Collective and single-particle properties of exotic atomic nuclei studied by measurement of gamma-rays

MICHAŁ CIEMAŁA

IFJ PAN, KRAKÓW

„THURSDAYS FOR THE YOUNG AT IFJ PAN”, 23/05/2024

Presentation plan

- The PARIS „"Photon Array for Studies with Radioactive Ion and Stable beams” project
- Giant Dipole Resonance (GDR) gamma-ray decay measurements: PARIS@Nuball1, Nuball2 and Giant Quadrupole Resonance (GQR) gamma-ray decay properties measured at CCB@IFJ
- Fission proces studies PARIS@VAMOS
- Double gamma decay proces measured with use of PARIS
- Three body term of nucleon interaction, experimental results with use of AGATA, PARIS and VAMOS setup
- Conclusions

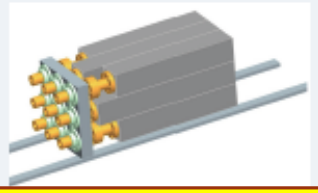
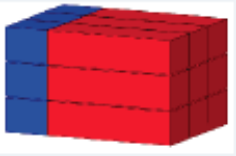
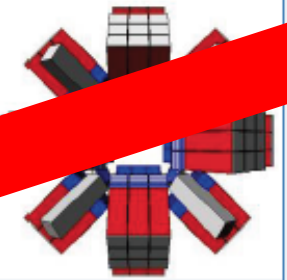
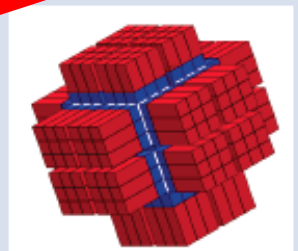
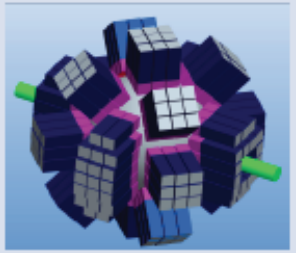
The PARIS:
"Photon Array for Studies with Radioactive Ion and Stable beams”
project

Photon Array for studies with Radioactive Ion and Stable Beam - PARIS (travelling detector)

PARIS Project Manager: A. Maj (IFJ PAN Kraków)

PARIS is a collaborative project between France, Poland, Italy, India, Romania, Germany, UK and Turkey

M.C.- responsible : physics event generators, off-line data analysis and data management

Phase 1 **2011/2012** PARIS cluster	1 cluster: 9 phoswiches		
2025? PARIS 2π	12 clusters: 108 phoswiches		
after2025	>24 phoswiches		

Today we have ~ 10 clusters (90 detectors)

PARIS is made of clusters:

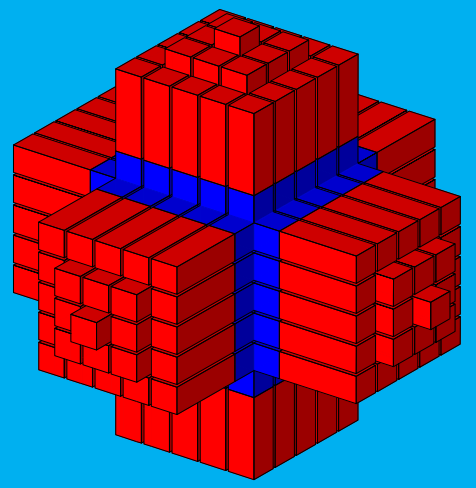
Cluster = 9 phoswiches of $LaBr_3$:NaI or $CeBr_3$:NaI

Digital electronic basing on V1730 digitizer, which can be coupled to NUMEXO2 boards. Also other electronic used, by example FASTER digitizers (NFS exp. and @IJCLab)

Goal of the new MoU

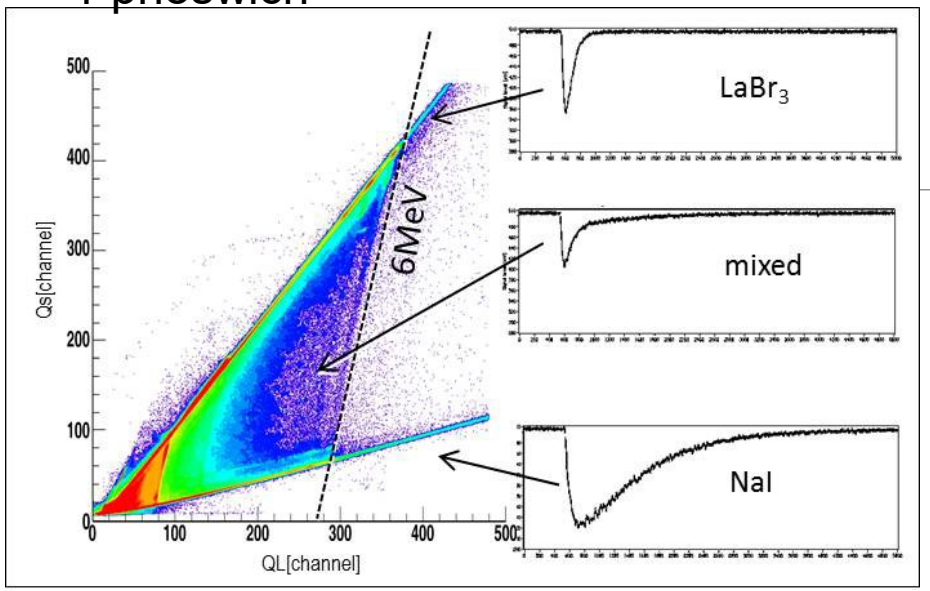
4π mini-cube

(150 phoswiches)

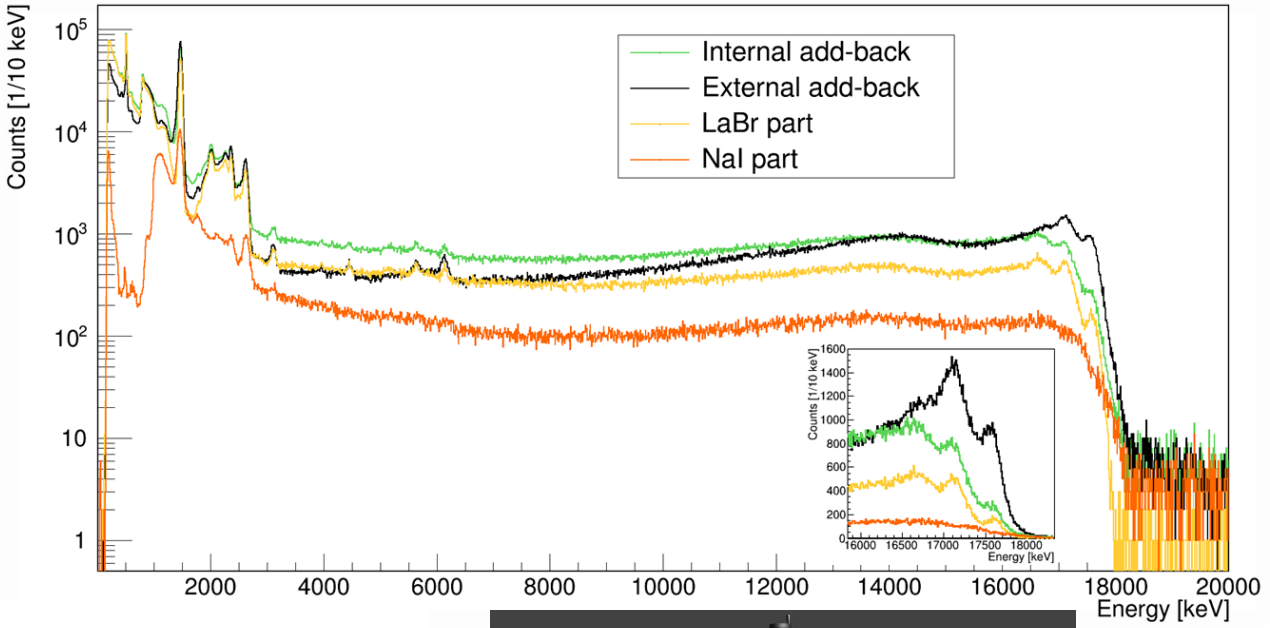


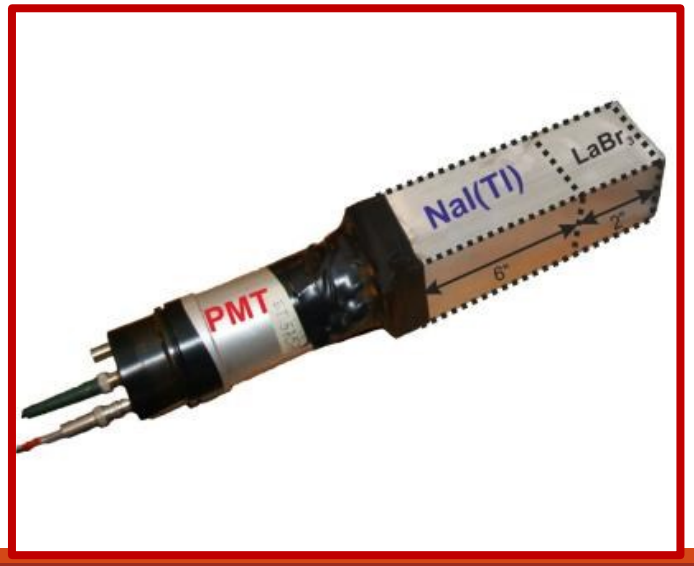
Examples of PARIS spectra

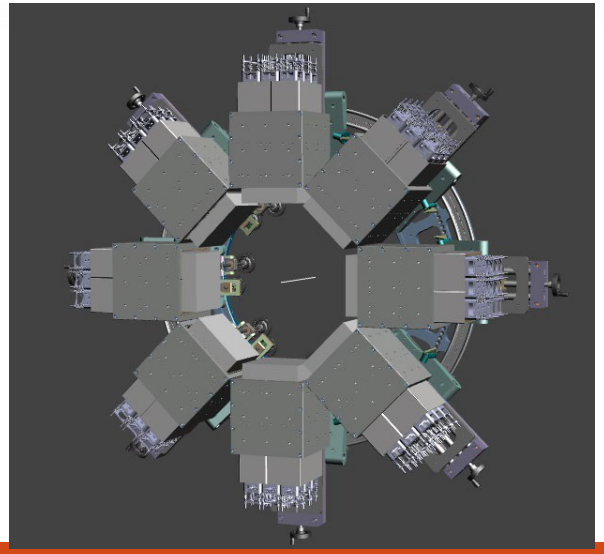
1 phoswich



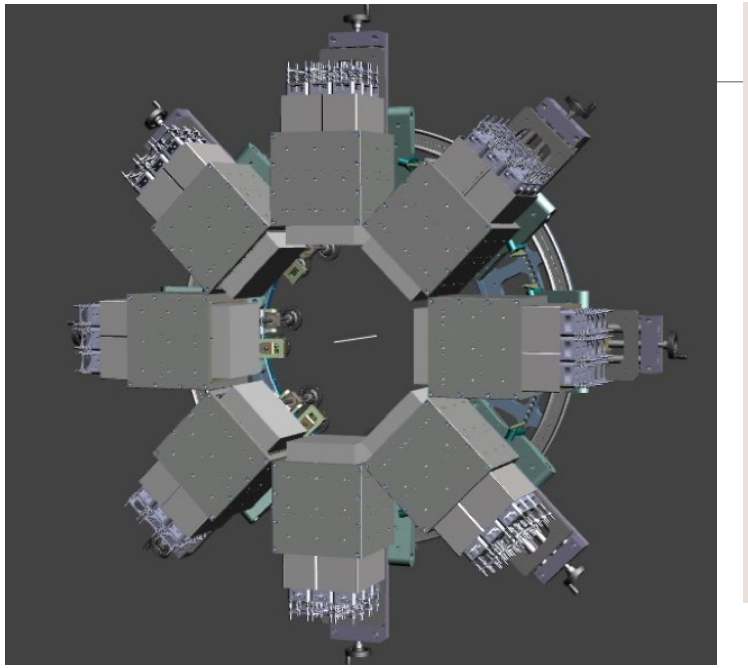
1 cluster







PARIS array properties



Good energy resolution for low and high energy γ-rays
35 keV @ 1.332 MeV
Excellent Time resolution (sigma ~ 0.5 ns)
Measurement of gamma multiplicity from frontal $LaBr_3$ or $CeBr_3$
Large efficiency for high energy γ-rays (~ 5% at 10 MeV for 8 clusters)
72 phoswiches in 8 clusters
72 LaBr3:Ce or CeBre 2”x2” crystals in 8 clusters
~ 28 liters of NaI in 8 clusters

PARIS campaigns:
GANIL, France (2017 and 2022) 4 exp.
IPN/IJCLab, France (2016-2023) 13 exp.
CCB@IFJ PAN, Poland (2016-2024) 4 exp.

future campaign PARIS coupled with AGATA LNL Legnaro, Italy, 2025/6?

