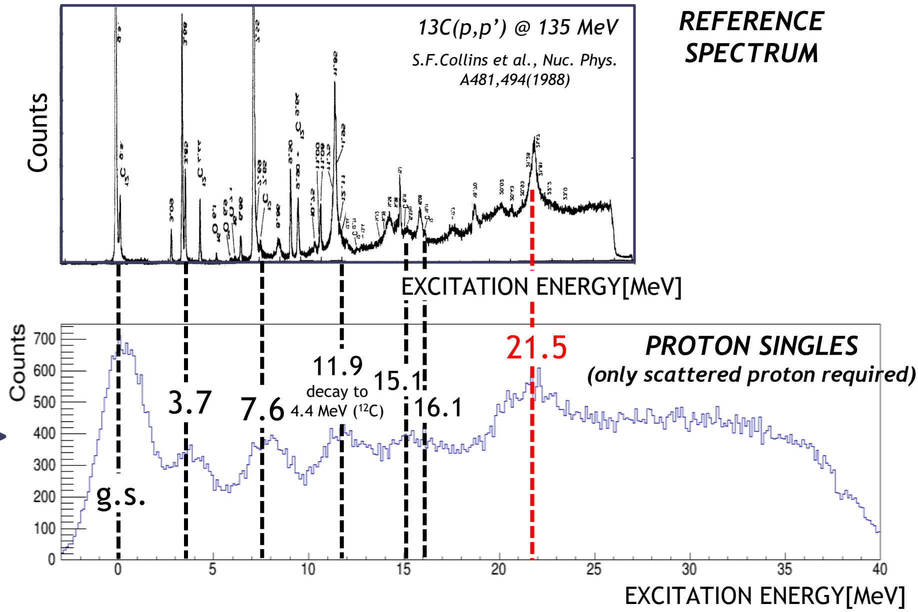
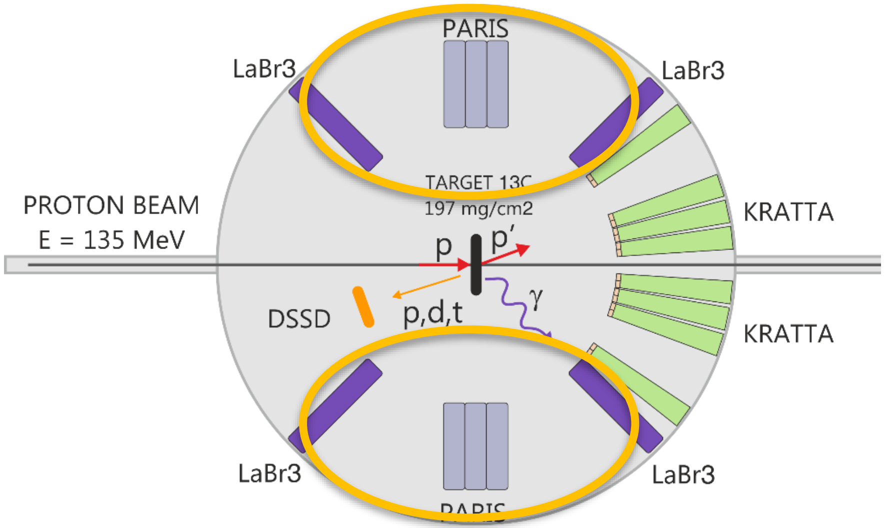
KRATTA – excitation energy spectra

Excitation energy spectra measured at ~36° corresponding to the excitations in the ^{13}C target nucleus measured as:

SINGLES (only scattered proton required)



Gamma-ray measurement



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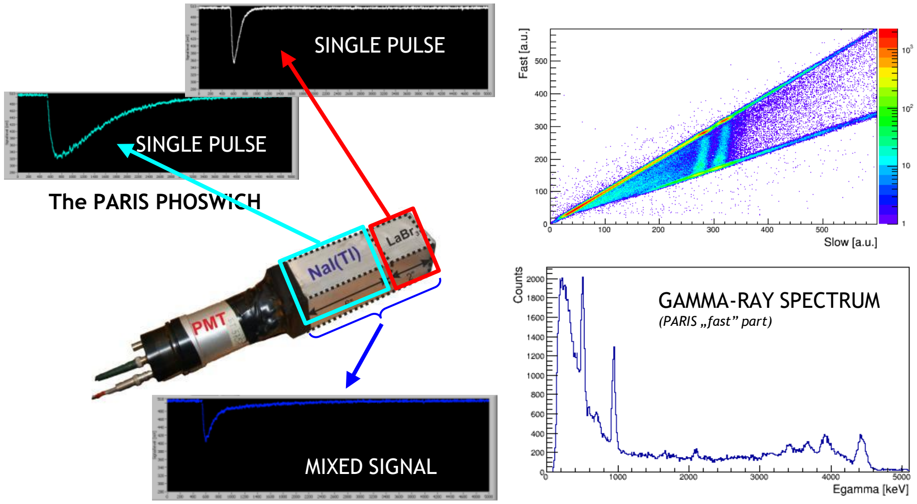
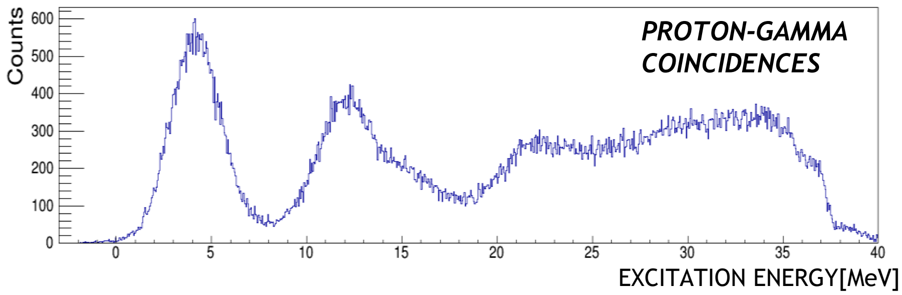
IN COINCIDENCE WITH γ RAYS

(4 big $LaBr_3$ detectors + 18 modules of PARIS)



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

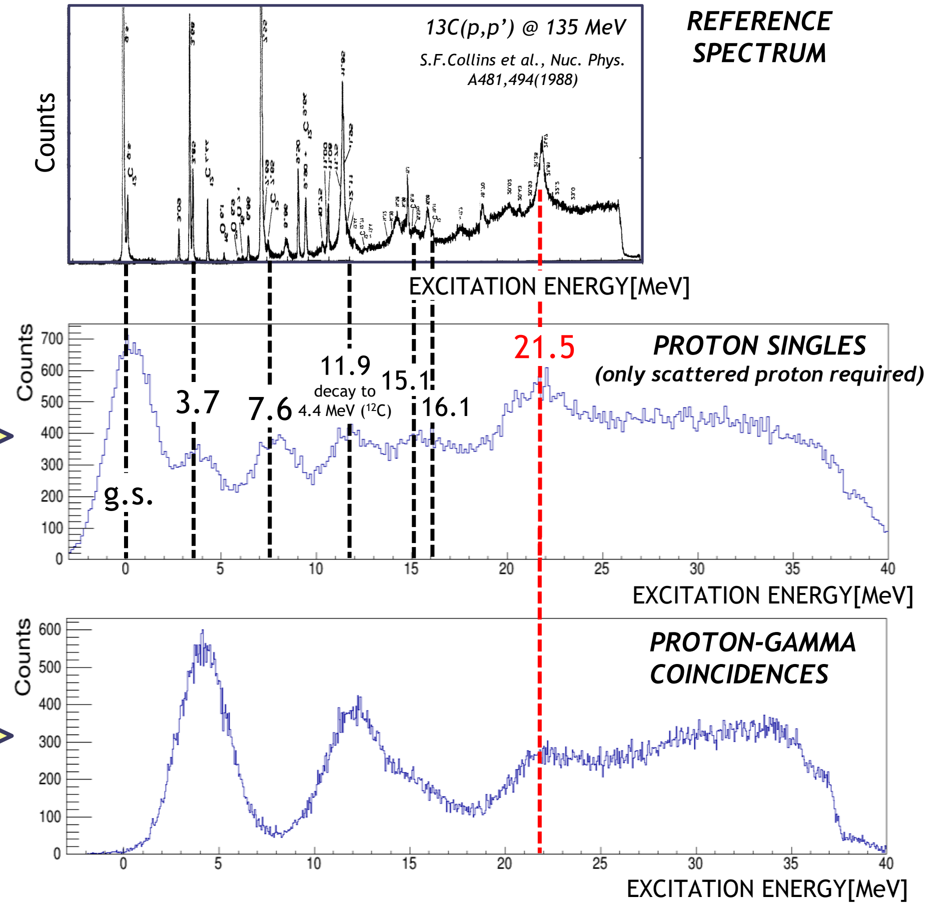


KRATTA – excitation energy spectra

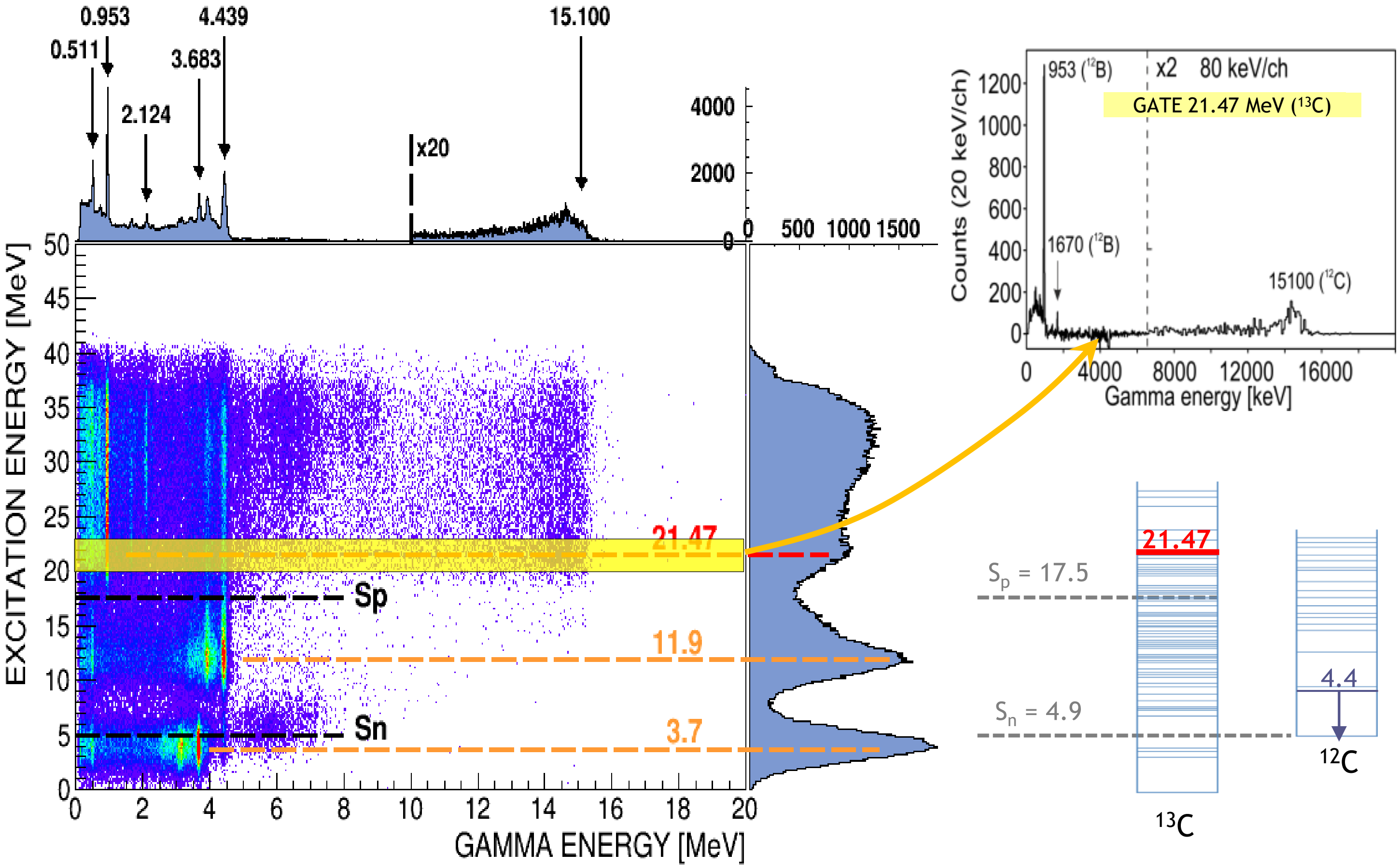
Excitation energy spectra measured at ~36° corresponding to the excitations in the ^{13}C target nucleus measured as:

