THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

NARODOWE CENTRUM NAUKI

Project no. 2020/39/D/ST2/03443

"Stretched" states decays studied at CCB IFJ PAN by gamma-particle coincidences

Participants and collaboration

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26 October 2023 – University of Warsaw, Poland

Outline

INTRODUCTION

WHAT IS A STRETCHED STATE AND WHY IT IS INTERESTING?

STRETCHED STATE IN ^{13}C: THE FIRST CASE STUDIED AT CYCLOTRON CENTRE BRONOWICE

EXPERIMENT AND RESULTS OF ANALYSIS:

- Scattered protons – gamma ray coincidences
- Scattered protons – light charged particles coincidences

GAMOW SHELL MODEL CALCULATIONS

Y. Jaganathen (IFJ PAN, Poland),
M. Płoszajczak (GANIL, France)

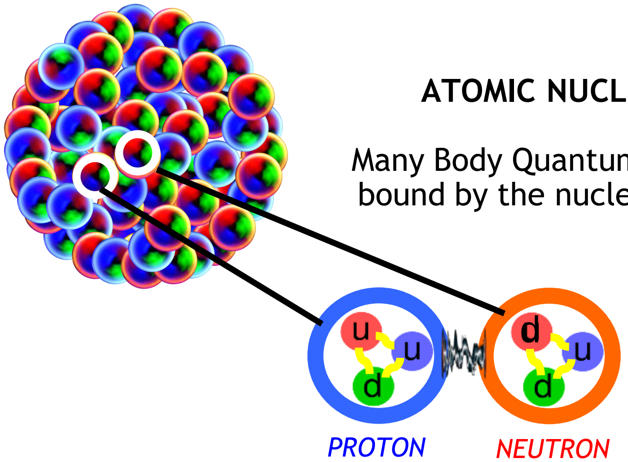
FURTHER STUDIES OF STRETCHED STATES AT CCB

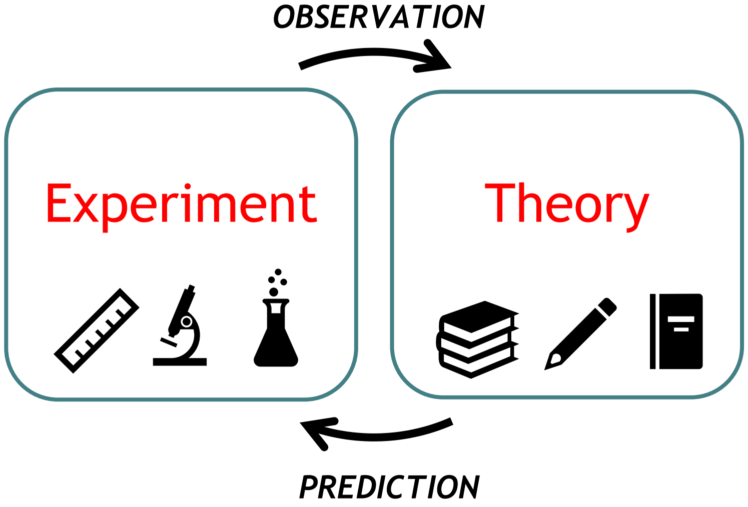
PRELIMINARY RESULTS OF EXPERIMENT FOR ^{14}N *AND* ^{16}O

Introduction

ATOMIC NUCLEUS

Many Body Quantum System
bound by the nuclear force





COMPLEXITY OF THE SYSTEM

QUARKS and GLUONS are the building blocks of nucleons, while nucleons are the building blocks of nuclei

COMPLEXITY OF THE NUCLEAR FORCE

nuclear force acting between nucleons arises from the residual force acting between quarks in different nucleons

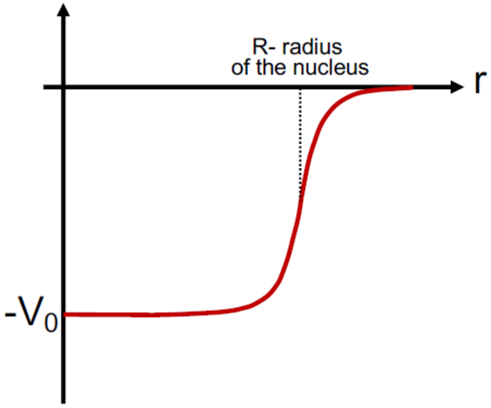
No a priori theory for nuclear interaction!

Until the nucleon-nucleon interaction can be derived from more fundamental theory such as Quantum Chromodynamics we have to use various parametrizations for different purposes.

Introduction - Shell Model

Quantum states in the nuclear mean field

The primary assumption of the nuclear shell model is that the movement of nucleons can be to a good approximation treated as the movement of independent particles in a potential that represents the average interaction with the other nucleons.

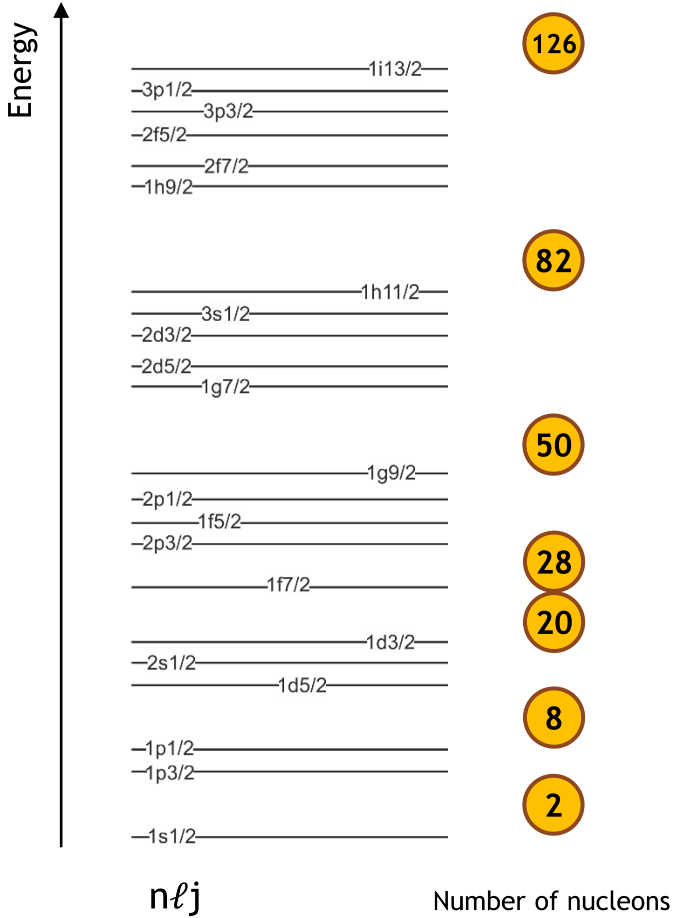


$$V_{mean}(r) + A(r)\hat{L} \cdot \hat{S}$$

The possible values of **state energies** for a particle moving in a potential are obtained by solving the Schrödinger equation:

$$\hat{H}\psi = E\psi$$

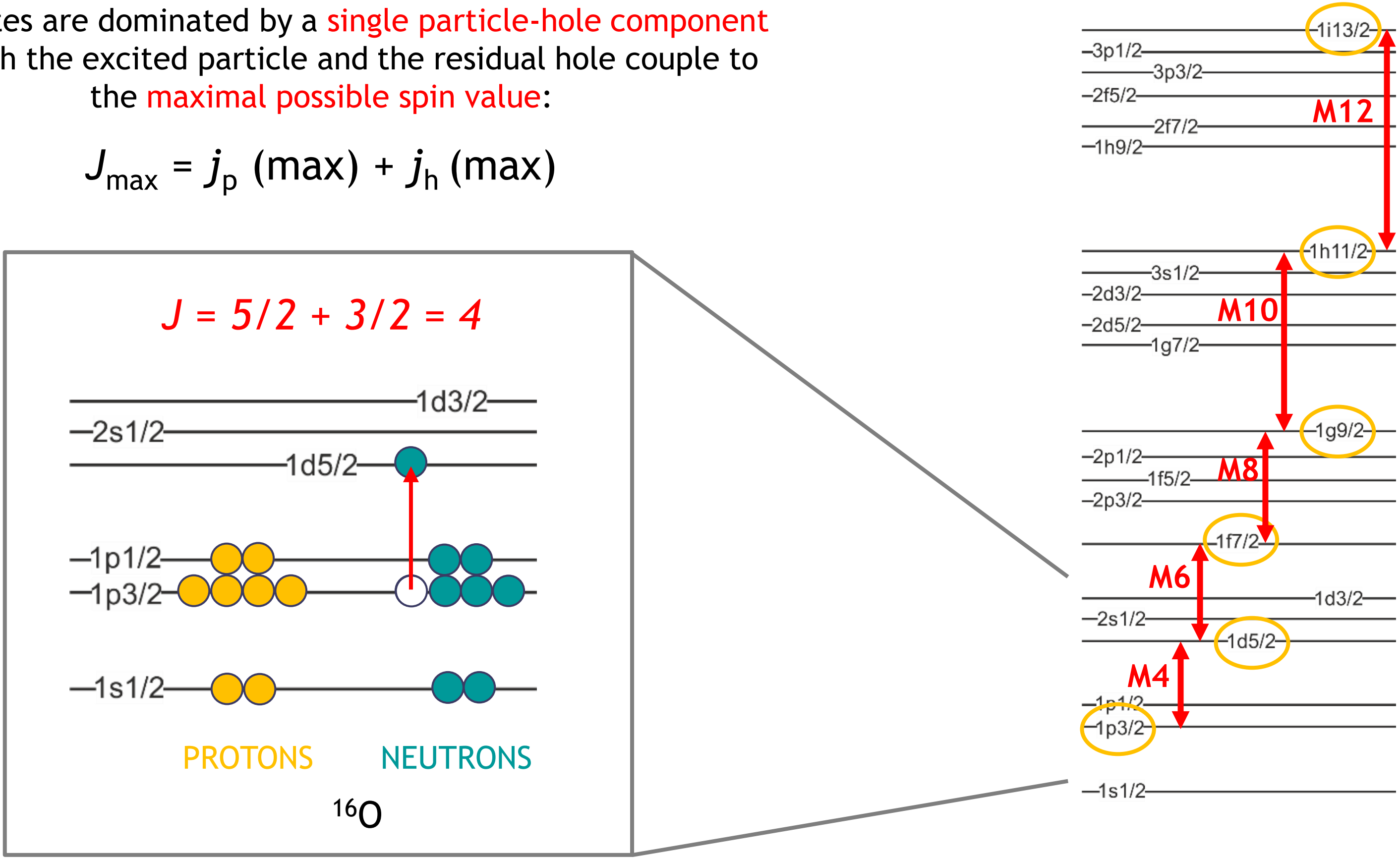
for this potential, where ψ is the particle's wave function.



Stretched states

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:

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



Stretched states

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:

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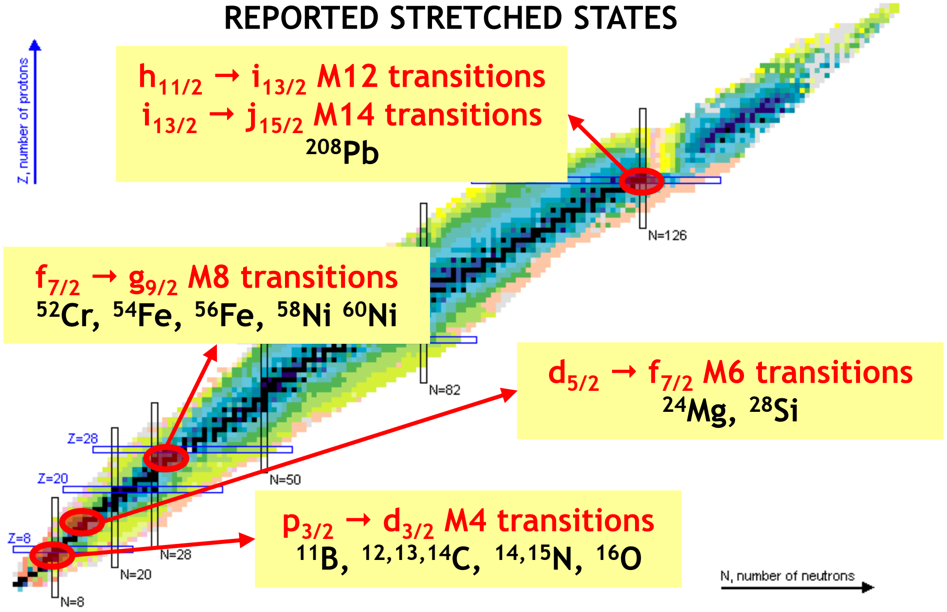
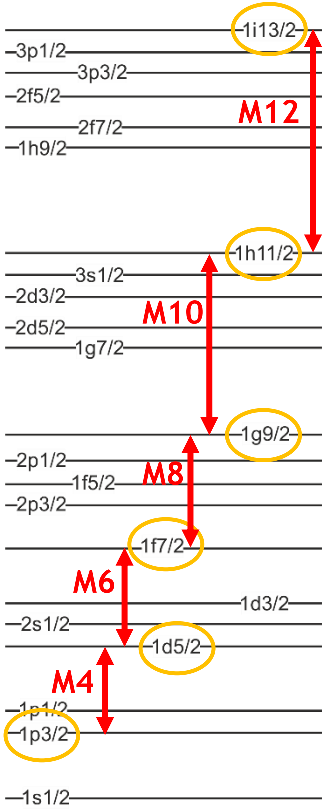
REPORTED STRETCHED STATES

