Gamma decay of GQR excited in ^{208}Pb by proton inelastic scattering at CCB

Maria Kmiecik

IFJ PAN 19.05.2022

Outline

- Giant Resonances
- Idea of the experiment
- The experimental setup
- Results
- Continuation

Collaboration

M. K., B. Wasilewska, M. Ciemała, A. Maj,
P. Bednarczyk, I. Ciepał, N. Cieplicka-Oryńczak, B. Fornal, J. Grębosz,
Ł. W. Iskra, M. Jeżabek, M. Krzysiek, P. Lasko, J. Łukasik,
M. Matejska-Minda, K. Mazurek, W. Parol, P. Pawłowski, B. Sowicki,
A. Szperłak, M. Ziębliński – **IFJ PAN Kraków**

F.C.L. Crespi, A. Bracco, S. Brambilla, S. Bottoni, F. Camera, S. Leoni,
A. Giaz, O. Wieland - **Università degli Studi di Milano and INFN, Milano**

M. Harakeh - **KVI Groningen**

P. Napiorkowski, M. Saxena – **SLCJ Warszawa**

A. Tamii, J. Isaak - **RCNP, Osaka**

A. Krasznahorkay, M. Csatlos - **ATOMKI, Debrecen**

M. Lewitowicz – **GANIL, Caen**

V. Guadilla – **IFIC Valencia**

Ch. Schmitt, S. Kihel – **IPHC Strasbourg**

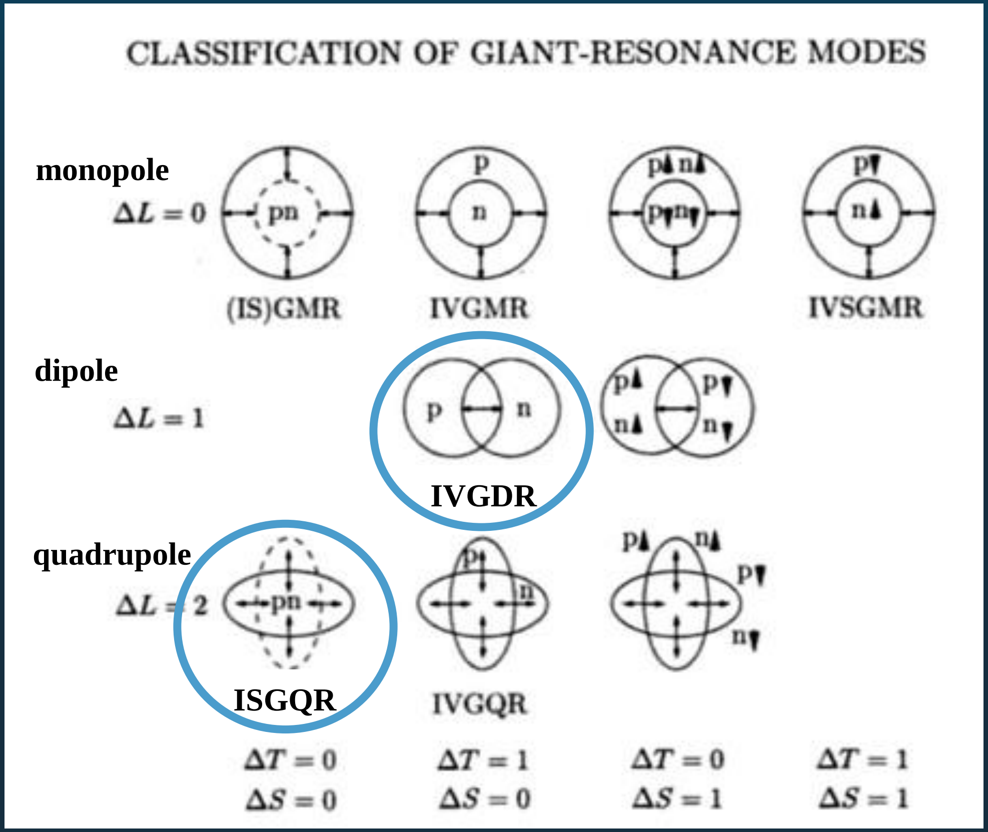
Li Q. Qi – **IPN Orsay**

M. Stanoiu – **NIPNE Bucharest**

Giant resonances

Giant resonances correspond to a collective motion involving many if not all the particles in the nucleus.

collective excitations



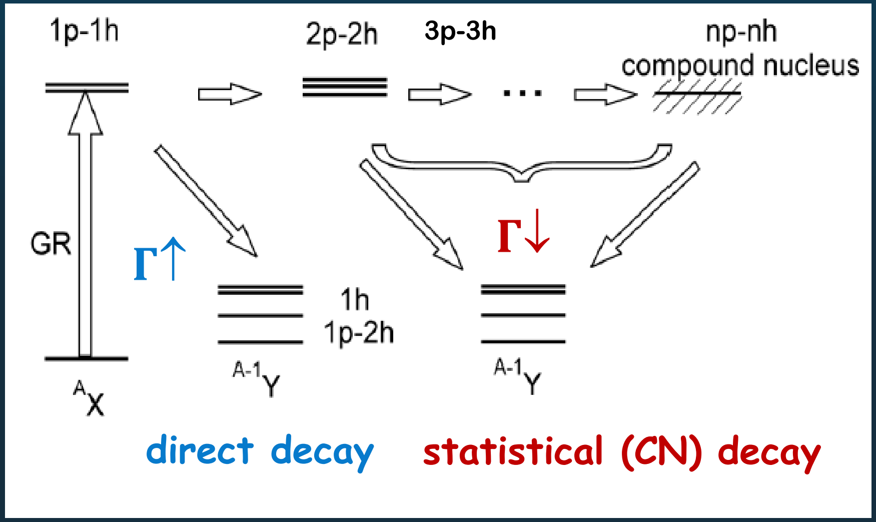
M. N. Harakeh and A. van der Woude,
„Giant Resonances; Fundamental High-Frequency Modes of Nuclear Excitation”,
Oxford University Press, Oxford (2001)