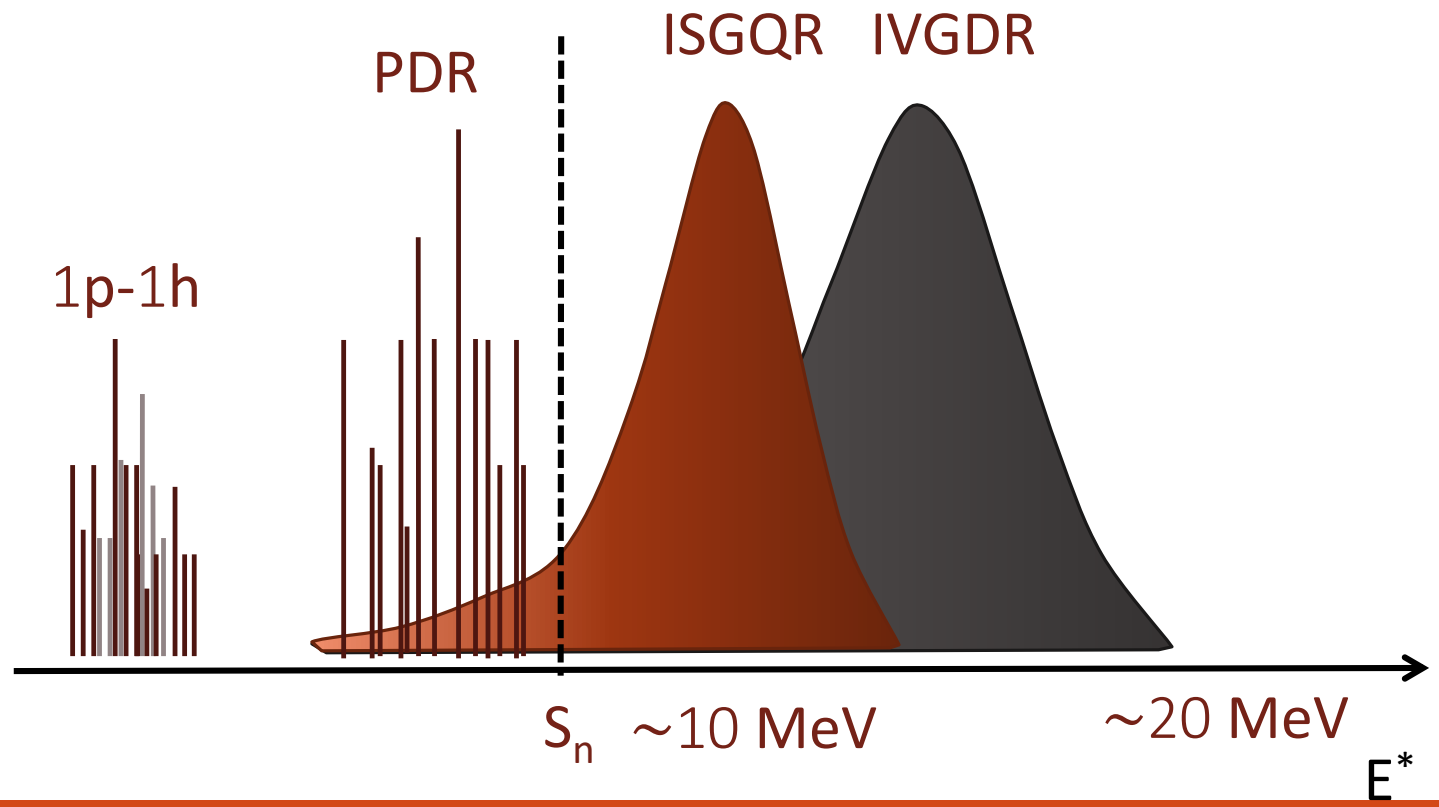
Giant Dipole Resonance (GDR) gamma-ray decay measurements
and
Giant Quadrupole Resonance (GQR) gamma-ray decay properties measured at CCB@IFJ

Giant Resonances – collective excitations

Proton and neutron oscillations, almost all nuclei take part in excitation.

IVGDR: rather well known, studied by γ emission for various temperatures and angular momenta, information on nuclear shape and deformation

ISGQR: not well known, studied mainly using (p,p') and (e,e') reactions –missing information on cross sections and branching **γ decay of GQR measurement difficult due to small yield**



The ^{192}Pt* decay to ^{188}Pt residue

M.C., Grant NCN MINIATURA, 2017

$^{18}O + ^{174}Yb \rightarrow ^{192}Pt$

Beam energy: 90 MeV

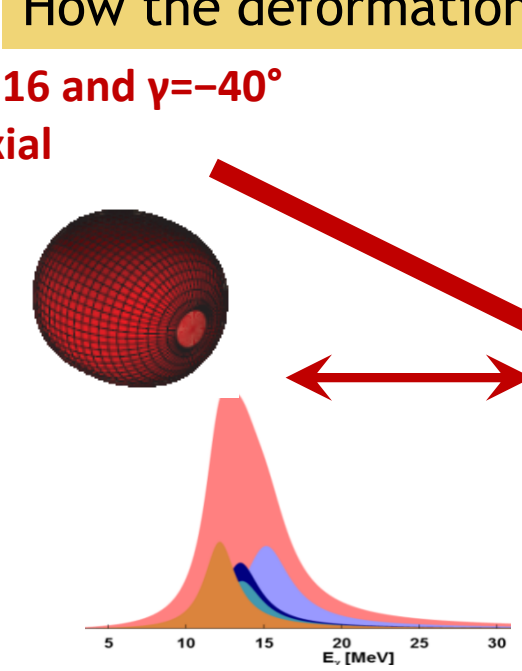
High-energy γ rays from ^{192}Pt* CN decay in **4n channel** in coincidence with low-energy transitions in ^{188}Pt

Experiment with PARIS@Nuball1, IPN/IJCLab, Orsay, France

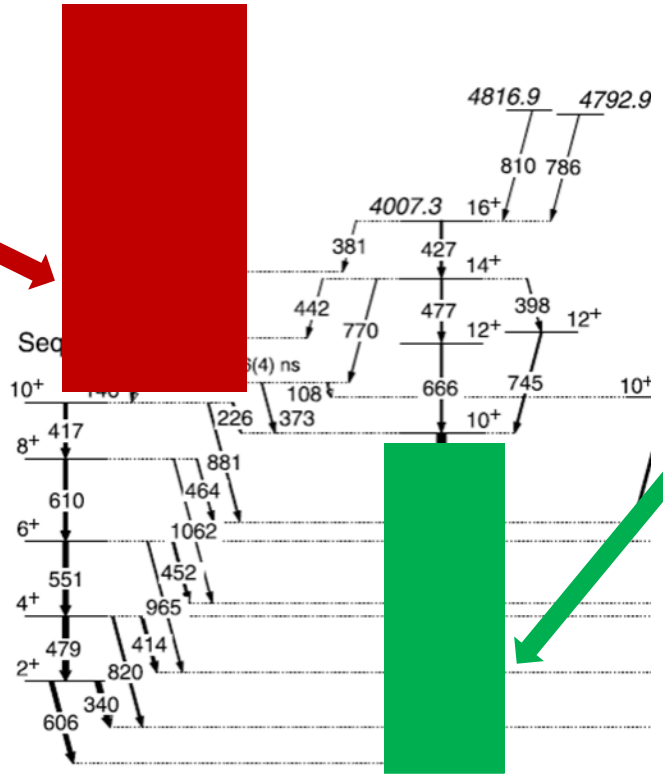
β =0.18 and γ=−6°
near prolate

How the deformation changes along the decay path?

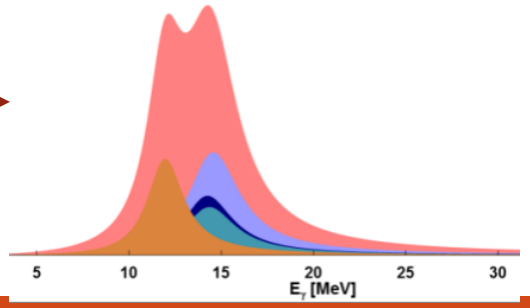
β=0.16 and γ=−40°
triaxial



Gate on transitions

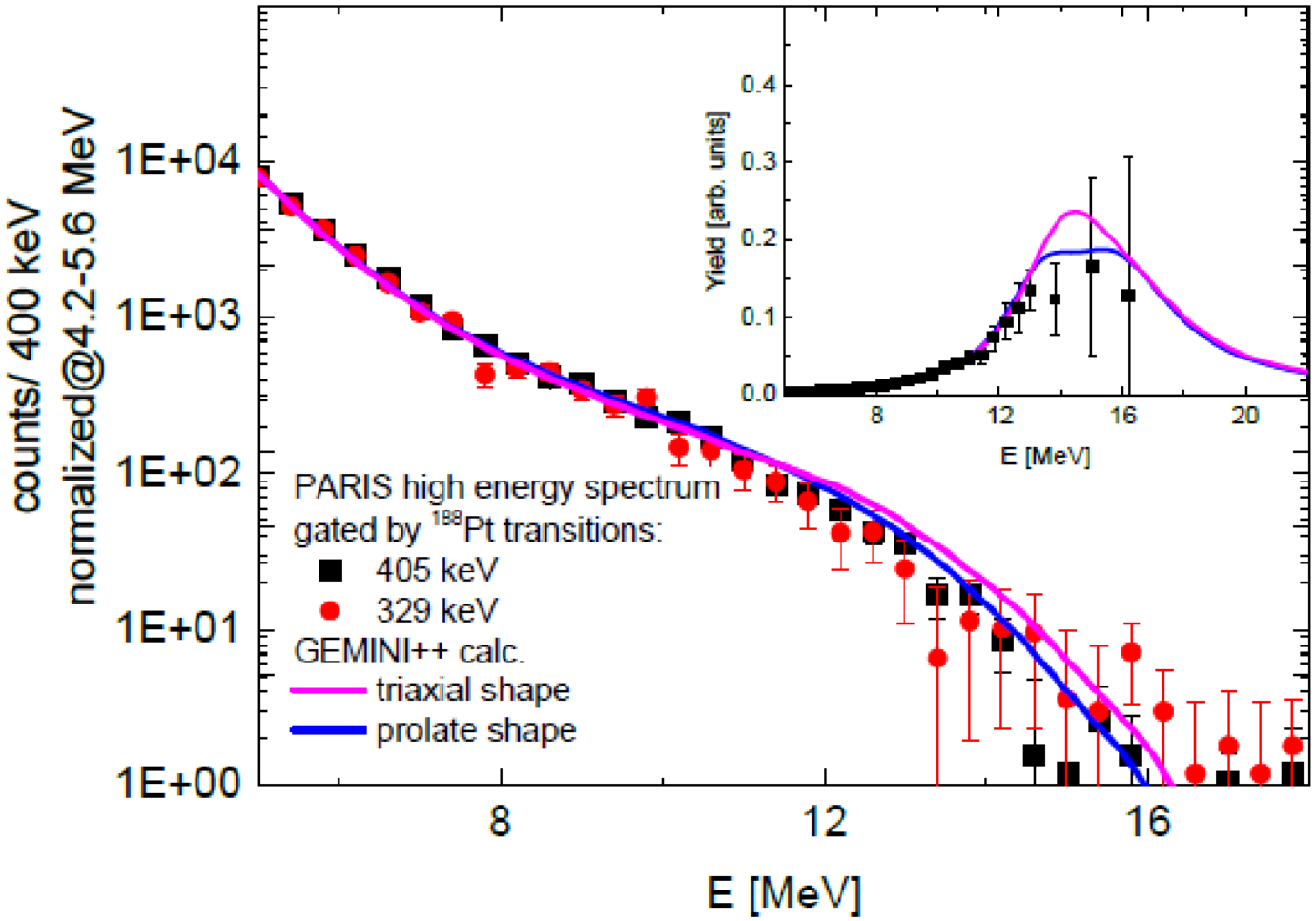


GDR strength functions for CN decaying to particular states of ^{188}Pt



S. Mukhopadhyay et al., Phys. Lett. B 739, 462 (2014)

Comparison to statistical model



Better agreement to experimental data is seen for the calculations assuming prolate-like shape of the nucleus.