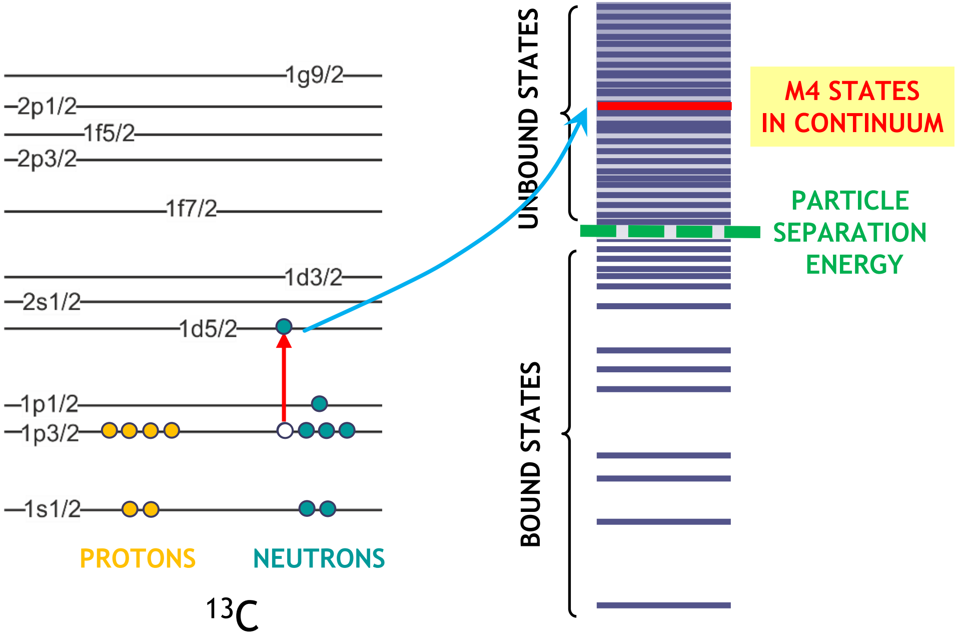


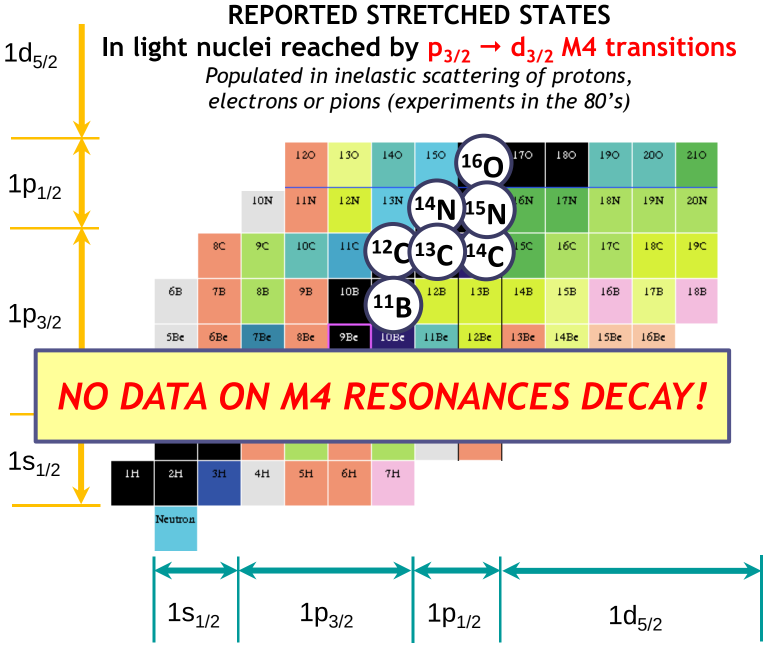


Stretched states in light nuclei – continuum region

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.)



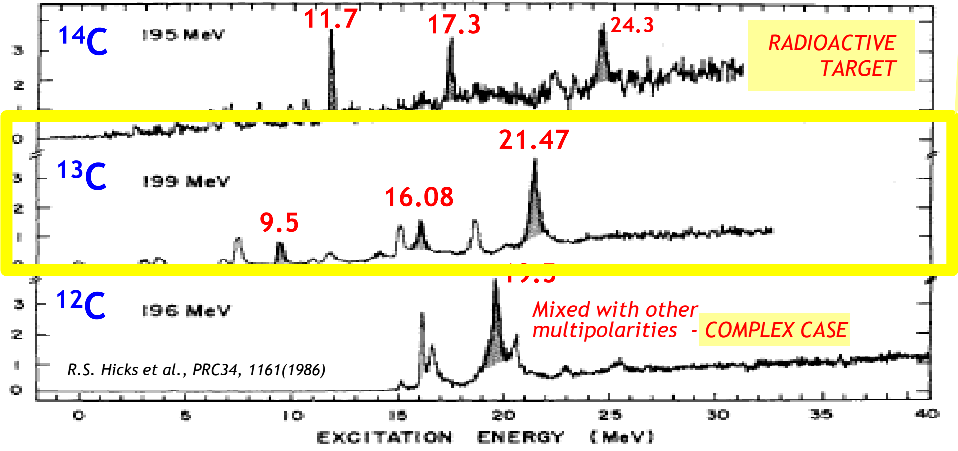


Stretched M4 resonances in light nuclei

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

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

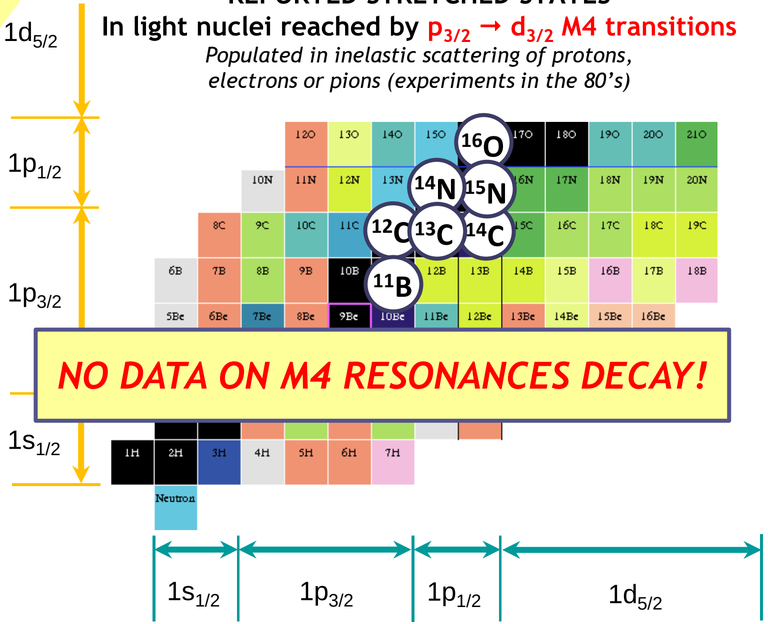
INELASTIC ELECTRON SCATTERING EXPERIMENTS



REPORTED STRETCHED STATES

In light nuclei reached by $p_{3/2} \rightarrow d_{3/2}$ M4 transitions

Populated in inelastic scattering of protons, electrons or pions (experiments in the 80's)



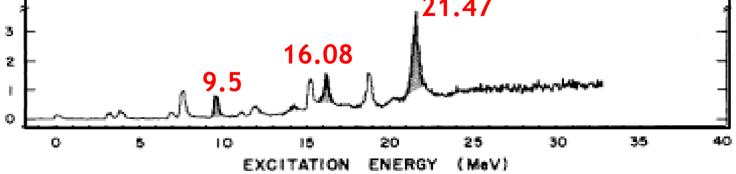
NO DATA ON M4 RESONANCES DECAY!

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

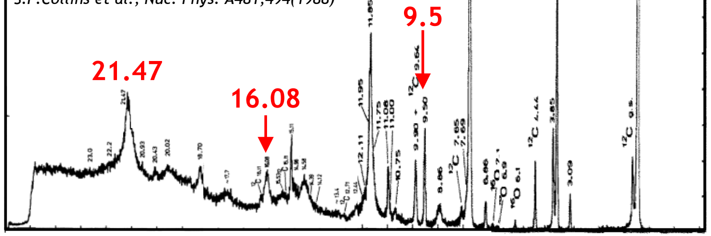
INELASTIC ELECTRON SCATTERING $^{13}C(e,e')$

R.S. Hicks et al., PRC34, 1161(1986)



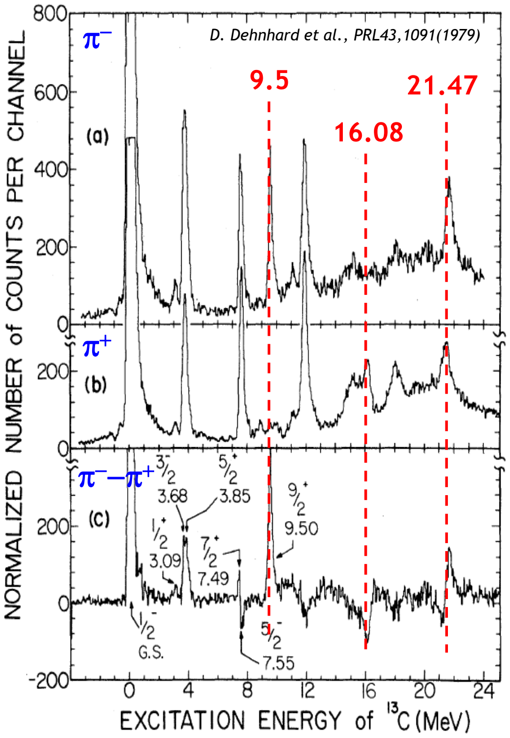
INELASTIC PROTON SCATTERING $^{13}C(p,p')$

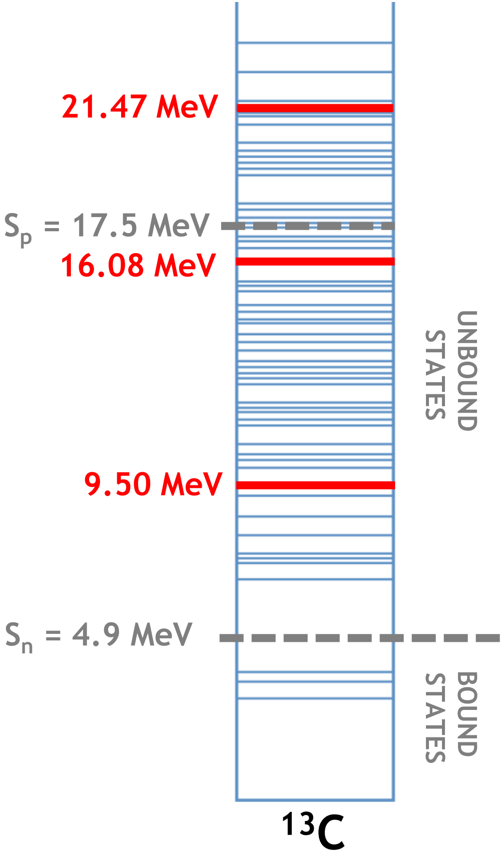
S.F.Collins et al., Nuc. Phys. A481,494(1988)



EXCITATION ENERGY (MeV)

INELASTIC PION SCATTERING $^{13}C(\pi,\pi')$





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

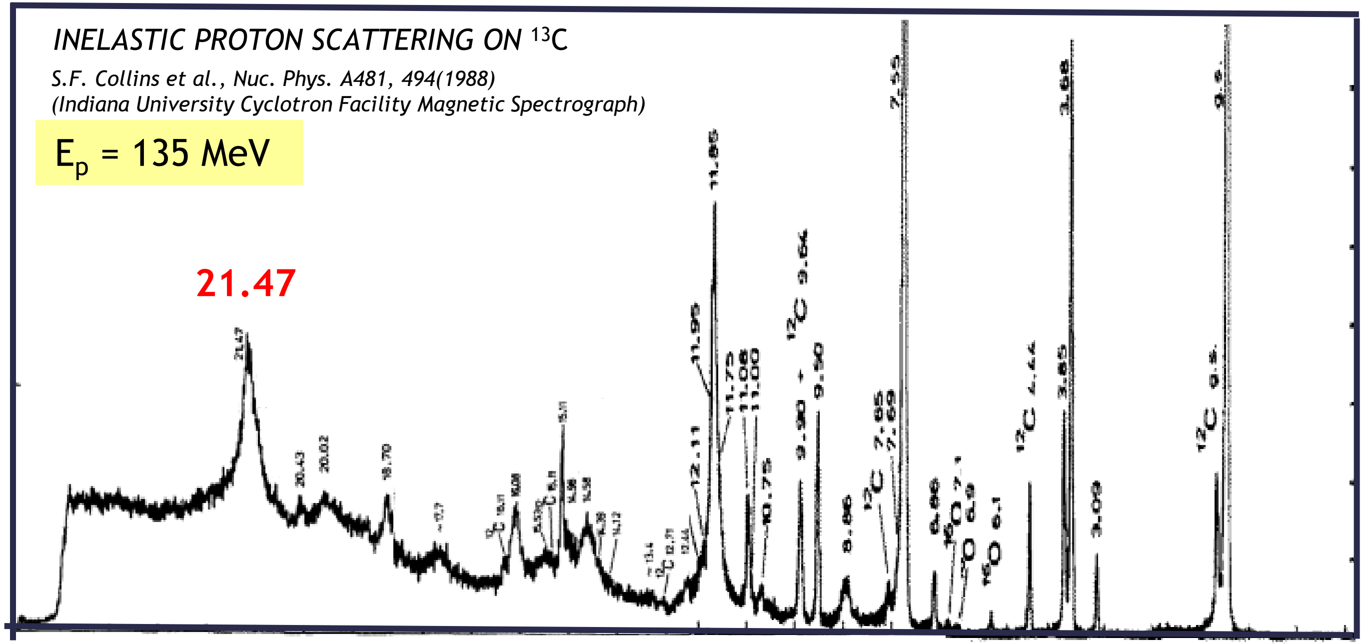
- **9.5 MeV** is $9/2^+$: pure neutron excitation
- **16.08 MeV** is $7/2^+$: mainly proton excitation
- **21.47 MeV** is $(7/2^+, 9/2^+)$ proton and neutron excitations