Giant resonances

microscopically:
coherent superposition of particle-hole excitations

two step decay:

$$\Gamma = \Gamma\uparrow + \Gamma\downarrow$$

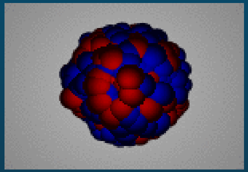


$\Gamma\uparrow$ - decay of single particle state (immediate emission of a particle) „escape width"

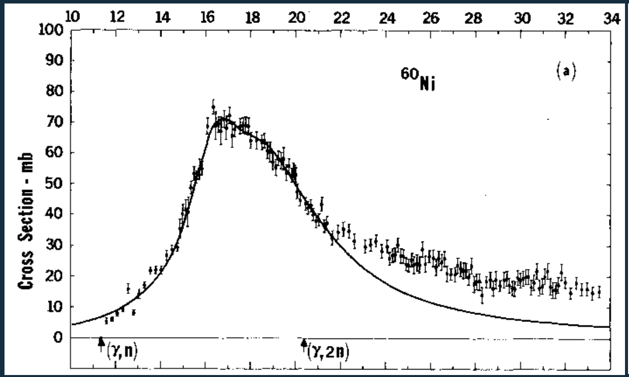
$\Gamma\downarrow$ - energy distributed among many-particle states „spreading width"

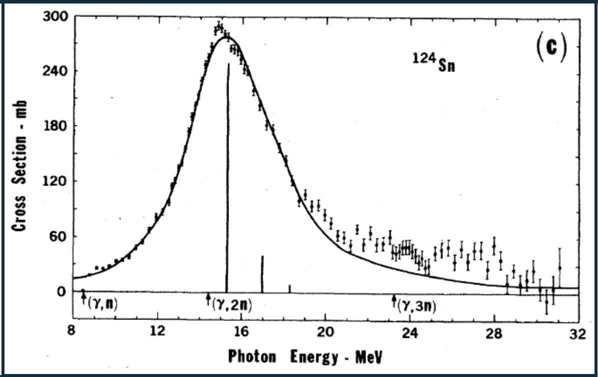
M. N. Harakeh and A. van der Woude, „Giant Resonances; Fundamental High-Frequency Modes of Nuclear Excitation", Oxford University Press, Oxford (2001)

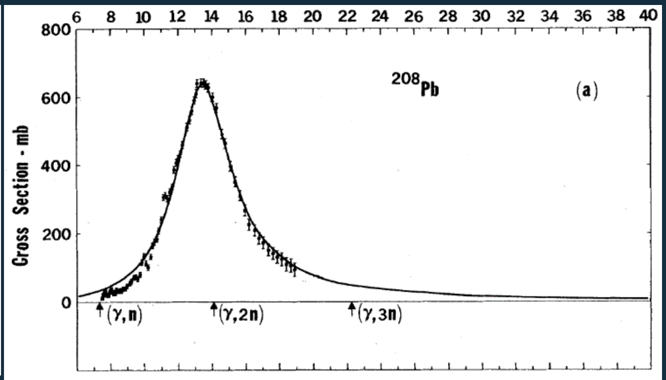
IVGDR (Isovector Giant Dipole Resonance)



- The giant electric dipole isovector resonance – giant dipole resonance (**GDR**) is the best known of the nuclear giant resonances.
- Observed for the first time in 1947 and 1948 by Baldwin and Klaiber in (γ,fission) and (γ,n) reactions
- Measured using photoabsorbtion reactions for different nuclei from ^{3}He to ^{238}U (Berman and Fultz 1975)





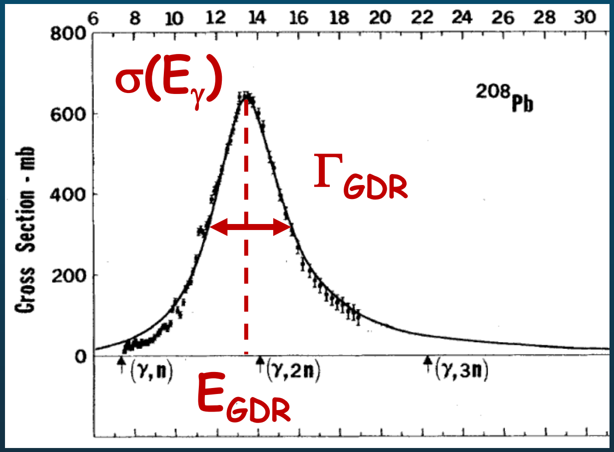


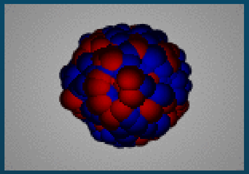
GDR γ-decay – the main subject of studies conducted by our group for many years

GDR

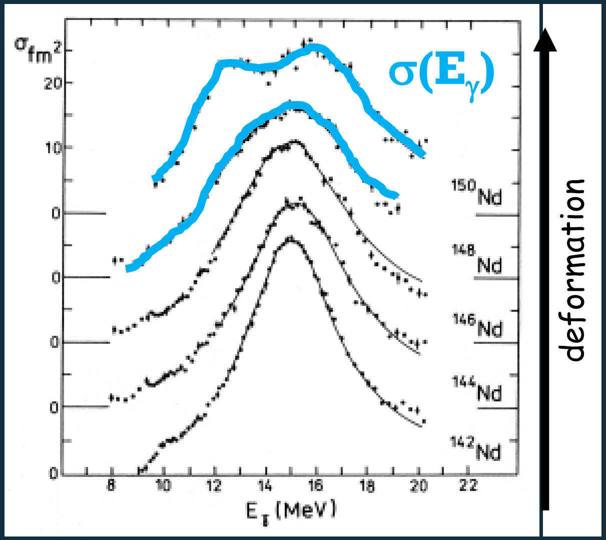
GDR strength function:

$$\sigma(E_\gamma) = \frac{\sigma_0 \Gamma_{GDR}^2 E_\gamma^2}{(E_\gamma^2 - E_{GDR}^2)^2 + \Gamma_{GDR}^2 E_\gamma^2}$$