Suggestion that either:
the assignment of the triaxial deformation for 12+ isomer is wrong
or
the nucleus does not preserve the shape during the decay.

M. Ciemała et al., Acta Phys. Pol B Proc. Suppl. 16, 4-A3 (2023)

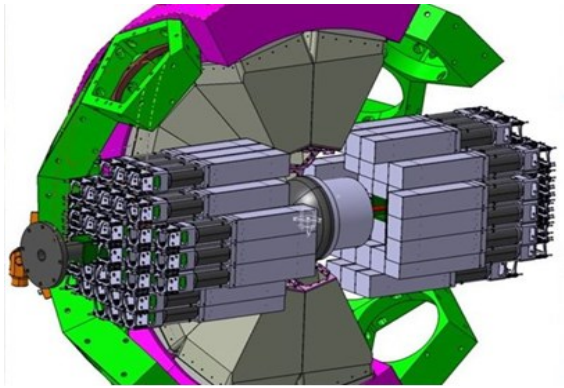
The PARIS + NuBall2 experiments

from November 2022 to June 2023

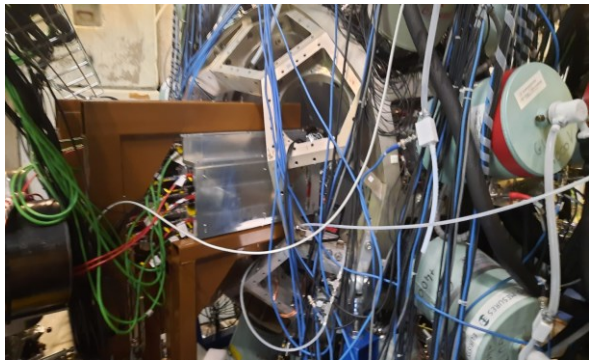
v-ball2 array: HPGe clovers coupled to 72 **PARIS** detectors

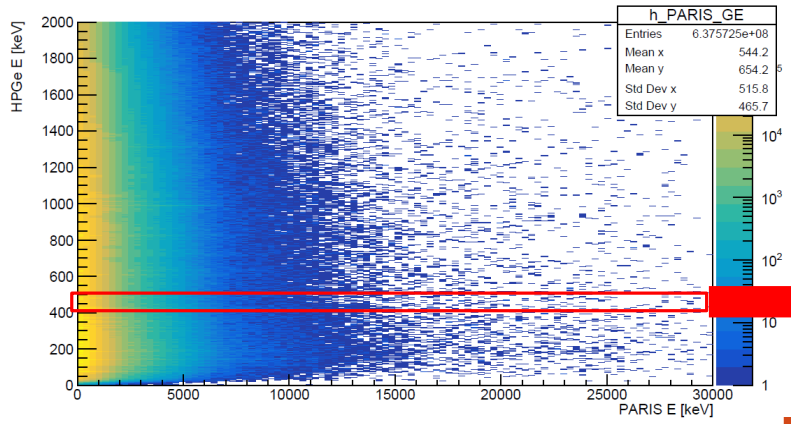
N-SI-122, November 2022: M. Ciemała et al. "Links between ^{80}Sr compound nucleus' shape and its residue's deformation studied with the GDR"

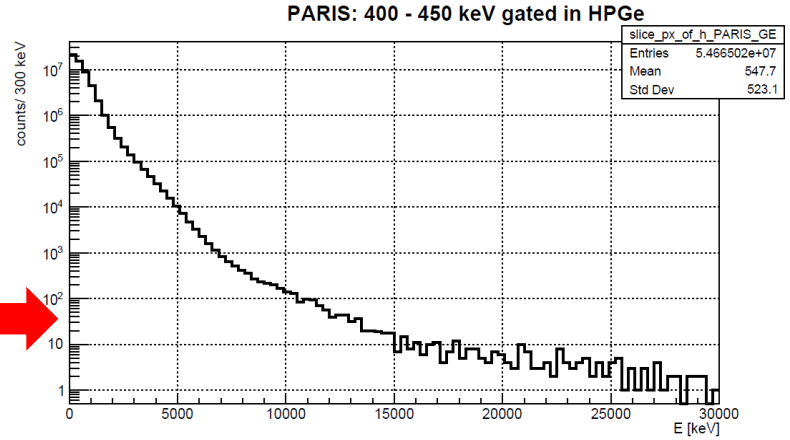
M.C. one month longer stay at IJCLab as „visiting profesor"

