Decay of "stretched" M4 resonance in ^{13}C
– first experimental studies at CCB IFJ PAN

Participants and collaboration

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Seminar of Division of Nuclear Physics and Strong Interactions IFJ PAN, 19 October 2020, Kraków, Poland

Outline

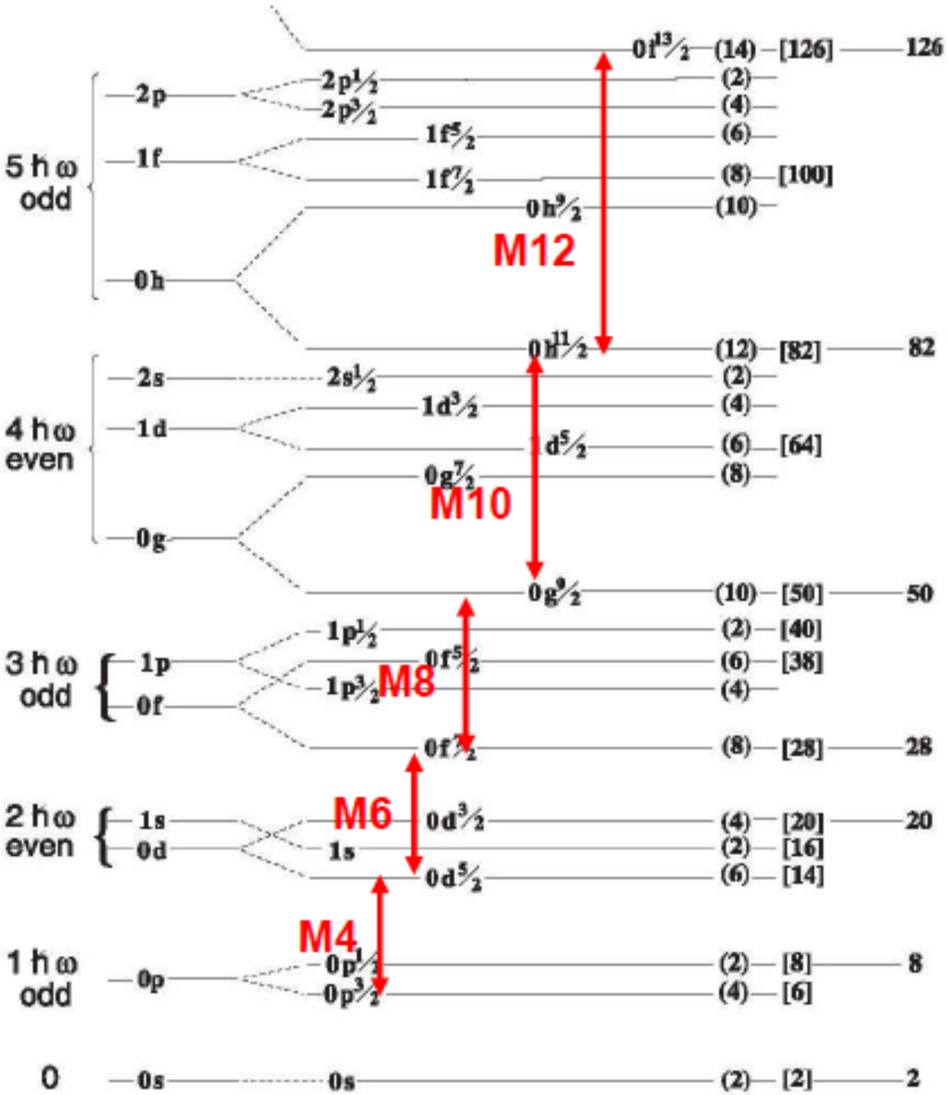
- What is a „stretched" state?

- The first case studied at CCB: ^{13}C

  experiment „Study of M4 stretched configuration decay in ^{13}C"
  proposed by S. Leoni (INFN and Univ. Milano), B. Fornal (IFJ PAN), M. Ciemała (IFJ PAN)

- Experiment and results of analysis:
  - Scattered protons – gamma ray coincidences
    experiment performed in May-June 2019
  - Scattered protons – light charged particles coincidences
    experiment performed in June 2020

- Theoretical calculations within Gamow Shell Model – preliminary results
  Y. Jaganathen (IFJ PAN), M Płoszajczak (GANIL)

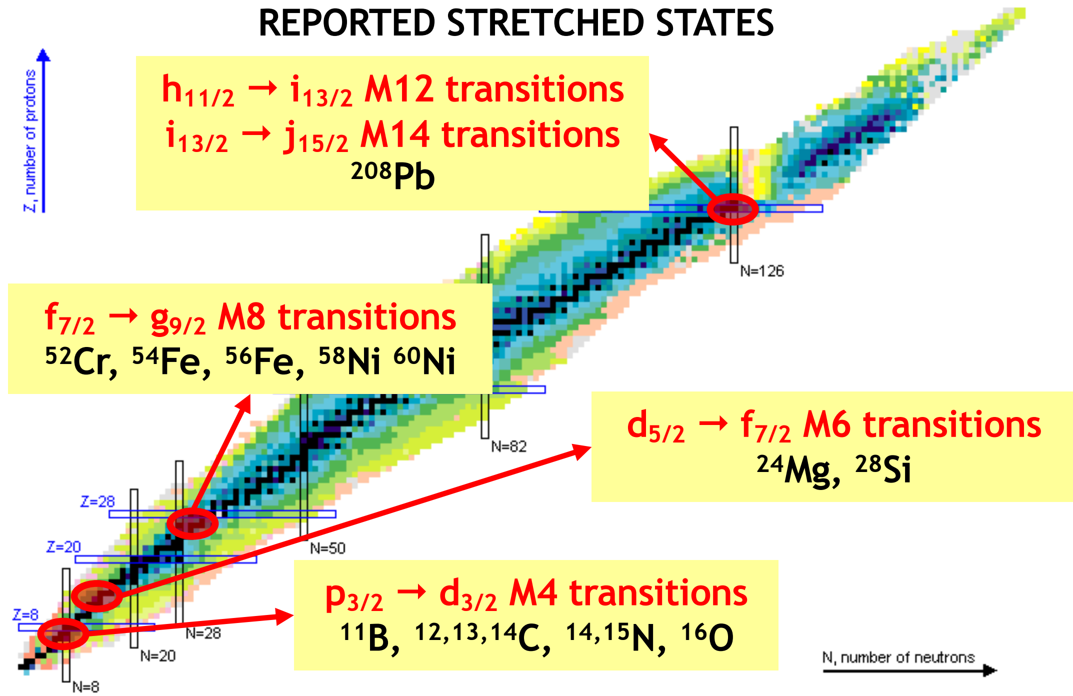


Stretched states

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:

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

REPORTED STRETCHED STATES



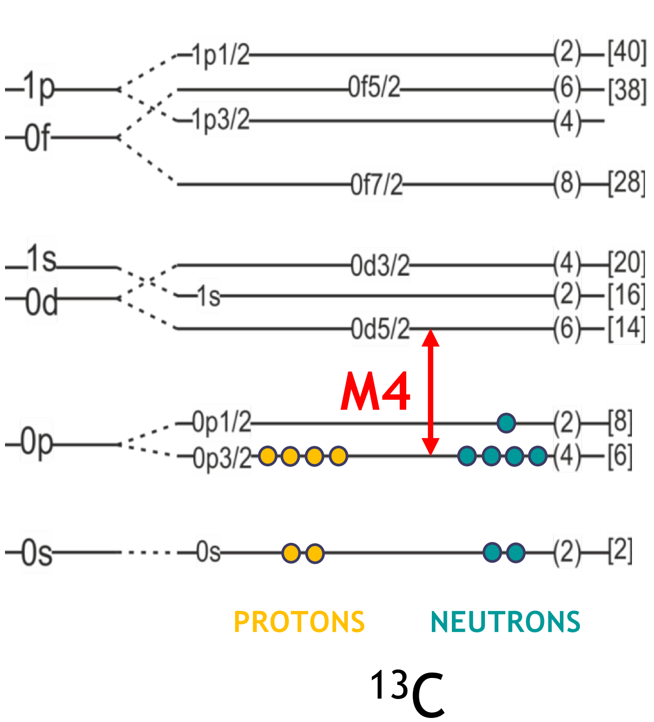
Stretched states in light nuclei – continuum region

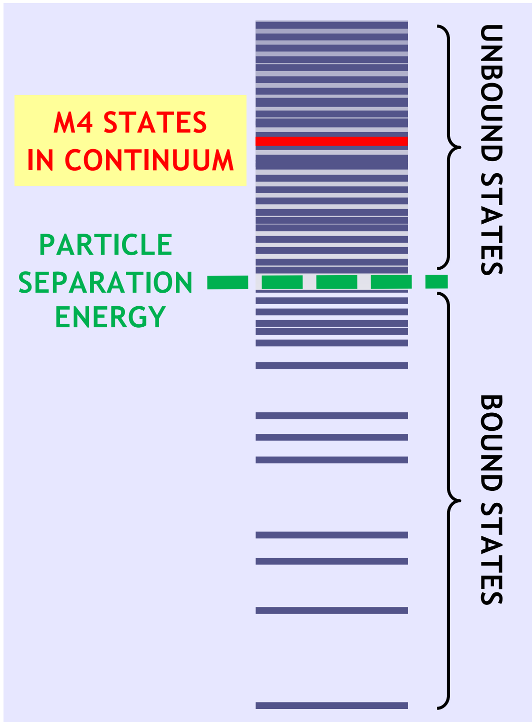
CONFIGURATIONAL PURITY

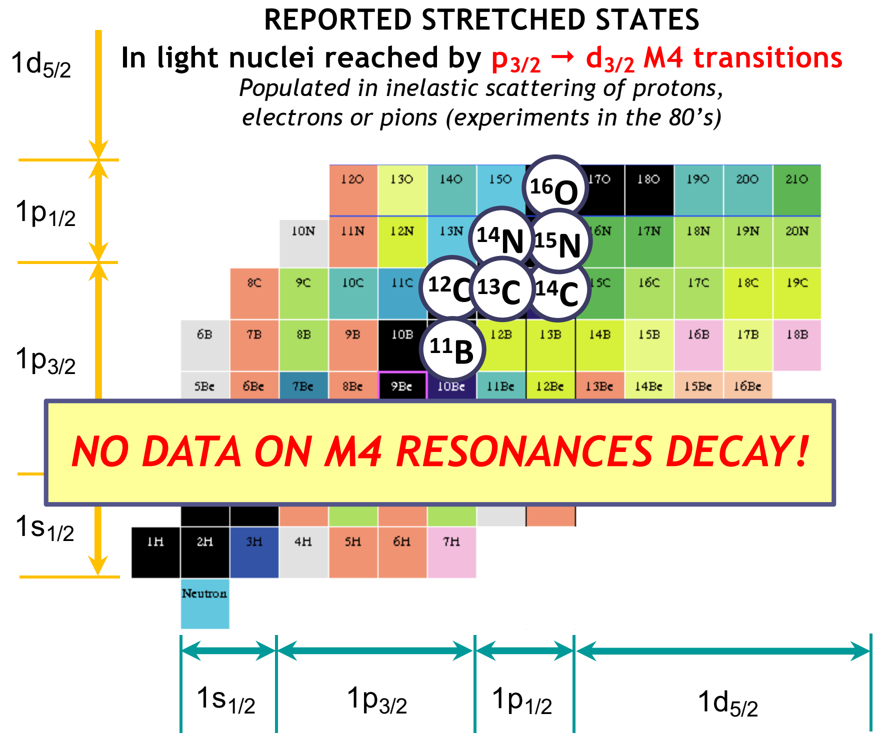
Stretched states are ones of the simplest known nuclear excitations which should provide the most **clean information on the details of nuclear force**.

TESTING GROUND FOR THEORETICAL CALCULATIONS

Direct measurement of the properties of stretched states, such as, for example, decay patterns, should provide data, which may be used as a very **demanding test of state-of-the-art theory approaches**, from Shell Model Embedded in the Continuum to ab-initio type calculations.