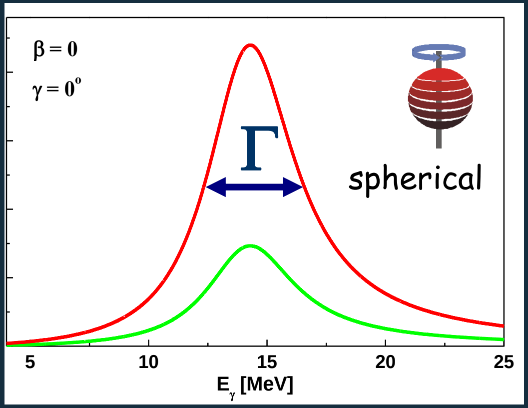


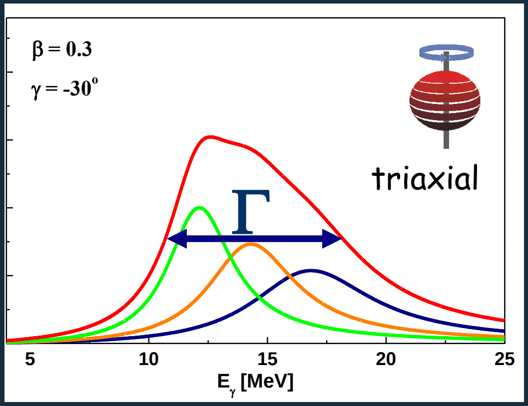


- Strength (calculated from Energy Weighted Sum Rule)
- Excitation energy – centroid (E_{GDR}), energy of oscillations ~ 1/R
- Width (Γ_{GDR}), Γ $_{GDR}$ ~ -1/t



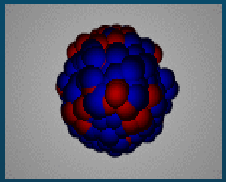
GDR strength function → nuclear deformation



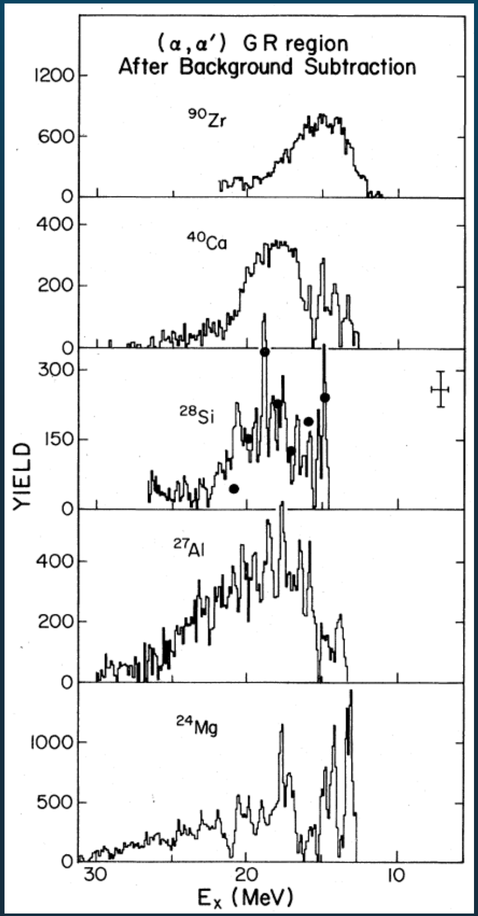


GDR is a very good tool for studying hot atomic nuclei

ISGQR (Isoscalar Giant Quadrupole Resonance)



D.H. Youngblood et al.,
Phys. Rev. C15, 1644 (1977)

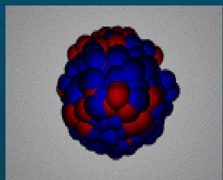


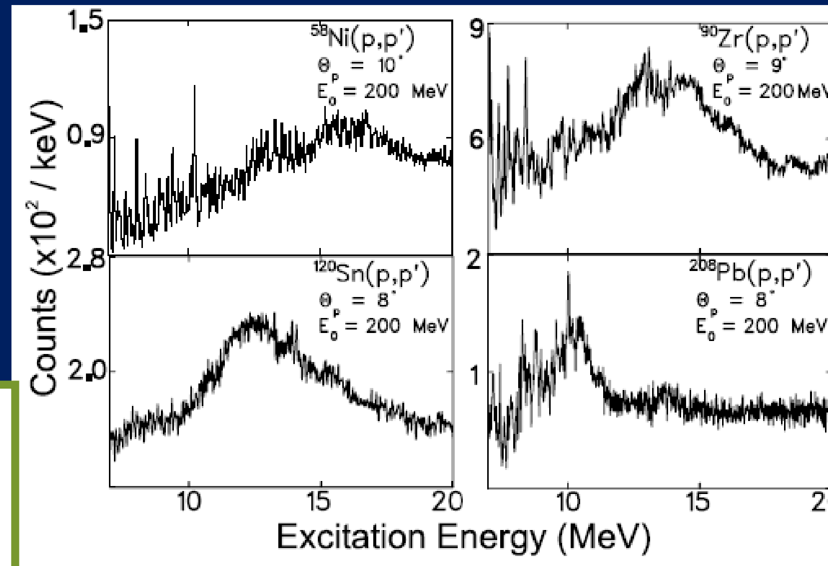
- First evidence of **GQR** in 1971 in inelastic scattering of electrons. Confirmed in 1972 by Fukuda and Torizuka using inelastic electron scattering and by Lewis and Bertrand with inelastic proton scattering.
- It has been observed in nuclei with $16 \leq A \leq 238$. In light nuclei its strength distribution is fragmented while for heavy it has Gaussian or Lorentzian distribution.