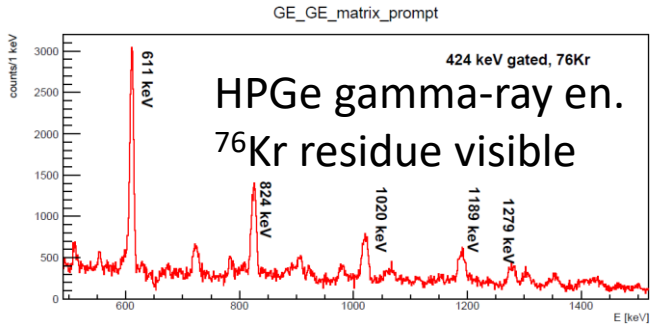


PARIS@Nu-Ball2



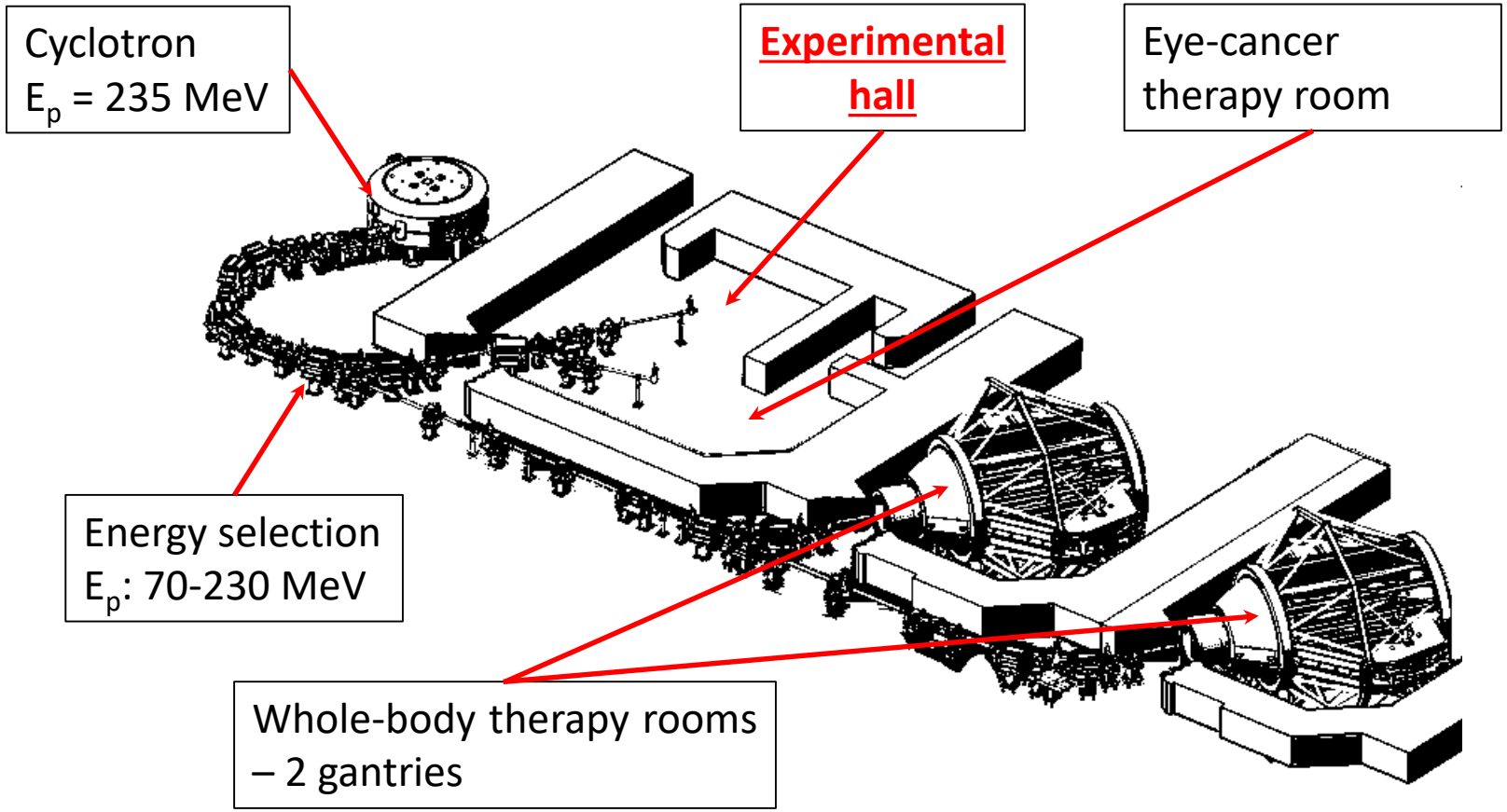




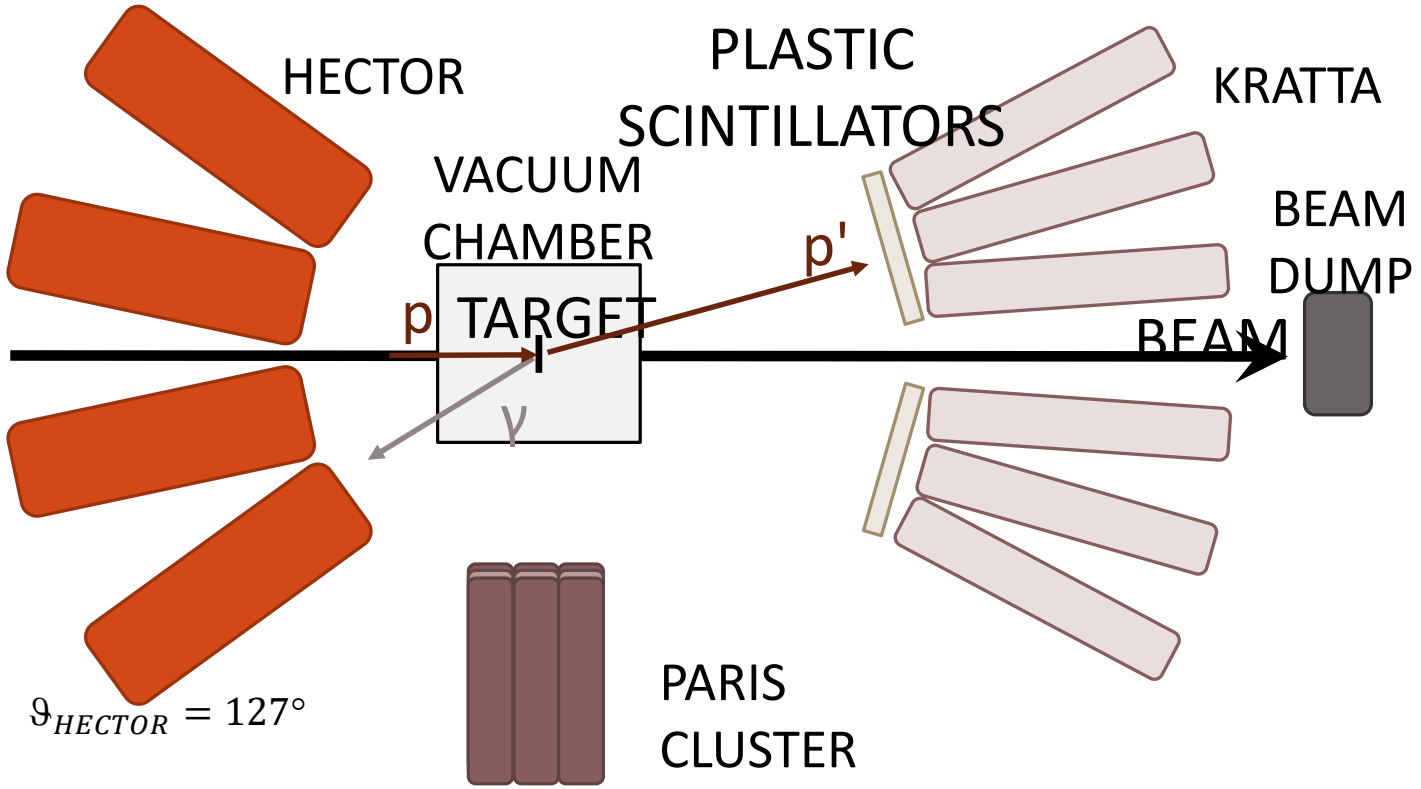


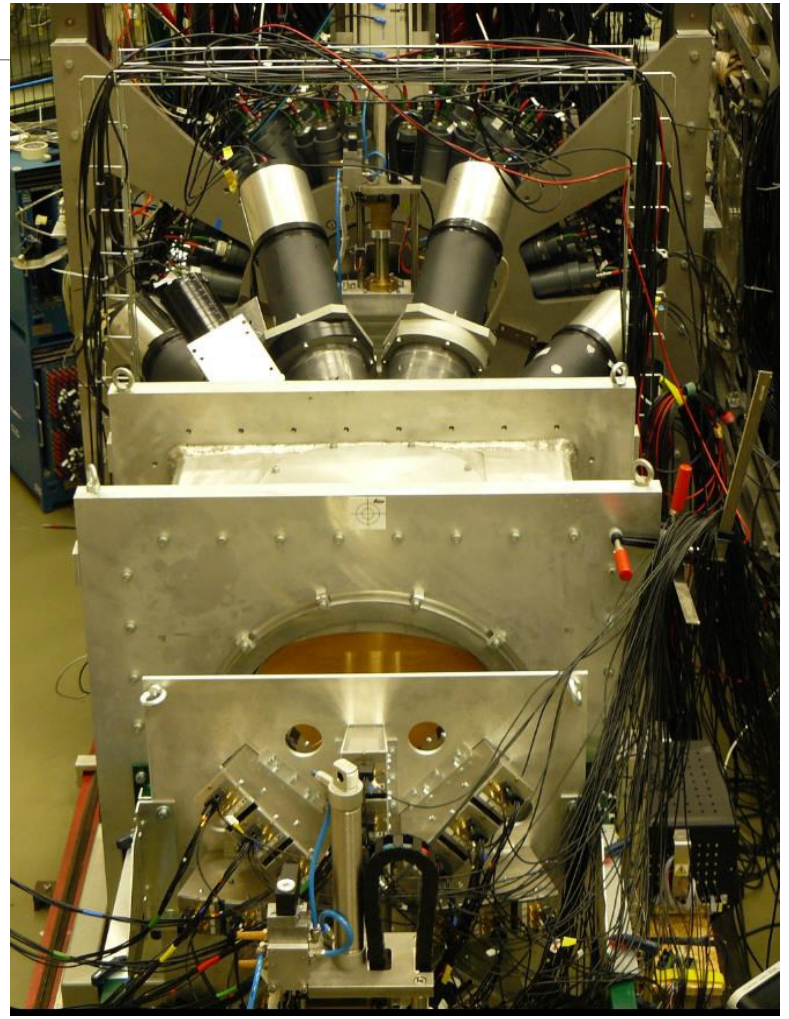
PARIS – HPGe gamma-gamma matrix PARIS gamma-ray spectrum gated by discrete gamma-ray range

GR studies at CCB@ IFJ PAN



GR studies at CCB@ IFJ PAN

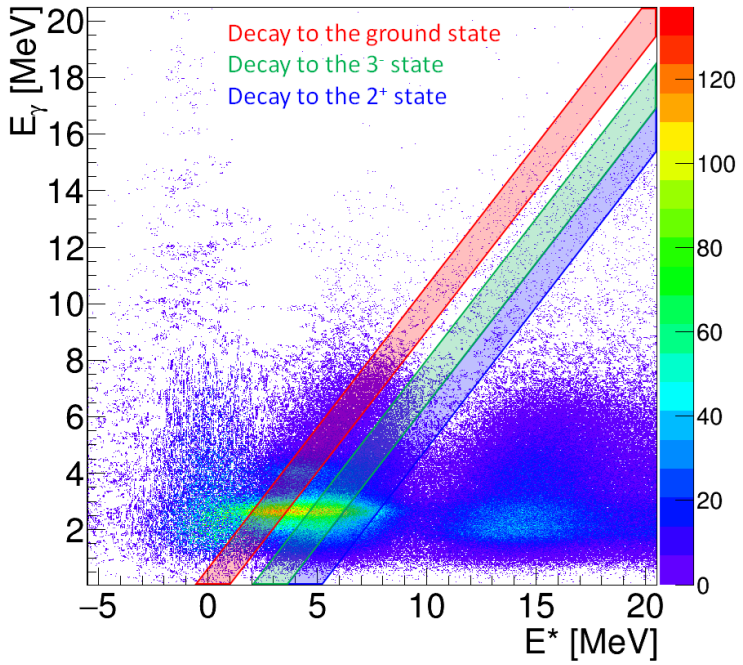


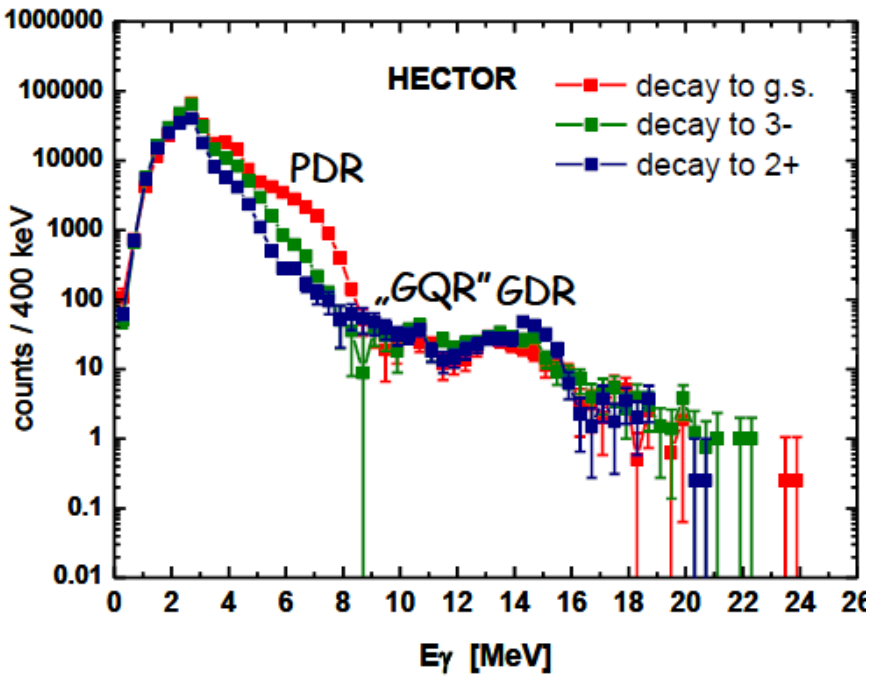


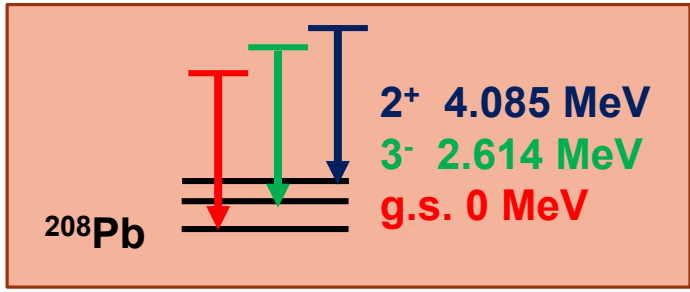
Inelastic scattering of protons @ 85 MeV on
^{208}Pb target 48 μm(54.5 mg/cm^2) thick

2017 – 2019 detection setup

GR studies at CCB@ IFJ PAN





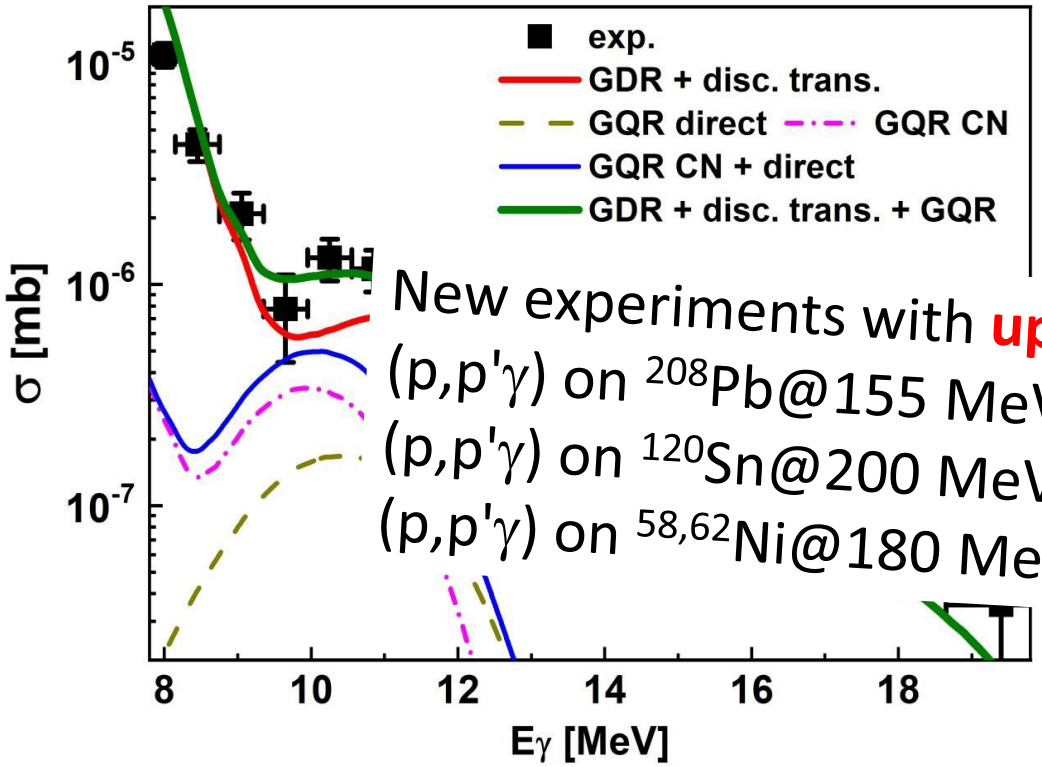


- GDR build on excited states observed –in agreement with Brink–Axel hypothesis
- strong enhancement of gamma strength below neutron binding energy (PDR) –only excited on ground state –Brink–Axel hypothesis not valid
- decay from GQR region to the ground state dominated by E1 transitions