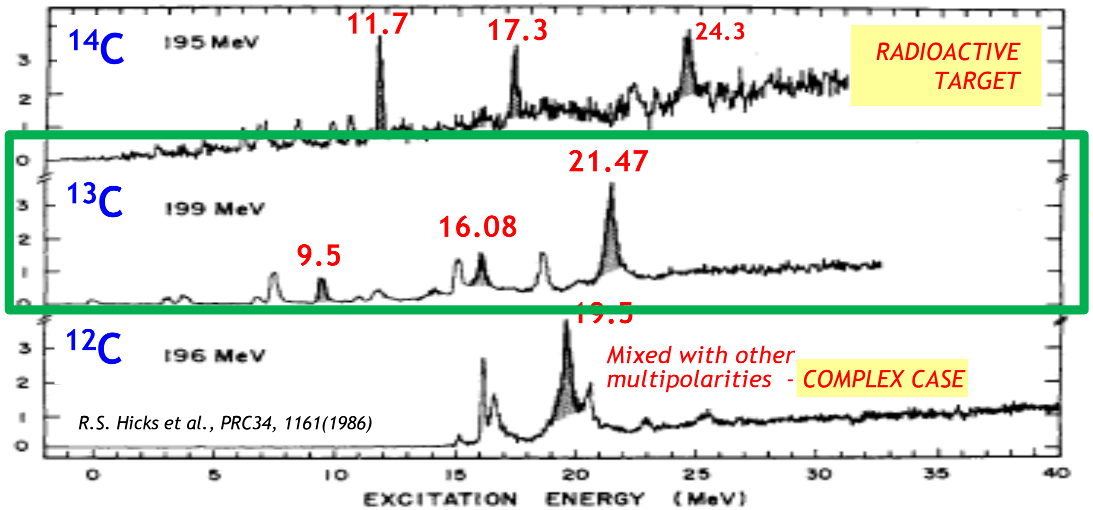


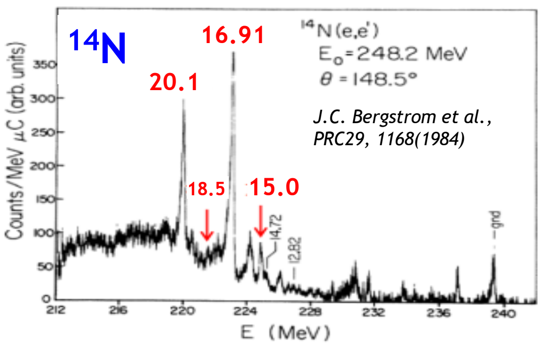


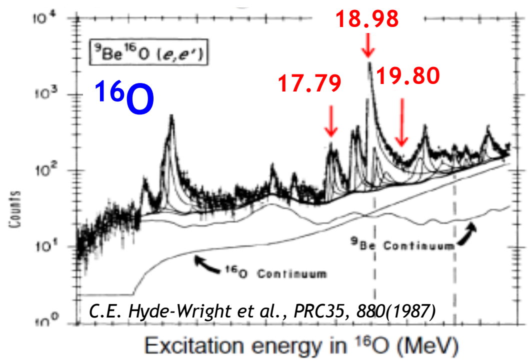
NO DATA ON M4 RESONANCES DECAY!

Stretched M4 resonances in light nuclei

INELASTIC ELECTRON SCATTERING EXPERIMENTS







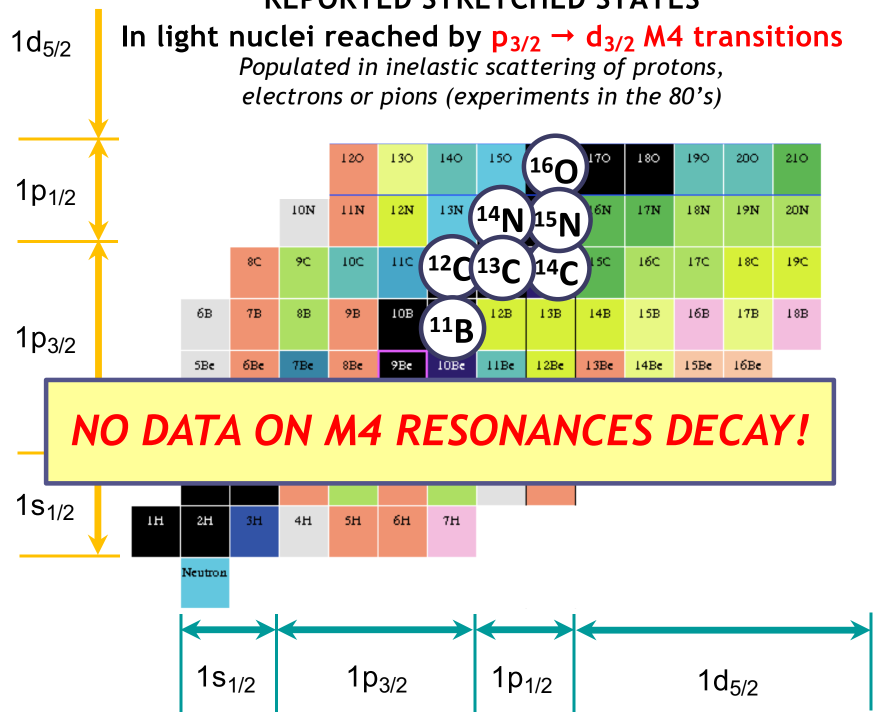
^{13}C is a perfect case to start:

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

REPORTED STRETCHED STATES

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

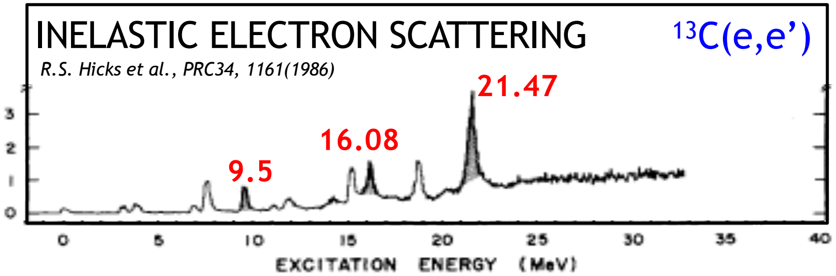
Populated in inelastic scattering of protons, electrons or pions (experiments in the 80's)

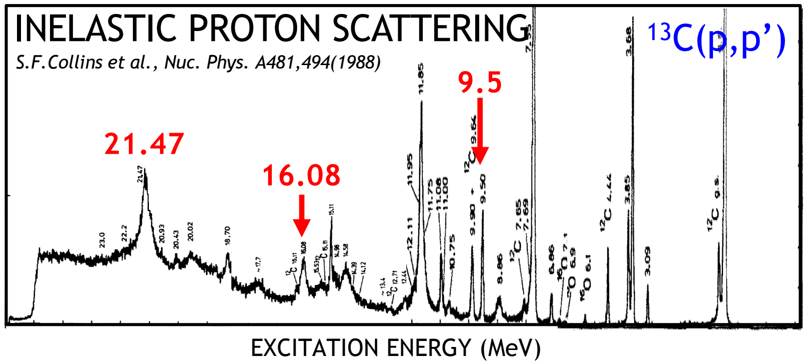


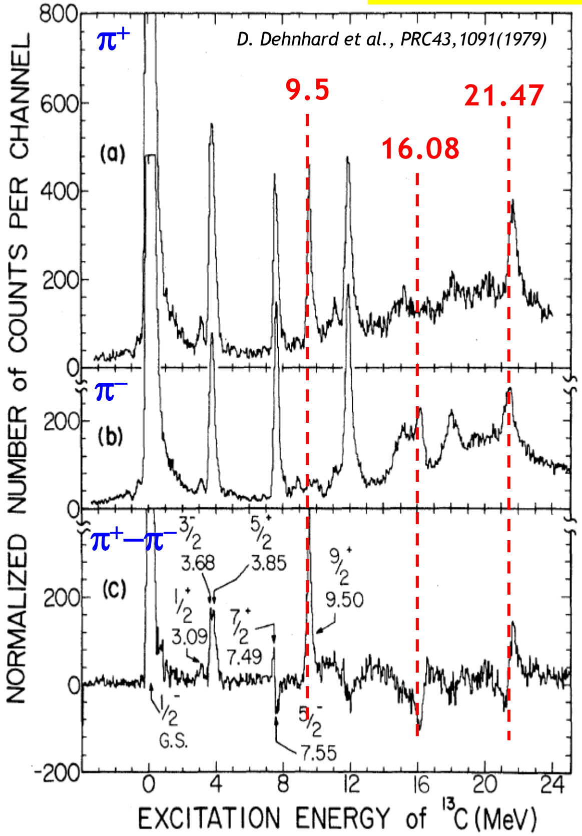
NO DATA ON M4 RESONANCES DECAY!

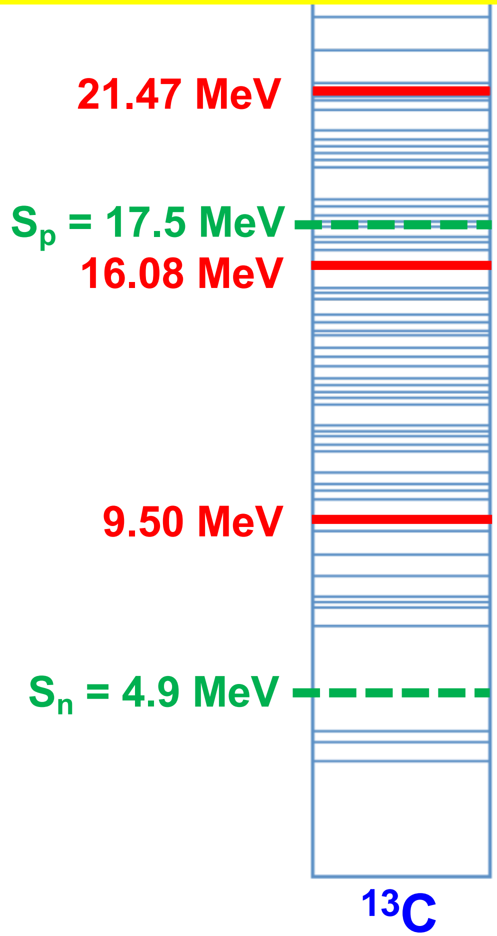
Previous studies of M4 resonances in ^{13}C