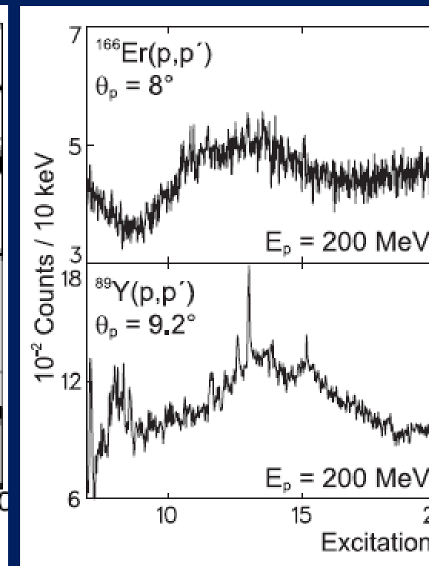
Still not well known

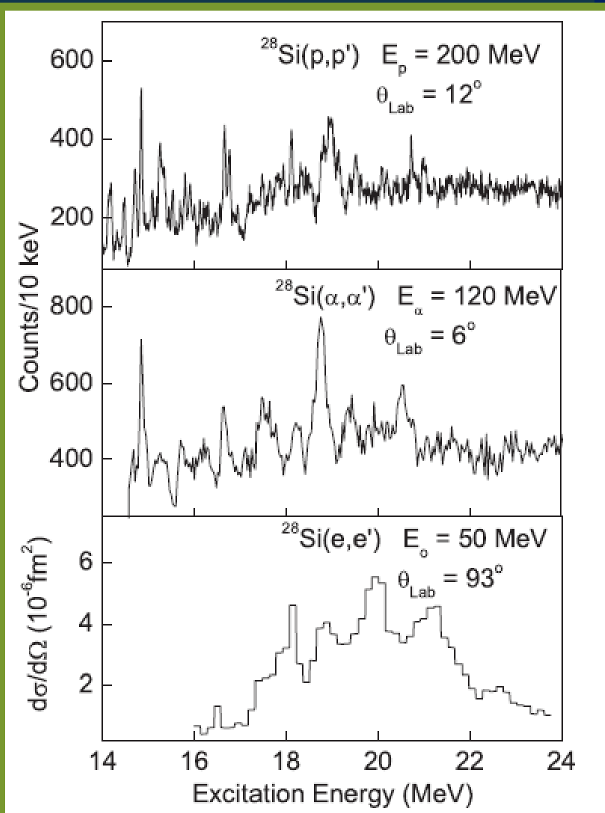
GQR - examples

A. Shevchenko et al., Phys. Rev. Lett. 93 (2004) 122501-1
A. Shevchenko et al., Phys. Rev. C79, 044305 (2009)









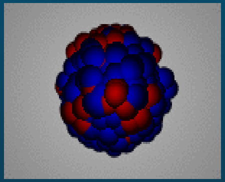
I.T. Usman et al.,
Phys. Rev. C94, 024308 (2016)

K. van der Borg et al.,
Nucl. Phys. A341, 219 (1980)

A. Richter, Prog. Part.Nucl.
Phys. 13, 1 (1985)

structrue, fragmented strength
and decay needed to be investigated

GQR γ-decay



GQR γ-decay observed previously only once, in 1980s

difficult to measure
very small probability ~10^{-4}

Inelastic scattering
of 381 MeV ^{17}O on ^{208}Pb

coincidence measurement
of gamma rays and scattered ions

excitation energy obtained from measured scattered beam energy

E* = E beam – E scattered ion

J.Beene et al., PRC39(1989)1307

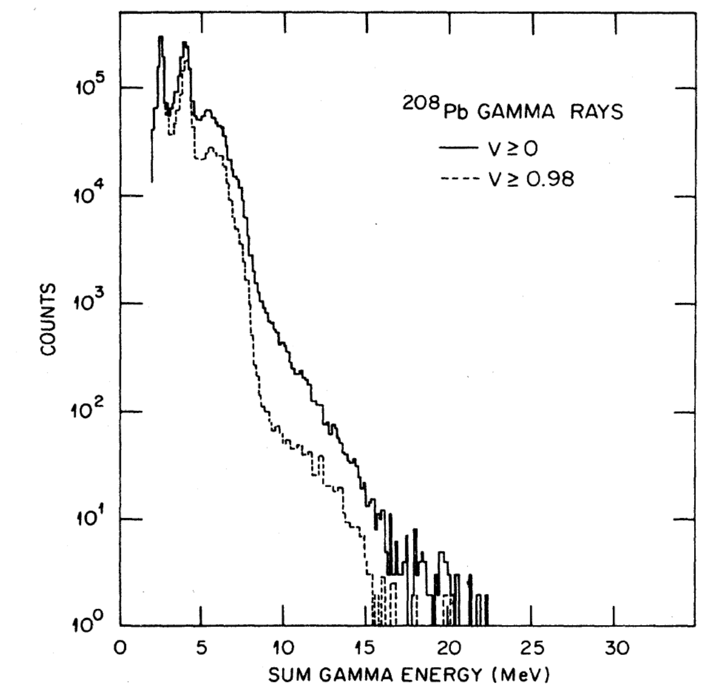


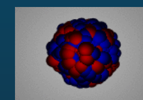
FIG. 5. Gamma-ray spectra from ^{208}Pb for $V \geq 0.98$ (only ground-state gamma rays), and $V \geq 0$ (all gamma rays).