Previous studies of stretched states in ^{13}C

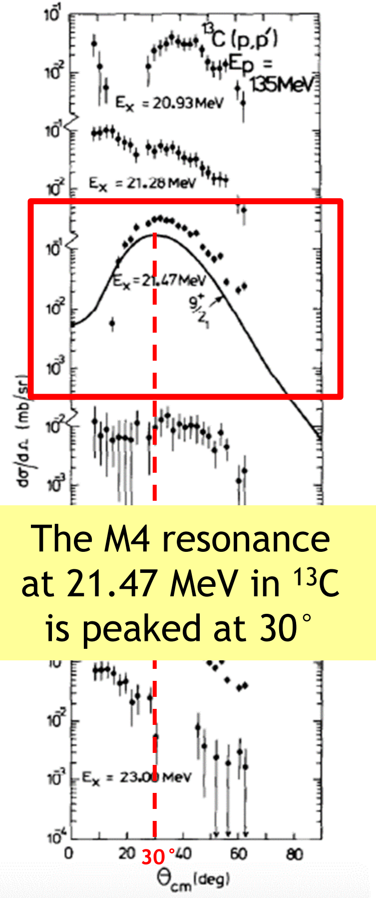
INELASTIC PROTON SCATTERING ON ^{13}C

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

E_p = 135 MeV

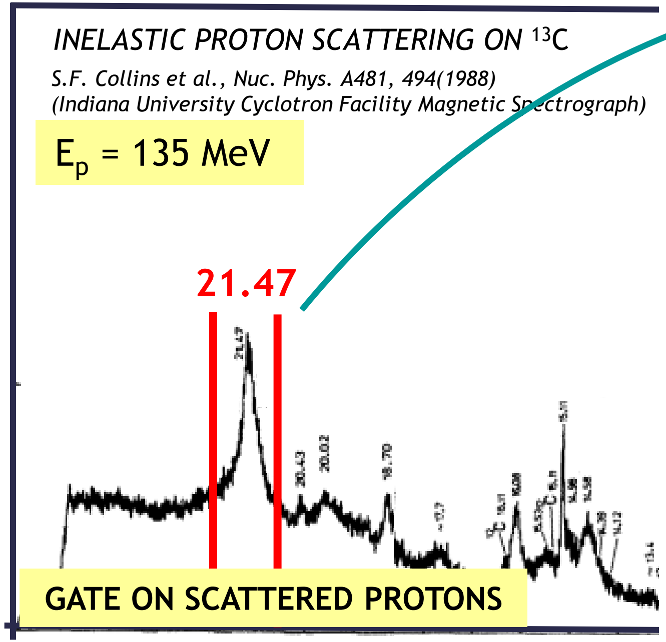


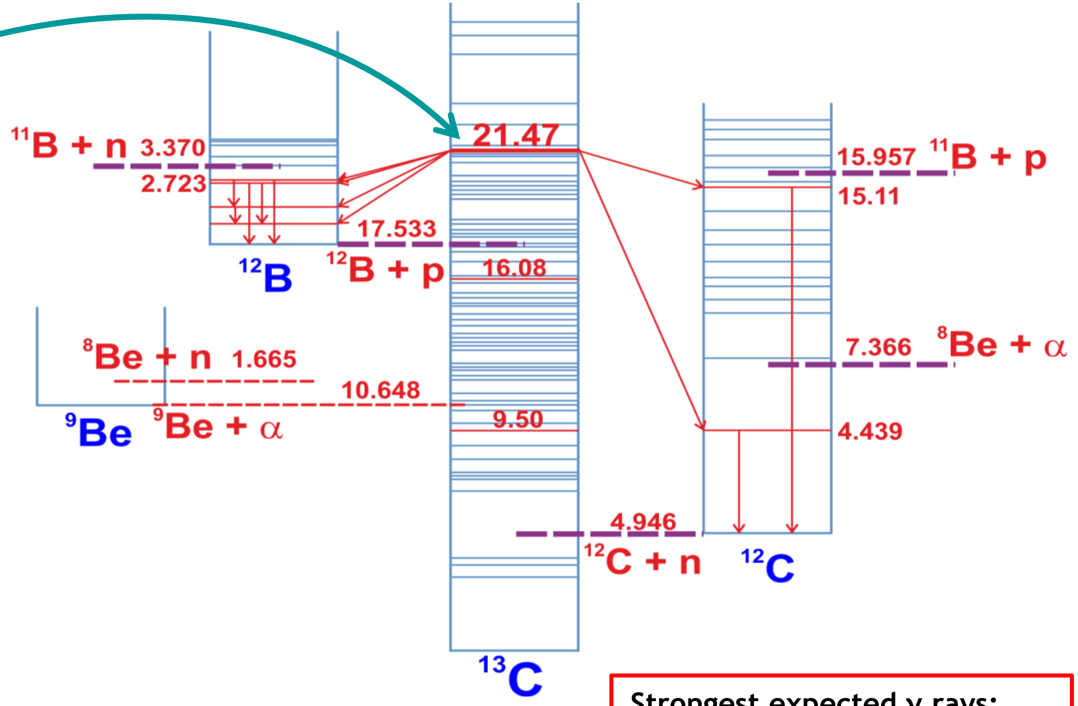
EXCITATION ENERGY [MeV]



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

Previous studies of stretched states in ^{13}C

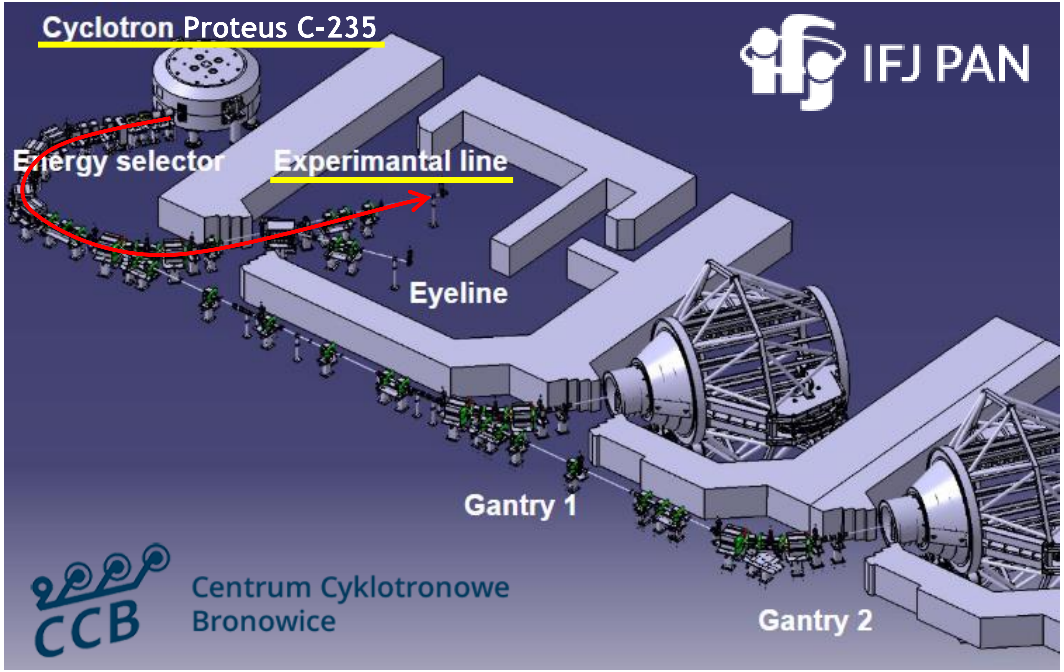




Strongest expected γ rays:
^{12}B: 953, 1668, 1674, 2723 keV
^{12}C: 4439, 15110 keV

Experimental setup – Cyclotron Centre Bronowice (Kraków, Poland)

Experiment: „STUDY OF M4 STRETCHED CONFIGURATION DECAY IN ^{13}C"
Spokespersons: B. Fornal (IFJ PAN), S. Leoni (INFN and Univ. Milano), M. Ciemała (IFJ PAN)



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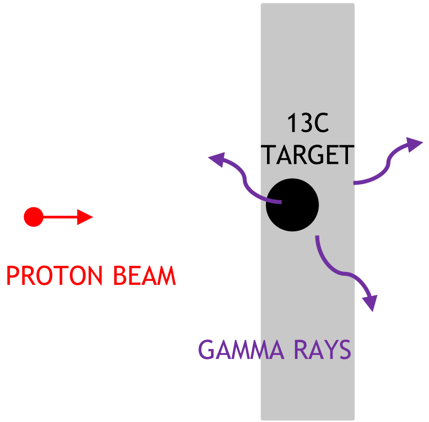
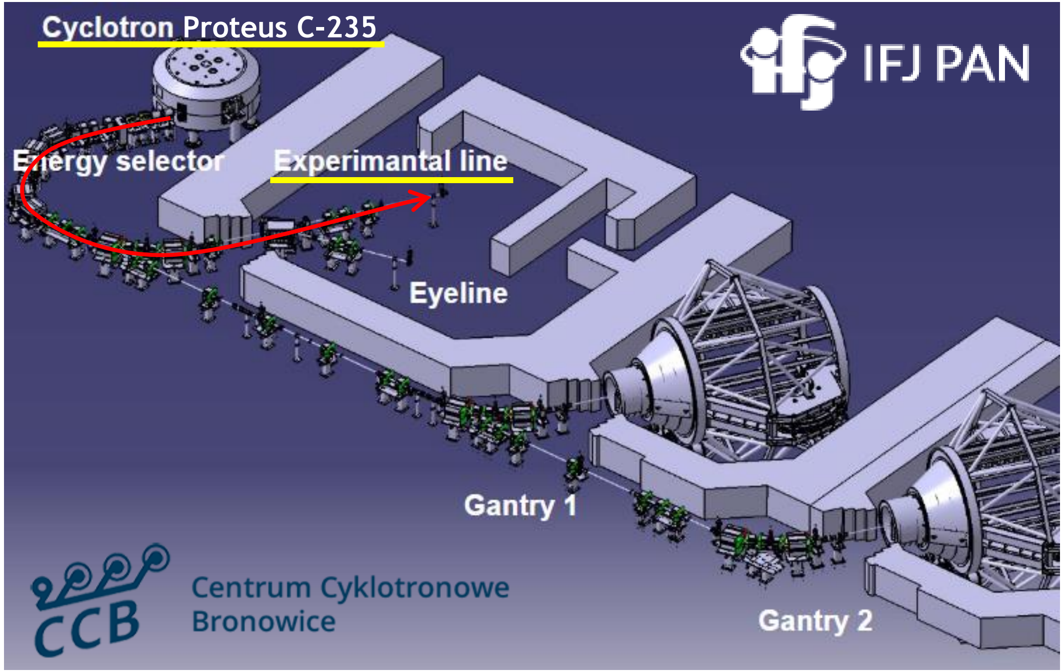
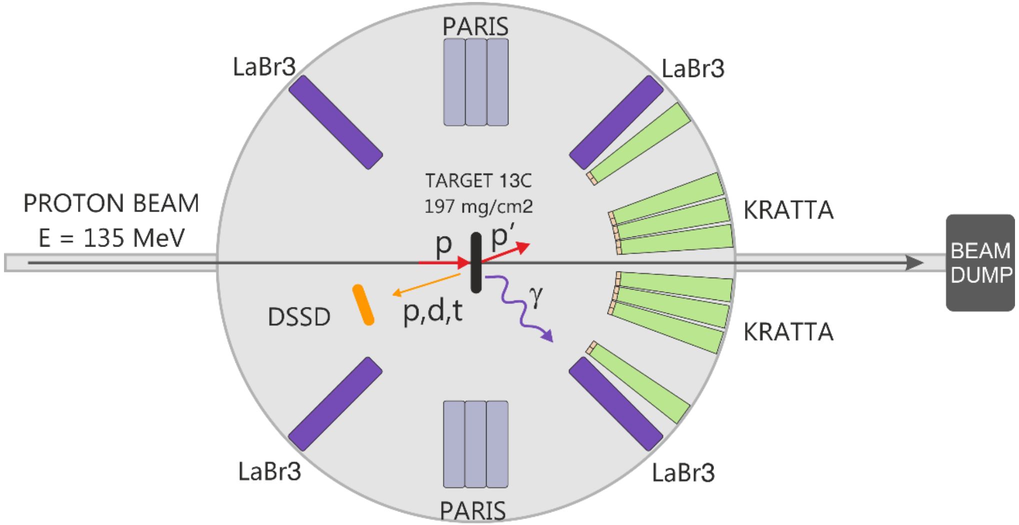
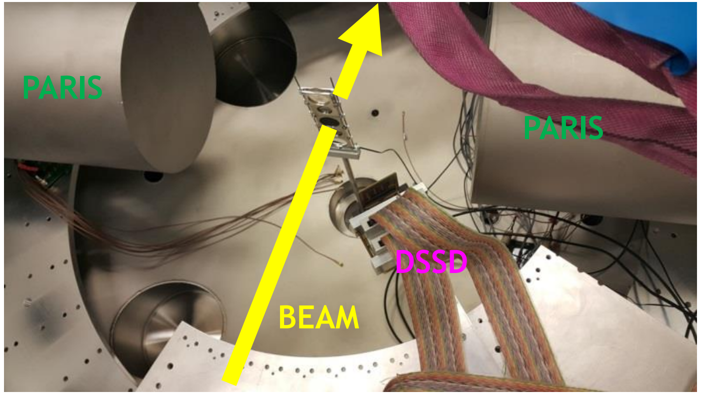