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







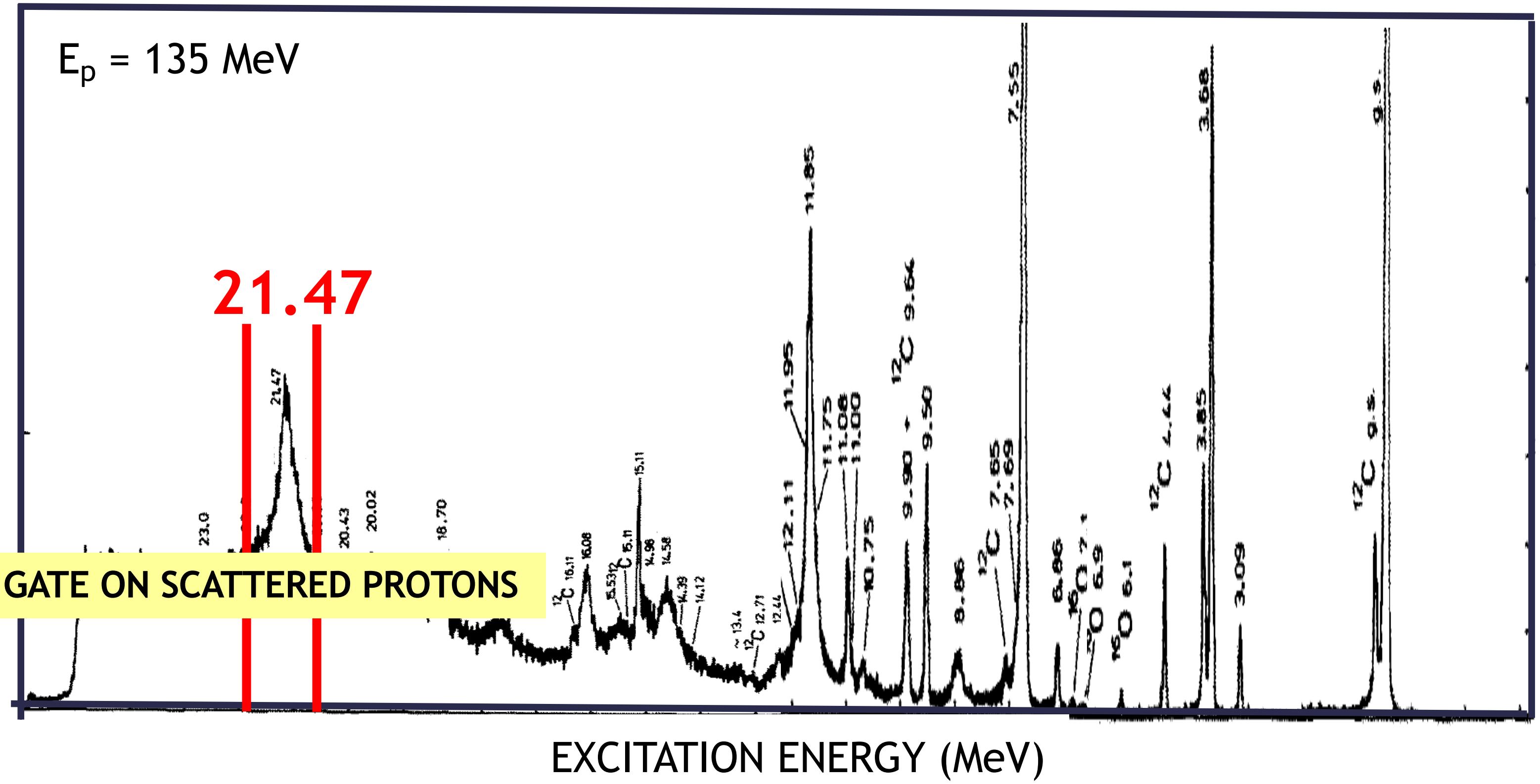


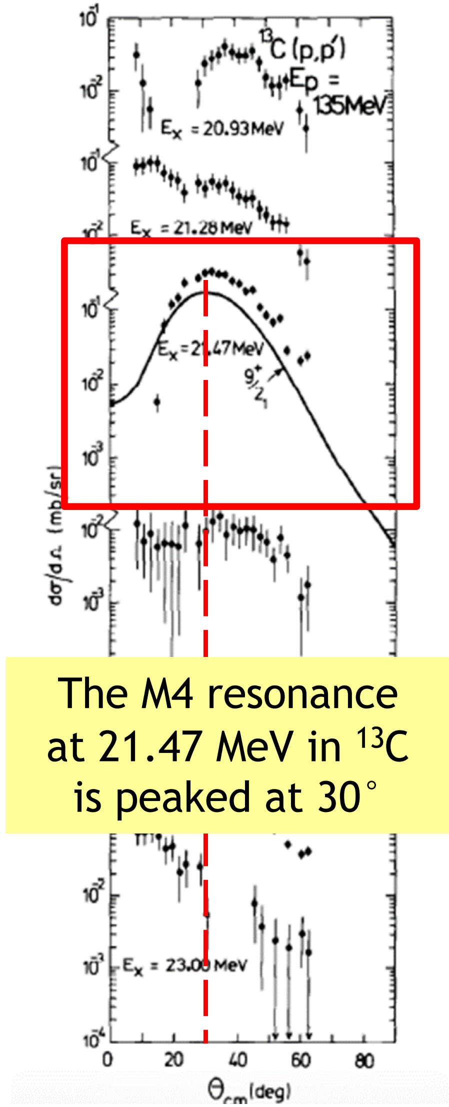
From $^{13}C(\pi,\pi')$ scattering:

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

Previous studies of M4 resonances in ^{13}C

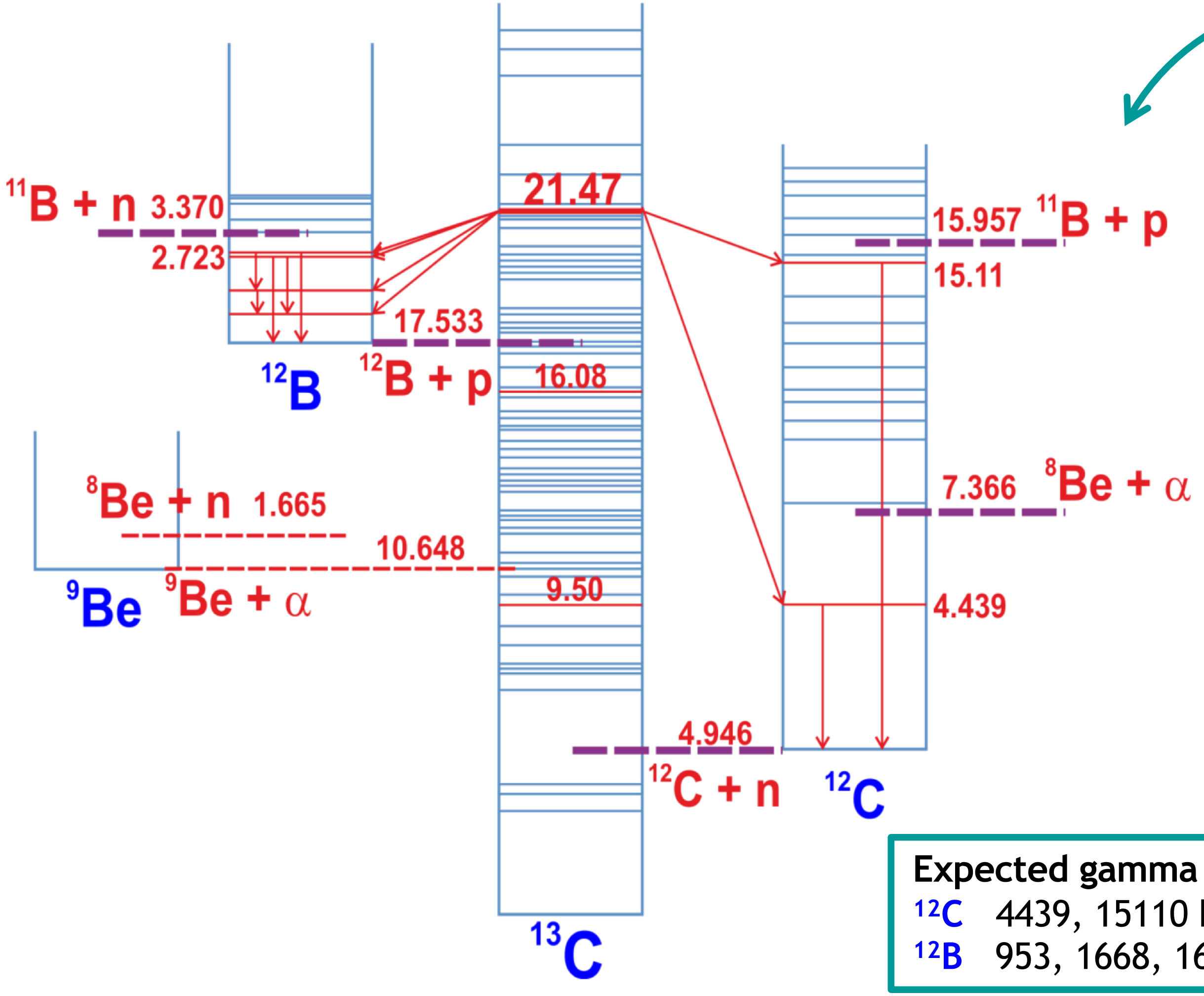
Inelastic proton scattering on ^{13}C

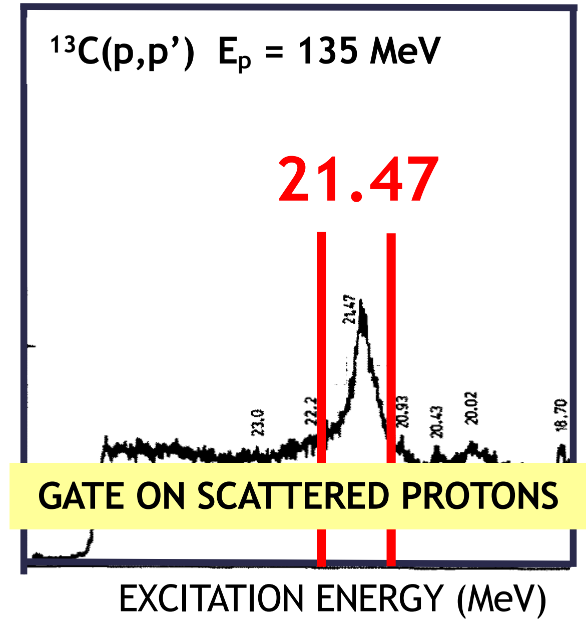




Indiana University Cyclotron Facility Magnetic Spectrograph, S.F. Collins et al., Nuc. Phys. A481, 494(1988)