SINGLES (only scattered proton required)

COINCIDENCES (scattered proton and gamma ray required)



Experimental results: proton-gamma coincidence measurement



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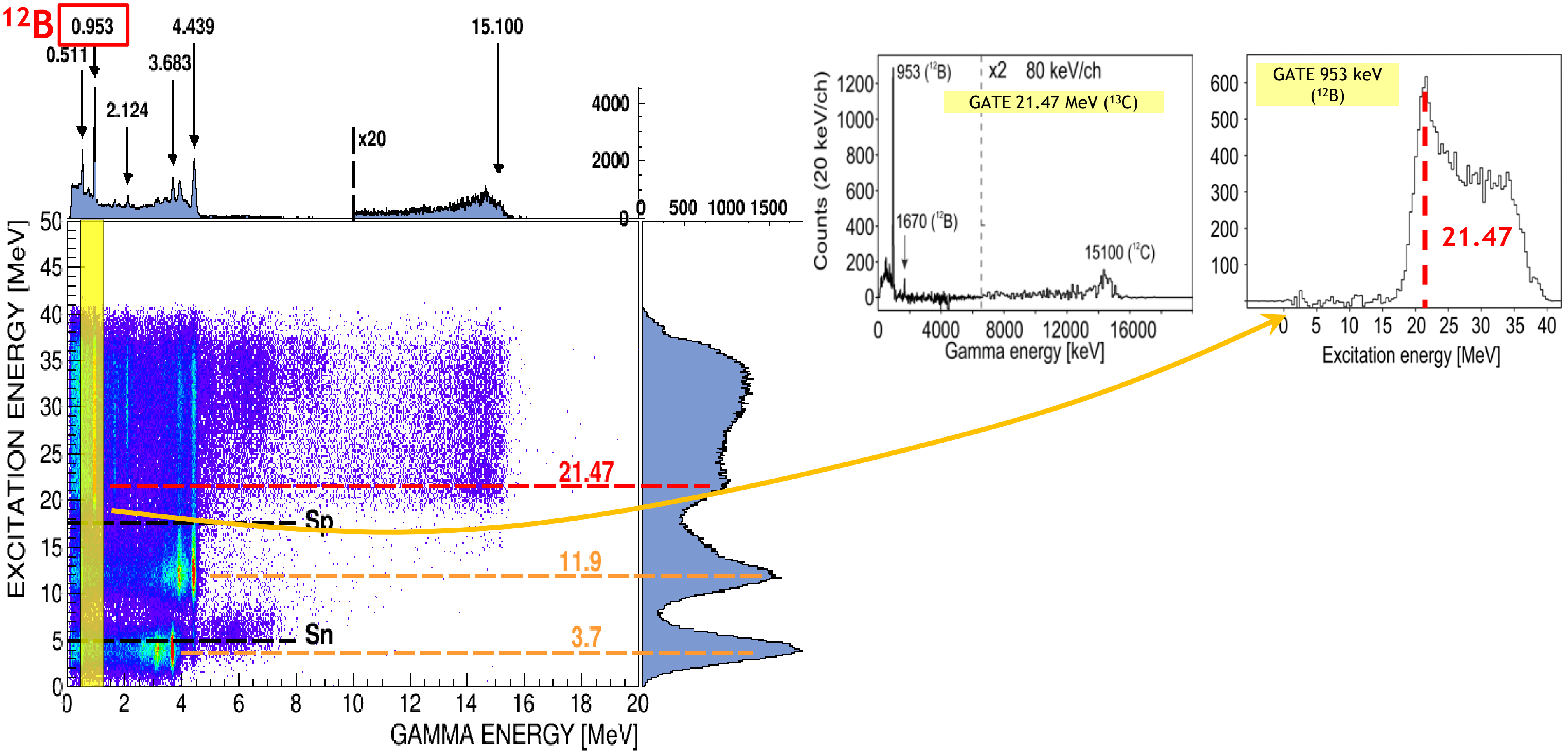

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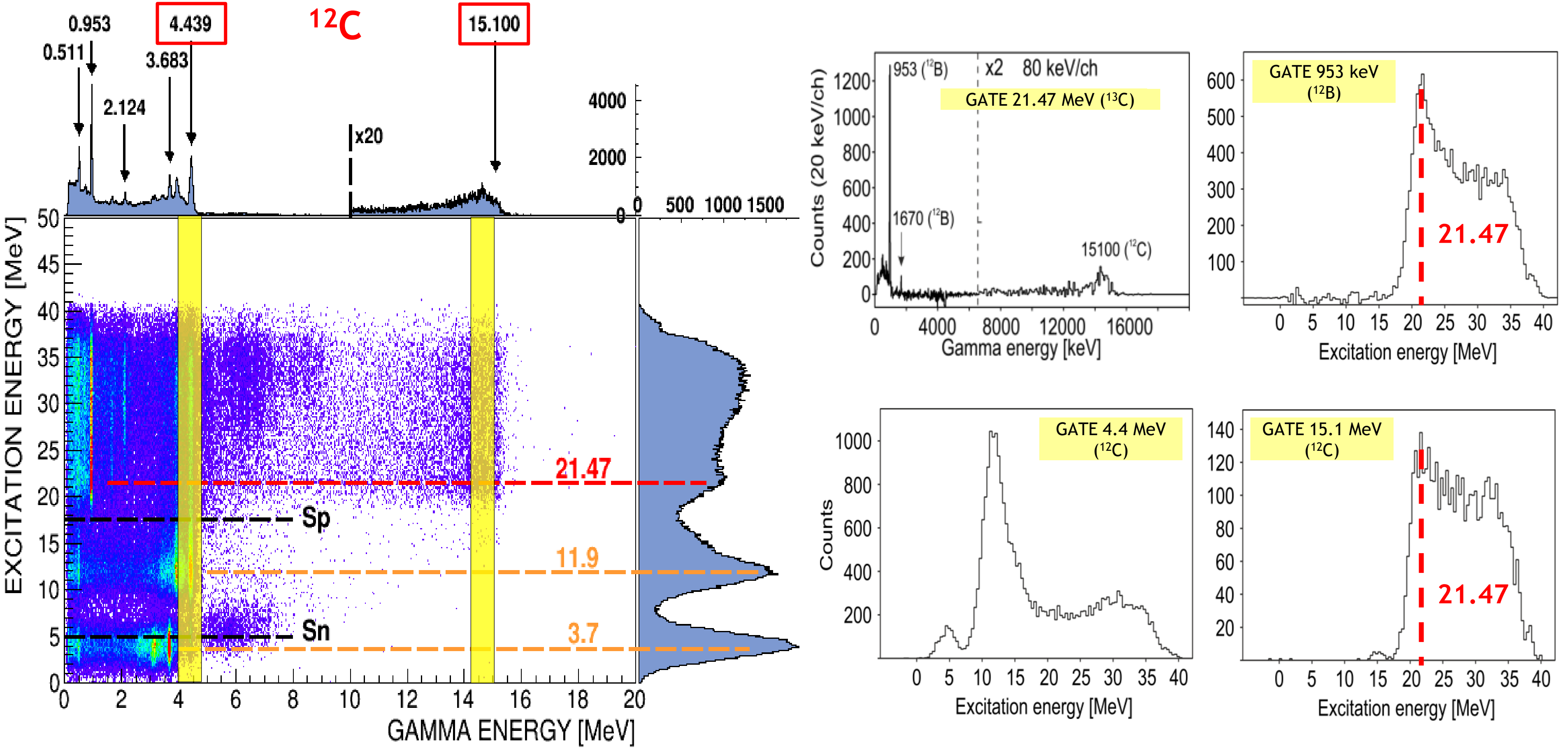

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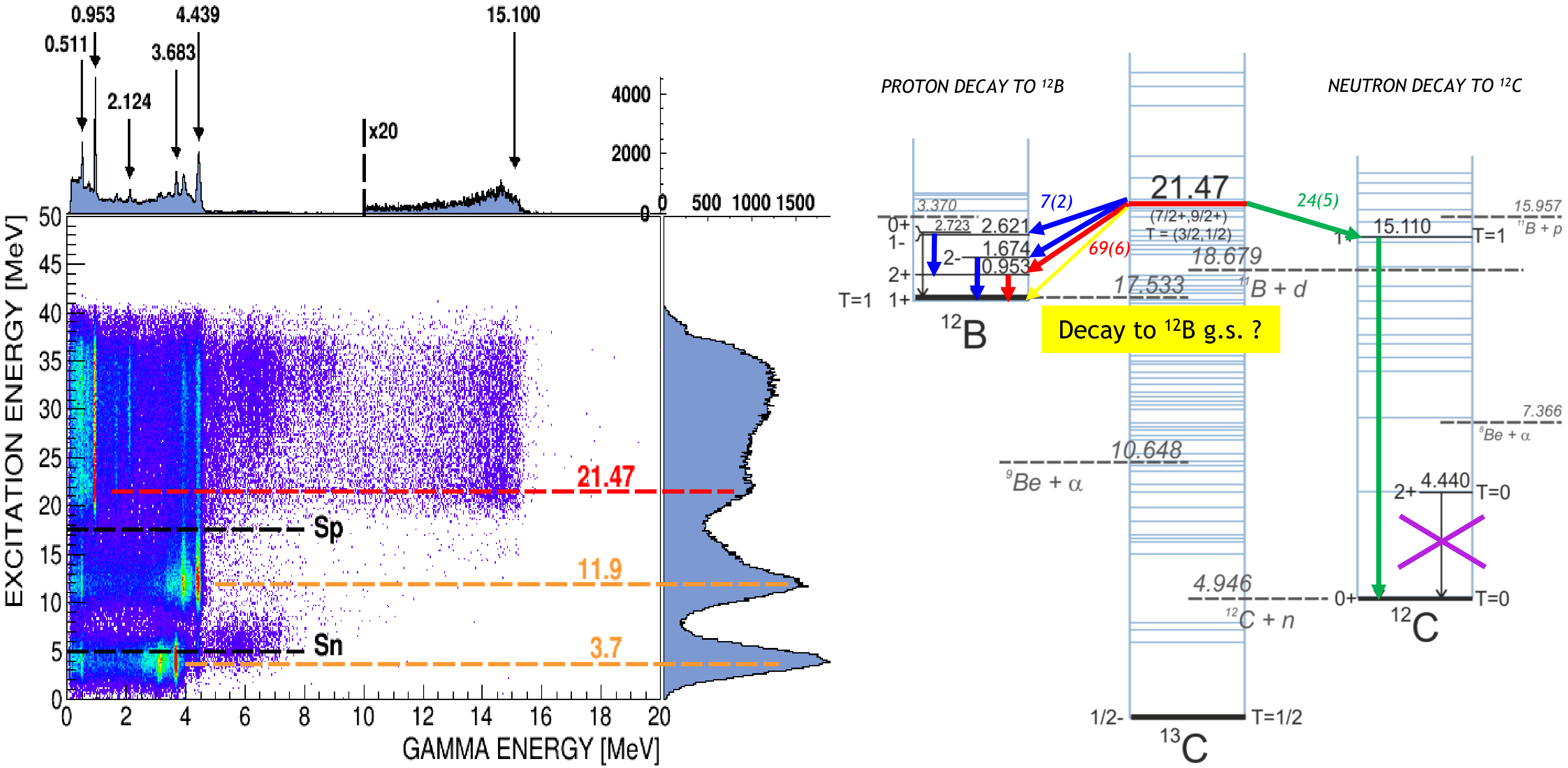
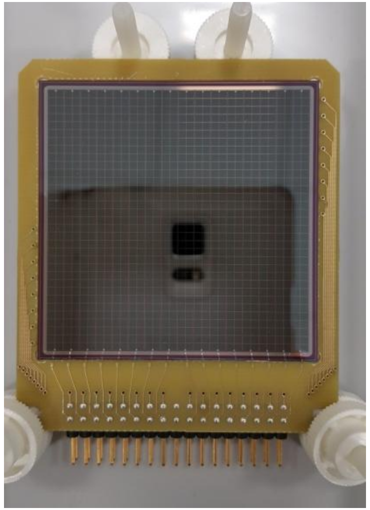