Eγ [MeV]

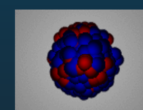
Idea of the experiment

nuclear excitations induced by proton inelastic scattering

IVGDR (Isovector Giant Dipole Resonance)

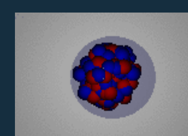


ISGQR (Isoscalar Giant Quadrupole Resonance)

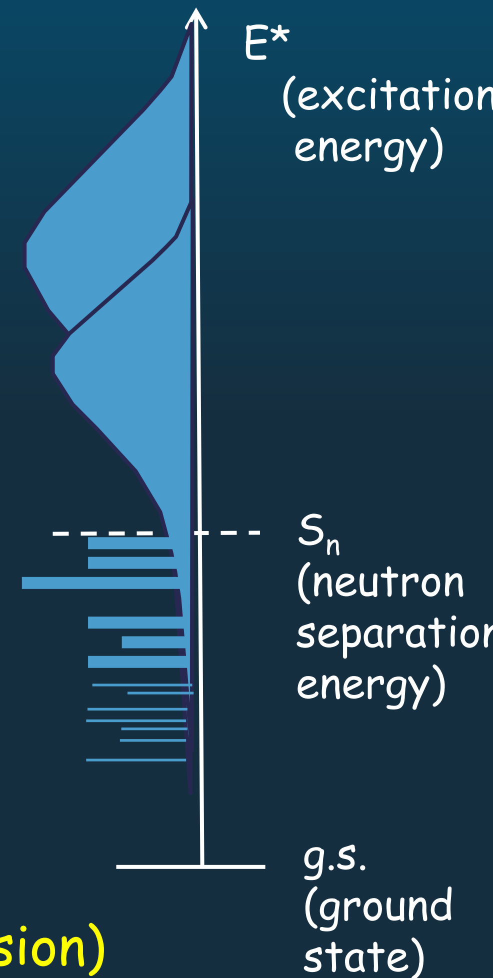


main aim – GQR γ decay

pygmy states, PDR
(Pygmy Dipole Resonance)