GR studies at CCB@ IFJ PAN

Proton probe: $\Gamma\gamma_0/\Gamma = 3\times10^{-4} \pm 1\times10^{-4}$

^{17}O : $\Gamma\gamma_0/\Gamma = 4\times10^{-4} \pm 1\times10^{-4}$

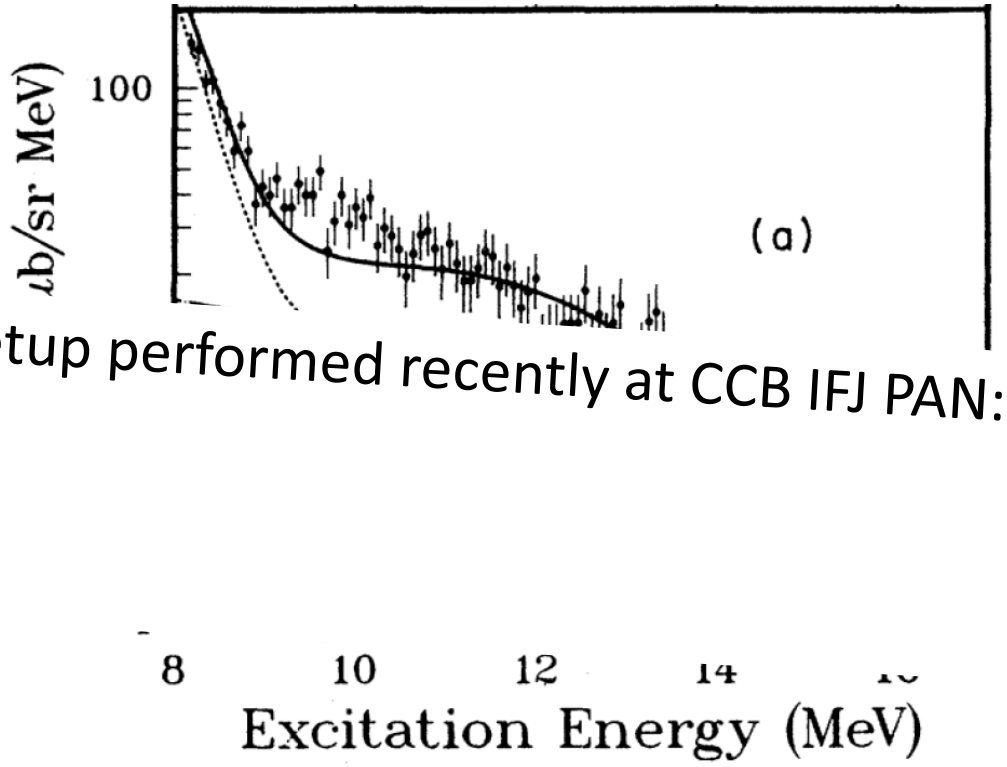


New experiments with **upgraded** setup performed recently at CCB IFJ PAN:

(p,p'γ) on ^{208}Pb@155 MeV

(p,p'γ) on ^{120}Sn@200 MeV

(p,p'γ) on ^{58,62}Ni@180 MeV



J. Beenet al., RC39(1989)1307

Branching ratio for the GQR gamma decay to the ground state obtained with the use of proton beam is in agreement to previous value measured with heavy ions.

Fission proces studies PARIS@VAMOS

Insight into fission from the gamma probe: Going beyond current status with PARIS@VAMOS

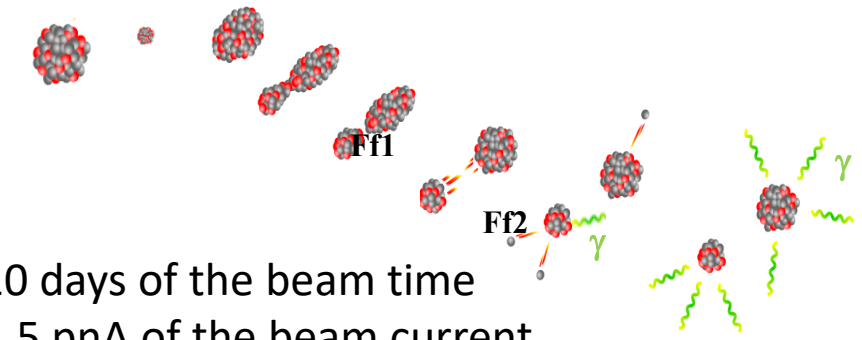
Ch. Schmitt, M. Ciemała, et al.

GANIL E826 : VAMOS+PARIS&EXOGAM experiment performed 2022

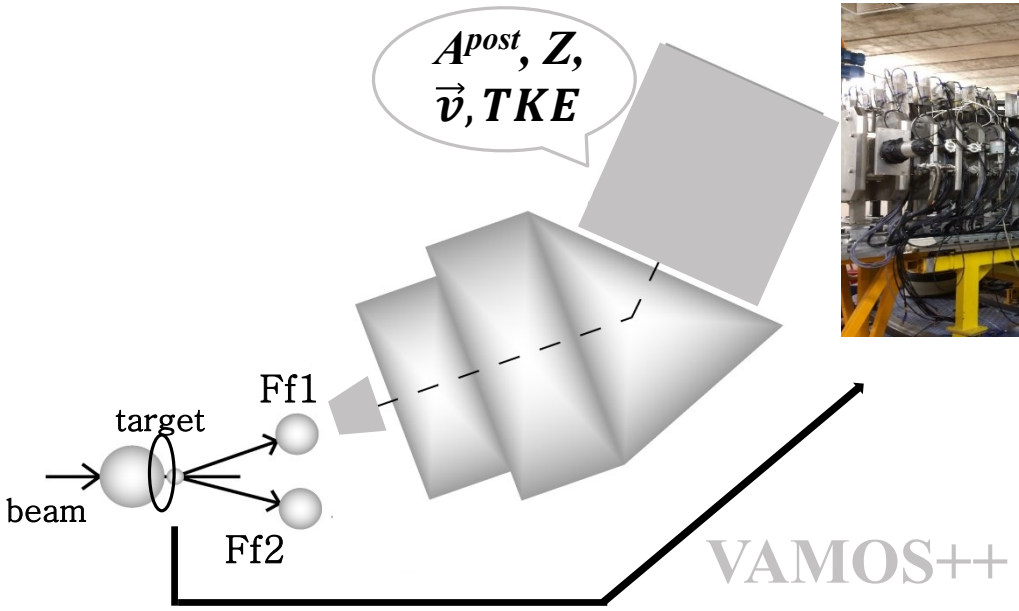
Fusion-fission in inverse kinematics

$^{238}U + {}^{9}Be \rightarrow {}^{247}Cm^{*}$ **(E^{*}~ 43MeV)**

(5.88MeV/u) **(500µg/cm2)**



10 days of the beam time
1.5 pnA of the beam current



ϑ=21°, Bρ=1.1Tm

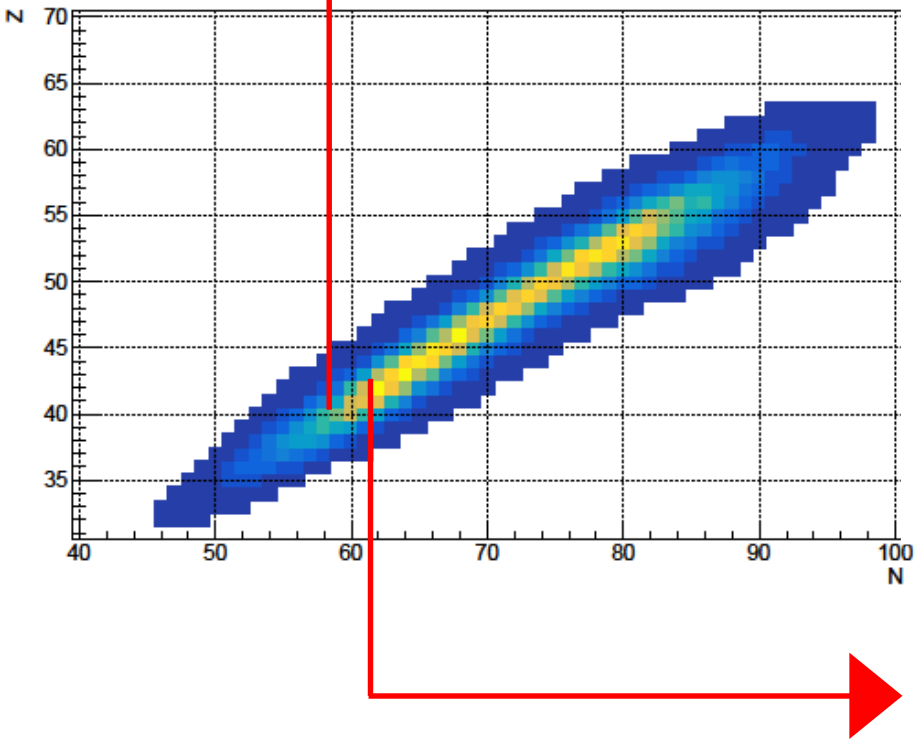
event by event

- ✓ **Ff's uniquely resolved / characterized in (A, Z, $\vec{v}$)**
- ✓ **Prompt Fission Gamma Spectrum and properties (E_γ, E_γ^{sum}, M_γ)**
- ✓ **Neutrons (E_n , M_n)**