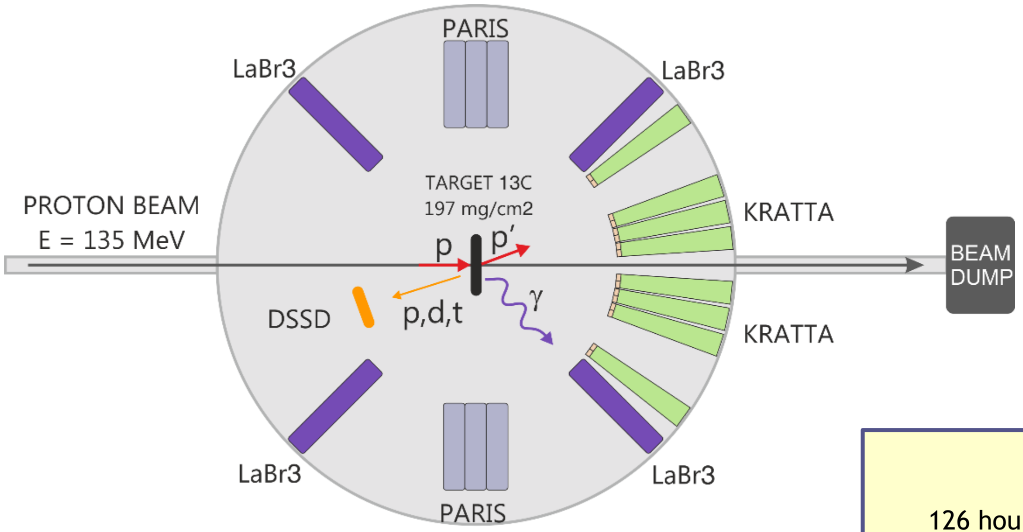
Experimental setup – measurements with thick and thin targets

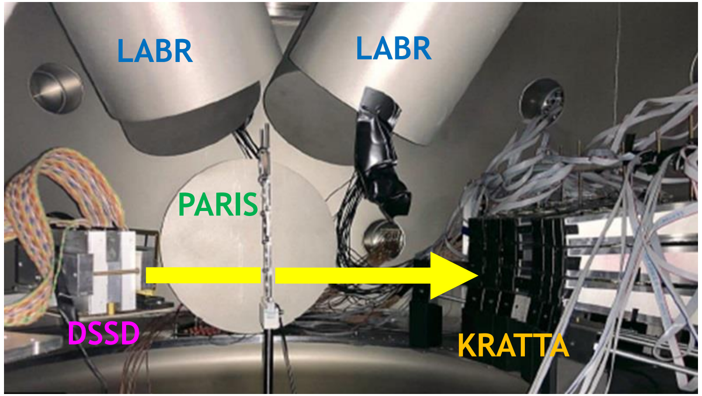




1) Scattered protons measurement: KRATTA telescope array
2) γ-ray detection:
   - four $LaBr_3$ detectors (3"x3")
   - two clusters of the PARIS scintillator array
3) Measurement of light charged particles produced in the reaction: a thick position-sensitive Si detector

Experimental setup – measurements with thick and thin targets





THICK ^{13}C TARGET 197 mg/cm^2: May-June 2019

126 hours of measurement + 17 hours for calibration + 24 hours for tests

6 KRATTA modules at ~36°

THIN ^{13}C TARGET 1 mg/cm^2: December 2019, March and June 2020

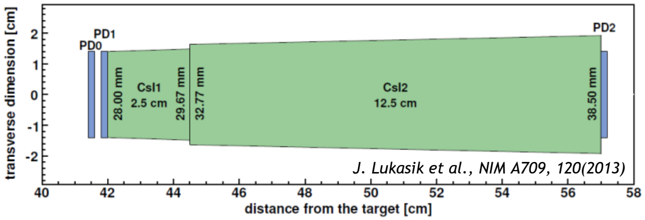
98 hours of measurement + 2 hours for calibration + 9 shifts for tests

30 KRATTA modules at ~36° (angular coverage: 30° -43°)

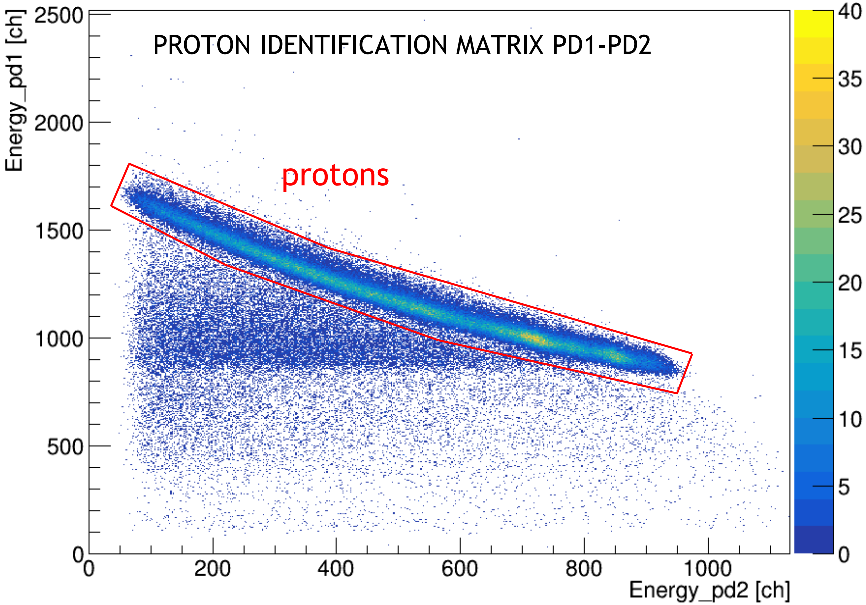
1) Scattered protons measurement: KRATTA telescope array
2) γ-ray detection:
   - four $LaBr_3$ detectors (3"x3")
   - two clusters of the PARIS scintillator array
3) Measurement of light charged particles produced in the reaction: a thick position-sensitive Si detector

Measurement of the scattered protons: KRATTA telescope array

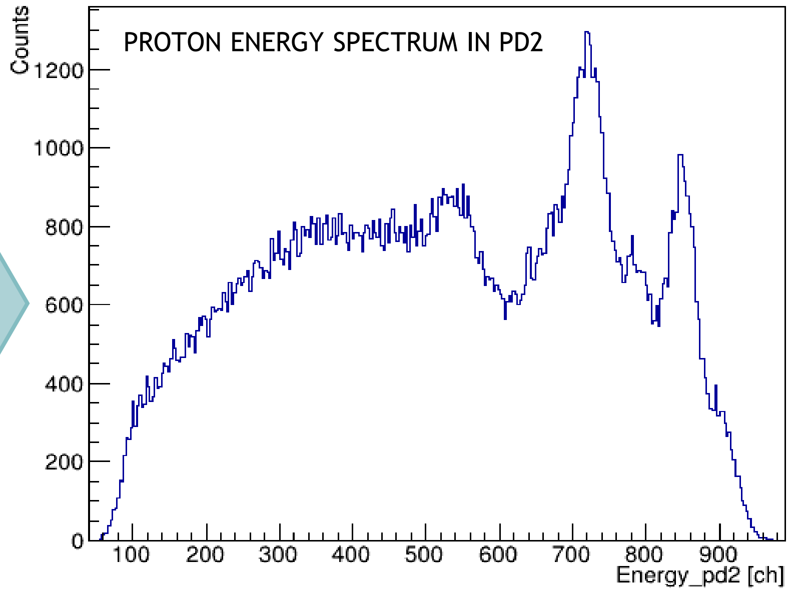
scattered protons



Other sorting conditions:
- Plastic multiplicity = 1
- Coincidence with corresponding plastic
- Gates on time in PD1 and PD2



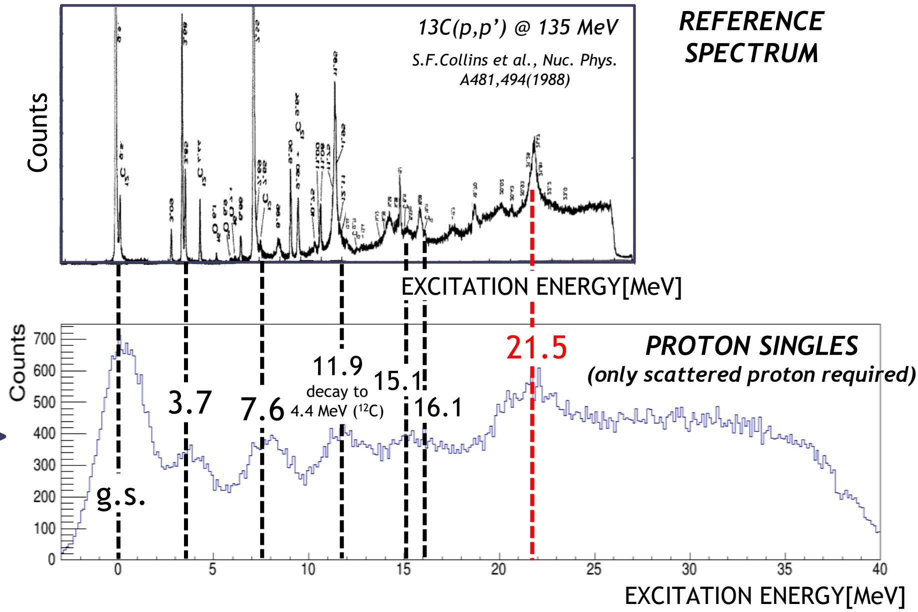
PROJECTION ON PD2 AXIS



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)



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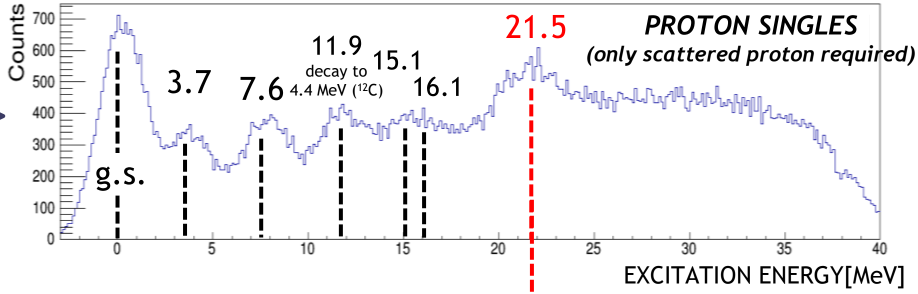
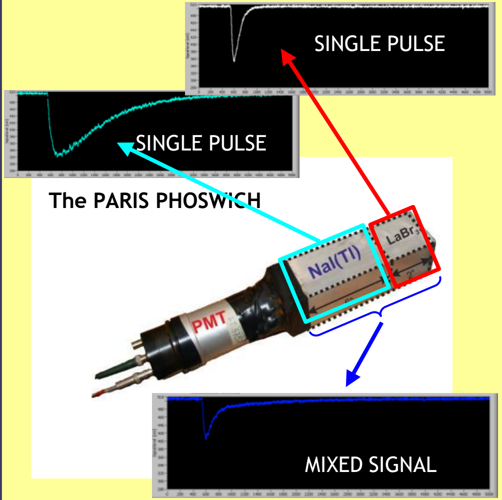
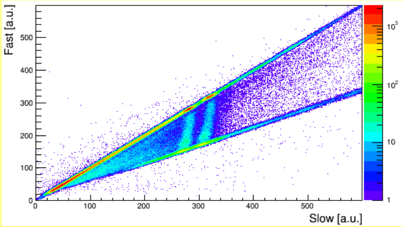