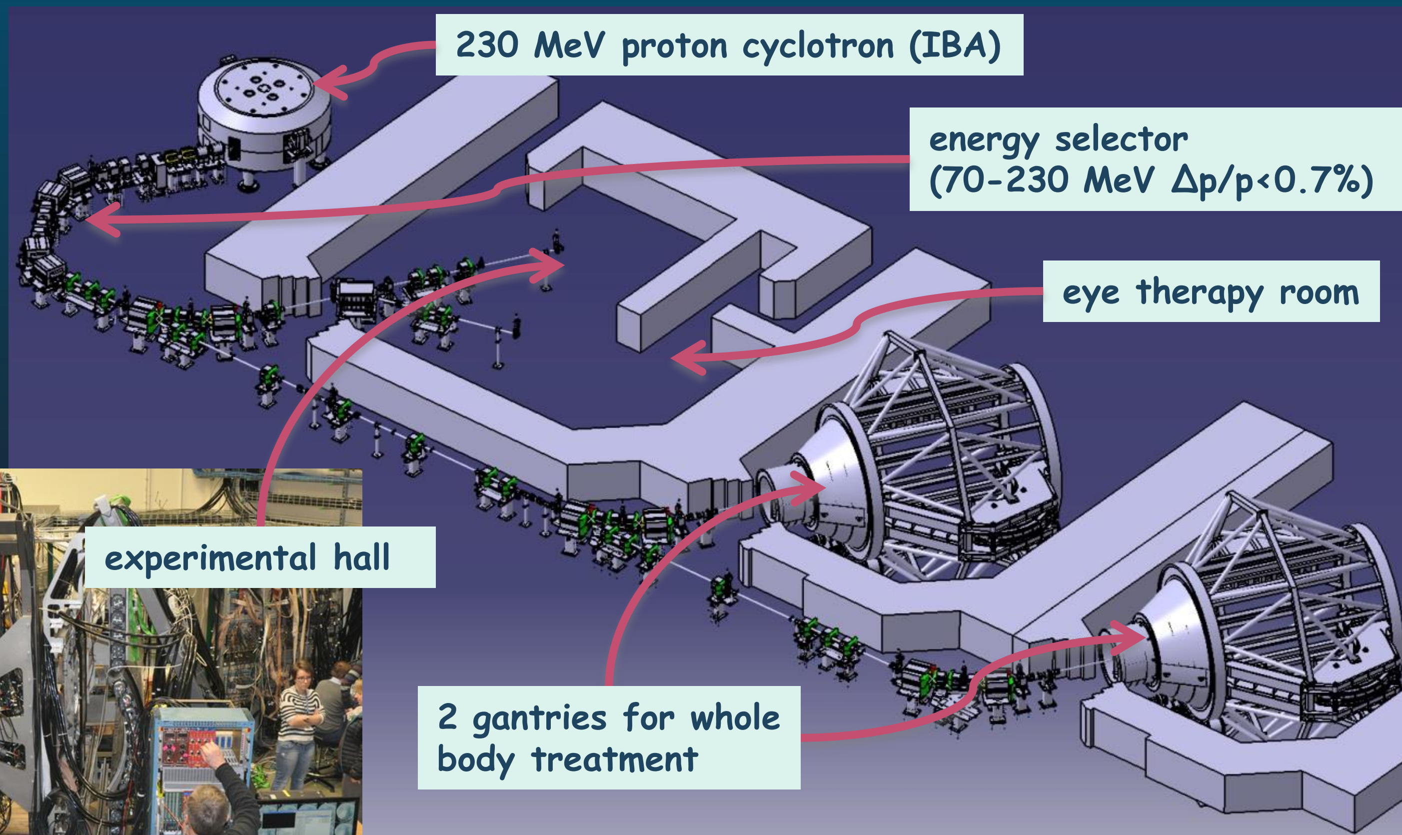
discrete transitions

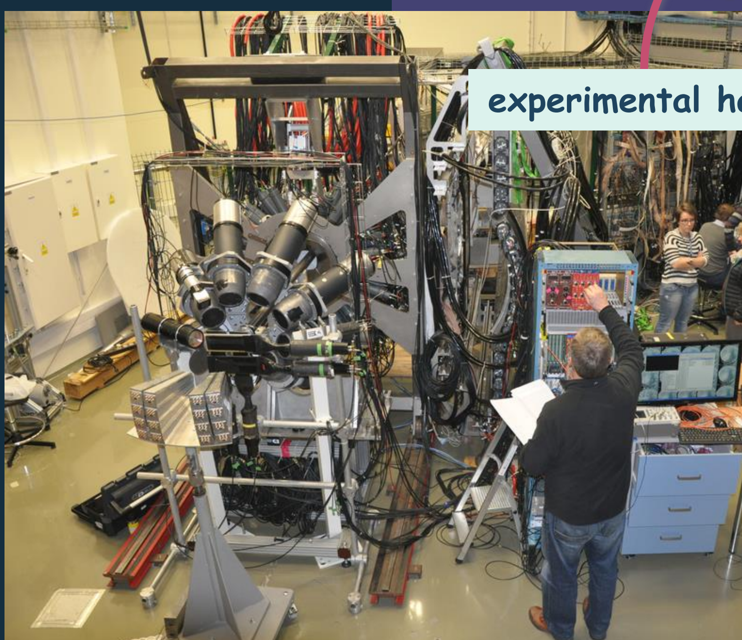


measurement of γ-rays emitted from the decay
(above neutron threshold hindered by neutron emission)