Studies of the M4 resonances in ^{13}C

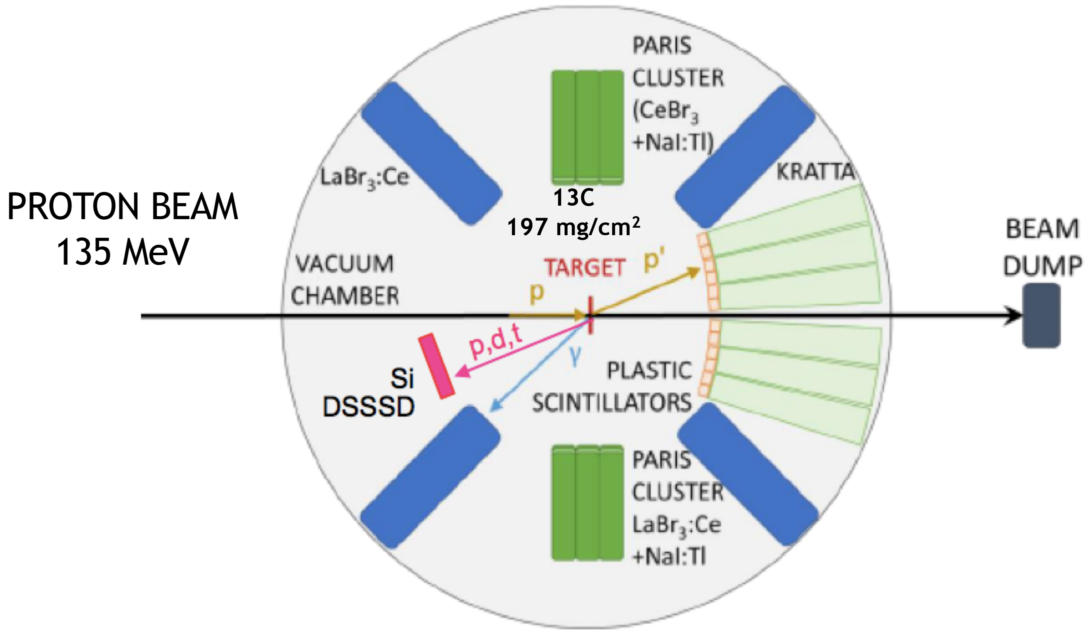


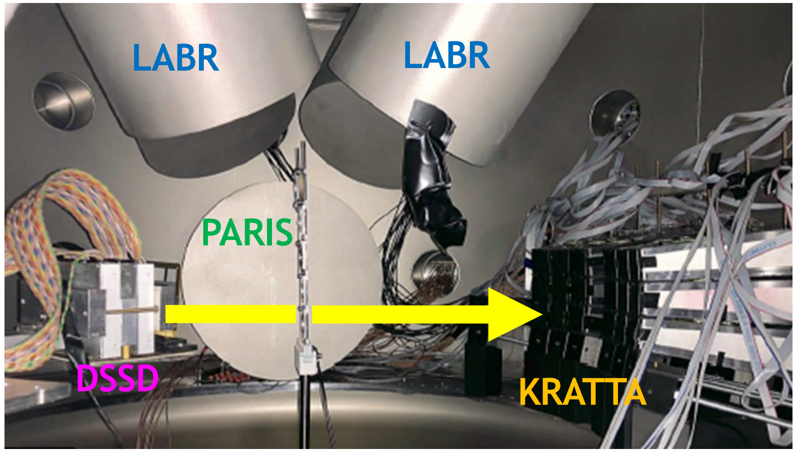


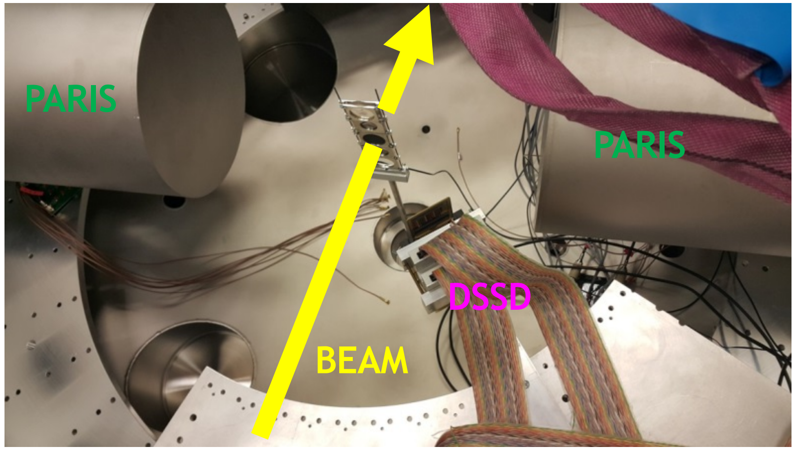
S.F. Collins et al., Nuc. Phys. A481, 494(1988)

Expected gamma rays:
^{12}C 4439, 15110 keV
^{12}B 953, 1668, 1674, 2723 keV

Experimental setup – measurements with thick and thin targets



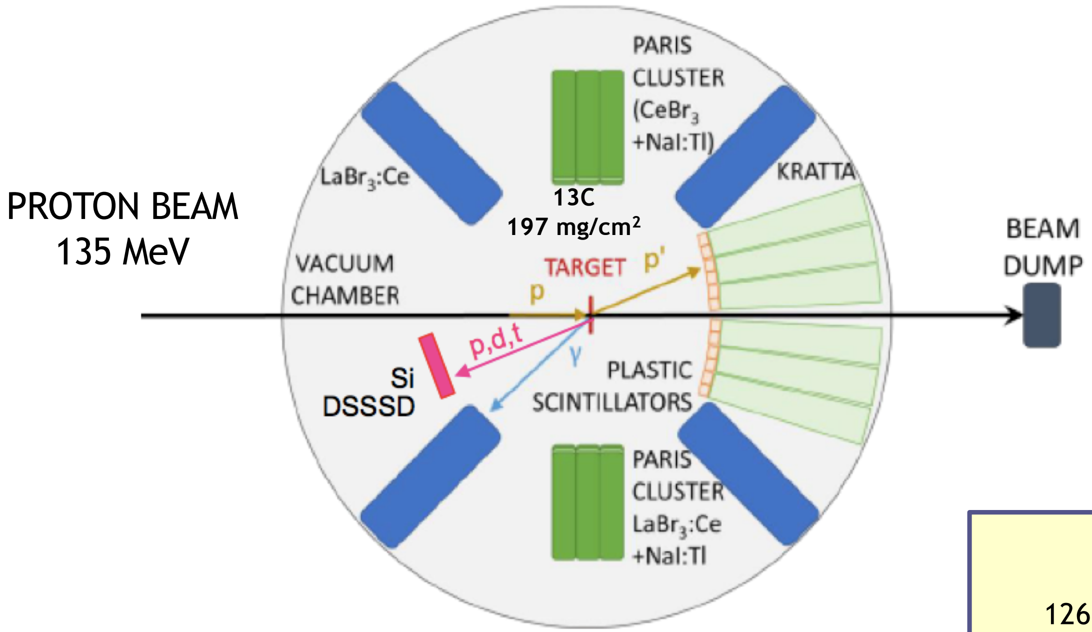


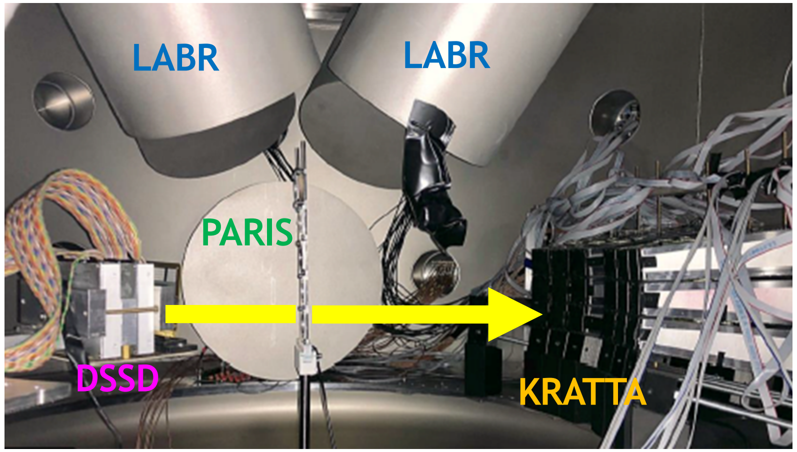


1) Scattered protons measurement: KRATTA telescope array
2) γ-ray detection:
- four $LaBr_3$ detectors (3”x3”)
- two clusters of the PARIS scintillator array

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/cm²**: 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/cm²**: December 2019, March and June 2020

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

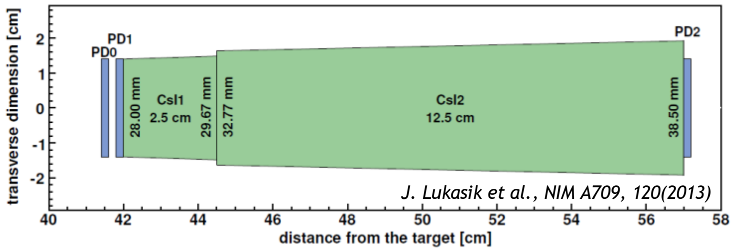
30 KRATTA modules at ~36° (angular coverage: 30° -43°)

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

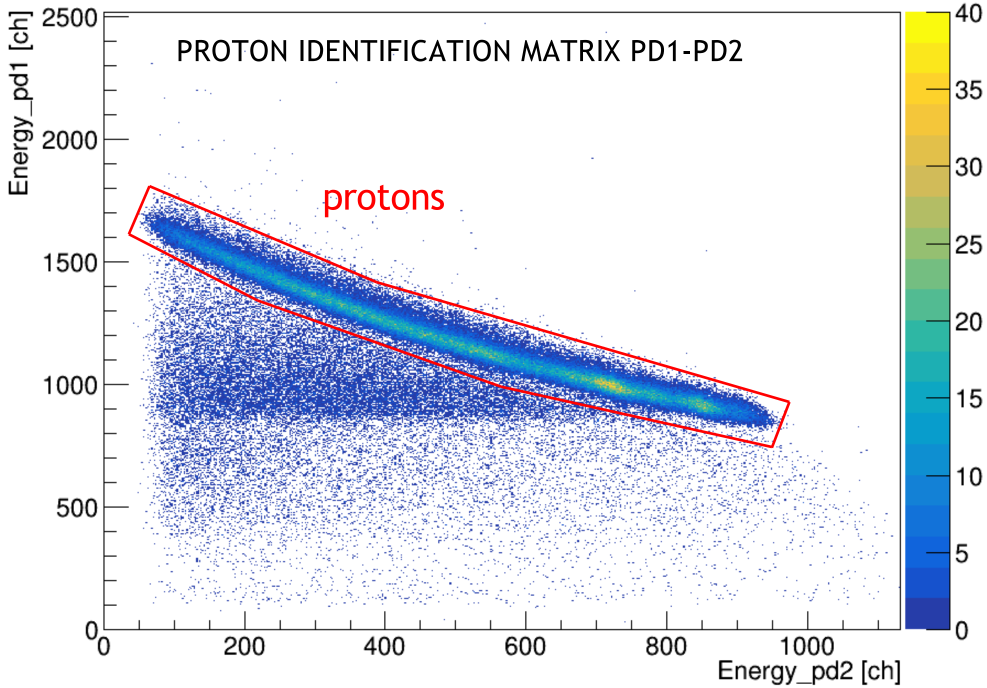
Measurement of the scattered protons: KRATTA telescope array

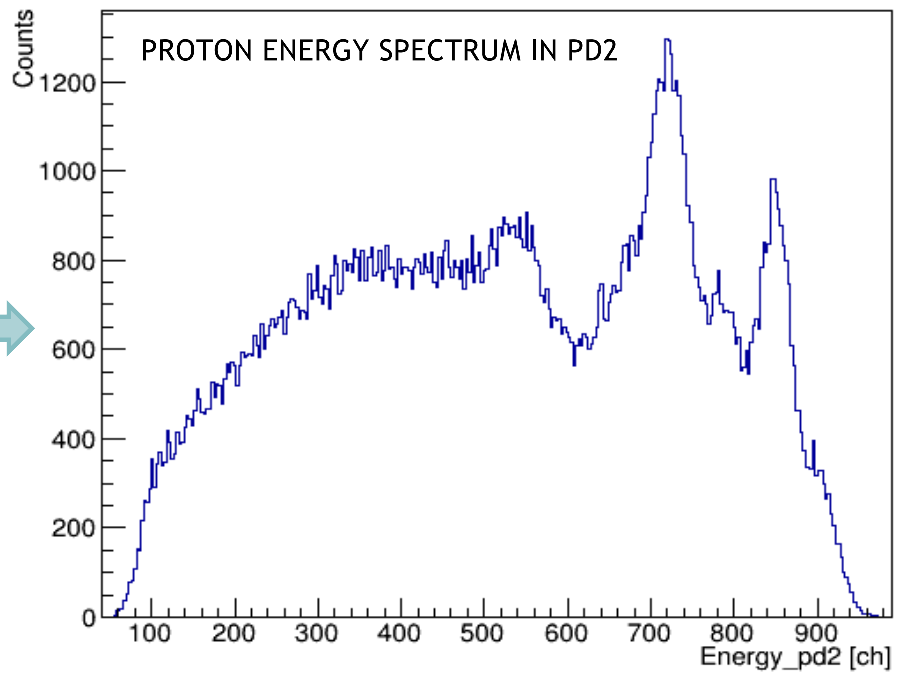
scattered protons



Other sorting conditions:

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

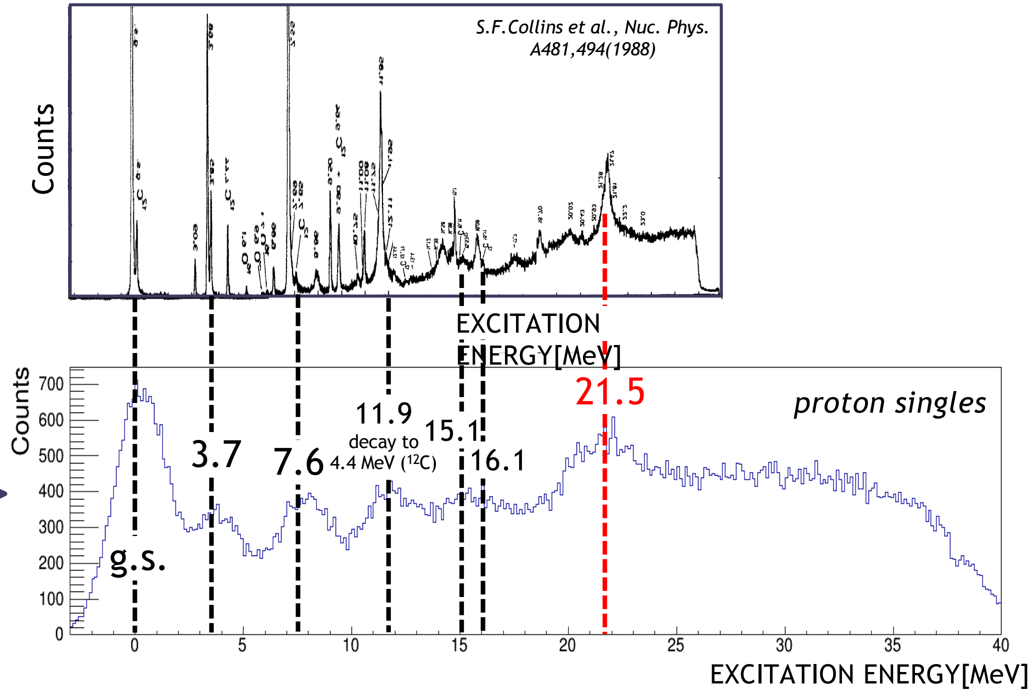




KRATTA – excitation energy spectra

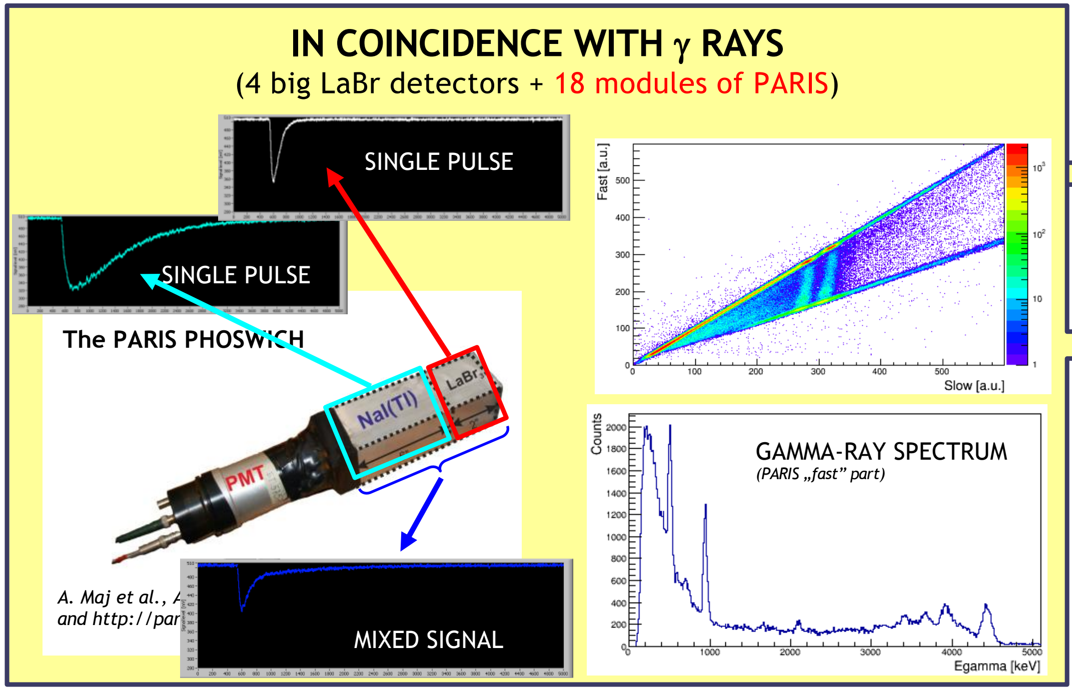
Excitation energy spectra measured at ~36° corresponding to the excitations in the ^{13}C target nucleus measured as:

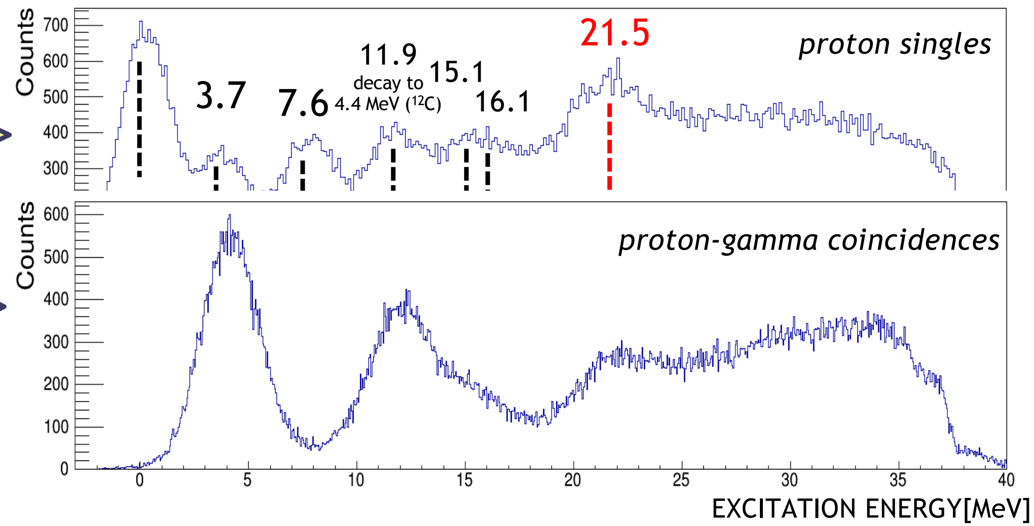
SINGLES (only scattered proton required)