PERFORMANCE OF DSSSD (FROM THICK ^{13}C TARGET EXPERIMENT)

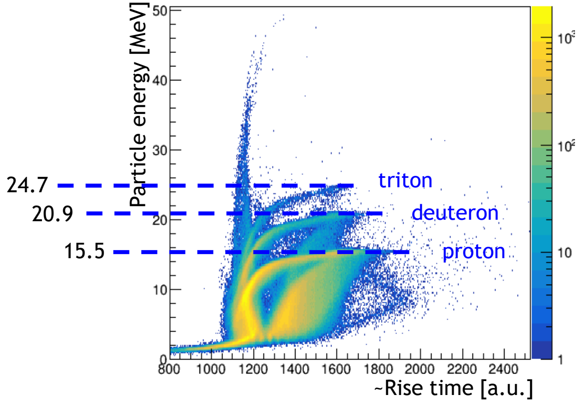
Double Sided Silicon Strip Detector (Micron Semiconductor Ltd)

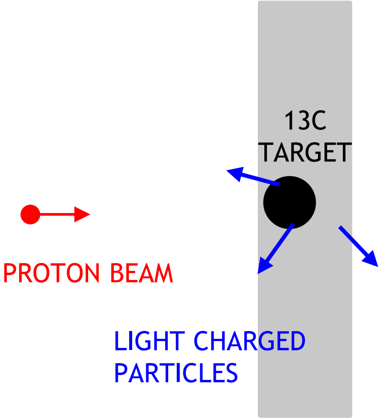
Active area:	50mm x 50mm
No. of strips:	32 (16 per side)
Thickness:	1.5 mm



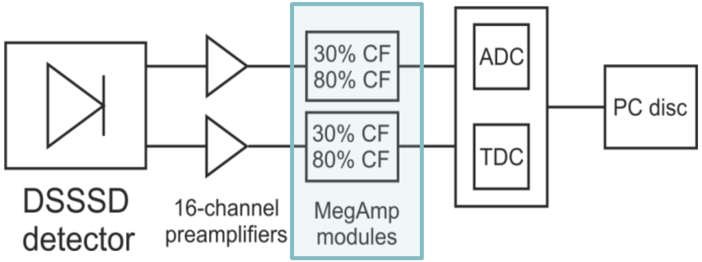
PARTICLE IDENTIFICATION MATRIX

(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 <u>**light particle identification**</u>

Thin 1 mg/cm^2 ^{13}C target experiment

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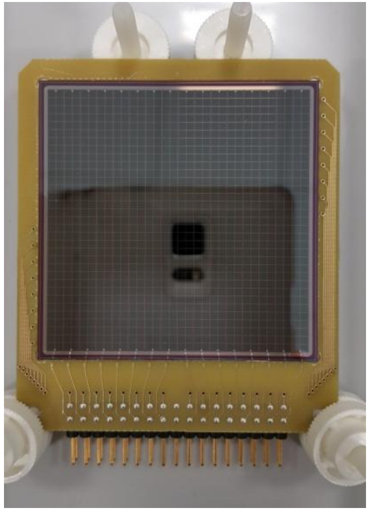
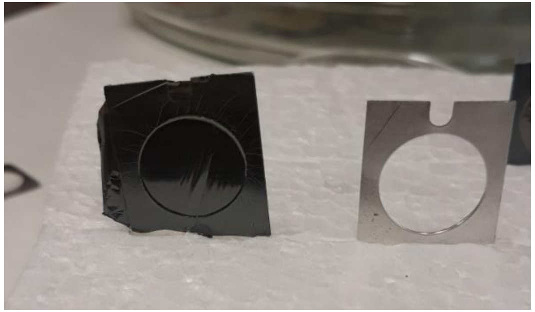




^{13}C target made of 10 foils in separate frames, total thickness 1 mg/cm^2
(Nicoleta Florea, Nicu Marginean IFIN-HH, Bucharest, Romania)

Why another experiment?

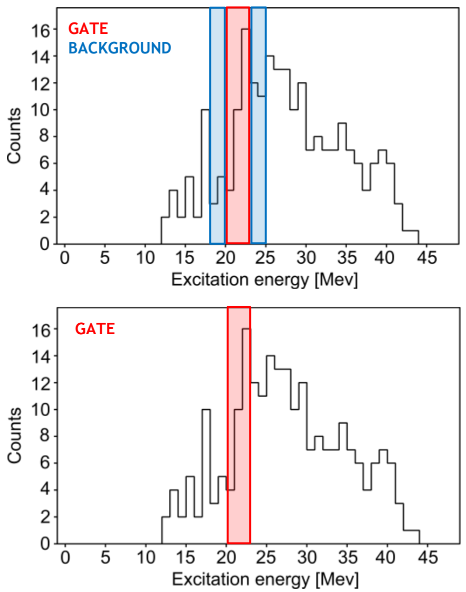
Expected energies of emitted protons are below 4 MeV so protons will stuck in the thick target

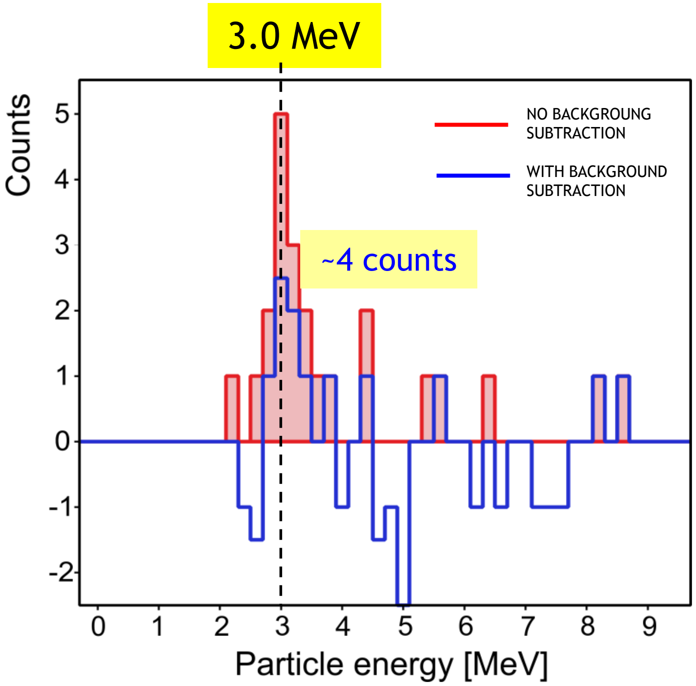
THIN TARGET NEEDED FOR LOW-ENERGY PROTONS!

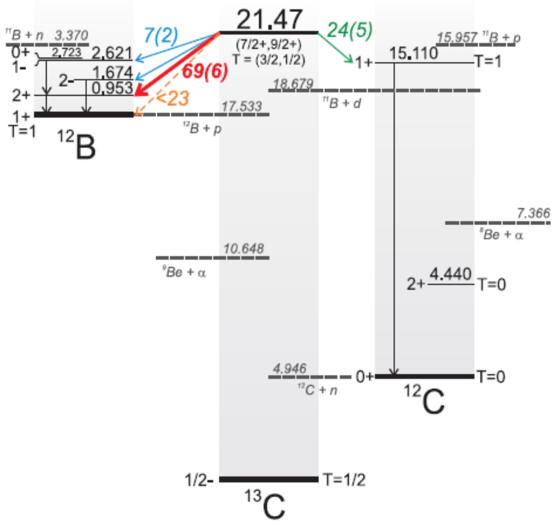
Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

Scattered proton – light charged particle coincidences

Projection of the excitation energy vs. particle energy matrix







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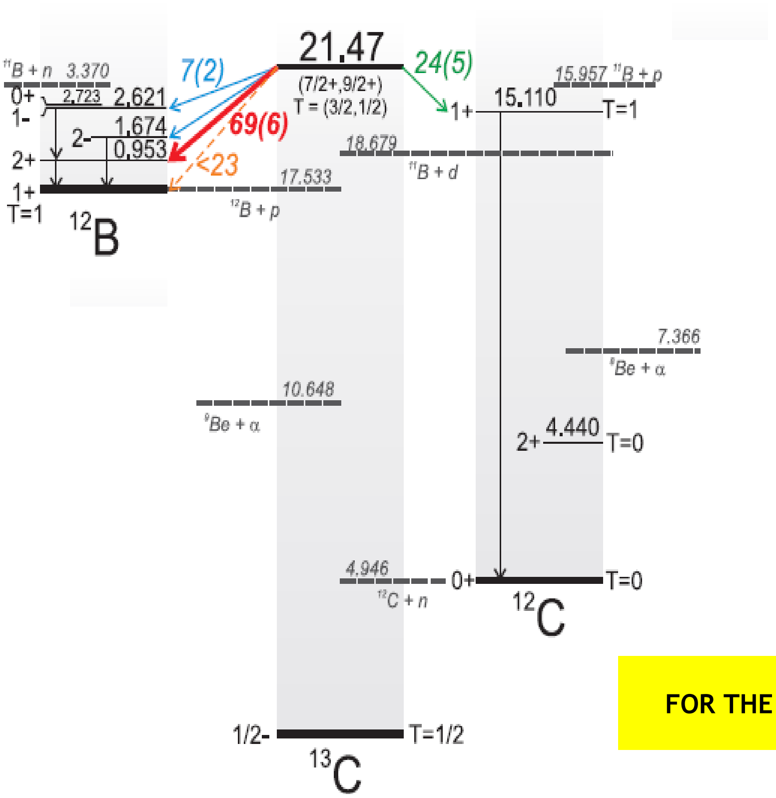
0.0	3.937

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

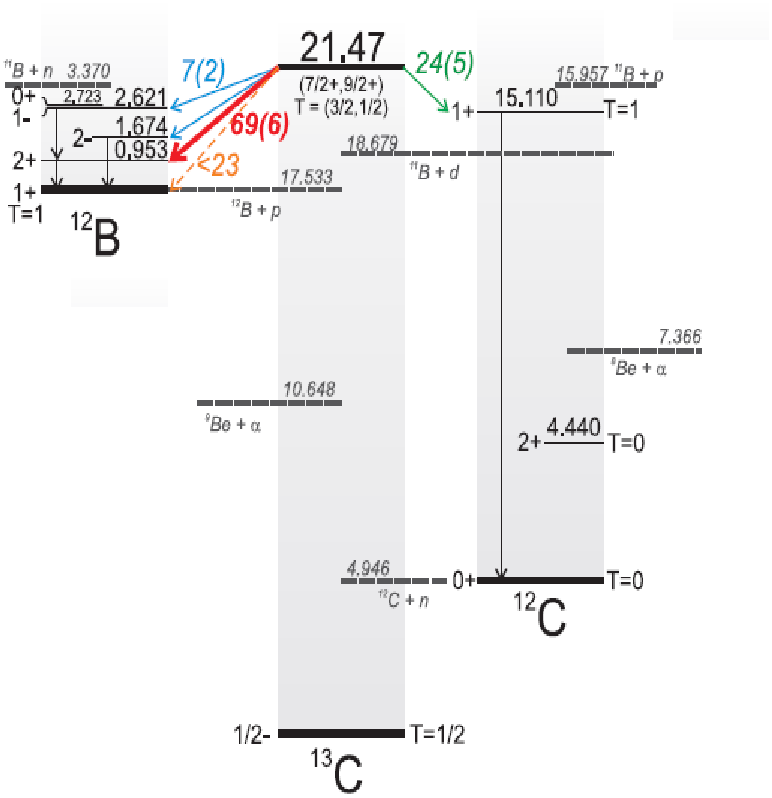
(by Y. Jaganathen (IFJ PAN) and M. Płoszajczak (GANIL))