10^{-2} for GDR and 10^{-4} for GQR

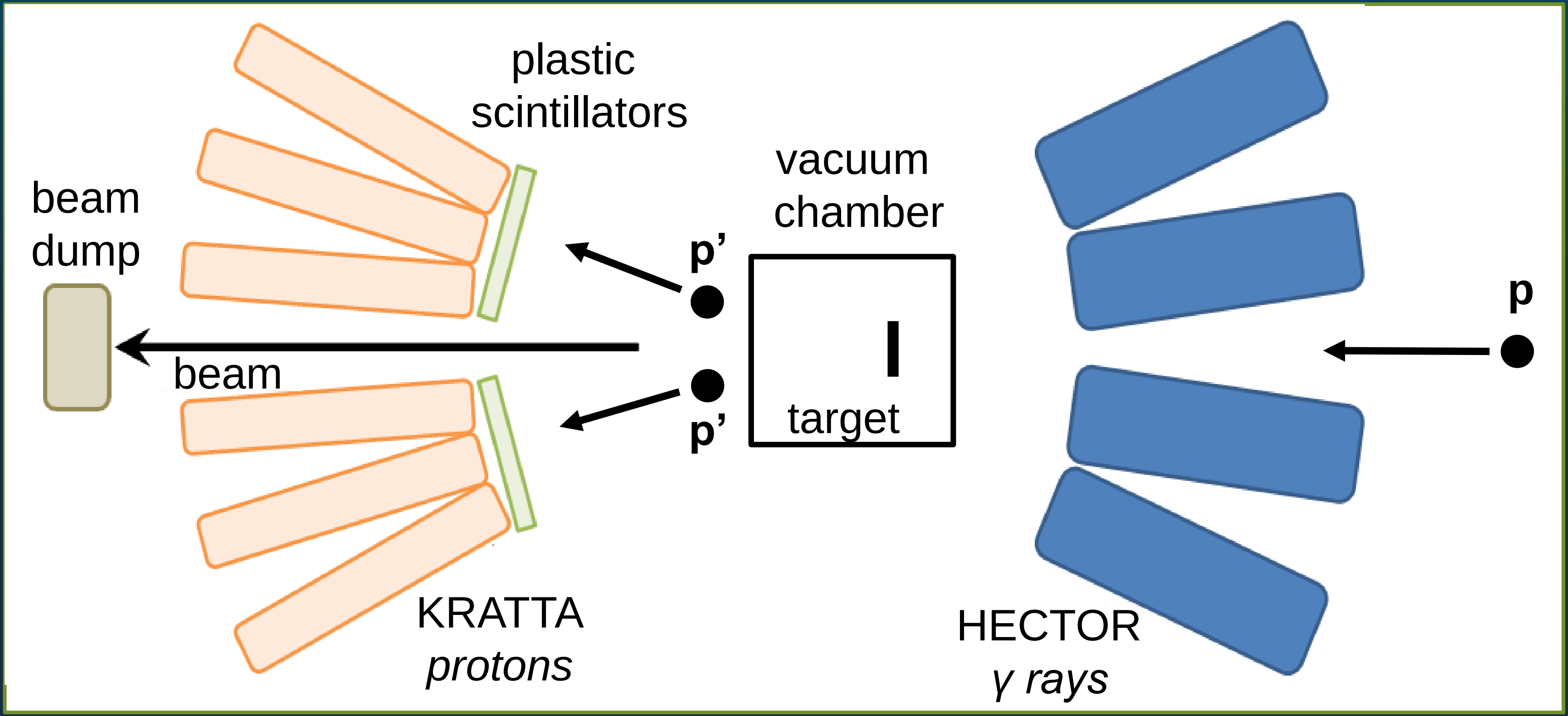
The experimental hall at CCB





The experimental setup scheme

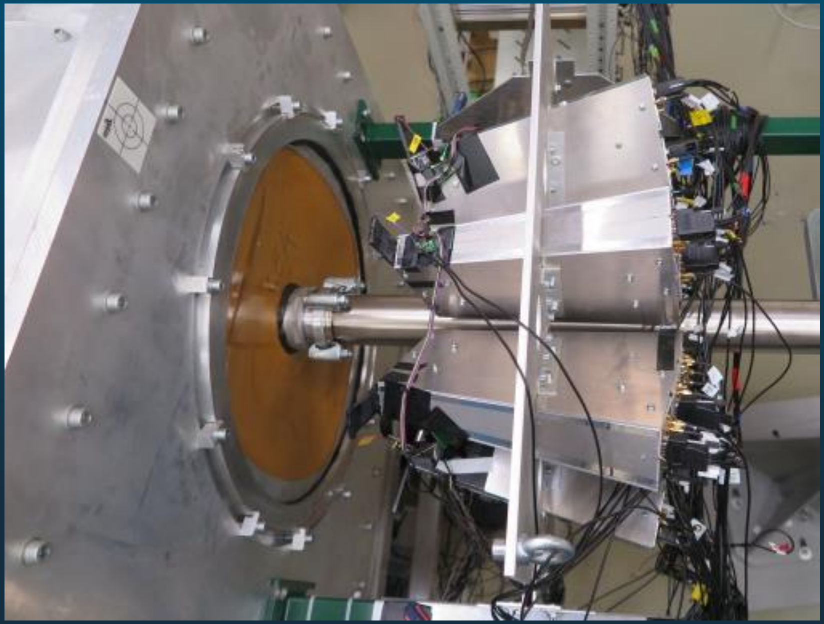
coincidence measurement of gamma rays and scattered protons

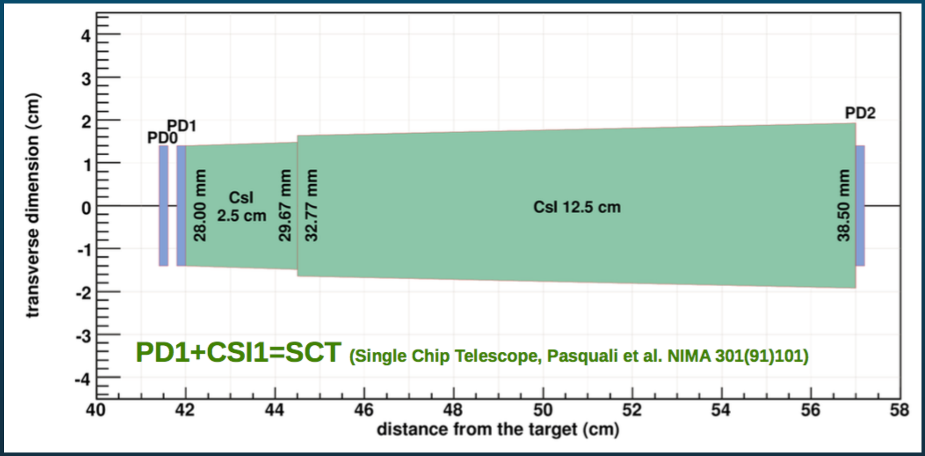


New experimental setup built

KRATTA (Kraków Triple Telescope Array)

scattered protons detectors



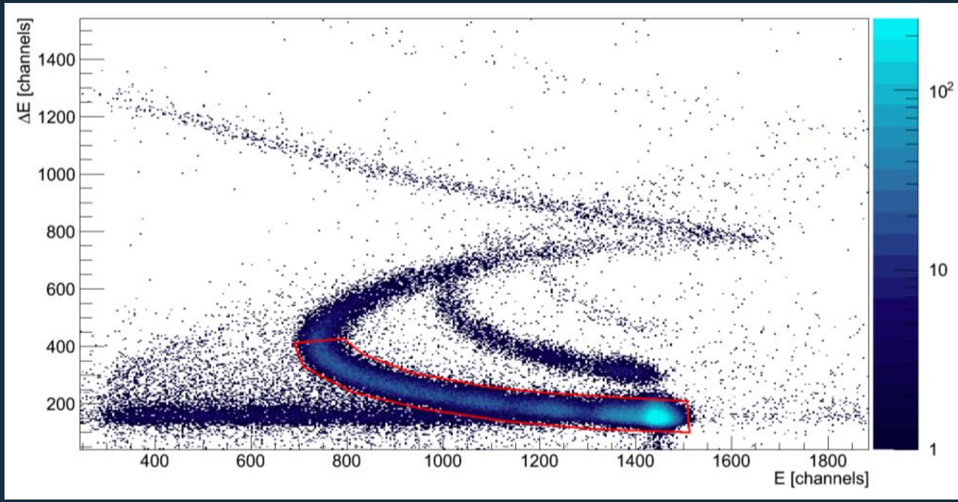


KRATTA (16 CsI telescopes)

Proton energy: 2.5 - 260 MeV
Energy resolution: 1-2%
Angular resolution at 40 cm: 3.9°

plastic scintillators
in front of KRATTA
0.5 cm thick
almost 100% efficiency
very good time definition