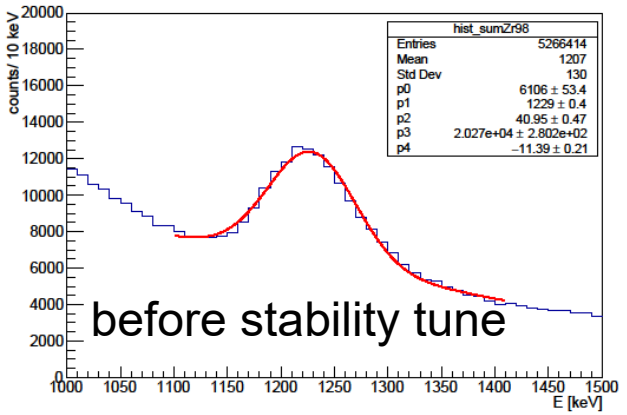
PFGS
E_γ, E_γ^{sum}, M_γ, M_n

PARIS
Exogam

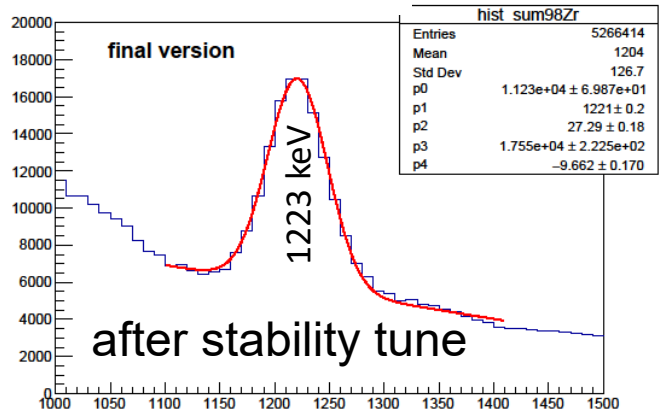
Isotopic identification in VAMOS++



^{98}Zr

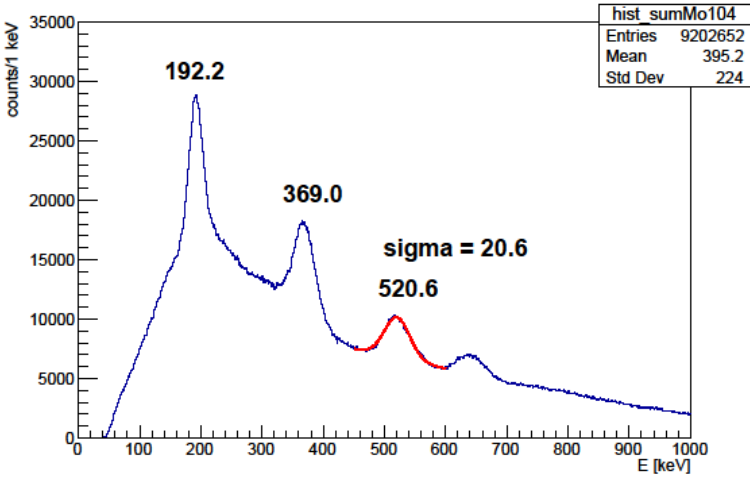


^{98}Zr

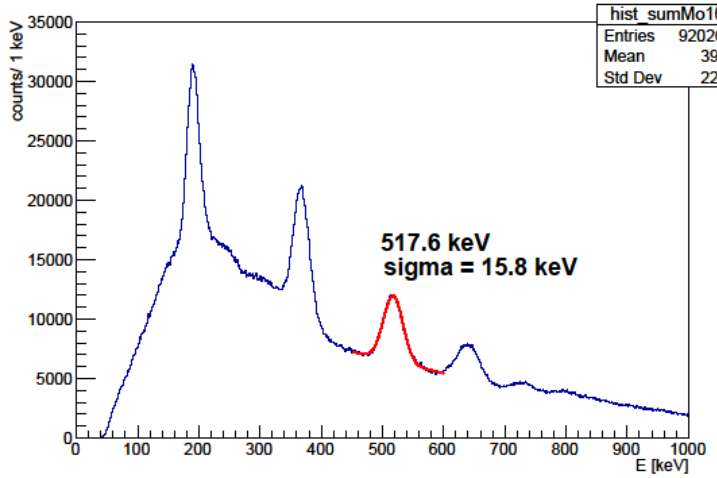


Prompt γ spectrum in PARIS

^{104}Mo



^{104}Mo

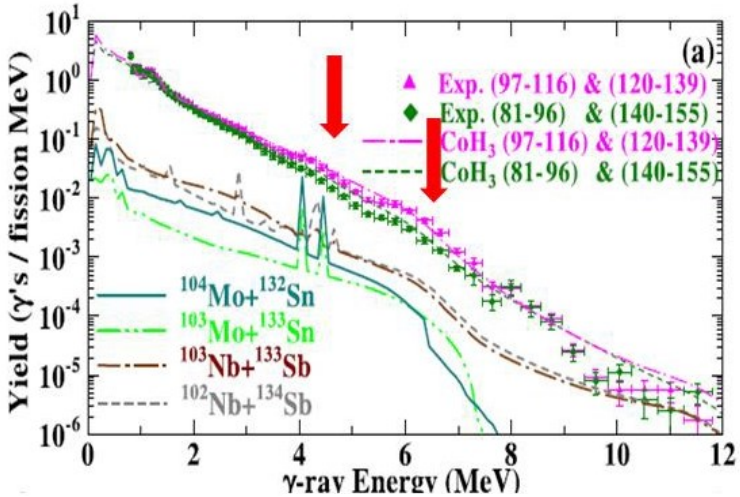


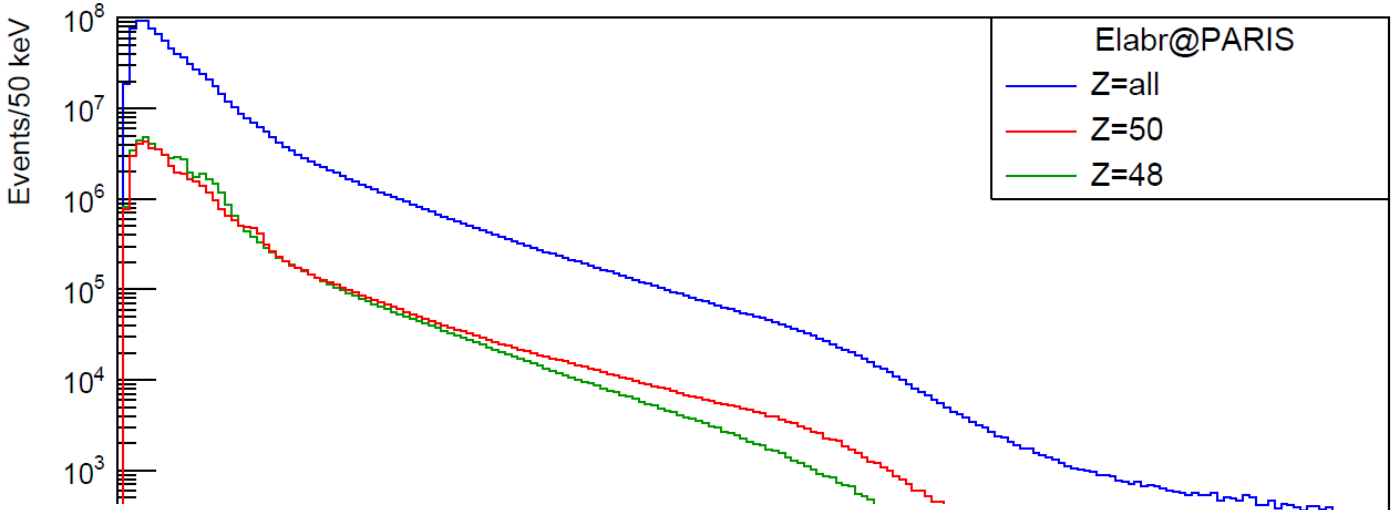
after tuned callibration

after stability tune based on 511 keV line

Z gated γ properties - PFGS

PFGS shape and "bump" ?





Experimental P
diamonds) for
^{236}U two differe
By H. Makii et
044610.

Undergoing careful **analysis** including **deconvolution** of FOLD and Energy spectra allowing to shed more light on the fission process, especially with comparison to the models available on the market (FIFRELIN).

Perfect time resolution provide very clean gamma-ray Energy spectrum in the high energy region.

Detailed shape of the prompt fission γ spectrum

Perspectives: proton induced fission experiments@CCB IFJ PAN

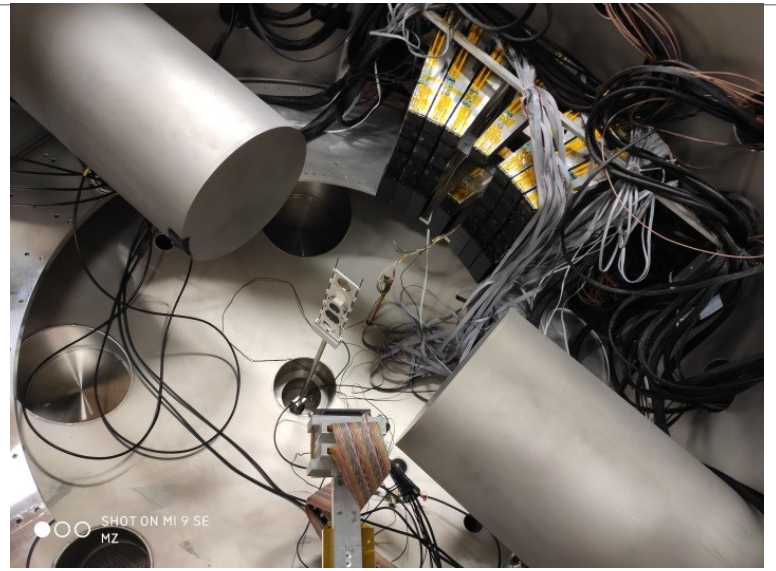
COFFEE: Cracow-Orsay Fission Fragment Exclusive Experiments

Proton induced fission

Detectors:

- KRATTA,
- plastic array,
- gamma-ray detection, PARIS, large volume $LaBr_3$

and possibly HPGe

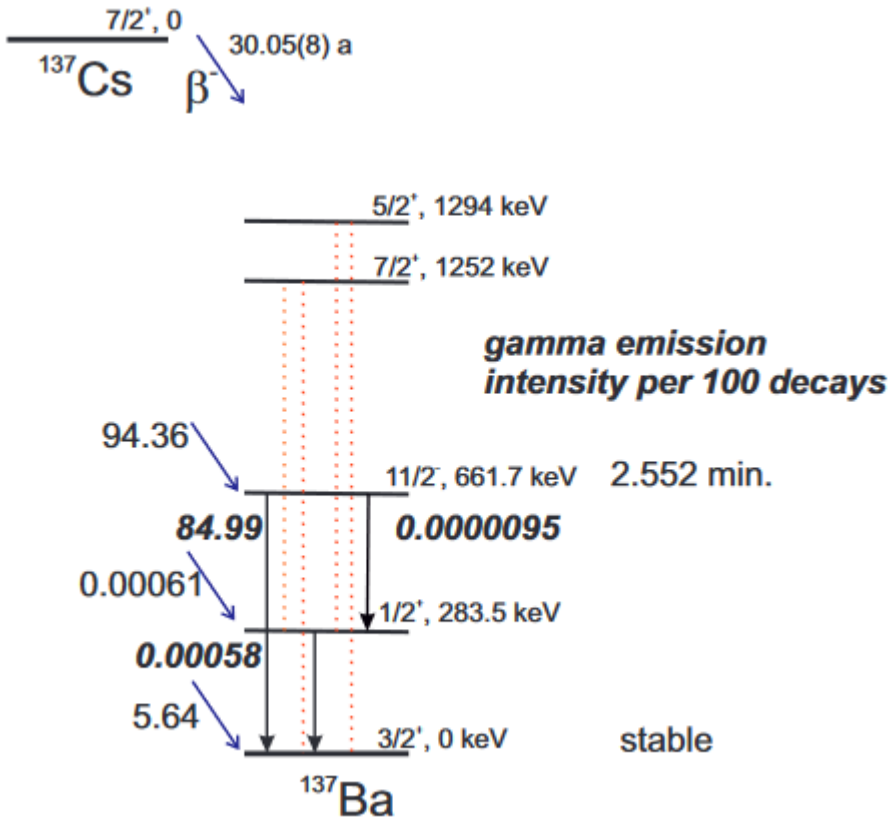


The high excitation energies at CCB will allow study of the fission of ^{232}Th as well as of *sub-actinide* nuclei such as ^{208}Pb, ^{197}Au, ^{196}Pt, ^{186}W, etc. where fission barrier heights are around 25-30 MeV. With addition of a fission fragment detector these fission events will come for “free” along with some of the future experiments in the current research program into giant collective resonances already underway at CCB.

Double gamma decay proces measured with use of PARIS

Double gamma decay process

M.C., Grant NCN SONATA 14, 2019



In this process, an excited nuclear state decays to a lower-lying state with **simultaneous** emission of two photons.

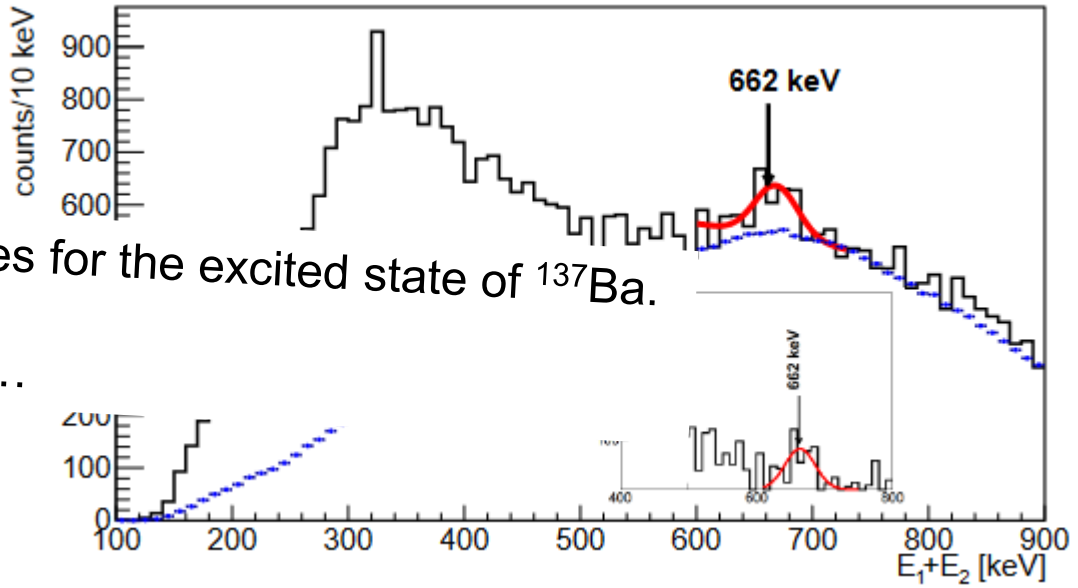
Recentlly studied competitive $\gamma/\gamma\gamma$ decay in the ^{137}Ba:
C. Waltz et al., Nature 526, 406 (2015)
P.-A. Söderström et al., Nat. Commun. 11, 3242 (2020)

Decay scheme of 137Cs with marked single and double gamma decays

Double gamma decay process

Confirmed observation of double gamma decay proces for the excited state of ^{137}Ba.