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



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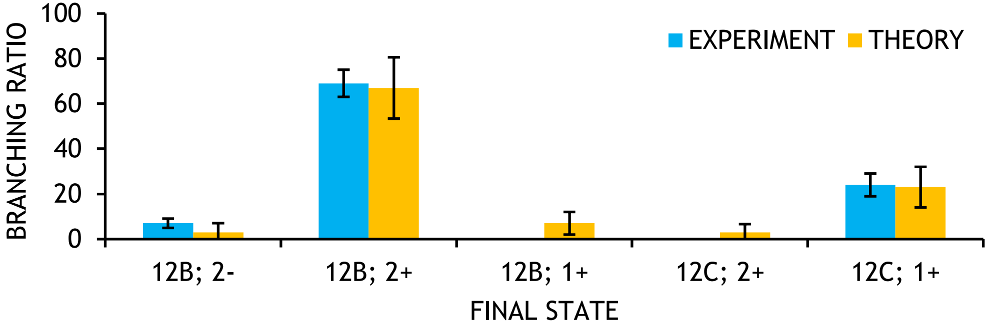
$J^\pi = (7/2^+, 9/2^+)$, $T = (1/2, 3/2)$
$E_{exp} = 21.47$ MeV
$\Gamma_{exp} = 270(20)$ keV

$J^\pi = 7/2^+_7$, $T = 1.36$
$E_{th} = 20.9(5)$ MeV
$\Gamma_{th} = 400(300)$ keV

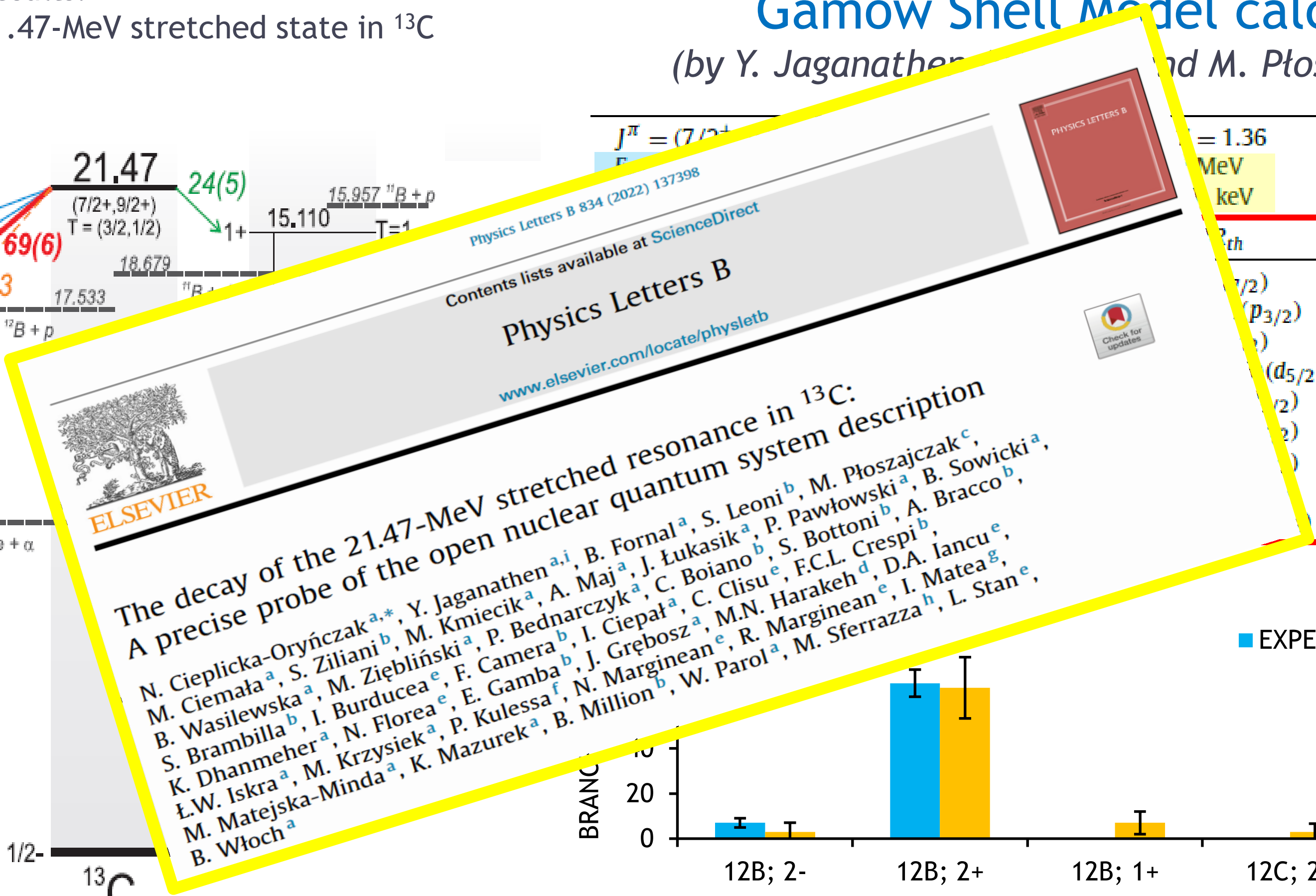
^AZ	$J^\pi;T$	E_{exp} [MeV]	BR_{exp}	E_{th} [MeV]	BR_{th}	S_f	Γ_p [keV]
^{12}B	$1^-;1$	2.621		2.810	$0(f_{7/2})$	0	0
	$2^-;1$	1.674	7(2)	1.979	$3(4)(p_{3/2})$	0.01	13(6)
					$0(f_{7/2})$	0	0
	$2^+;1$	0.953	69(6)	0.867	$60(13)(d_{5/2})$	0.19	221(48)
					$7(4)(d_{3/2})$	0.02	26(16)
	$1^+;1$	0.0	<23	−0.030	$7(5)(d_{5/2})$	0.01	26(20)
^{12}C	$2^+;1$	16.106		15.7	$2(3)(d_{5/2})$	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. Jaganathen ... nd 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

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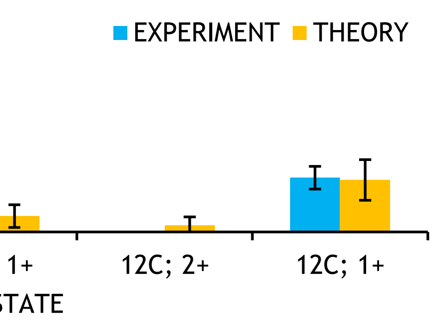
$J^{\pi} = (7/2^+ \ldots$ $= 1.36$ MeV, keV

$\ldots_{th}$	S_f	Γ_p [keV]
...$/2)$	0	0
...$(p_{3/2})$	0.01	13(6)
...$)$	0	0
...$(d_{5/2})$	0.19	221(48)
...$/2)$	0.02	26(16)
...$)$	0.01	26(20)
...$)$	0.47	6(10)
...	0.22	3(6)
...$)$	0.08	86(35)



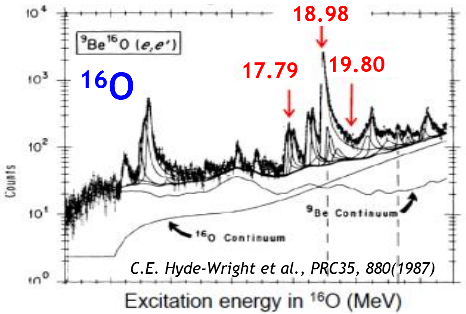
^{14}N AND ^{16}O

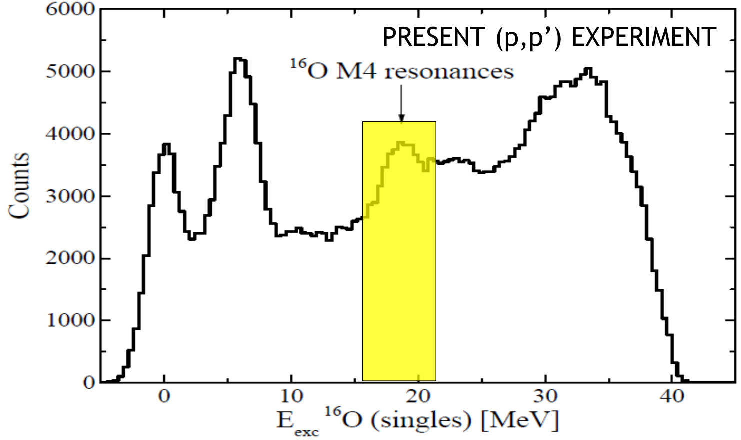
December 2019 – March 2020

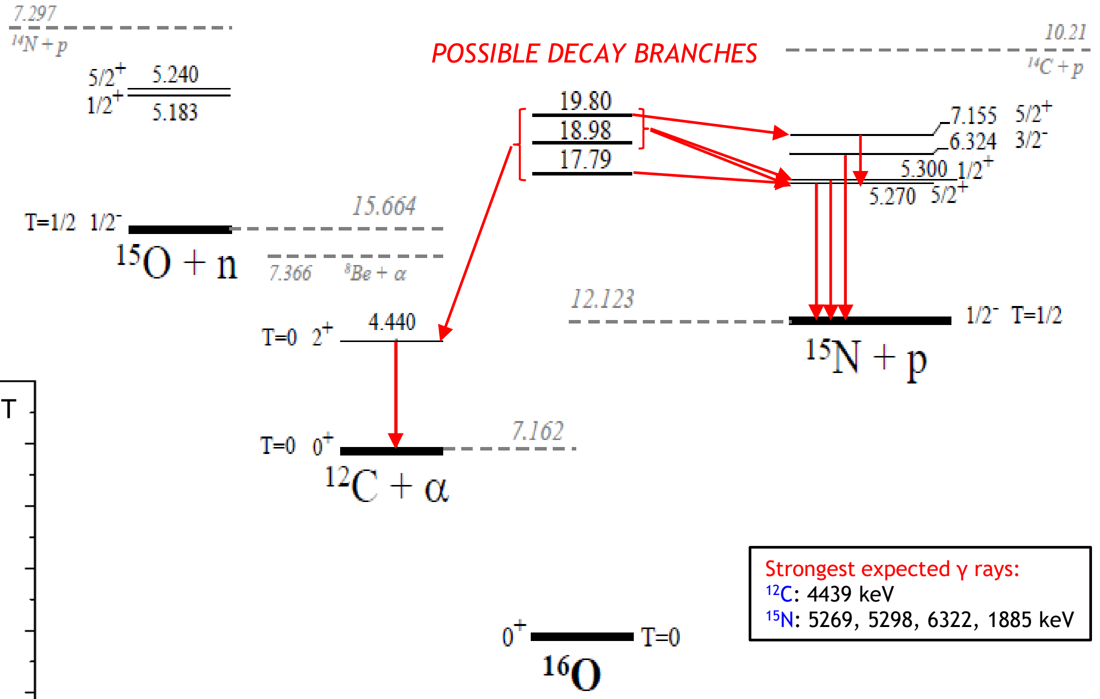
Spokepersons: S. Ziliani (Univ. of Milan and INFN Milan), N. Cieplicka-Oryńczak (IFJ PAN)

Stretched resonances in ^{16}O

^{7}Li-^{14}N-H_2 + (^{16}O contamination) target 160 mg/cm^2





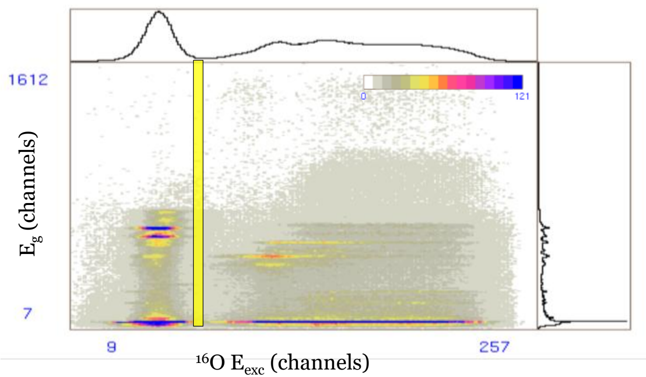


Strongest expected γ rays:
^{12}C: 4439 keV
^{15}N: 5269, 5298, 6322, 1885 keV

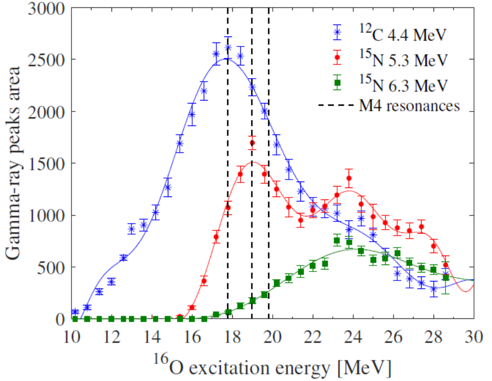
S.Ziliani, PhD thesis, University of Milan (2021)