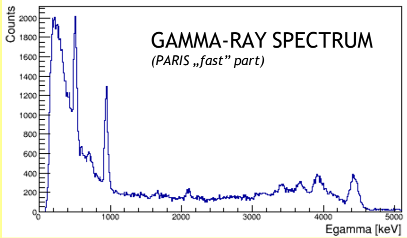
IN COINCIDENCE WITH γ RAYS

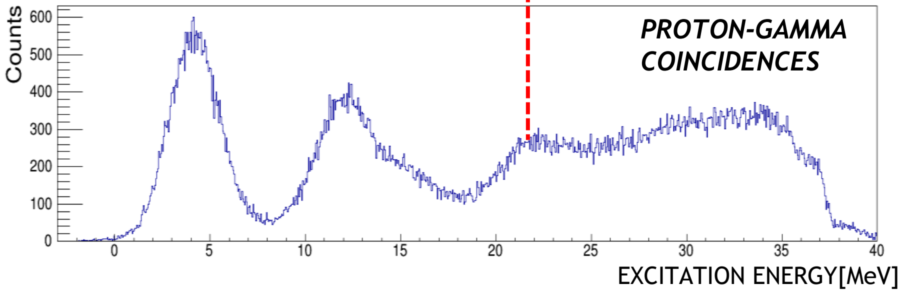
A. Maj et al., Acta Phys. Pol. B40, 565(2009) and http://paris.ifj.edu.pl

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

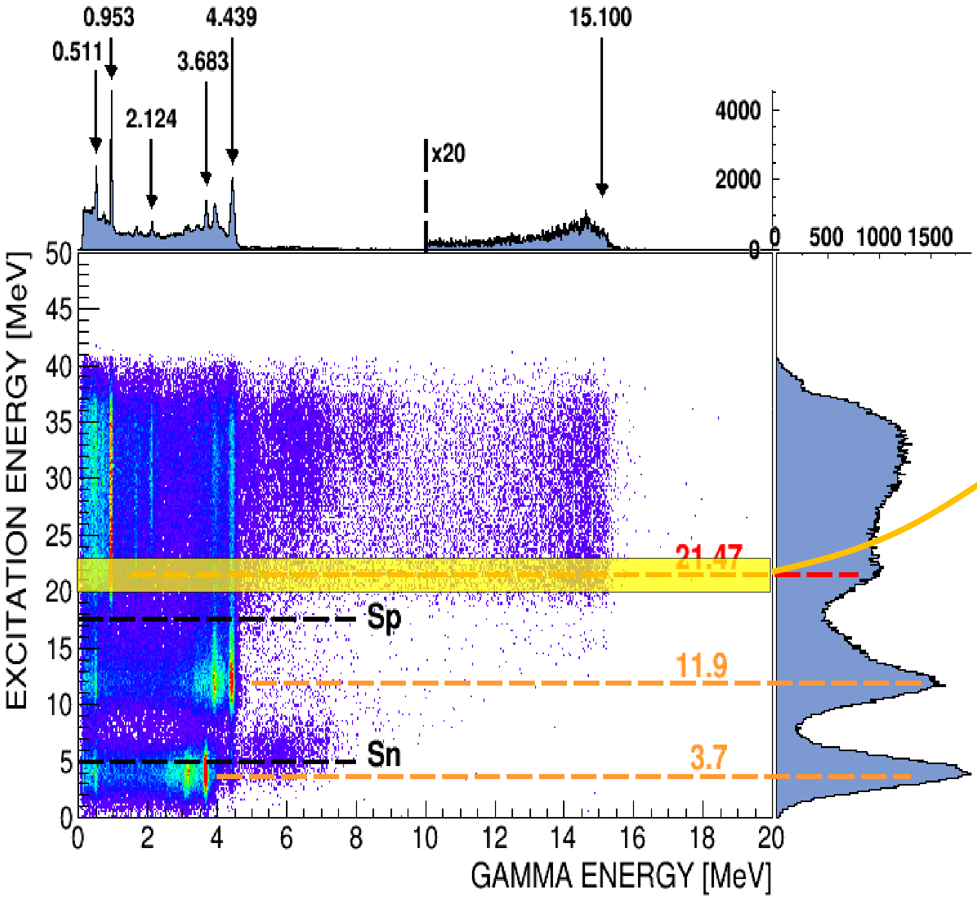


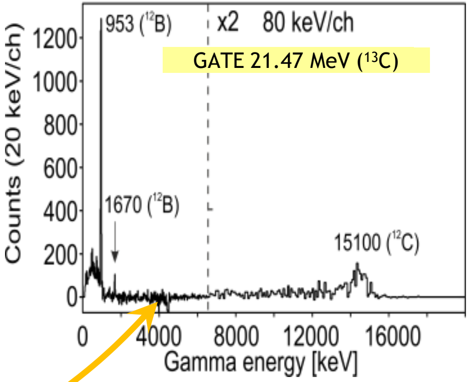






Experimental results: proton-gamma coincidence measurement





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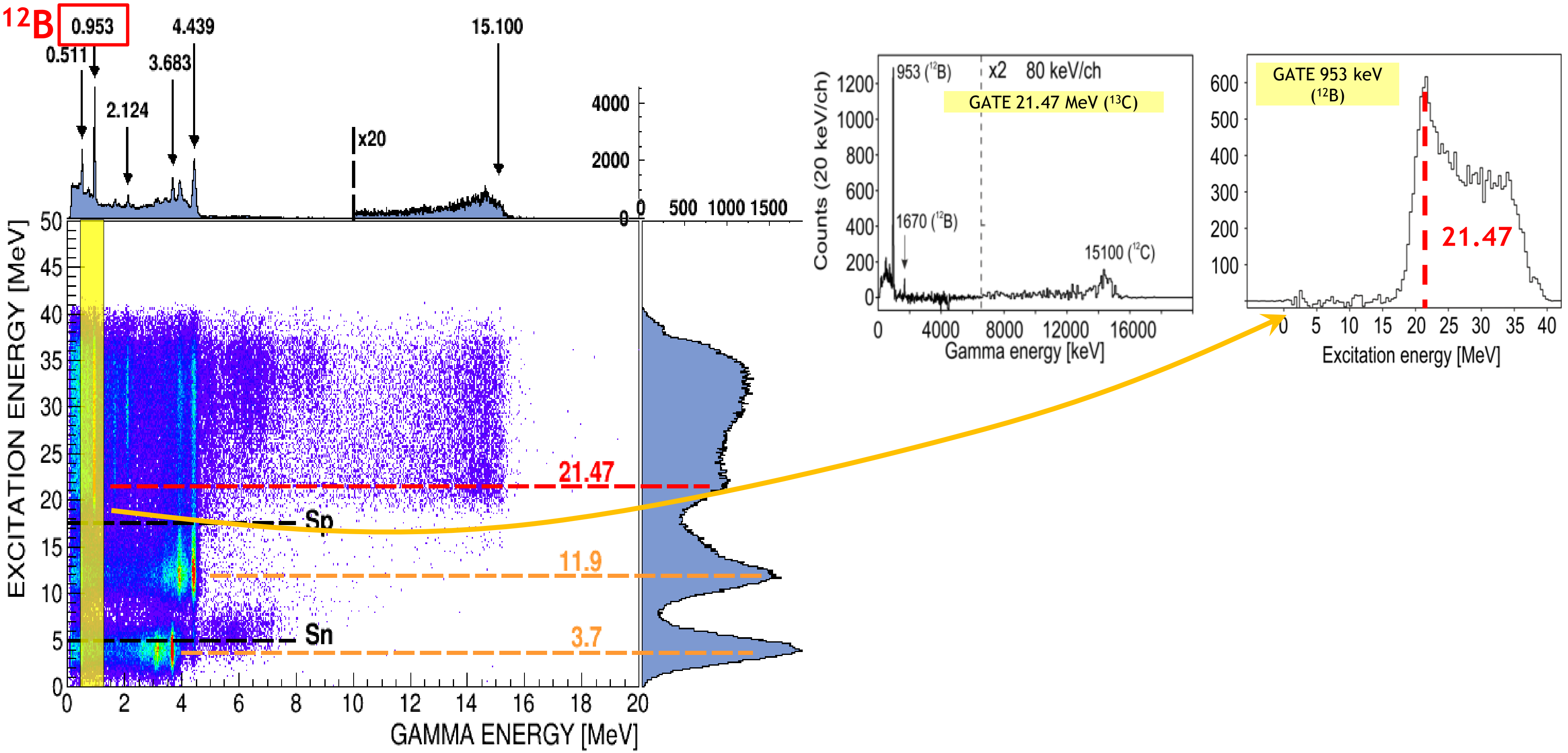

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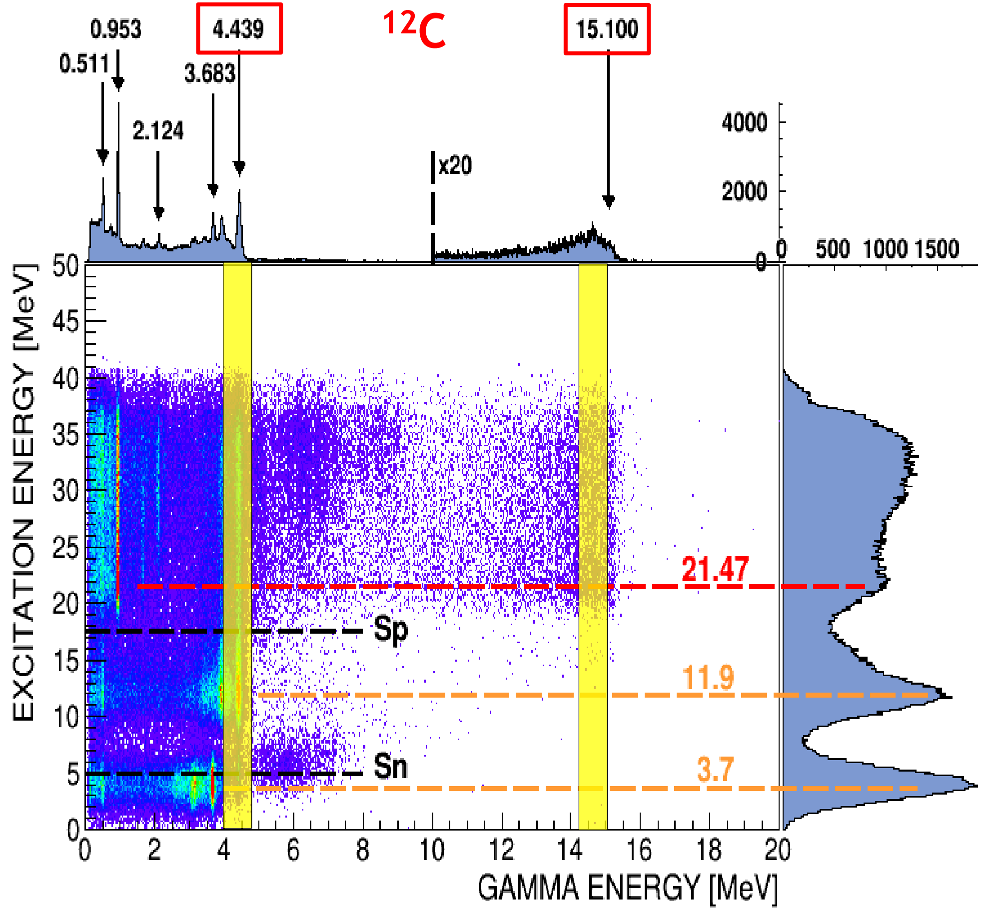