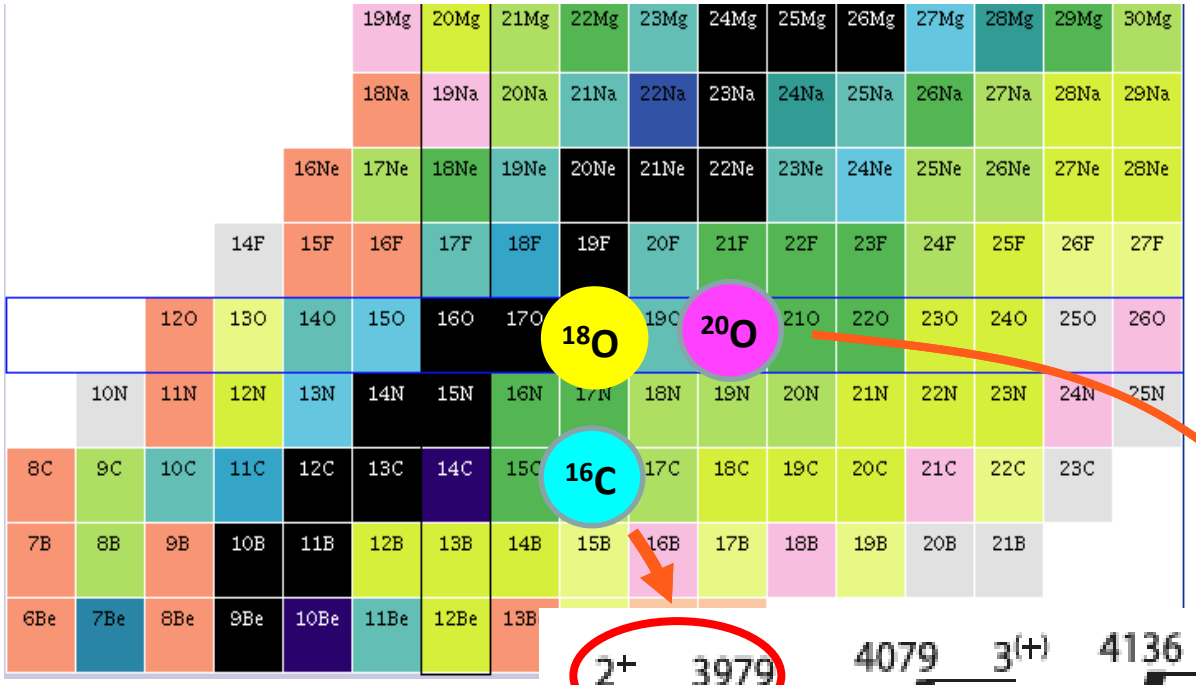
Possible other nuclei worth to investigate ^{207}Pb, ^{72}Ge,…

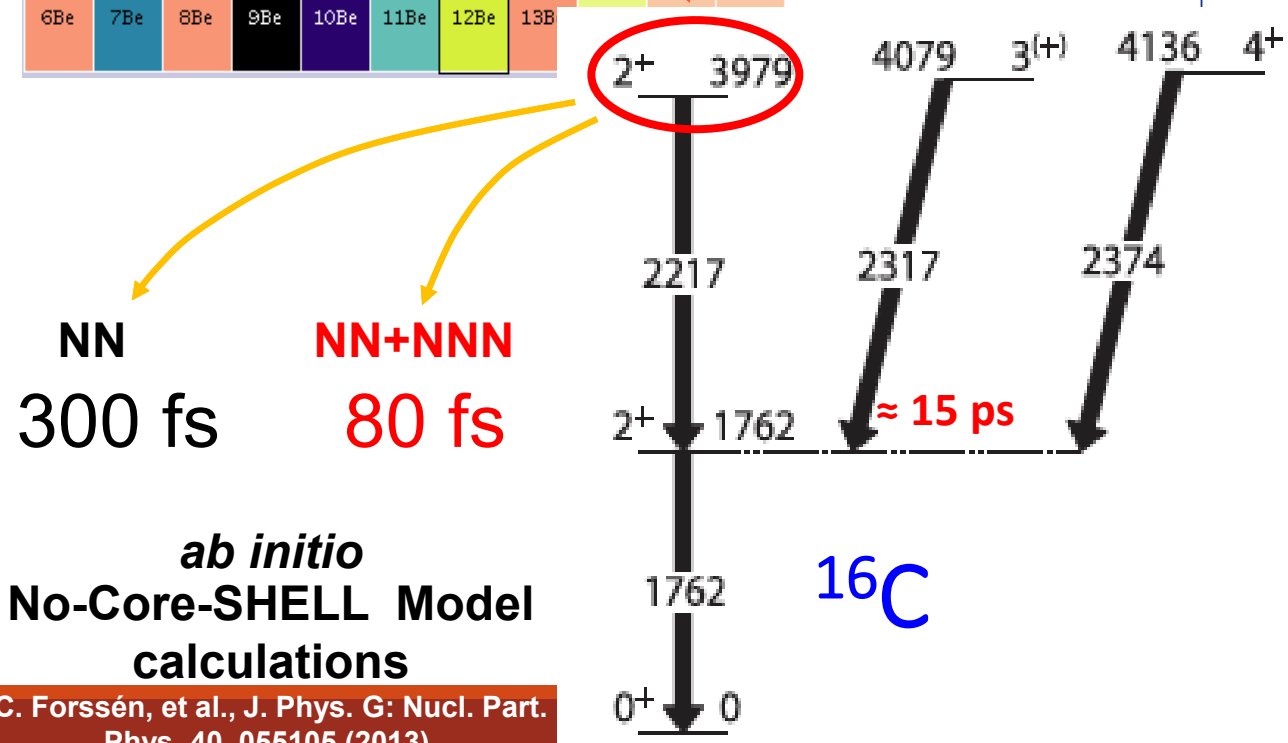


Two CeBr3:NaI PARIS phosiwches (1 – $CeBr_3$, 2 – NaI parts), surrounded by tungsten (3) and lead (shielding) in the newly created laboratory room at IFJ PAN (radioisotope Z class room)

50 day measurement results, prompt, time gated, summed energy deposits in two phoswiches, blue - random coincidence, with red marked peak of summed two photons from double gamma decay equal to difference of energy levels.

Three body term of nucleon interaction, experimental results with use of AGATA, PARIS and VAMOS setup





NN
300 fs

NN+NNN
80 fs

ab initio
No-Core-SHELL Model calculations

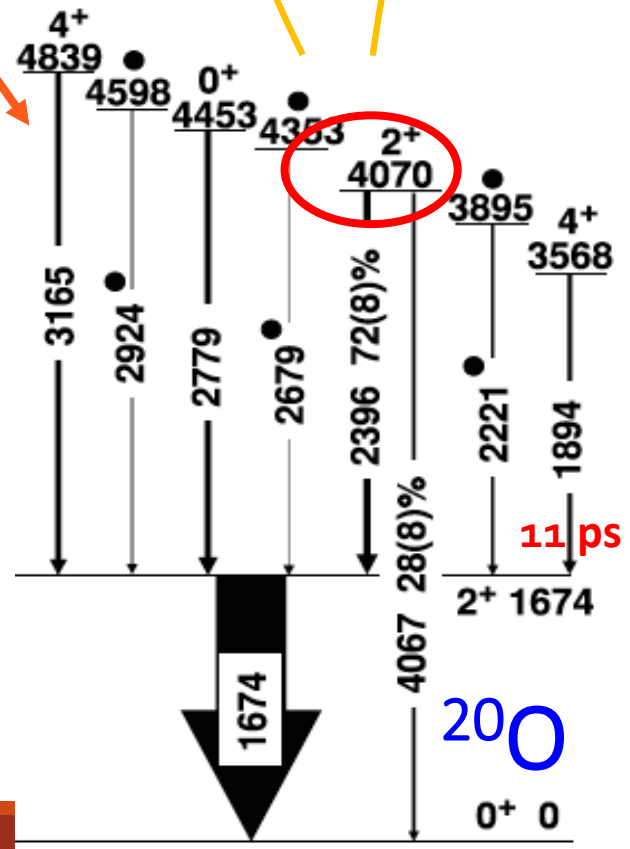
C. Forssén, et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013).

ab initio
Many-Body-Pert. Theory calculations of the 2^+_2 lifetimes

J.D. Holt, et al., Eur. Phys. J. A49, 39 (2013).