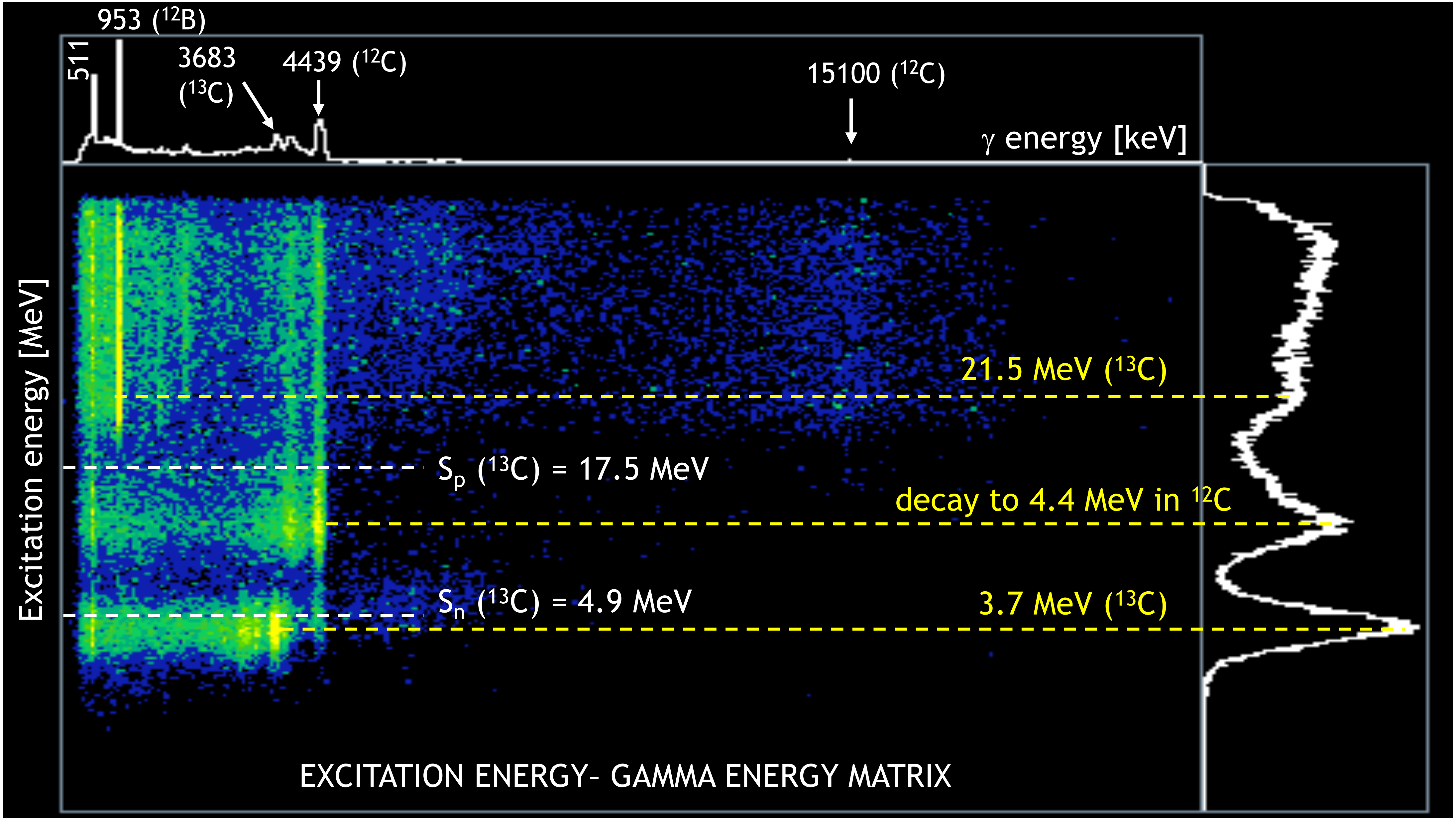


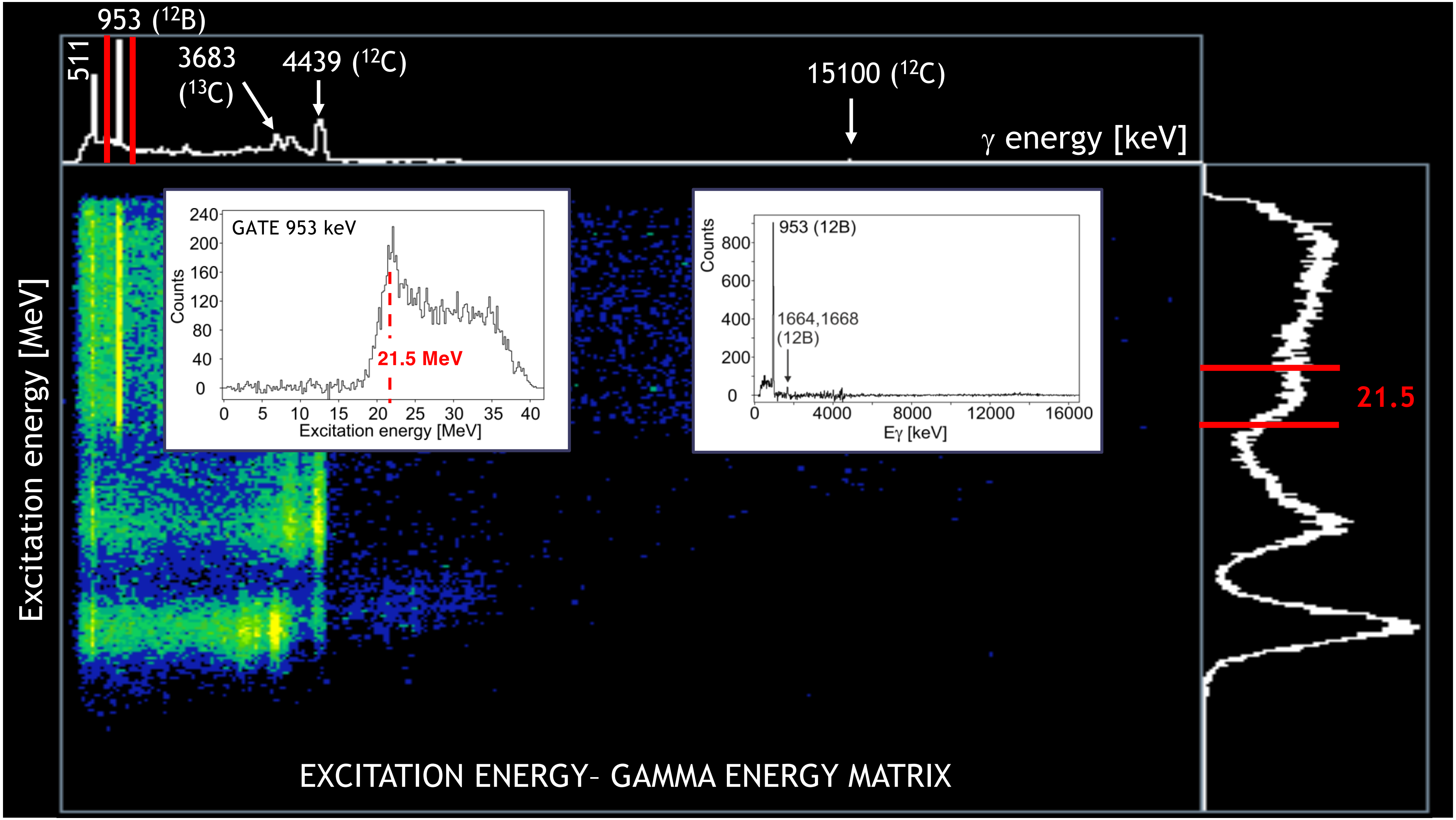
KRATTA – excitation energy spectra

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

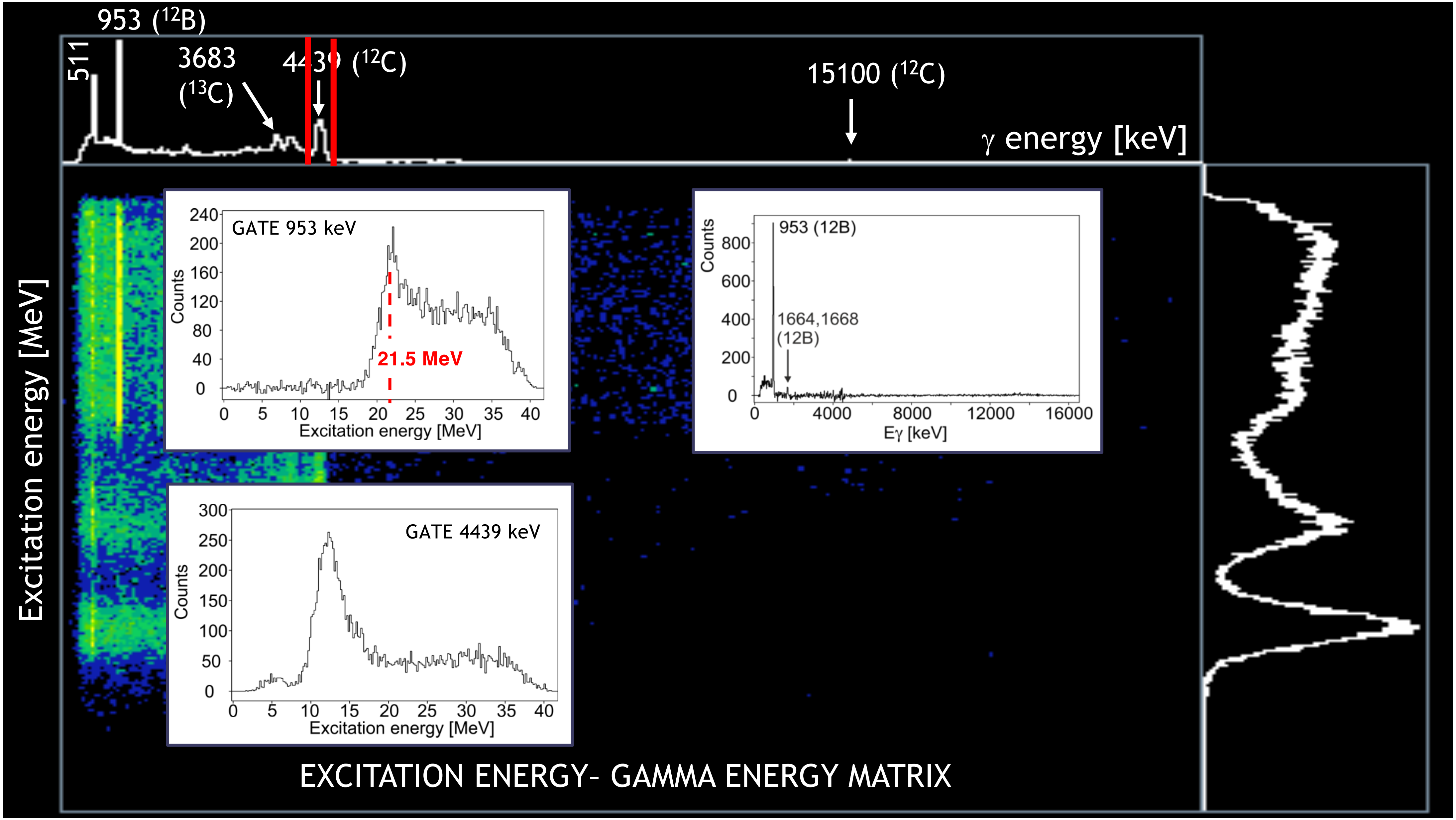





953 (^{12}B)
511
3683 (^{13}C)
4439 (^{12}C)
15100 (^{12}C)
γ energy [keV]
Excitation energy [MeV]
21.5 MeV (^{13}C)
S_p (^{13}C) = 17.5 MeV
decay to 4.4 MeV in ^{12}C
S_n (^{13}C) = 4.9 MeV
3.7 MeV (^{13}C)
EXCITATION ENERGY– GAMMA ENERGY MATRIX



953 (^{12}B)
511
3683
(^{13}C)
4439 (^{12}C)
15100 (^{12}C)
γ energy [keV]
Excitation energy [MeV]
GATE 953 keV
Counts
21.5 MeV
Excitation energy [MeV]
953 (12B)
1664,1668
(12B)
Eγ [keV]
21.5
EXCITATION ENERGY– GAMMA ENERGY MATRIX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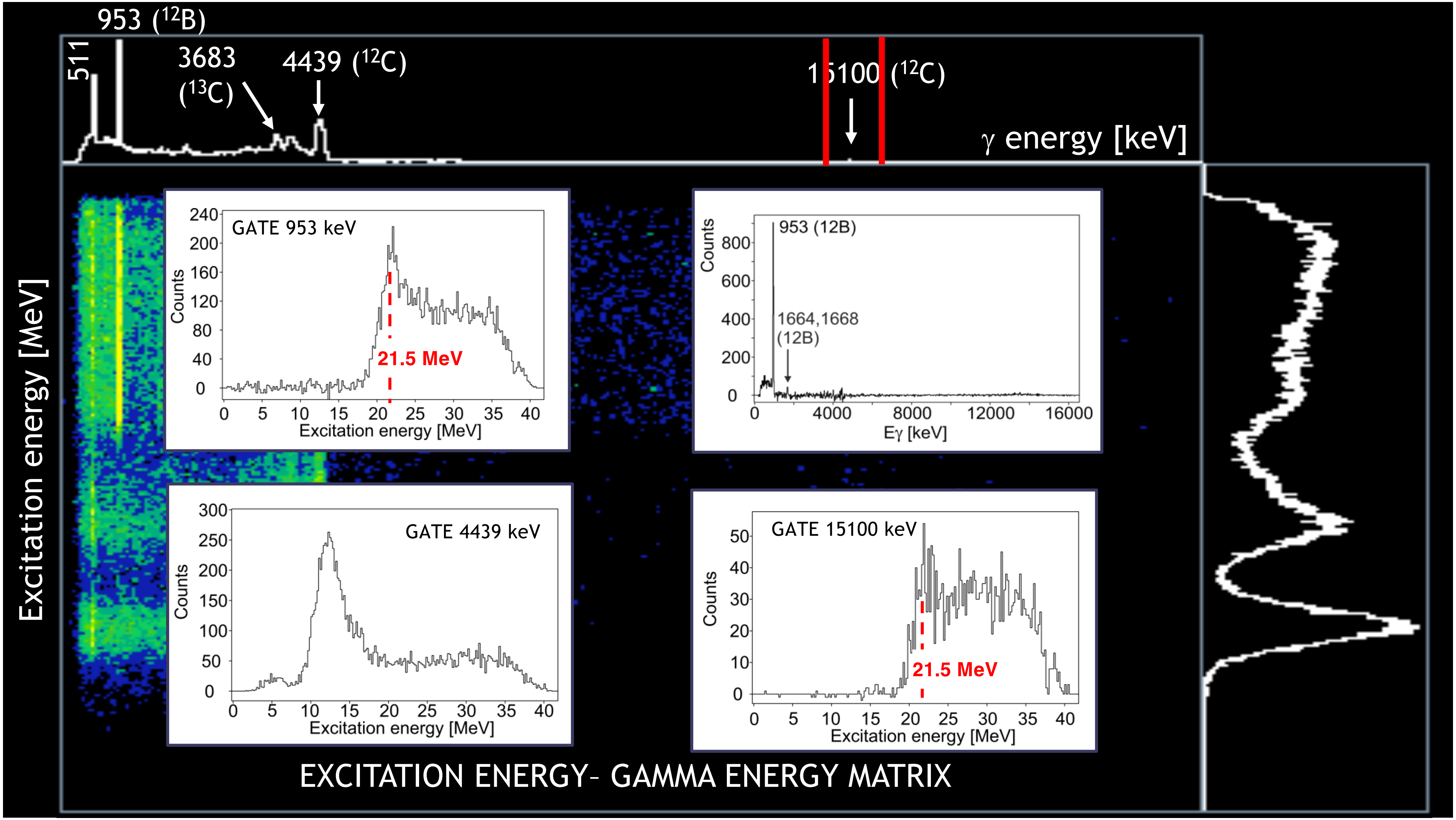
Eγ [keV]
GATE 4439 keV
Counts
Excitation energy [MeV]
EXCITATION ENERGY– GAMMA ENERGY MATRIX



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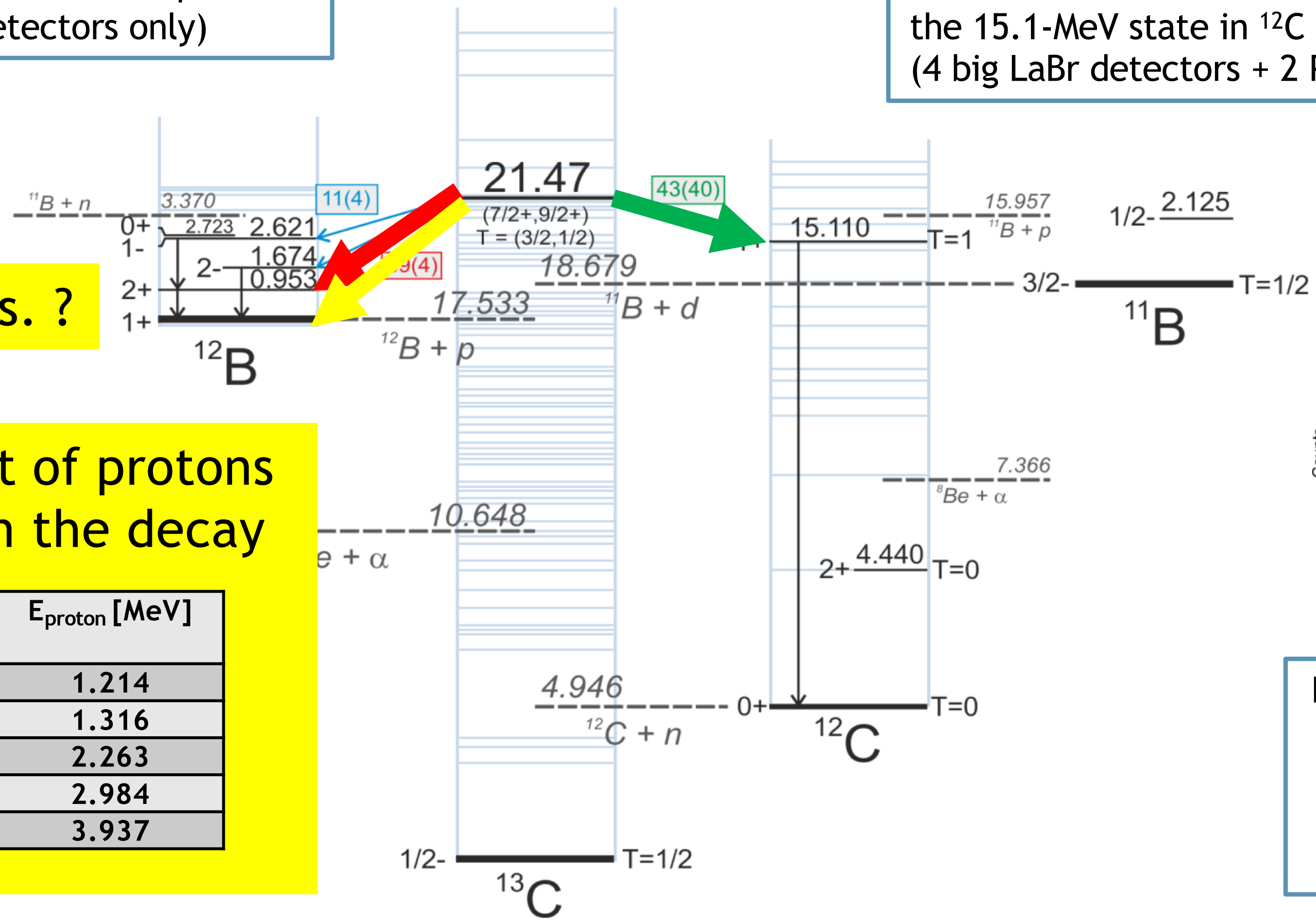
Excitation energy [MeV]
GATE 15100 keV
Counts
21.5 MeV
Excitation energy [MeV]
EXCITATION ENERGY– GAMMA ENERGY MATRIX