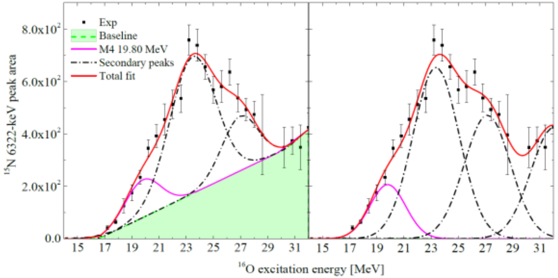
Stretched resonances in ^{16}O

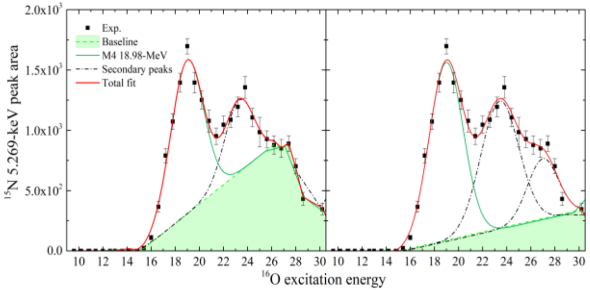
AREA SCANNING (600-keV-wide gates)

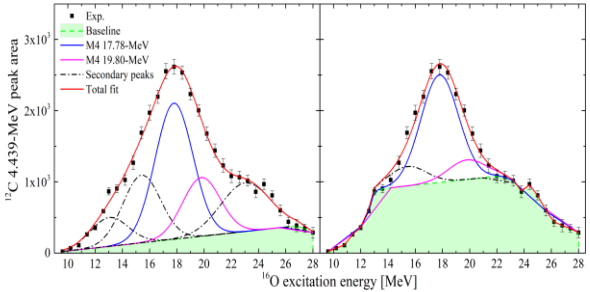


AREA OF GAMMA RAY PEAKS
AS FUNCTION OF EXCITATION ENERGY









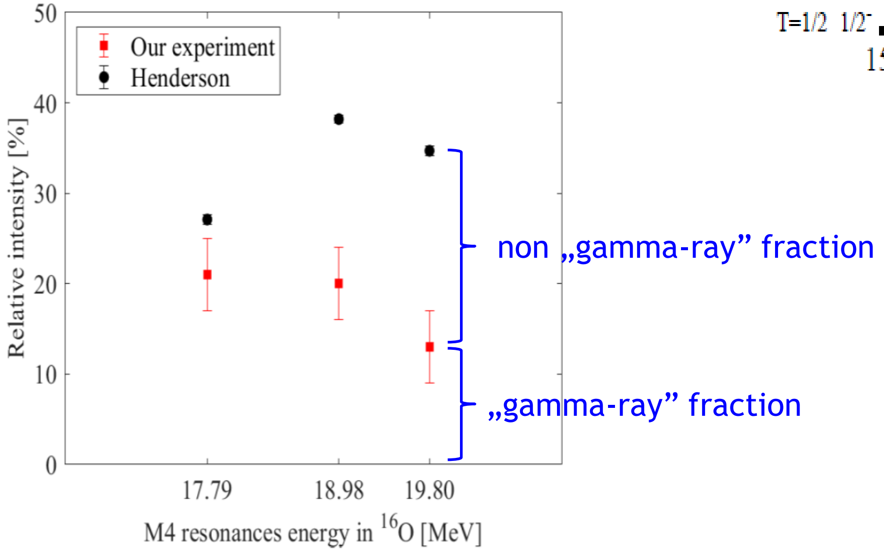
EXTRACTION OF DECAY BRANCHINGS ASSOCIATED TO GAMMA EMISSION

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

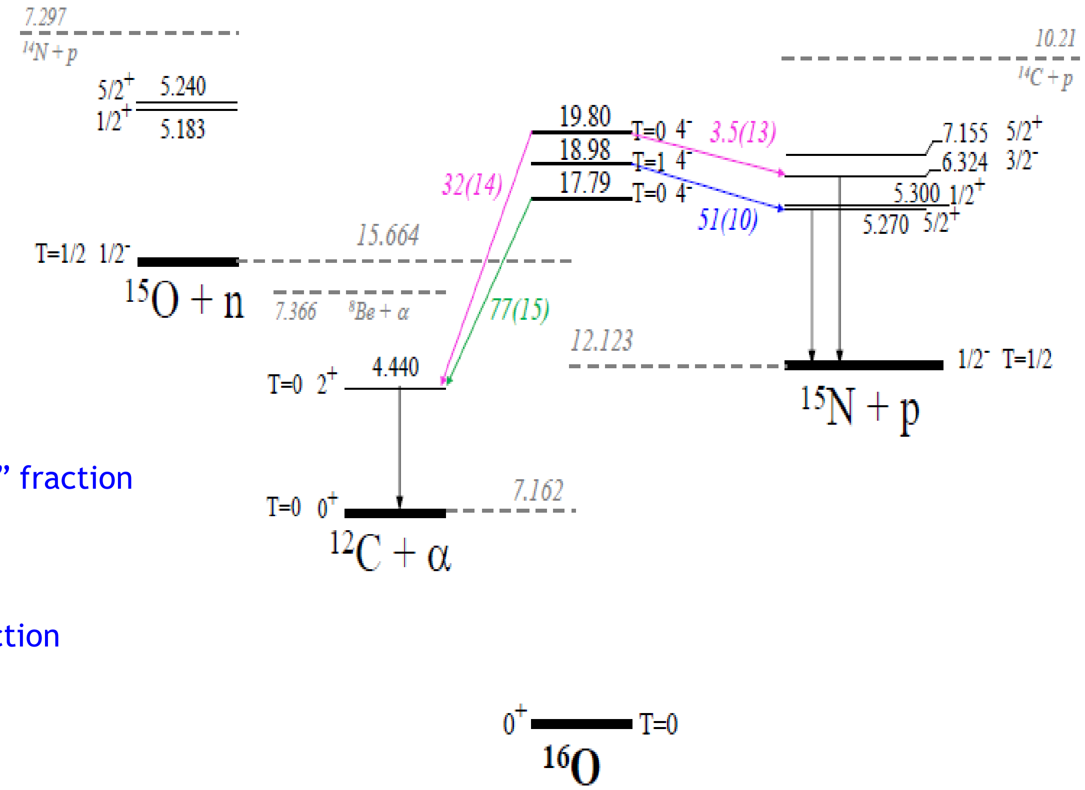
Branching ratios in ^{16}O

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

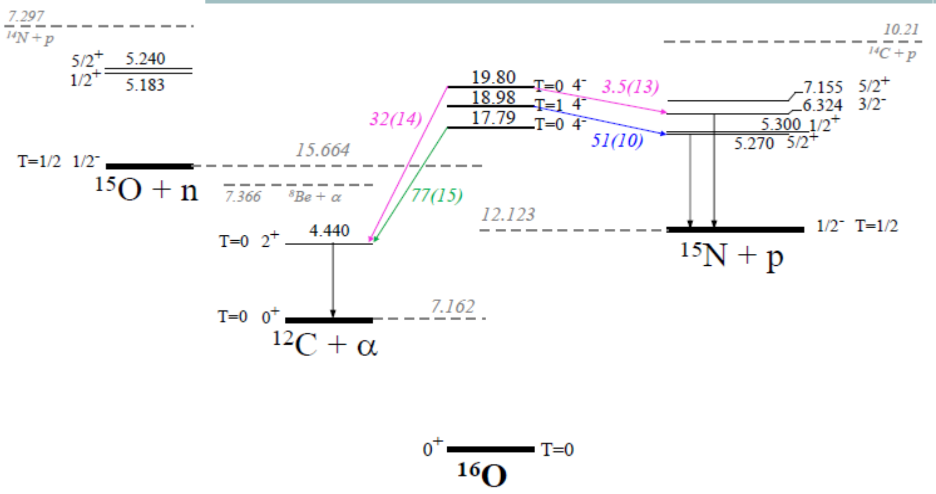
R.S. Henderson et al., Aust.J.Phys.32,411(1979)



RESULTS FROM PRESENT (p,p') EXPERIMENT

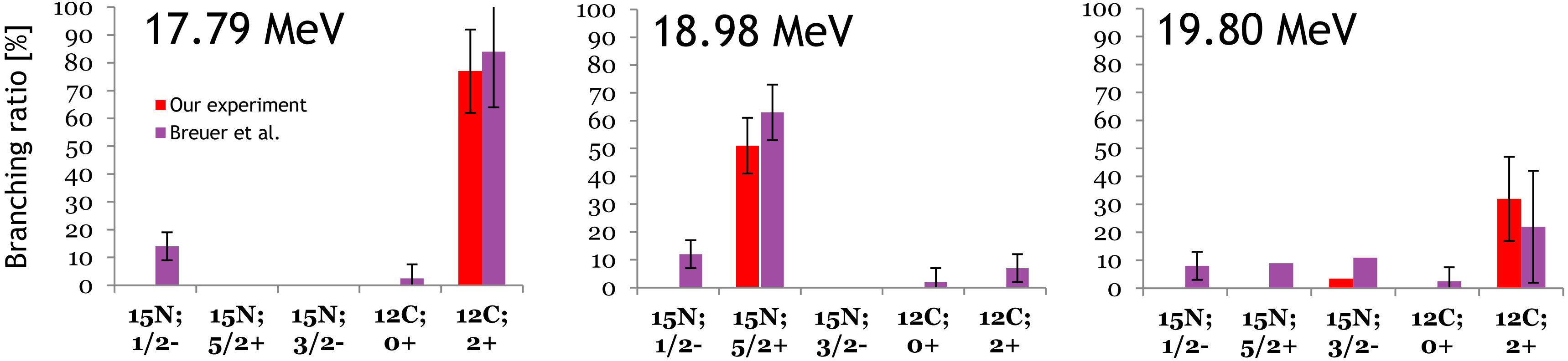


Branching ratios in ^{16}O



COMPARISON OF BR WITH PREVIOUS
17O(d,t) AND 17O(3He,alpha) EXPERIMENTS

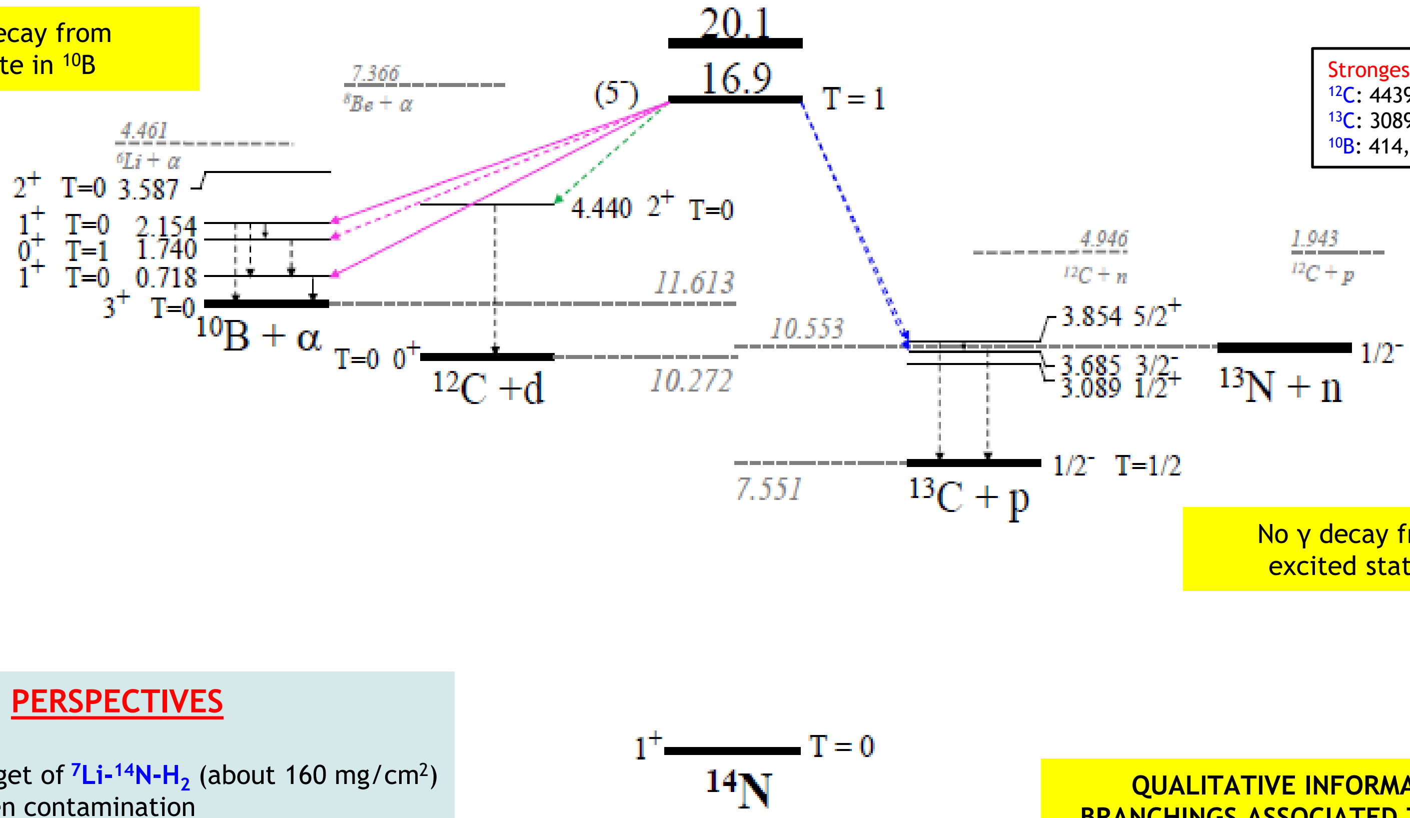
H. Breuer et al., Phys.Lett. 96B, 35 (1980)