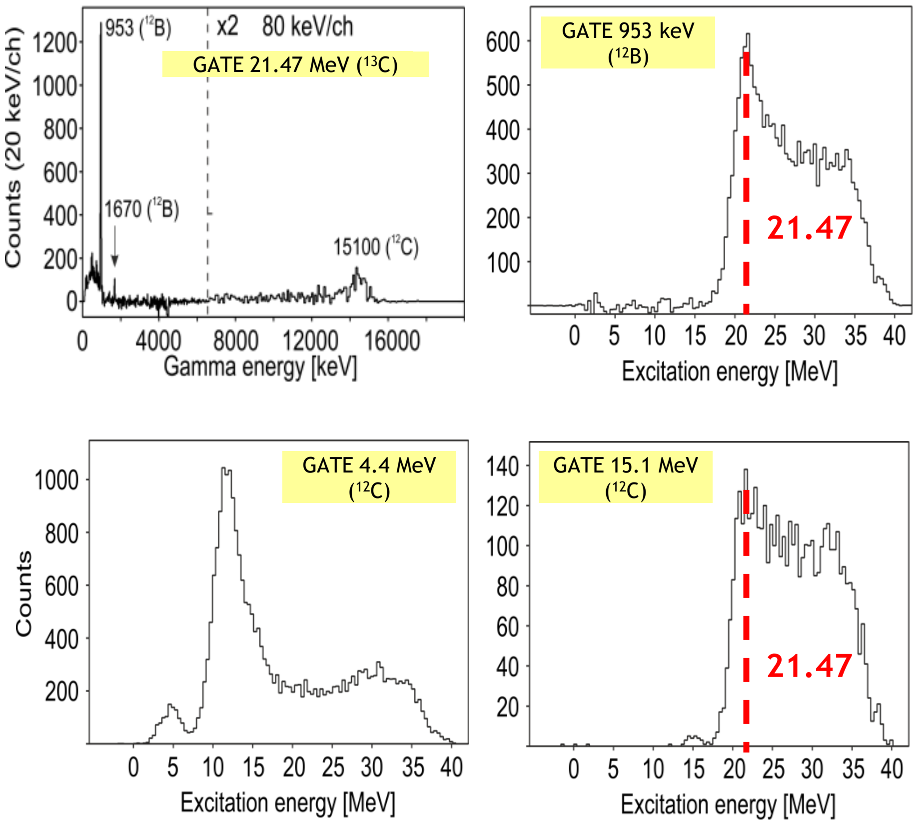

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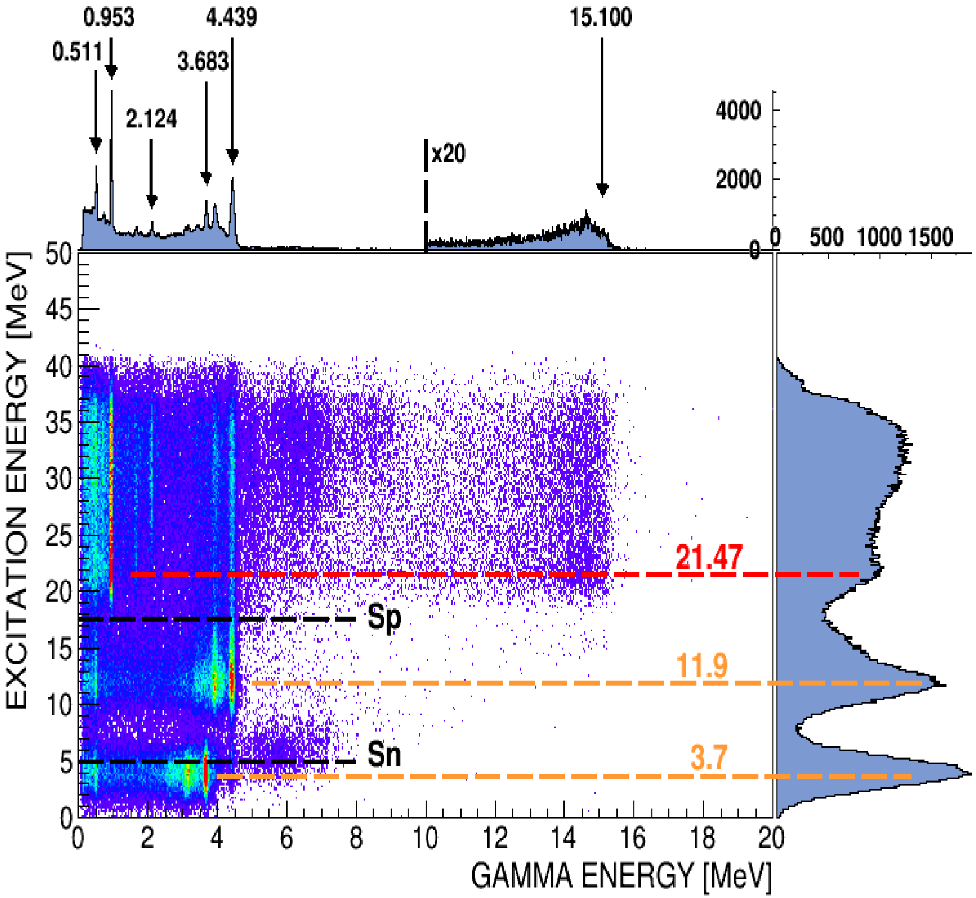
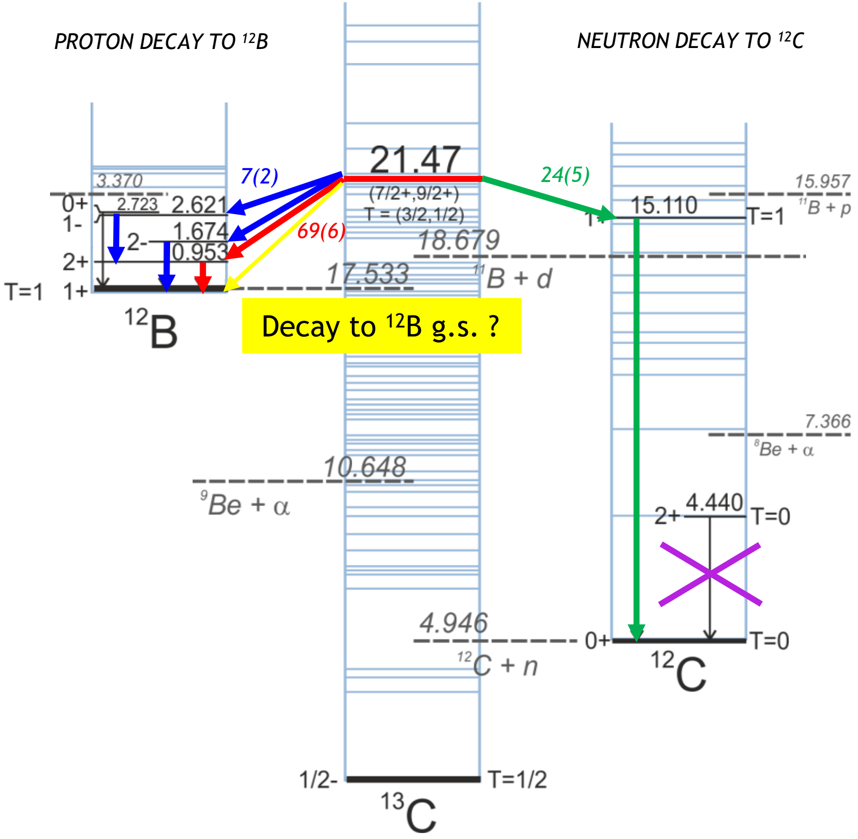
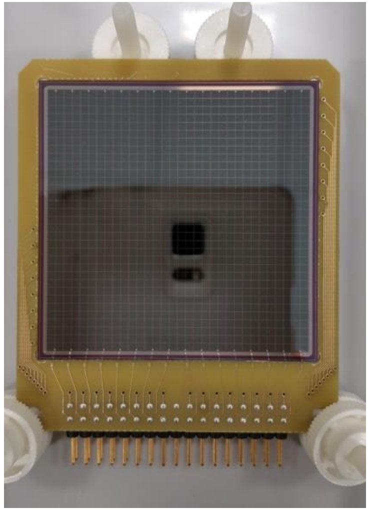




PERFORMANCE OF DSSSD (FROM THICK ^{13}C TARGET EXPERIMENT)

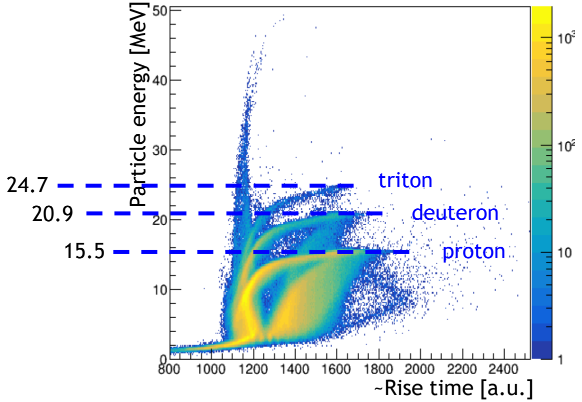
Double Sided Silicon Strip Detector (Micron Semiconductor Ltd)

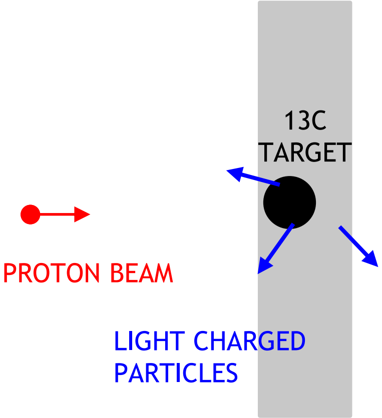
Active area:	50mm x 50mm
No. of strips:	32 (16 per side)
Thickness:	1.5 mm



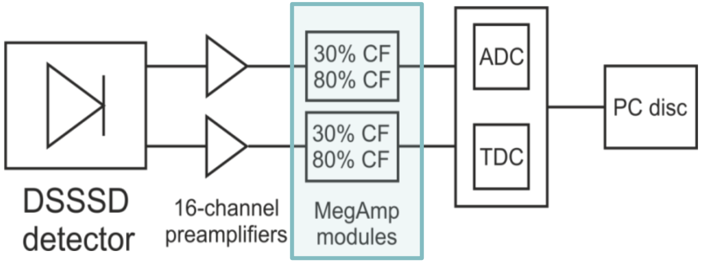
PARTICLE IDENTIFICATION MATRIX

(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 **light particle identification**

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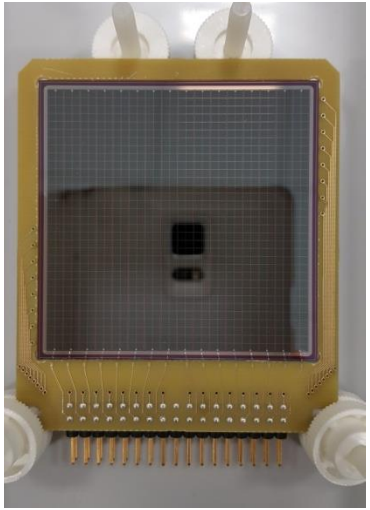

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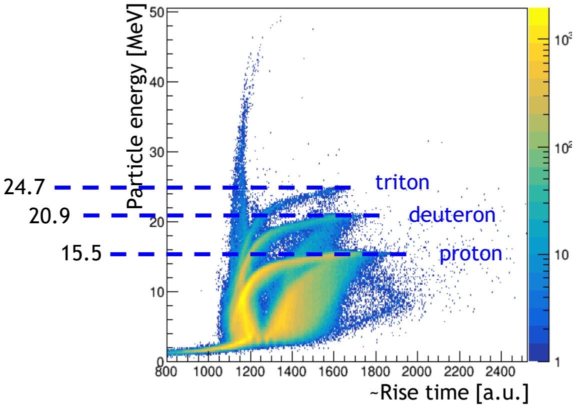
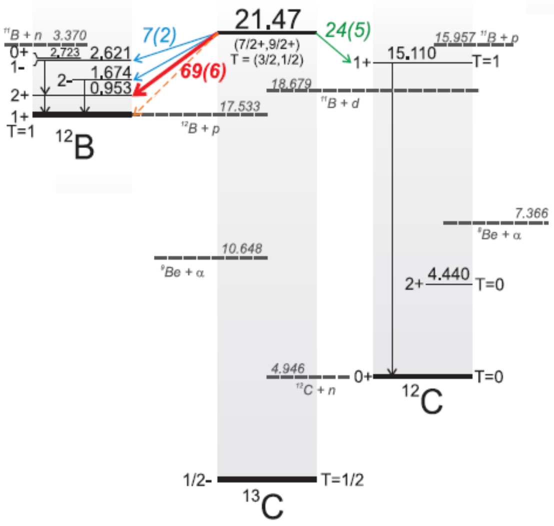




Why another experiment?

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

THIN TARGET NEEDED FOR LOW-ENERGY PROTONS!

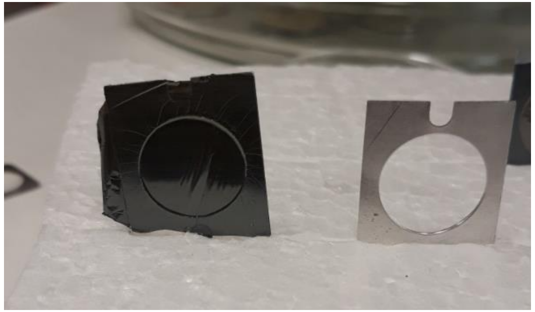
Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

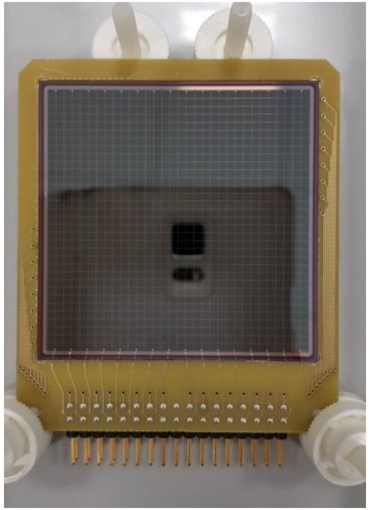
Thin 1 mg/cm^2 ^{13}C target experiment

Double Sided Silicon Strip Detector
(Micron Semiconductor Ltd)

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

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





^{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?