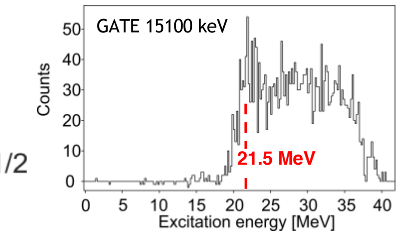
Decay of the 21.47-MeV stretched state in ^{13}C: first experimental information

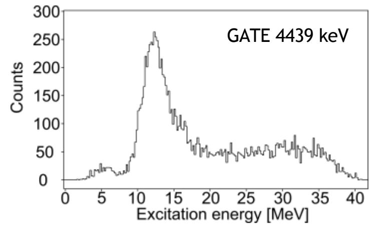
Preliminary branching ratios from partial statistics (4 big LaBr detectors only)

Confirmation of the neutron decay branch to the 15.1-MeV state in ^{12}C from full statistics (4 big LaBr detectors + 2 PARIS clusters)



Decay to ^{12}B g.s. ?





Measurement of protons emitted from the decay

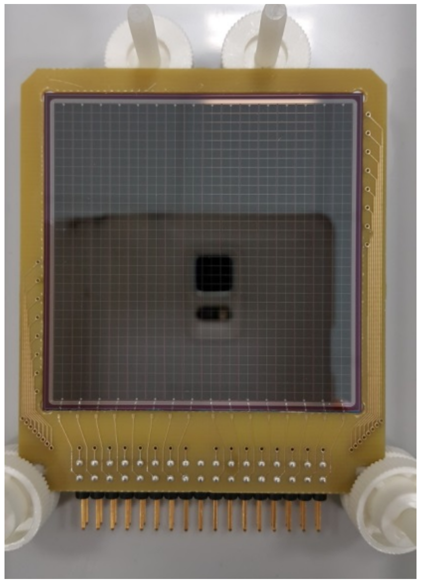
Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

Fraction of the decay with gamma-ray emission from daughter nucleus: **59(18)%**

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

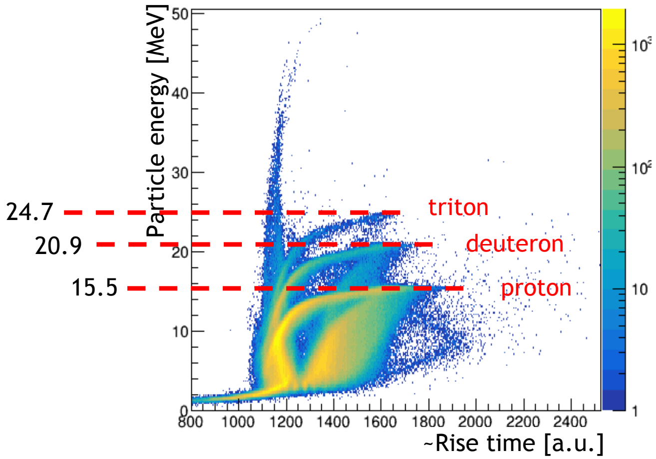
Double Sided Silicon Strip Detector (Micron Semiconductor Ltd)

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

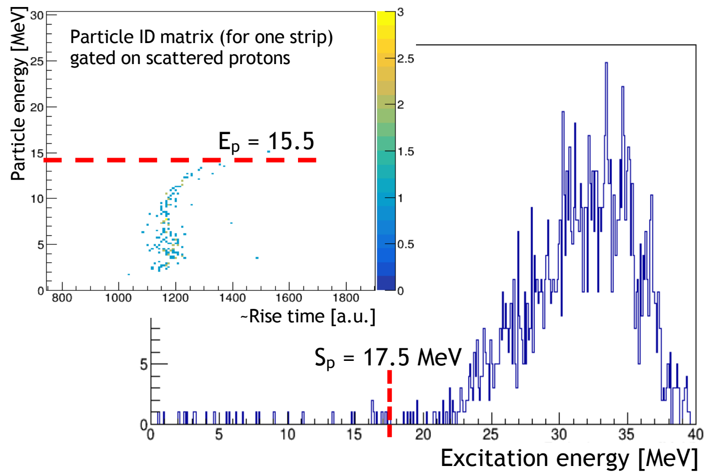


PARTICLE IDENTIFICATION MATRIX

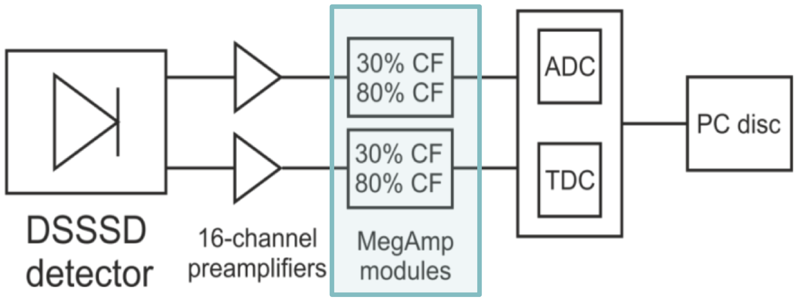
(for one strip, representative example)



PROJECTION OF EXCITATION ENERGY VS. PARTICLE ENERGY MATRIX



SCHEME OF ACQUISITION LINE



MegAmp Pulse Shape Amplifier (INFN Milano)

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

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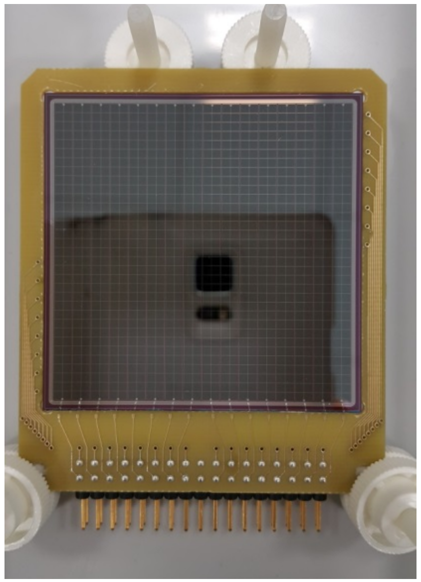

PARTICLE IDENTIFICATION MATRIX

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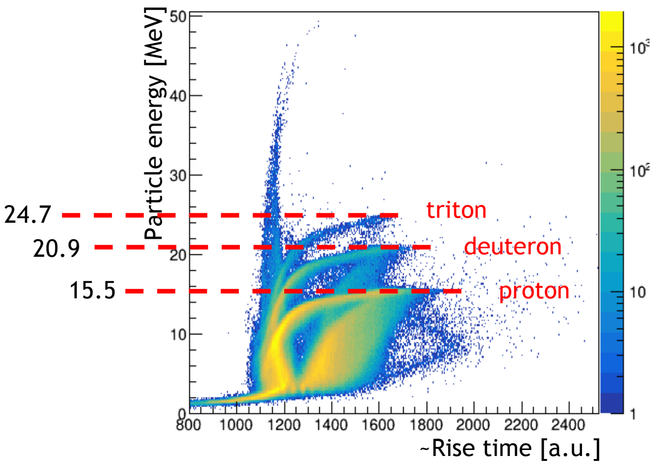
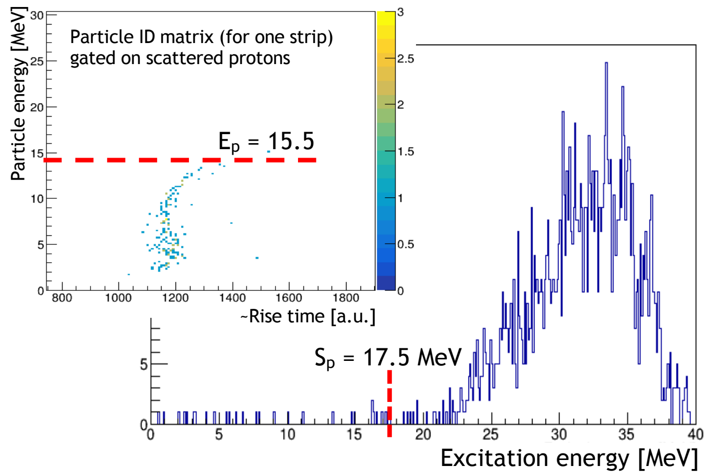


PROJECTION OF EXCITATION ENERGY VS. PARTICLE ENERGY MATRIX



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!