Stretched M4 resonances in ^{14}N

^{7}Li-^{14}N-H_2 + (^{16}O contamination) target 160 mg/cm^2

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}Li-^{14}N-H_2 (about 160 mg/cm^2) without oxygen contamination
- Similar experimental setup

QUALITATIVE INFORMATION ON DECAY BRANCHINGS ASSOCIATED TO GAMMA EMISSION

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

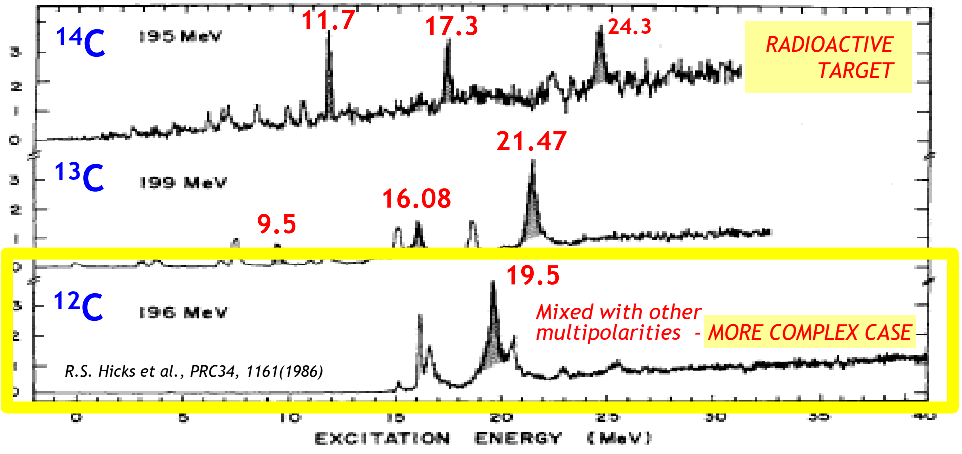
Very recent experiment: ^{12}C

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

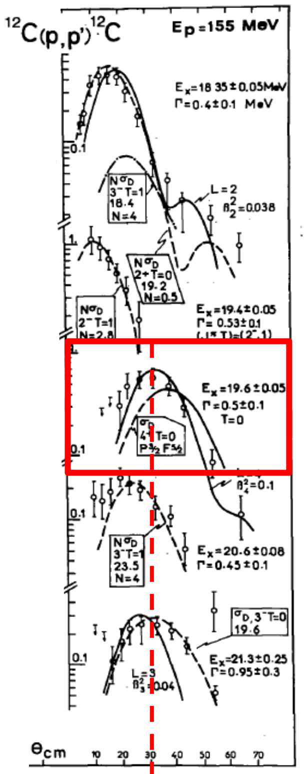


- comparison of cross sections measured in ($\pi^+,\pi^{+'}$) and ($\pi^-,\pi^{-'}$) experiments was interpreted as due to isospin mixing between **two or more 4^- levels of T = 1 and T = 0 character**
- a **significant 2^- strength** was found for the 19.4-MeV peak identified in the inelastic scattering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

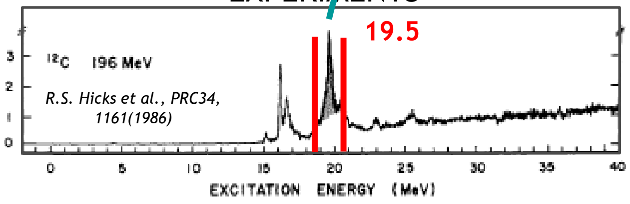
Expected decay scheme of the 19.5-MeV state in ^{12}C



M. Buenerd et al., NPA286, 377(1977)

30°

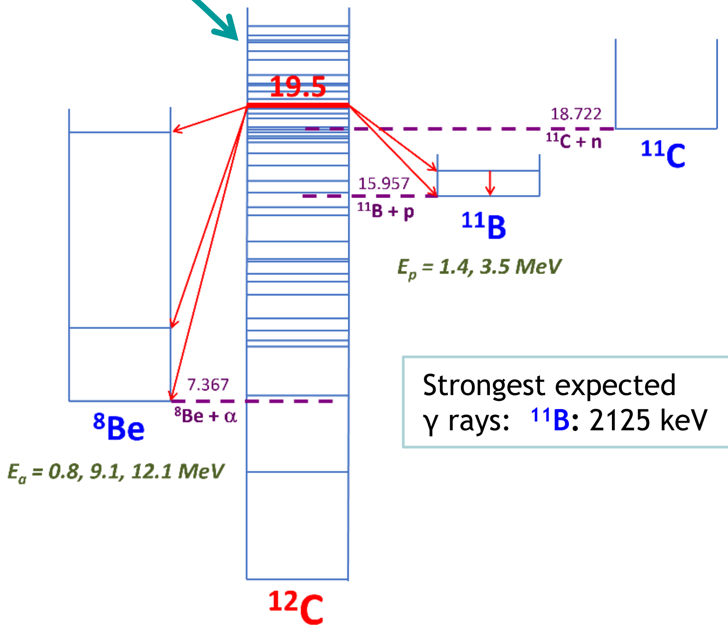
INELASTIC ELECTRON SCATTERING EXPERIMENTS



GATE ON THE SCATTERED PROTONS

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

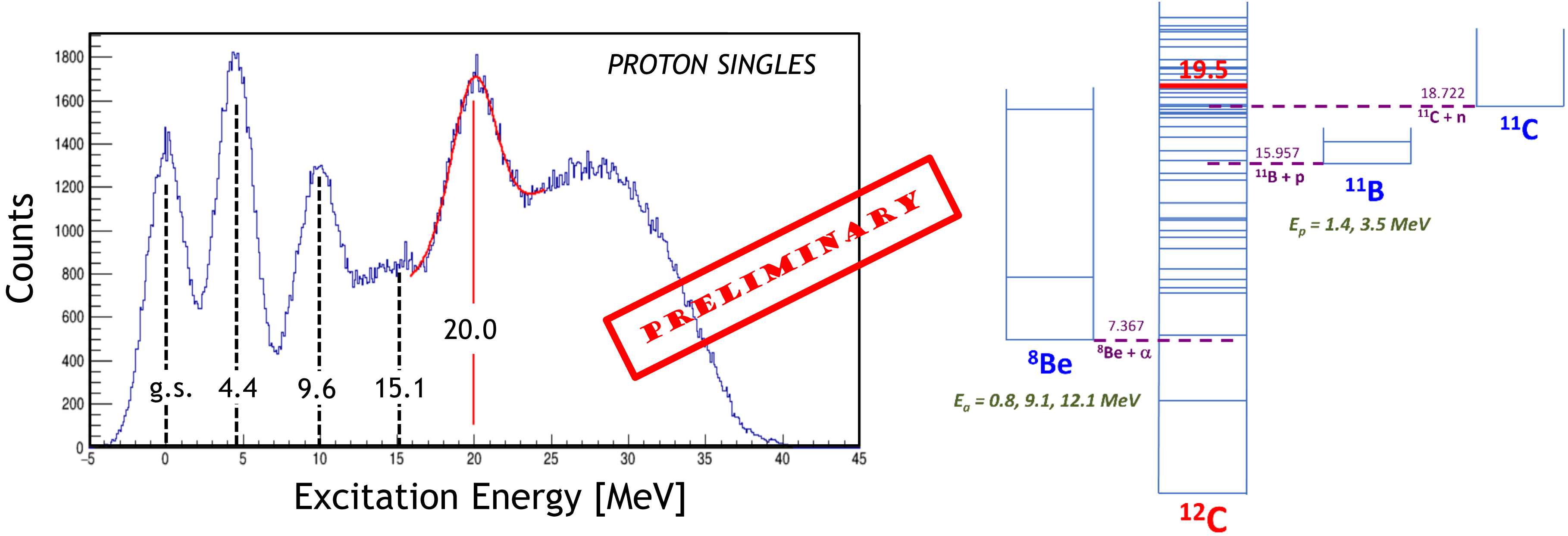
The aim of the proposed experiment is to **identify the decay of the 19.5-MeV** $1p_{3/2} \rightarrow 1d_{5/2}$ resonance in ^{12}C



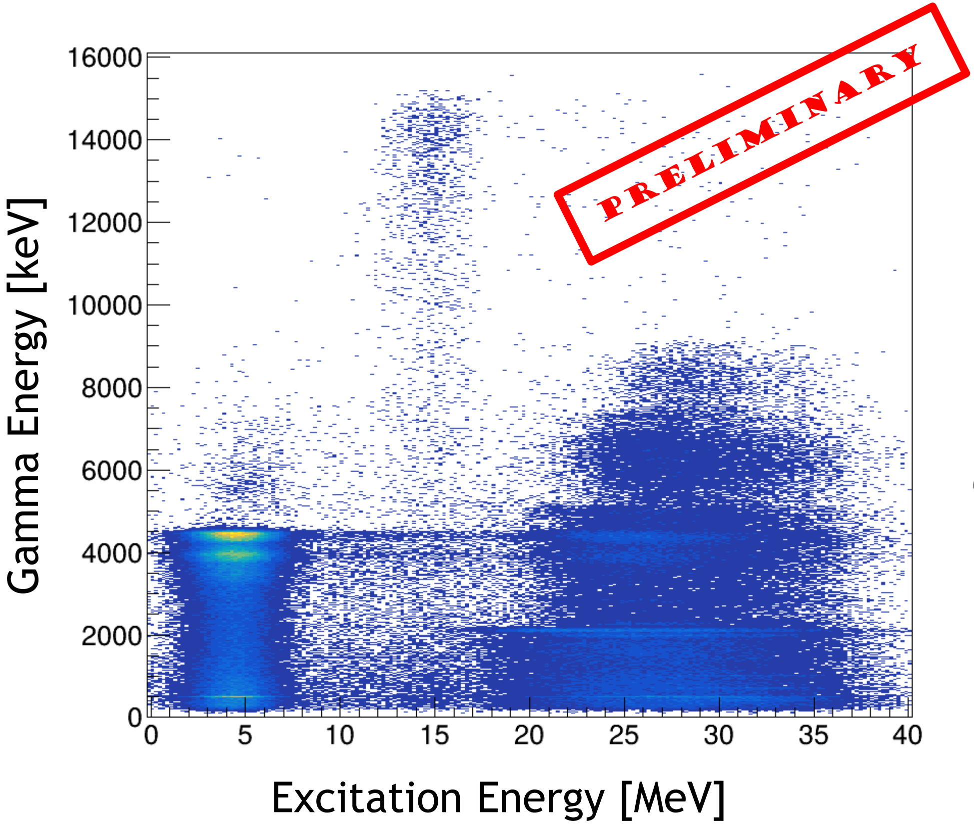
Strongest expected γ rays: ^{11}B: 2125 keV