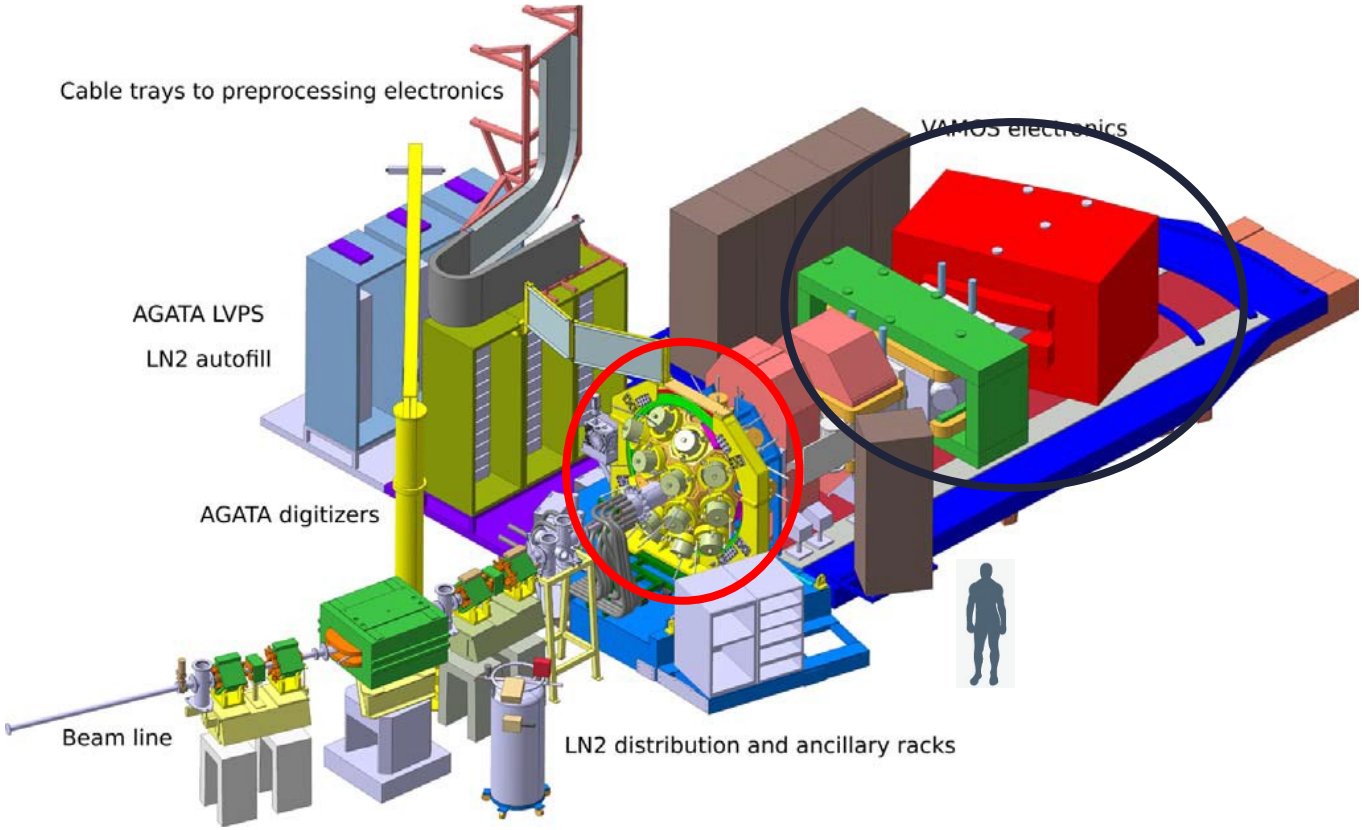
NN
320 fs

NN+NNN
200 fs



Experiment at GANIL, Caen, France

One of the most sophisticated setups: VAMOS+AGATA+PARIS



E. Clement et al. NIMA 885, 1-12 (2017)

Experiment Spokespersons: S. Leoni, B. Fornal, M. Ciemała

Beam: ^{18}O ions, 7.0 MeV/A

Target: ^{181}Ta $4\ \mu m$ thick

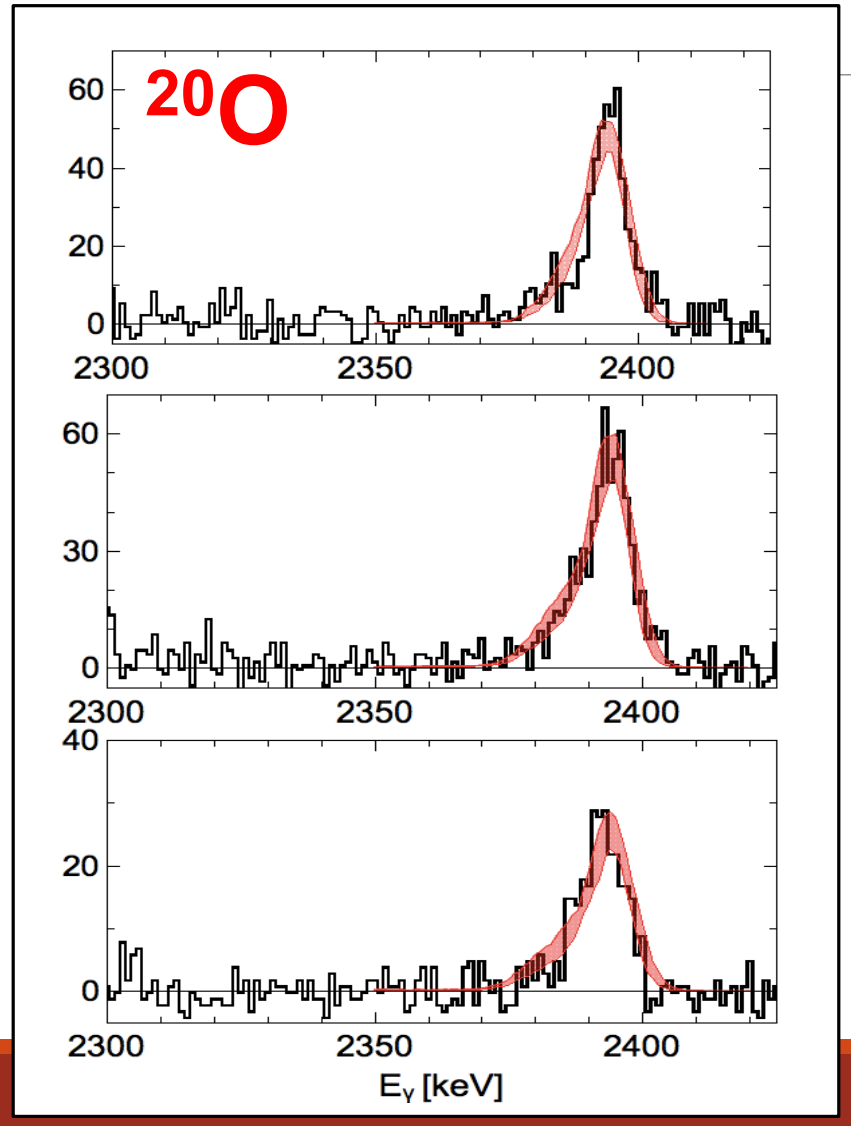
Goal:
excited state lifetime determination

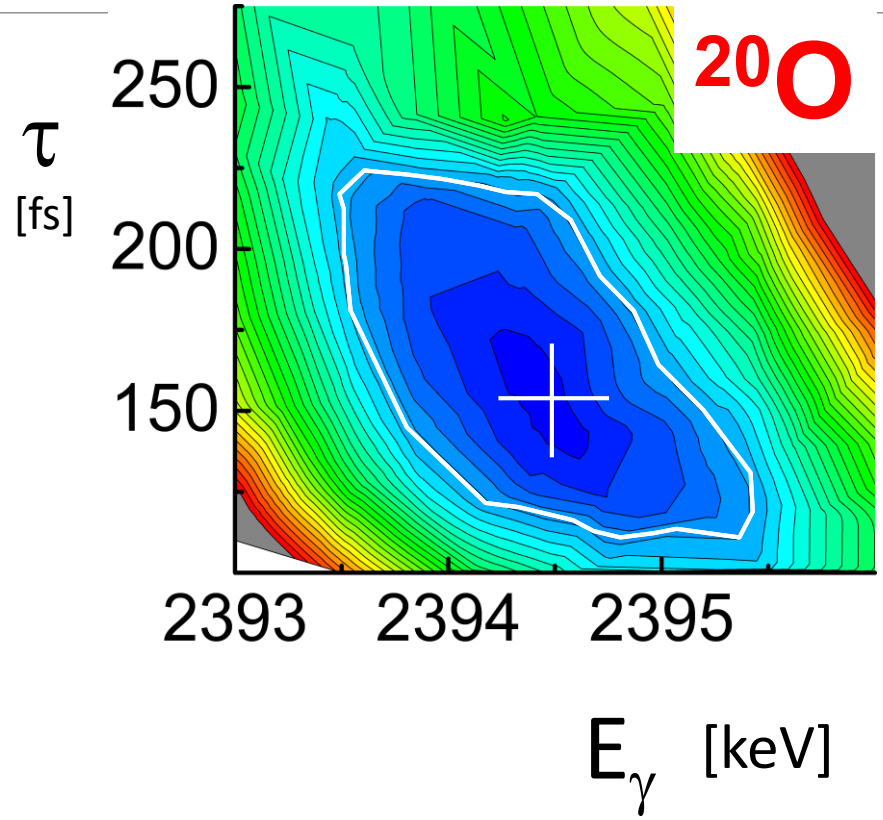
Detectors used:
AGATA+PARIS+VAMOS setup

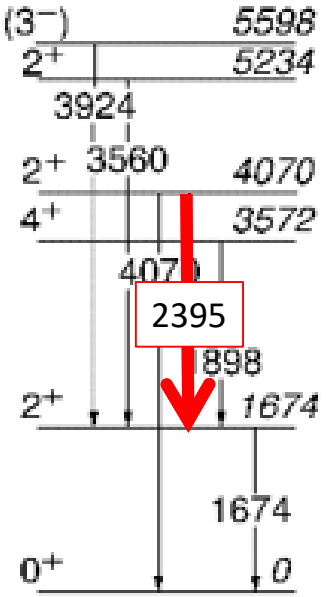
Beam time:
10 days data taking in July 2017

Case of interest – ^{20}O

^{18}O (7 MeV/A) + ^{181}Ta target (6 mg/cm^2)

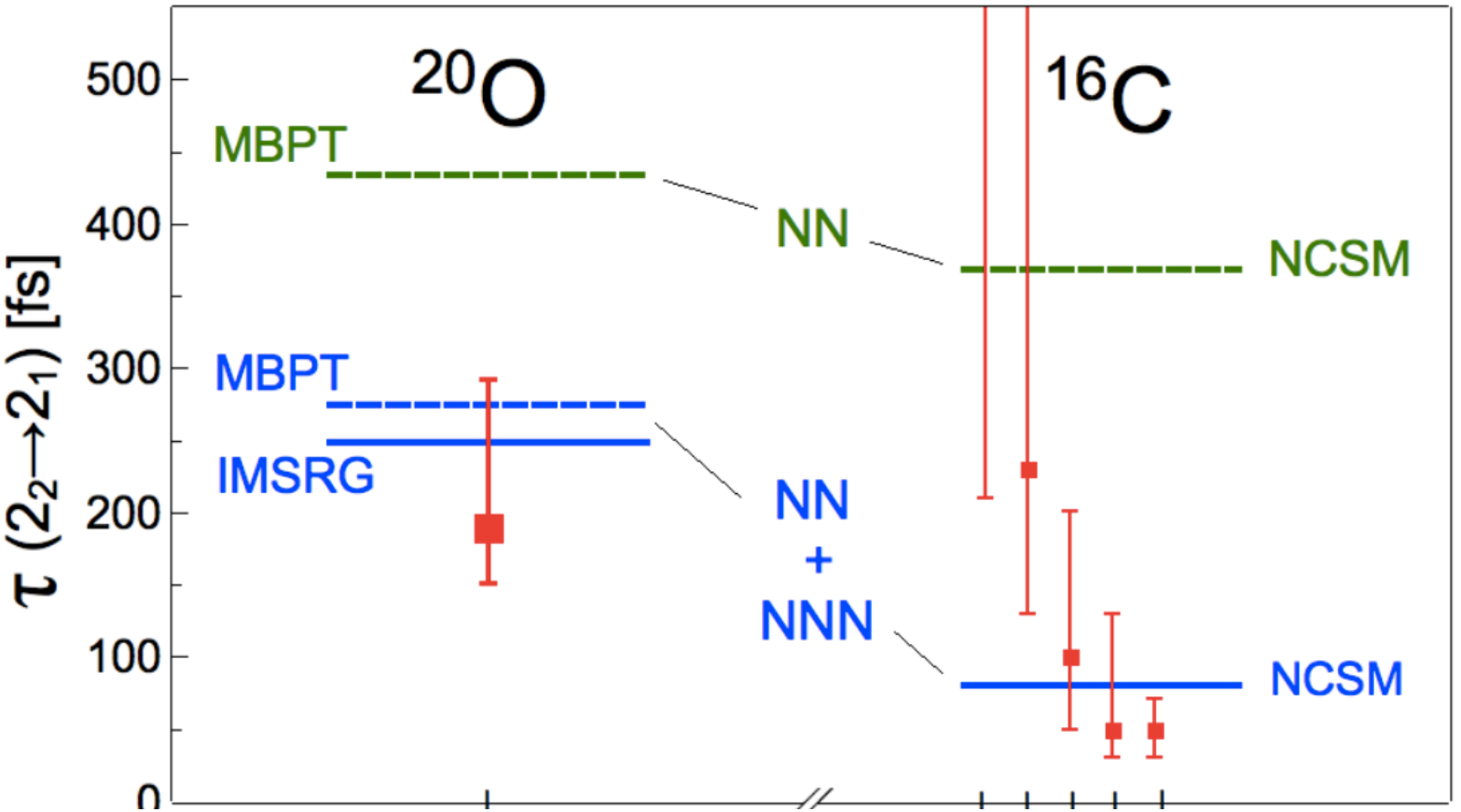






$\tau = 150^{+80}_{-30}$ fs

Literature Eγ = 2395(1) keV



For ^{20}O, our result is fully consistent with the *ab initio* calculations which include three-nucleon forces (calculation employing only NN interaction are NOT satisfactory).

Partial lifetimes, with branching taken into account.

and K. Hebeler, et al., Annu. Rev. Nucl. Part. Sci. 65, 457 (2015).
NCSM: C. Forssén, et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013).
NN:D.R. Entem and R. Machleidt, Phys. Rev. C 68, 041001(R) (2003); J. Simonis, et al., Phys. Rev. C 93, 011302(R) (2016).

Summary

I have presented selected experimental results obtained with use of PARIS (**high effieicncy, good Energy resolution and perfect time resolution**) - travelling gamma-ray detector, in which development I am strongly involved.

More experimental effort needed to check the connection between the shape of the compound nucleus formed in fusion reactions and the deformation of the residual nucleus following particle evaporation.

Observation of the gamma decay of the GQR in ^{208}Pb at CCB and establishing the branching ratio, confirming the only existing result obtained in the past.

Unique dataset for the PFGS (and PFNS) together with isotopically identified fission fragments was collected during experiment at GANIL with use of coupled VAMOS++ and PARIS+EXOGAM. New program of fission studies emerging at CCB (IFJ PAN) using fission induced by high Energy protons.

Confirmed observation of double gamma decay proces for the excited state of ^{137}Ba.

Tested experimentally the impact of the **NNN interactions** to nuclear structure observables in the case of ^{20}O and ^{16}C second 2^+ lifetimes.

Related papers:

M. C., et al., Phys. Rev. C 101, 021303(R), 2020
M. C., et al., Eur. Phys. J. A 57, 156, 2021
S. Ziliani, **M. C.**, , et al., Phys. Rev. C 104, L041301, 2021
B. Wasilewska, M. Kmiecik, **M. C.**, et al., Phys. Rev. C 105, 014310, 2022

M. C., et al., Acta Phys. Pol B 50(2019), No. 3, 615
S. Ziliani, **M. C.**, et al., Acta Phys. Pol B 50(2019), No. 3, 625
B. Wasilewska, M. Kmiecik, **M. C.**, et al., Acta Phys. Pol. B50 (2019) 469
M. C., et al., Acta Phys. Pol B 51(2020), No. 3, 699
S. Ziliani, **M. C.**, et al., Acta Phys. Pol B 51(2020), No. 3, 709
B. Wasilewska, M. Kmiecik, **M. C.**, et al., Acta Phys. Pol. B51 (2020) 677
M. C., et al., Acta Phys. Pol B Proc. Suppl. 16, 4-A3 (2023)
M. C., et al., Acta Phys. Pol B Proc. Suppl. 16, 4-A40 (2023)

Co-supervisor: 1 PhD thesis
Supervisor: 3 MsC thesis
Supervisor: 2 BsC thesis