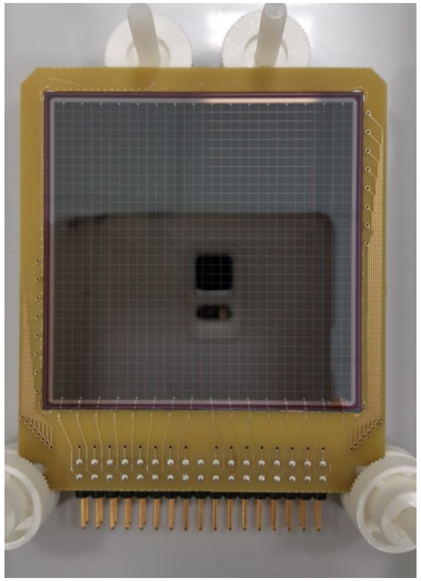
Excit.Energy in ^{12}B [MeV]	E_{proton} [MeV]
2.723	1.214
2.621	1.316
1.674	2.263
0.953	2.984
0.0	3.937

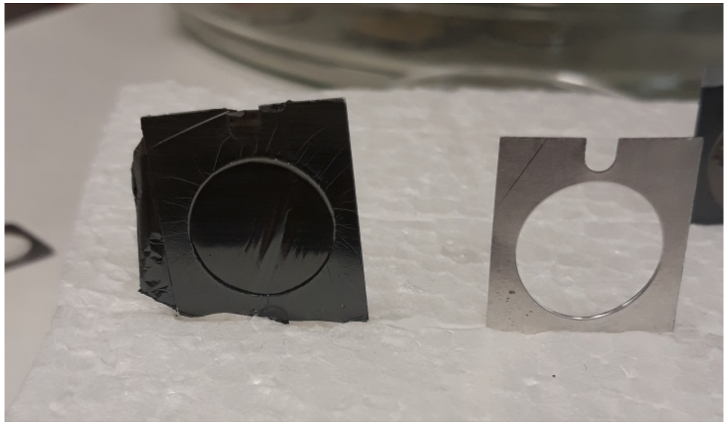
Thin 1 mg/cm^2 ^{13}C target experiment

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)

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Scattered proton – light charged particle coincidences

Sorting conditions:
- gate on protons in KRATTA
- gate on times in KRATTA
- plastic mult = 1
- plastic ID corresponding to KRATTA ID

+ KINEMATIC CORRECTION (by M. Ciemała)
- Kinetic energy of proton in DSSD was reconstructed, that is, corrected on the energy of ^{13}C recoil (all angles of Plastics and DSSD pixels included)
- Energy loss of the particle in the middle of the target was included
- Energy of ^{12}B recoil was added

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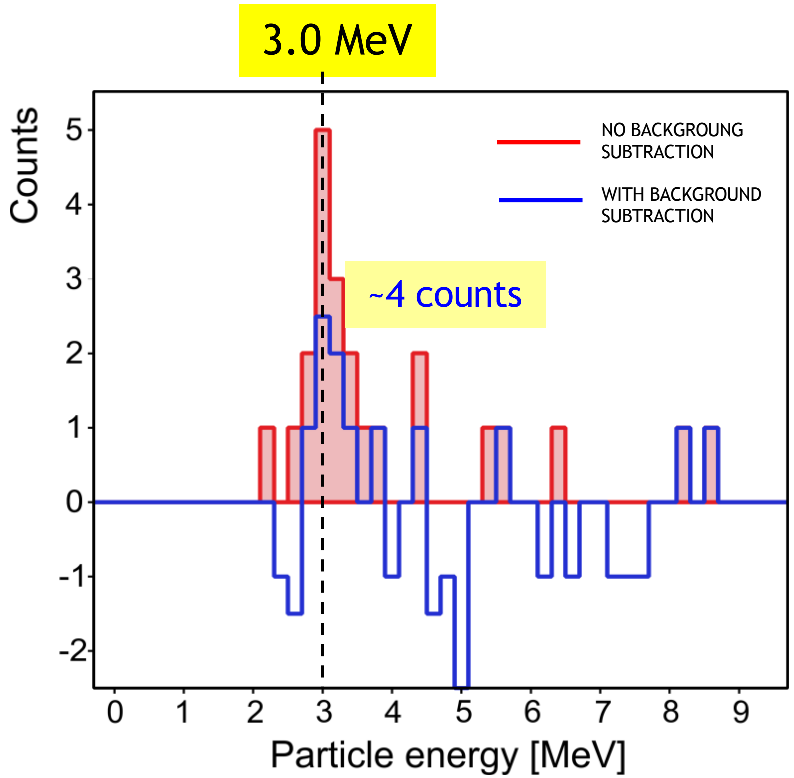
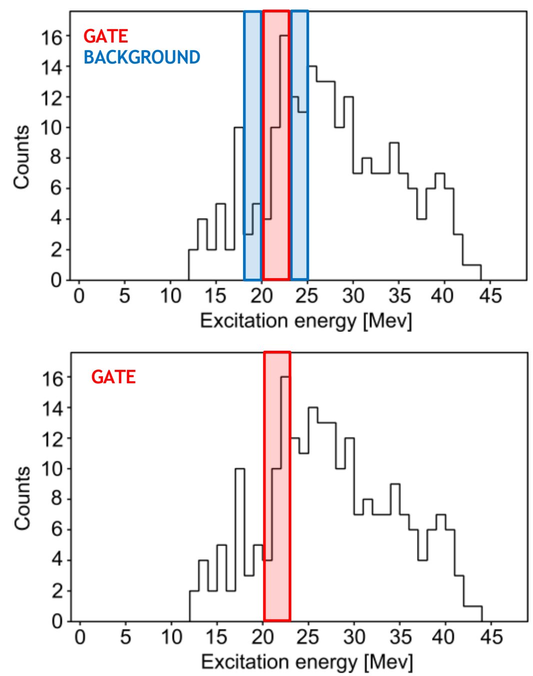


Projection of the excitation energy vs. particle energy matrix



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 the many-body correlations and the coupling to the resonant and non-resonant particle continuum.

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

- A core of ^{4}He was used.
- The configuration space used in the calculations is the *psd* space.
- The $p_{3/2}$ shell is chosen to be semi-frozen with a maximum of 3 neutron+proton holes allowed to model the existence of a non-inert ^{12}C core.
- Such truncation should allow to describe simple states in ^{12}C, ^{12}B, ^{13}C, ^{13}N, in particular the *M4* state which is assumed to be an almost pure particle-hole excitation from the $p_{3/2}$ shell to the $d_{5/2}$ shell.

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

Nucleus	State	Isospin	E_{calc} [MeV]	E_{exp} [MeV]	Γ_{calc} [keV]	Γ_{exp} [keV]
^{12}C	0^+	$T=0$	-0.173	0		
^{12}C	2^+	$T=0$	4.239	4.440		
^{12}C	1^+	$T=1$	15.010	15.110		
^{12}B	1^+	$T=1$	0.115	0		
^{12}B	2^+	$T=1$	1.151	0.953		
^{12}B	2^-	$T=1$	1.573	1.673		
^{12}B	1^-	$T=1$	2.776	2.621		
^{12}B	0^+	$T=1$	2.977	2.723		

Very good agreement in terms of energies!

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

$J=7/2^+$	$T=1/2$	$E = 19.5$ MeV	$\Gamma = 550$ keV
$J=9/2^+$	$T=1/2$	$E = 21.7$ MeV	$\Gamma = 450$ keV
$J=9/2^+$	$T=3/2$	$E = 23.5$ MeV	$\Gamma = 700$ keV

THE NEXT STEP: TO COMPUTE THE BRANCHING RATIOS AND TO COMPARE THEM WITH THE EXPERIMENTAL RESULTS

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 with thick ^{13}C target.

- The most of the intensity of the proton-decay channel (89(4)%) was found to be associated with the population of the 0.953-MeV first excited state in ^{12}B, while the remaining (11(4)%) is distributed between the 2.621- and/or 1.674-MeV higher-lying states. For the neutron decay channel leading to ^{12}C, only the population of the 15.11-MeV state was observed.

A test experiment with a thin ^{13}C target, aiming at **measuring the protons** emitted from the decay of the 21.47-MeV M4 resonance in ^{13}C was performed.

- Indication is obtained for a 3-MeV proton branch which is consistent with the population of the first excited state in ^{12}B, in agreement with what observed in the gamma-ray analysis. Using this method, an estimation of the decay branch leading to the ground state in ^{12}B, which cannot be observed in proton-gamma coincidences, should also be possible. The present data already point to an upper limit of the order of 1/3 of the first excited state population.

For the first time **Gamow Shell Model** calculations were performed for such „heavy” system.

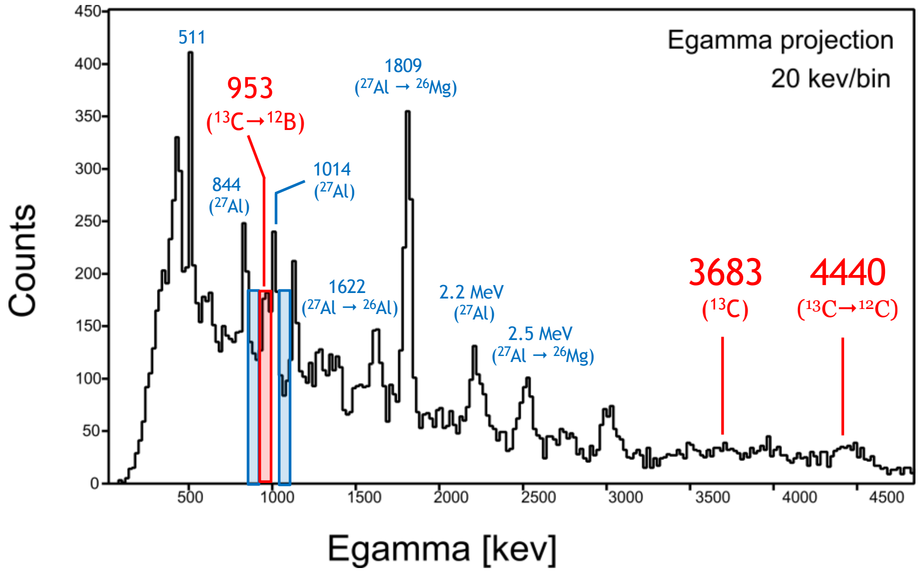
Comparisons with experiment in terms of **states energies and decay branchings** are being performed for the first time and they seem to be successfull.

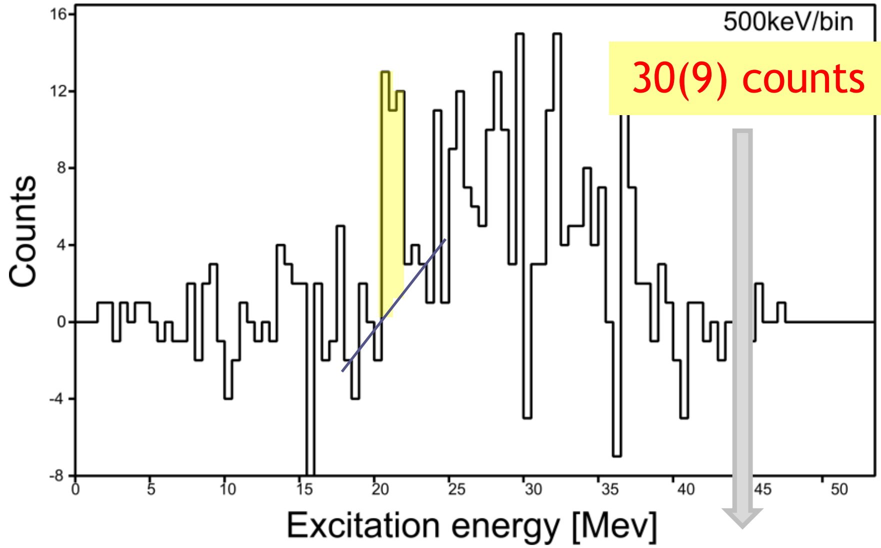
This newly developed approach will be crucial in predicting structures in the continuum in other nuclei in this key region of nuclear chart.

Thank you for your attention!

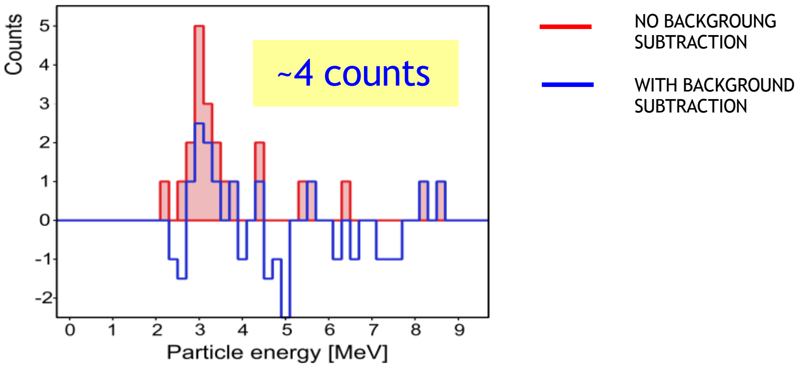
Estimation of the expected number of counts from excitation energy – gamma energy matrix

ExEgamma matrix projection (from ^{13}C thin target experiment)





LaBr absolute efficiency for 953 keV: 0,88%



3409(1041) events from e019 exp.

- e019+e020 experiments
- angular coverage of DSSD: 0.36%
- deadtime
- no high-counting plastics

~12(4) expected counts in DSSD at 3 MeV

Stretched M4 states in other light nuclei

Inelastic electron scattering on $^{12,13,14}C$ (*R.S.Hicks et al.,PRC34,1161(1986)*)