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

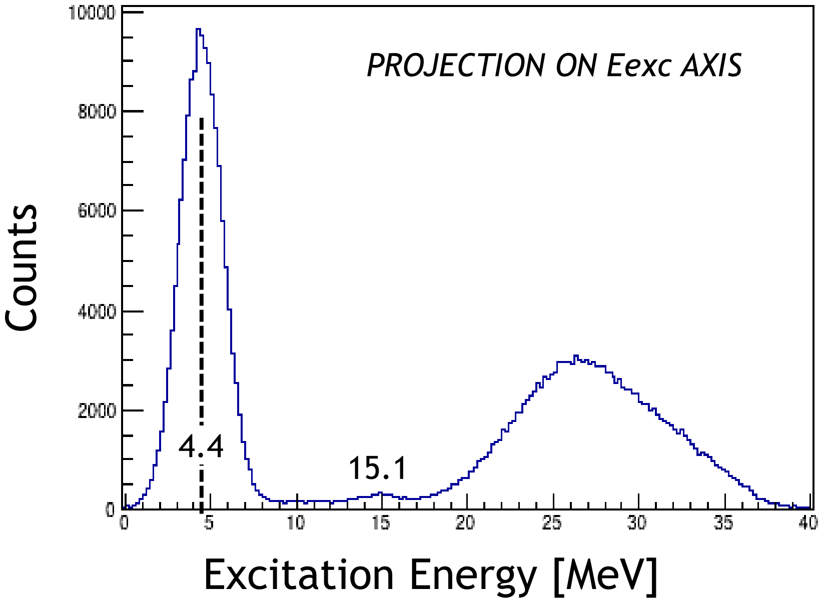
- Excitation Energy from proton measurement (150 mg/cm² target)
- No gamma ray detection required („proton singles")



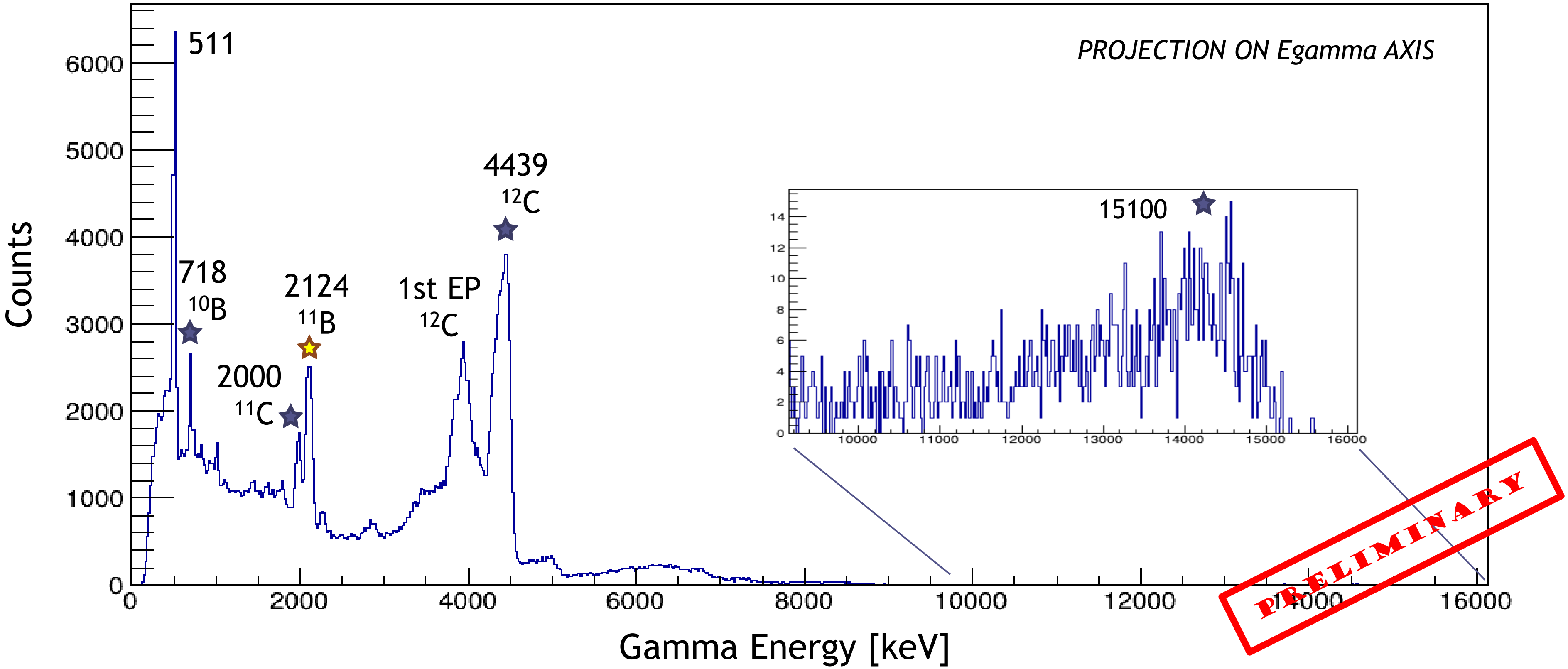
Experimental results: proton-gamma coincidence measurement



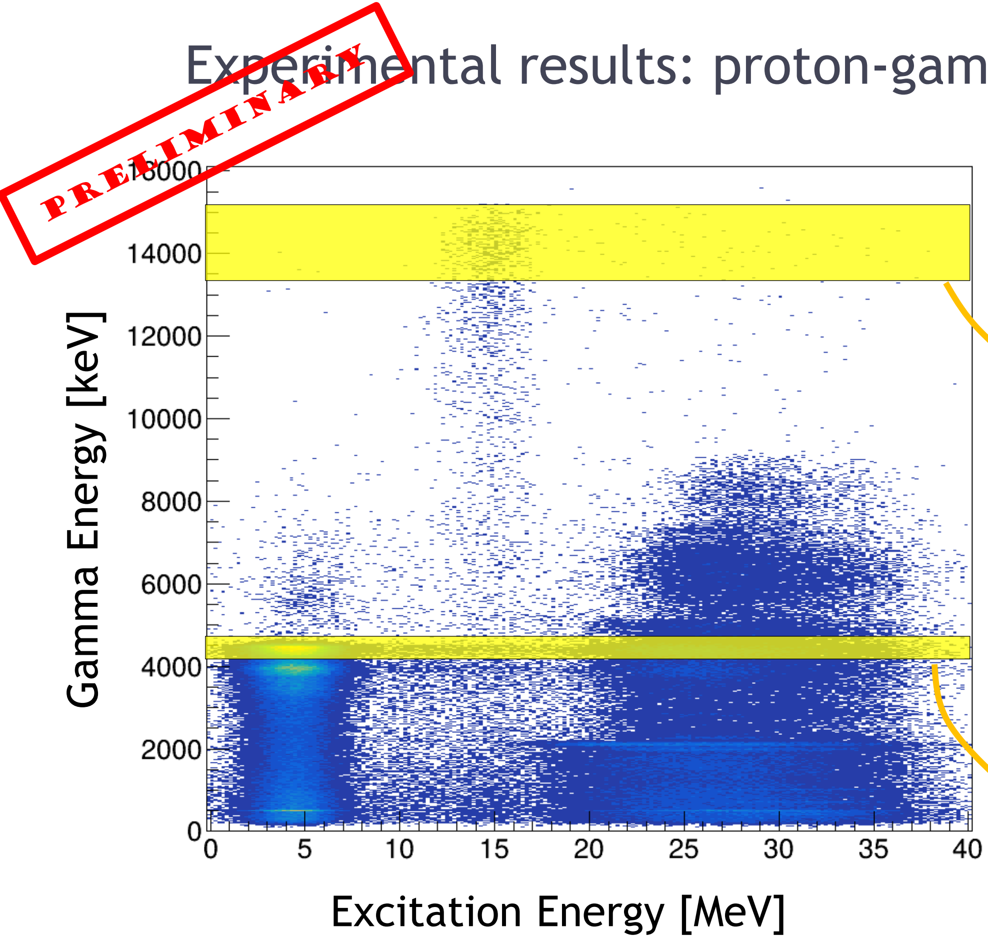
- ❑ One weekend only
- ❑ Coincidences with 4 big LaBr only

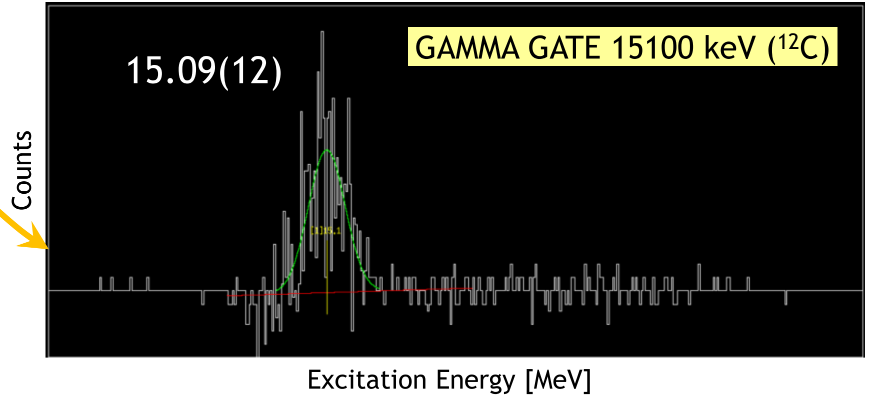


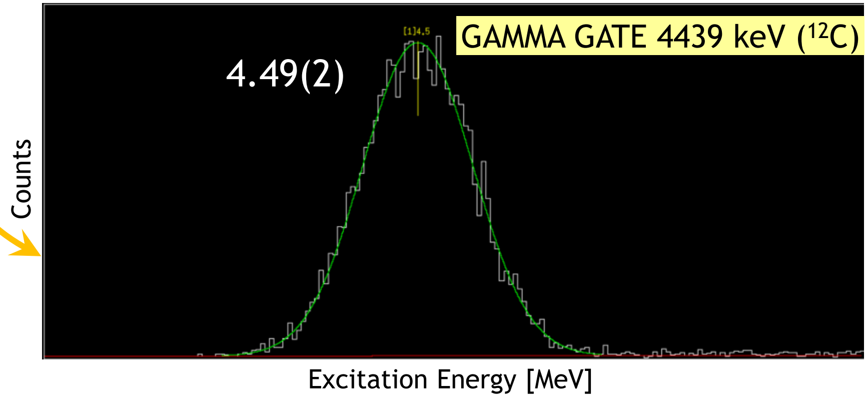
Experimental results: proton-gamma coincidence measurement