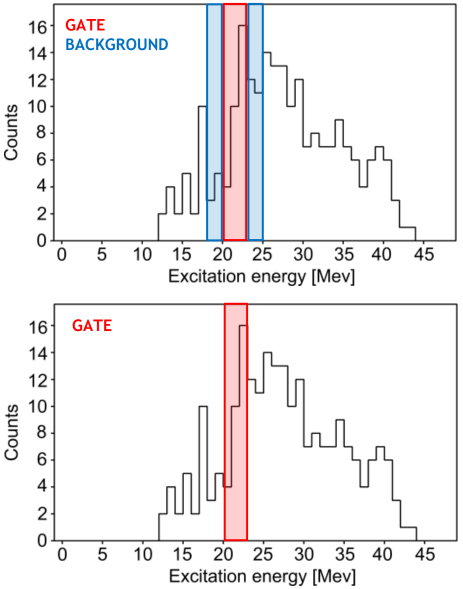
Expected energies of emitted protons are below 4 MeV so protons will stuck in the thick target

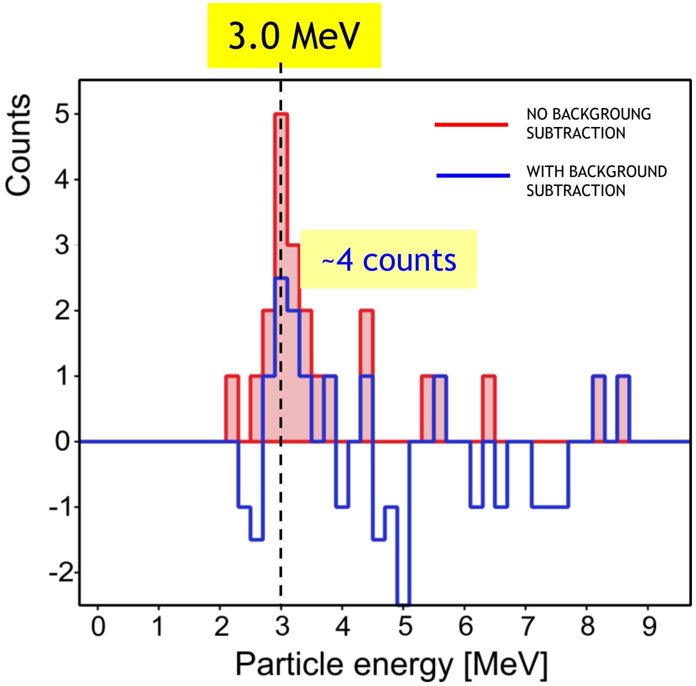
THIN TARGET NEEDED
FOR LOW-ENERGY PROTONS!

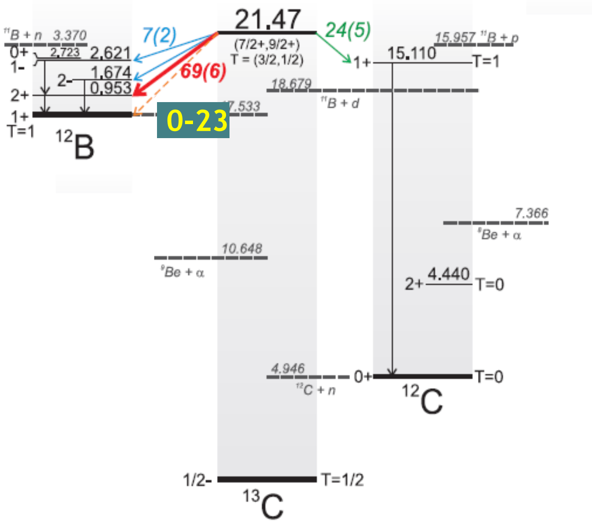
Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

Scattered proton – light charged particle coincidences

Projection of the excitation energy vs. particle energy matrix







Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
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Stretched states in the continuum – Gamow Shell Model calculations

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

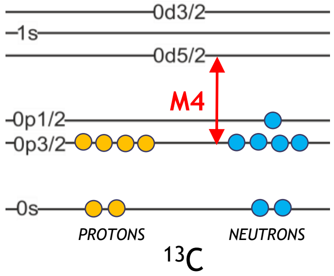
Calculations by Y. Jaganathen (IFJ PAN) and M. Płoszajczak (GANIL)

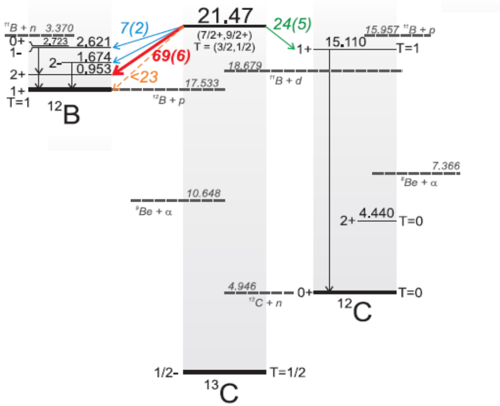
- The interaction was made of two parts:
  - a Woods-Saxon potential with a spin-orbit and a Coulomb term to **model the effective ^{4}He core**
  - an effective finite-range two-body potential with **central, spin-orbit and tensor Gaussian terms**
- Model space was **specifically adapted** to describe the M4 state: *psd*+$f_{7/2}$, 3 effective holes max. in the ^{12}C core
- The depths of the one-body W-S potential and the 7 parameters of the two-body interaction were adjusted to the low-lying spectra of ^{12}B, ^{12,13,14}C, ^{12,13,14}N, and ^{14}O

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

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%





Stretched states in the continuum – Gamow Shell Model calculations

The **Gamow Shell M**… **…m extension of the traditional Shell Model**, which provides:

- a rigorous treatmen… …xcitations, including coupling to a continuum of non-resonant particles
- a fully consistent ca… …y and width and their mutual relation

SPECTROSCOPIC FACTORS CALCULATED
Mostly built on the 1⁺ states of:
^{12}B ($1^+\otimes d_{5/2}$, S_f=0.25)
^{12}C ($1^+\otimes d_{5/2}$, S_f=0.58)

Calculations by Y. Jaganathen (…AN) and M. Płoszajczak (GANIL)

- The interaction was…
  - a Woods-Saxo… Coulomb term…
  - an effective finite-range two-body potential with **central, spin-orbit and tensor Gaussian terms**
- Model space was **specifically adapted** to des… the M4 state: $psd+f_{7/2}$, 3 eff… core
- The depths of the o… parameters of the t… …d to the low-lying spectr…

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%~~
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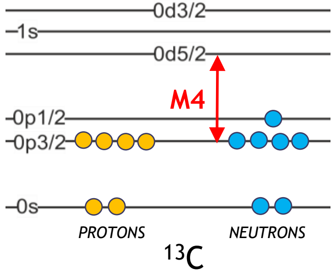
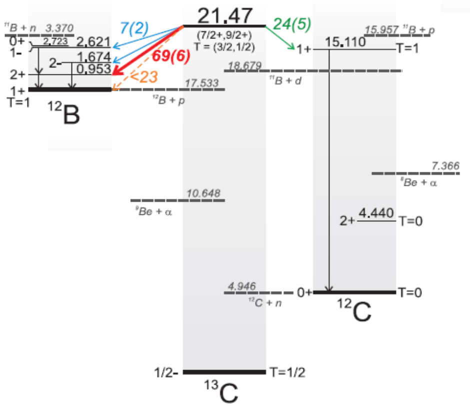


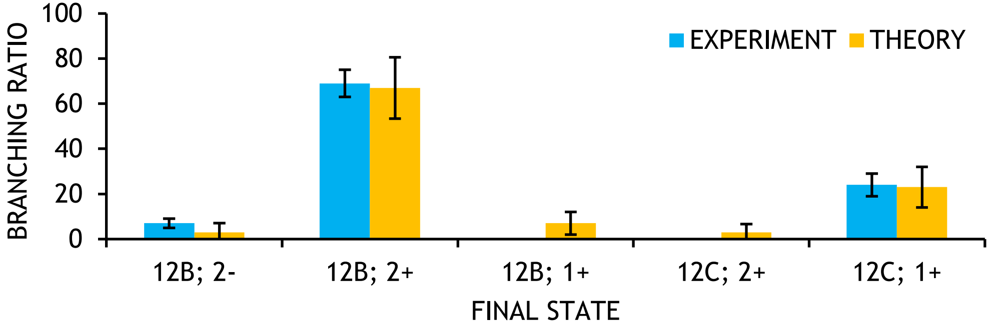


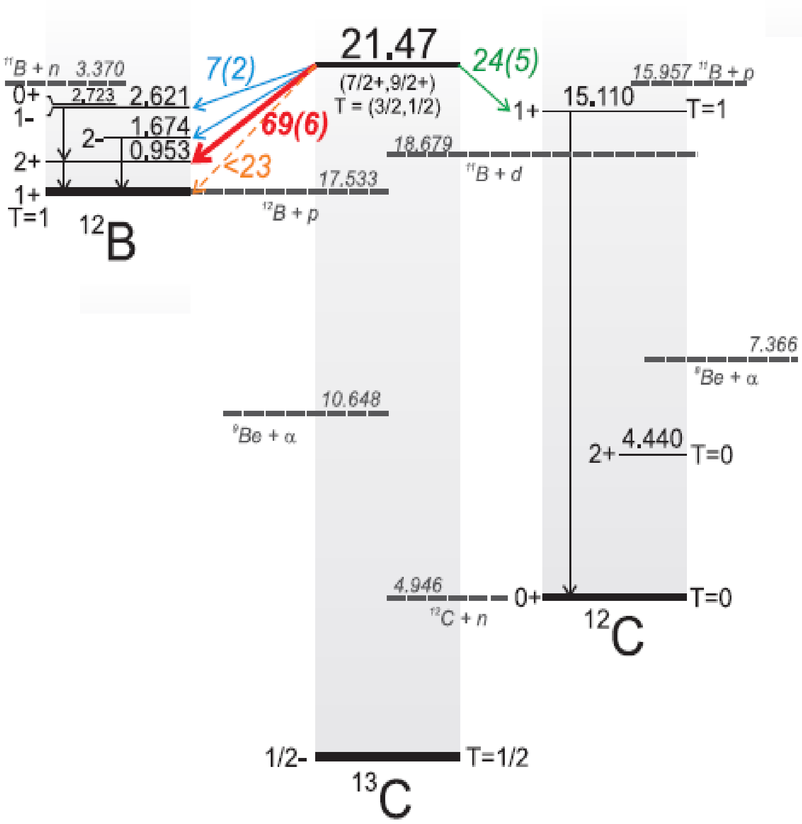
FOR THE FIRST TIME GSM CALCULATIONS WERE PERFORMED FOR SUCH „HEAVY" SYSTEM

Stretched states in the continuum – Gamow Shell Model calculations

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

$J^\pi = (7/2^+, 9/2^+)$, $T = (1/2, 3/2)$				$J^\pi = 7/2^+_7$, $T = 1.36$			
$E_{exp} = 21.47$ MeV				$E_{th} = 20.9(5)$ MeV			
$\Gamma_{exp} = 270(20)$ keV				$\Gamma_{th} = 400(300)$ 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)





Summary

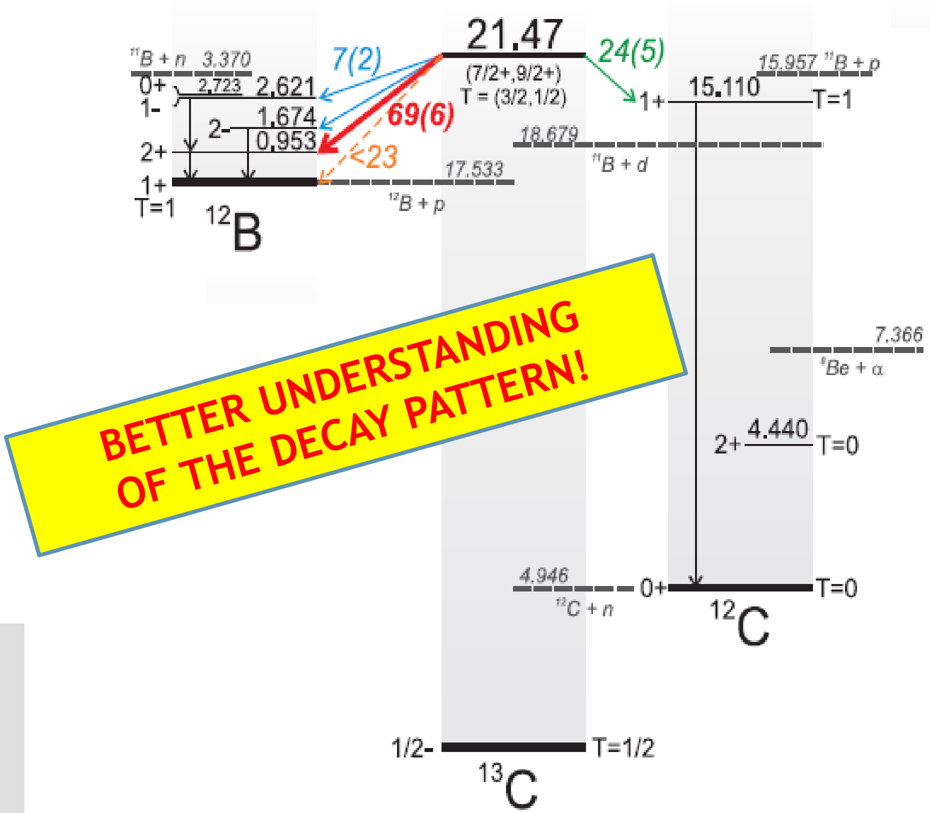
EXPERIMENT

- ☑ 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.