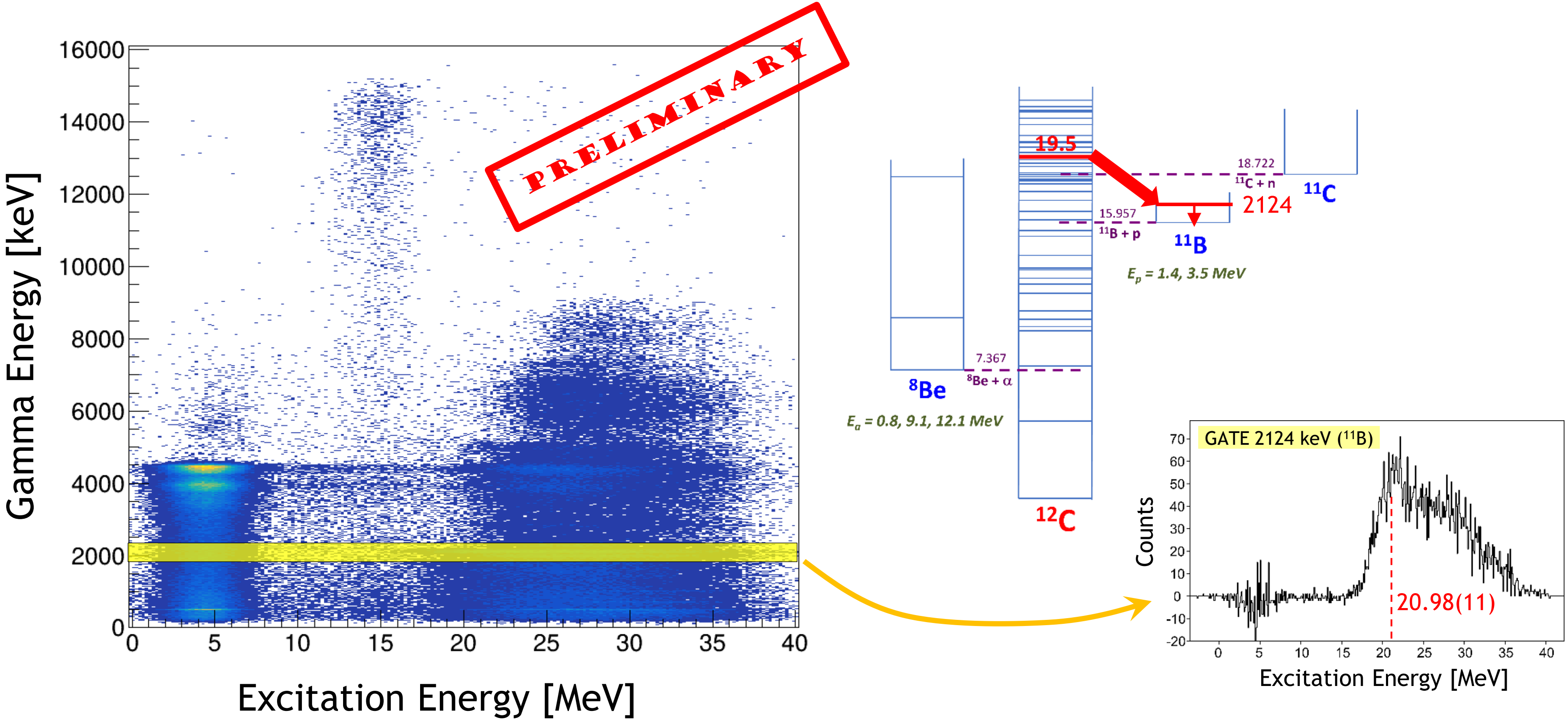
Experimental results: proton-gamma coincidence measurement





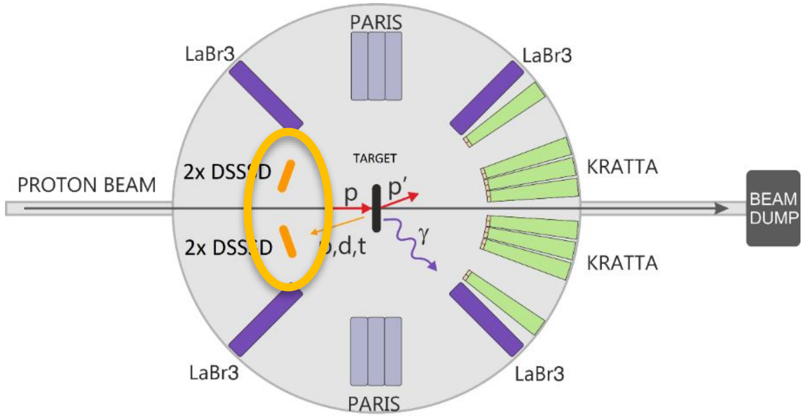


Experimental results: proton-gamma coincidence measurement



Light charged particles measurements: 4 DSSD detectors

NARODOWE CENTRUM NAUKI
Project no. 2020/39/D/ST2/03443



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

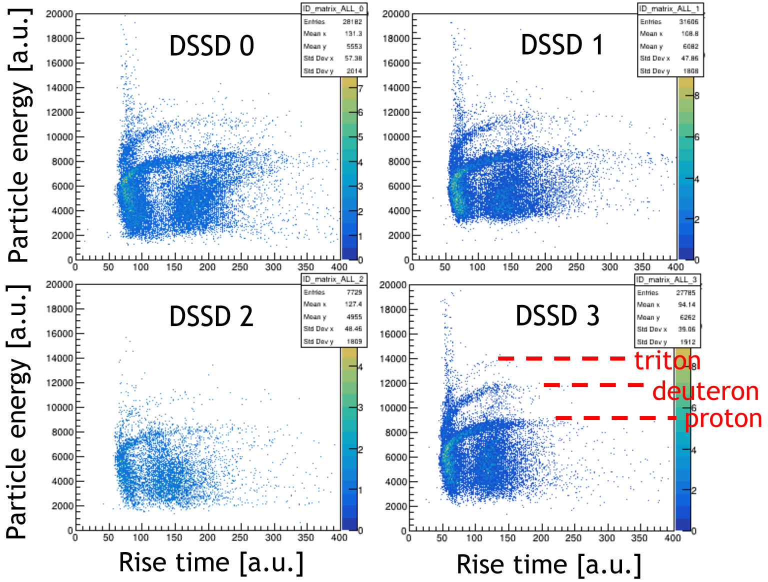
Scattered proton – light charged particle coincidences

PRELIMINARY

- Excitation Energy from proton measurement (150 mg/cm^2 target)
- Statistics from one weekend only

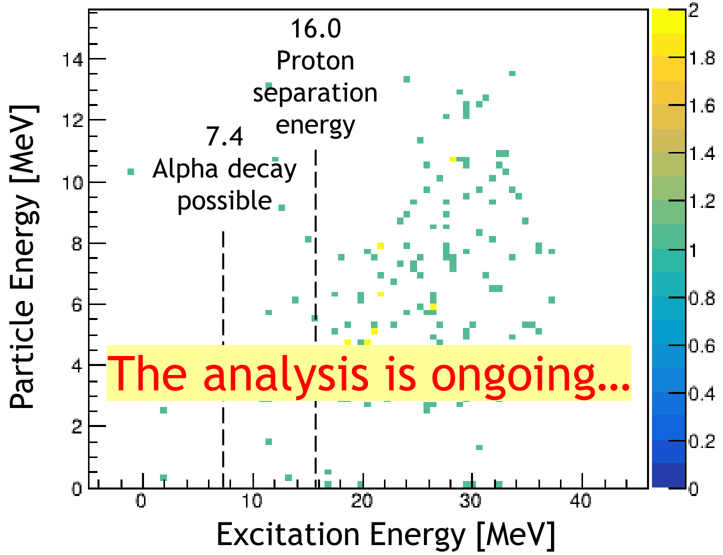
PARTICLE IDENTIFICATION MATRICES

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



EXCITATION ENERGY - PARTICLE ENERGY MATRIX

from ^{12}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.

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

- ✓ 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.

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)

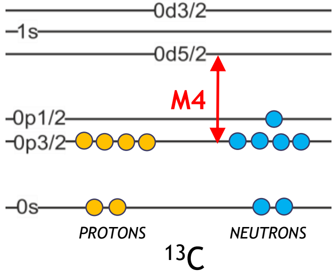
CANDIDATES FOR THE 21.5-MeV M4 RESONANCE IN ^{13}C:

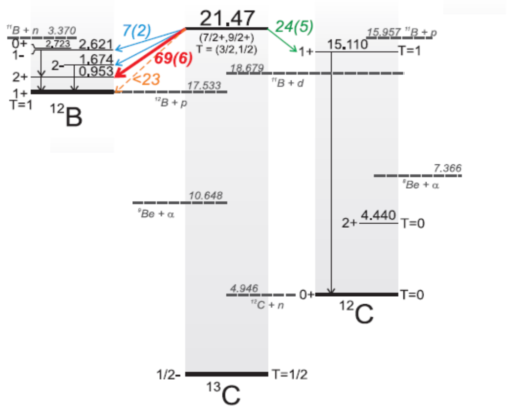
State	T	E	Γ	%M4(n)	%M4(p)
~~$7/2^+_6$~~	~~1.44~~	~~19.9(5)~~	~~1500(200)~~	~~32%~~	~~22%~~
$7/2^+_7$	1.36	20.9(5)	400(300)	32%	19%
~~$7/2^+_8$~~	~~0.90~~	~~22.1(8)~~	~~2500(1000)~~	~~8%~~	~~9%~~
~~$9/2^+_3$~~	~~1.49~~	~~21.8(7)~~	~~150(300)~~	~~38%~~	~~27%~~

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

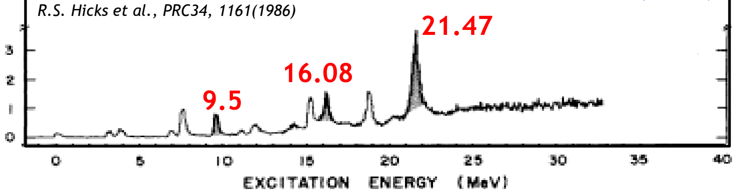




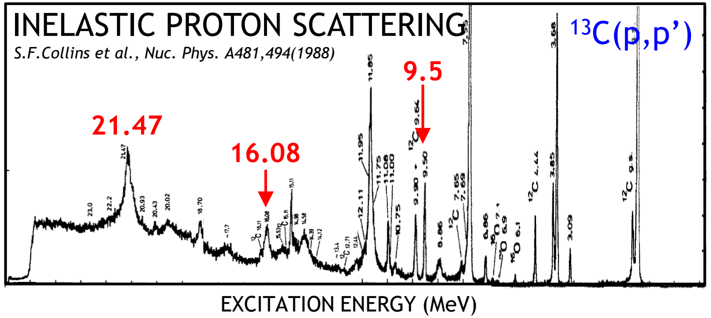
Previous studies of M4 resonances in ^{13}C

The aim of the present investigations is to **identify the decay of the 21.5-MeV** $1p_{3/2} \rightarrow 1d_{5/2}$ resonance in ^{13}C

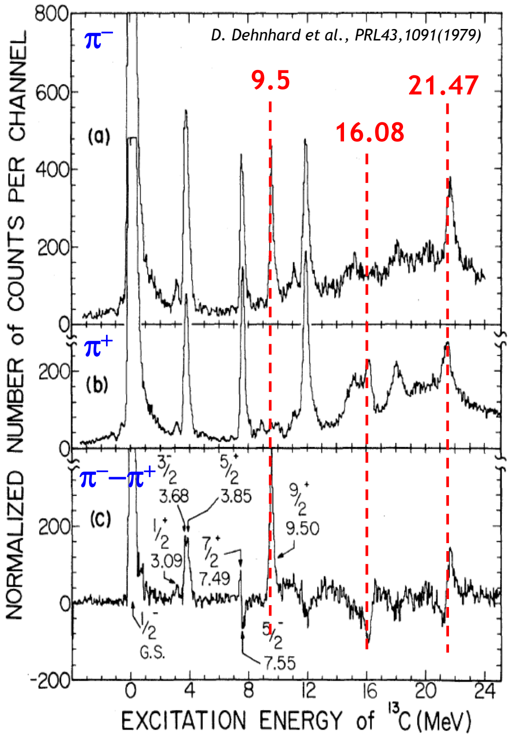
INELASTIC ELECTRON SCATTERING

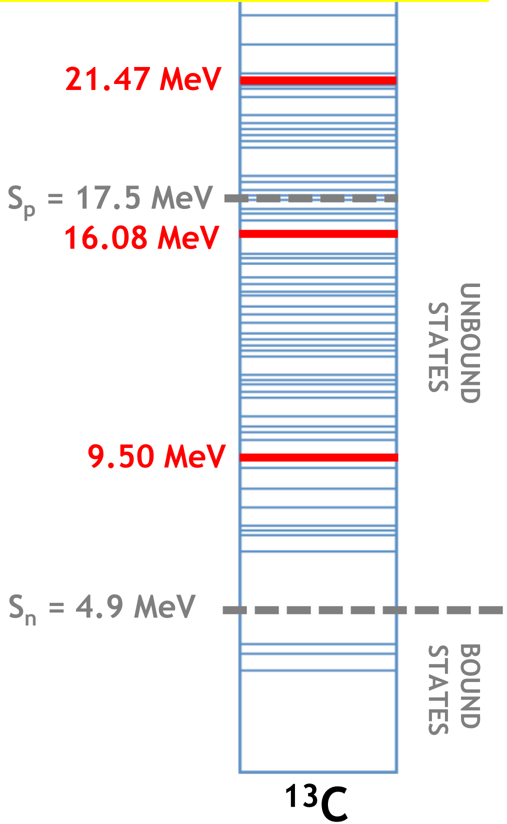


INELASTIC PROTON SCATTERING



INELASTIC PION SCATTE





From ^{13}C(π,π') 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