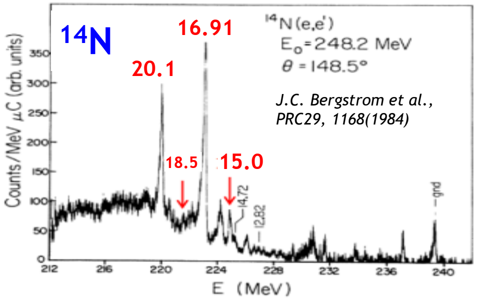
GAMOW SHELL MODEL CALCULATIONS

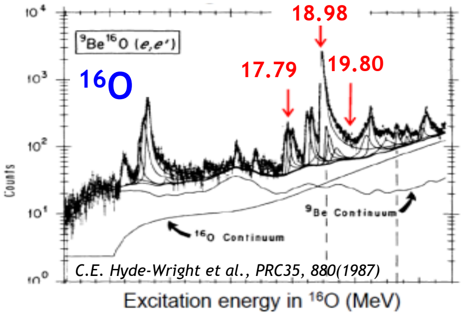
- ☑ Performed for the first time for such „heavy" system.
- ☑ Successful comparison with experiment in terms of **state energy, width and decay branchings** proves the high quality and precision of the GSM wave-function calculations

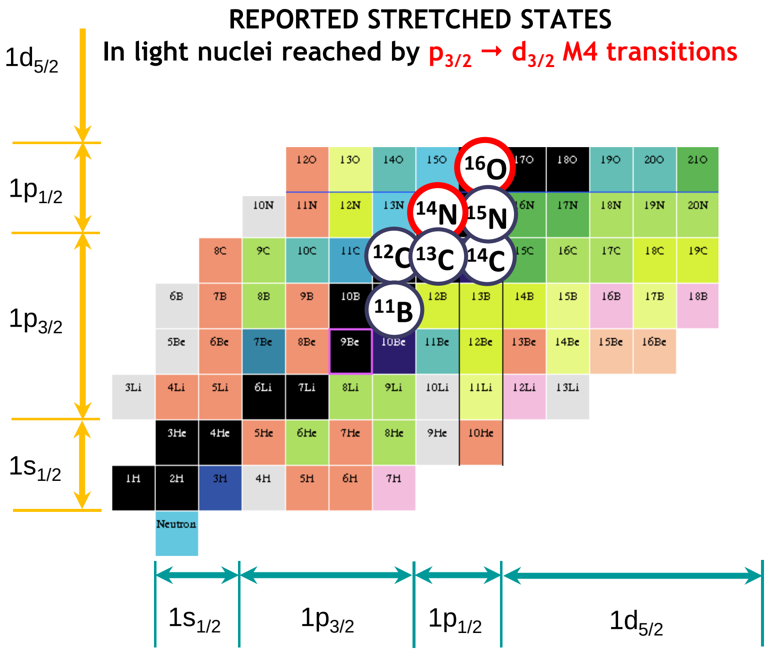
This newly developed approach will be crucial in predicting structures in the continuum in other nuclei in this key region of nuclear chart.



Stretched resonances in ^{14}N and ^{16}O







EXPERIMENT:
„STUDY OF M4 STRETCHED CONFIGURATIONS DECAY IN ^{14}N"
Spokepersons: S. Ziliani, N. Cieplicka-Oryńczak, et al.

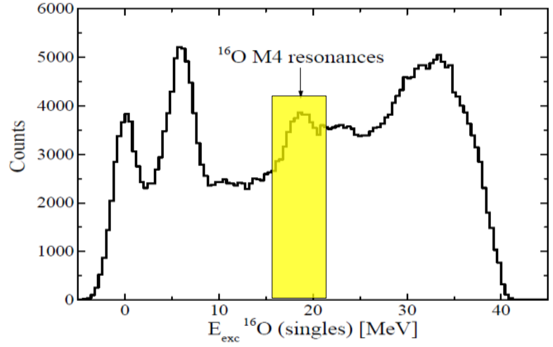
^{7}Li-^{14}N-H_2 + (^{16}O contamination) target 160 mg/cm^2

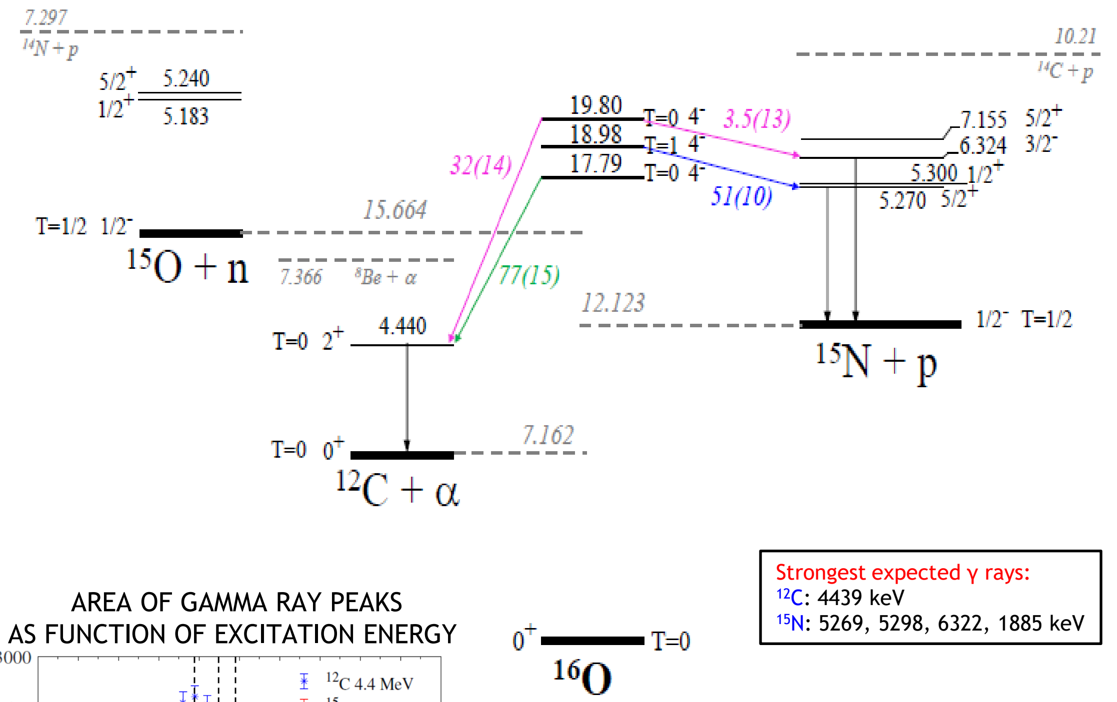
Performed in 2019/2020 at CCB IFJ

- ❑ 30 KRATTA modules at ~36° (angular coverage: 30°-43°)
- ❑ 2 PARIS clusters
- ❑ 4 $LaBr_3$ detectors

Stretched M4 resonances in ^{16}O

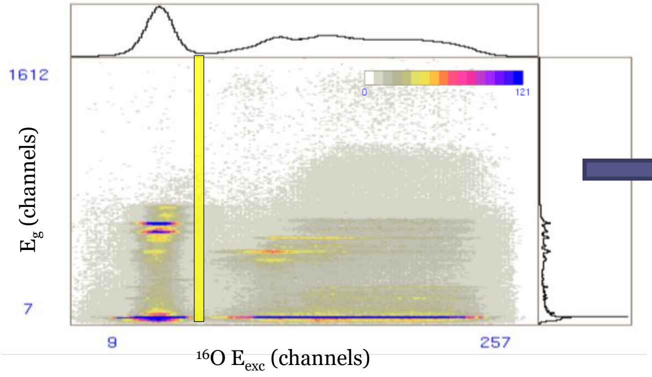
PRESENT (p,p') EXPERIMENT



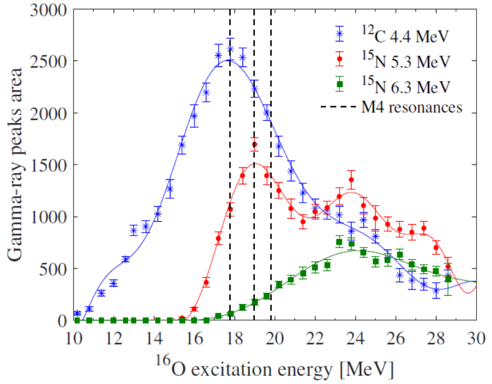


Strongest expected γ rays:
^{12}C: 4439 keV
^{15}N: 5269, 5298, 6322, 1885 keV

AREA SCANNING



AREA OF GAMMA RAY PEAKS
AS FUNCTION OF EXCITATION ENERGY

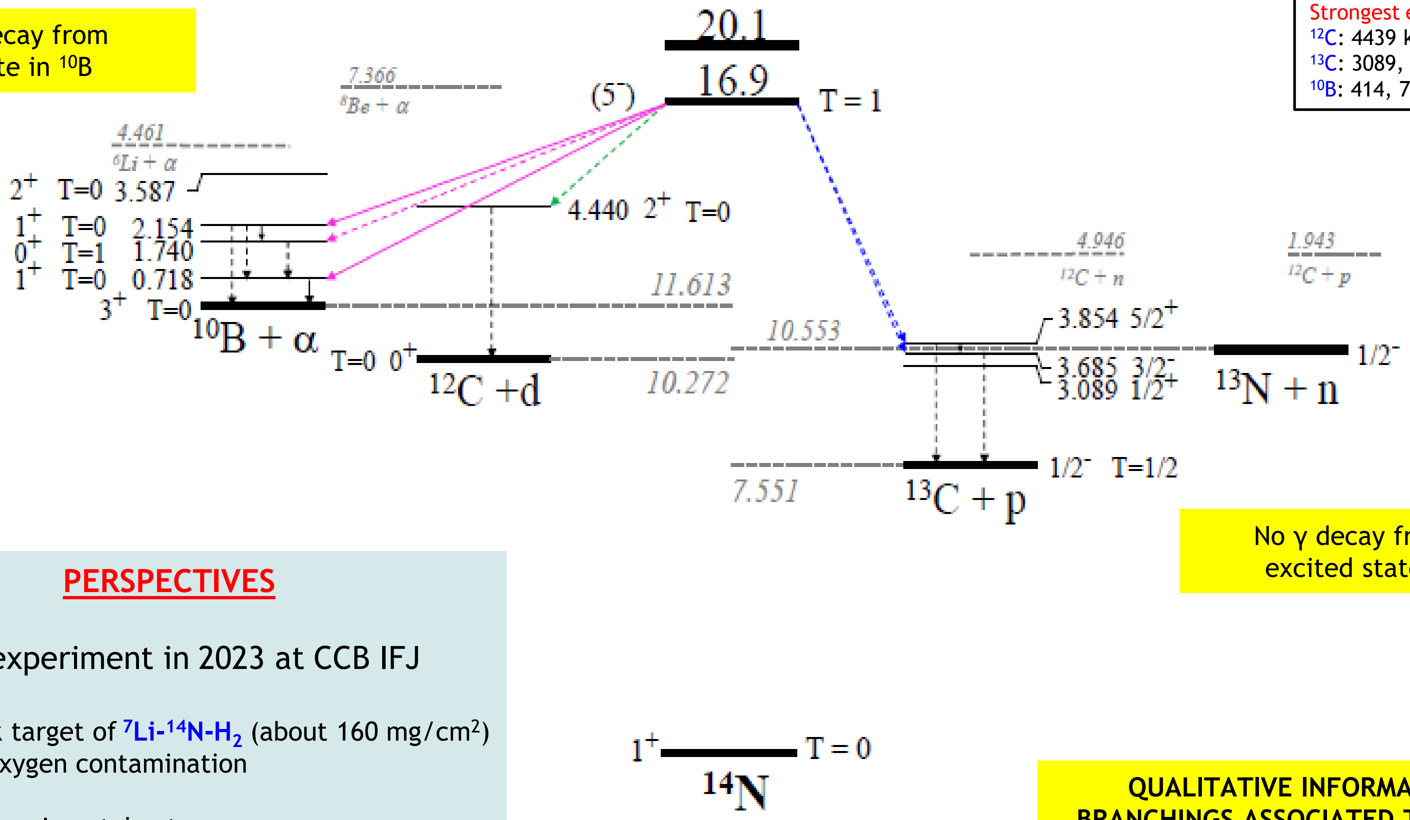


EXTRACTION OF DECAY BRANCHINGS ASSOCIATED TO GAMMA EMISSION

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

Stretched M4 resonances in ^{14}N

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 experiment in 2023 at CCB IFJ

- 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)

Physics Letters B 834 (2022) 137398

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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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Thank you for your attention!