90 cm from the target



γ-ray detectors

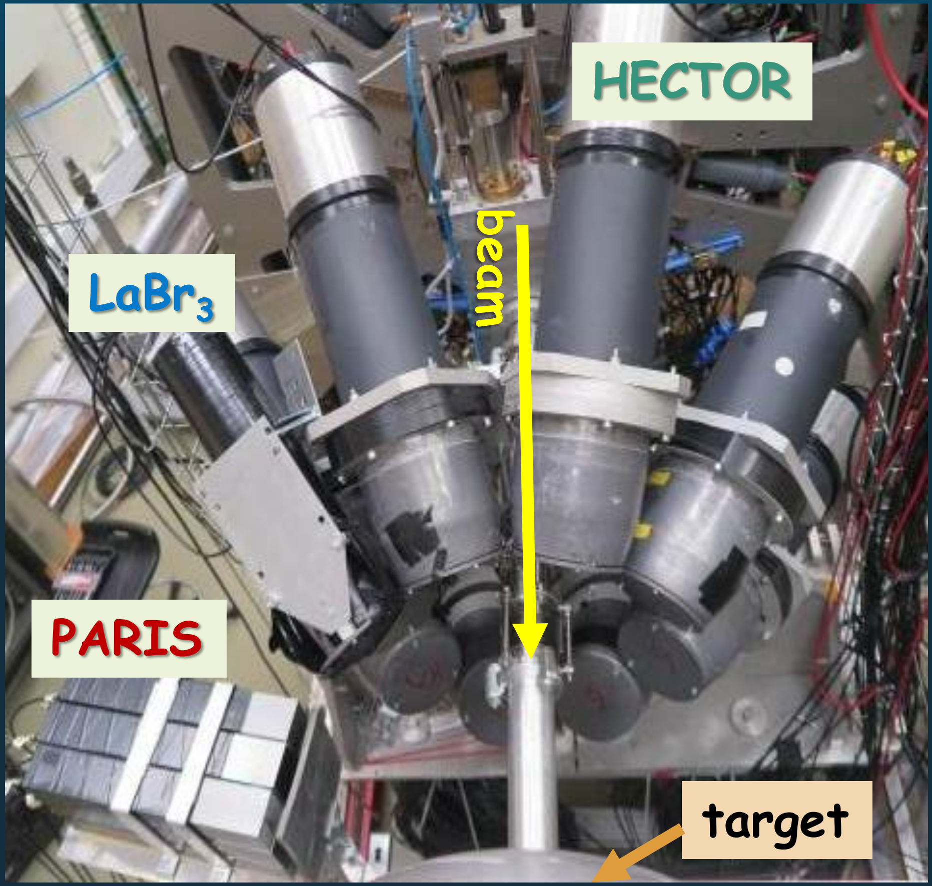
HECTOR - 8 BaF_2
(14.5 cm (φ) x 17.5 cm)

$LaBr_3$ (large volume 3.5"x8")

PARIS (cluster of 9 „phoswiches"
$LaBr_3/CeBr_3$ + NaI
2"x2"x2" + 2"x2"x6")

- High efficiency
- Good time resolution

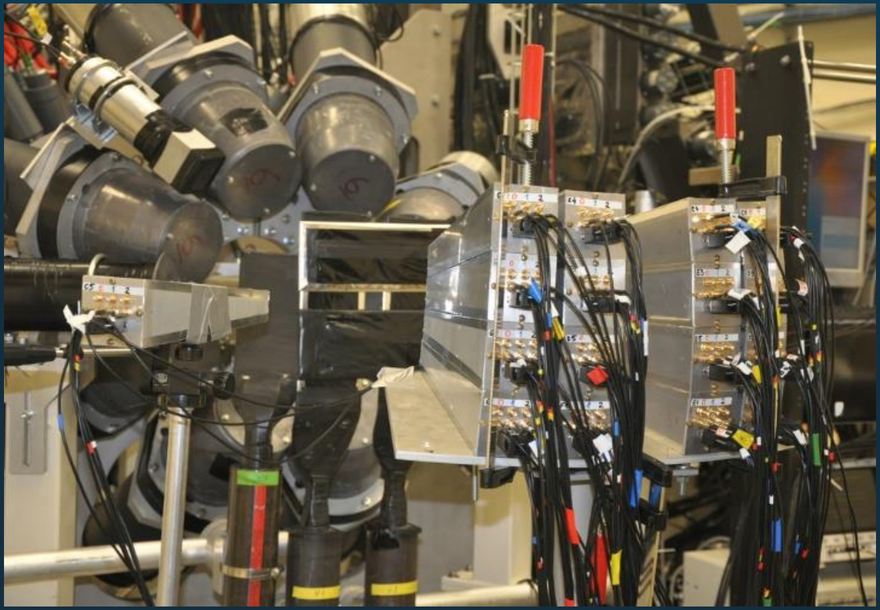
35 cm from the target



Test measurements

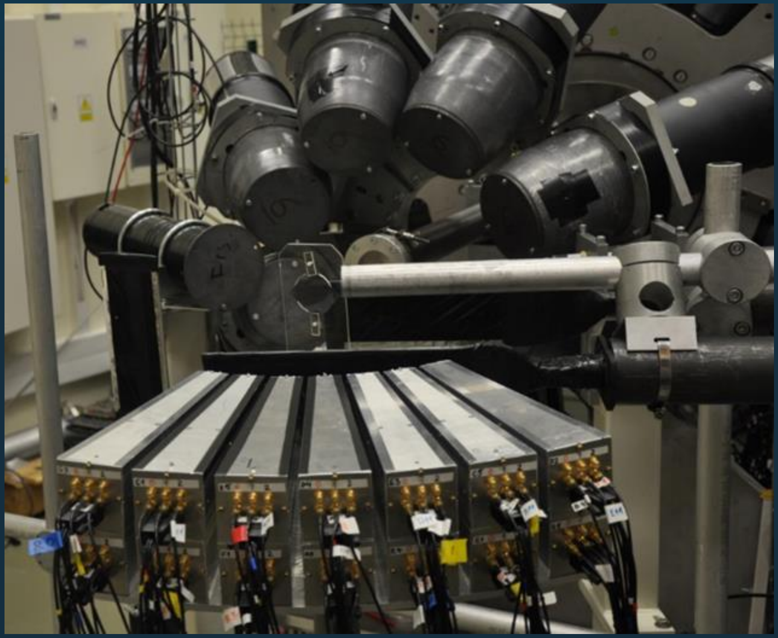
First coincidence test experiment
(KRATTA and HECTOR) - December 2015

p @ 80 MeV on ^{12}C
(graphite) target – 1mm



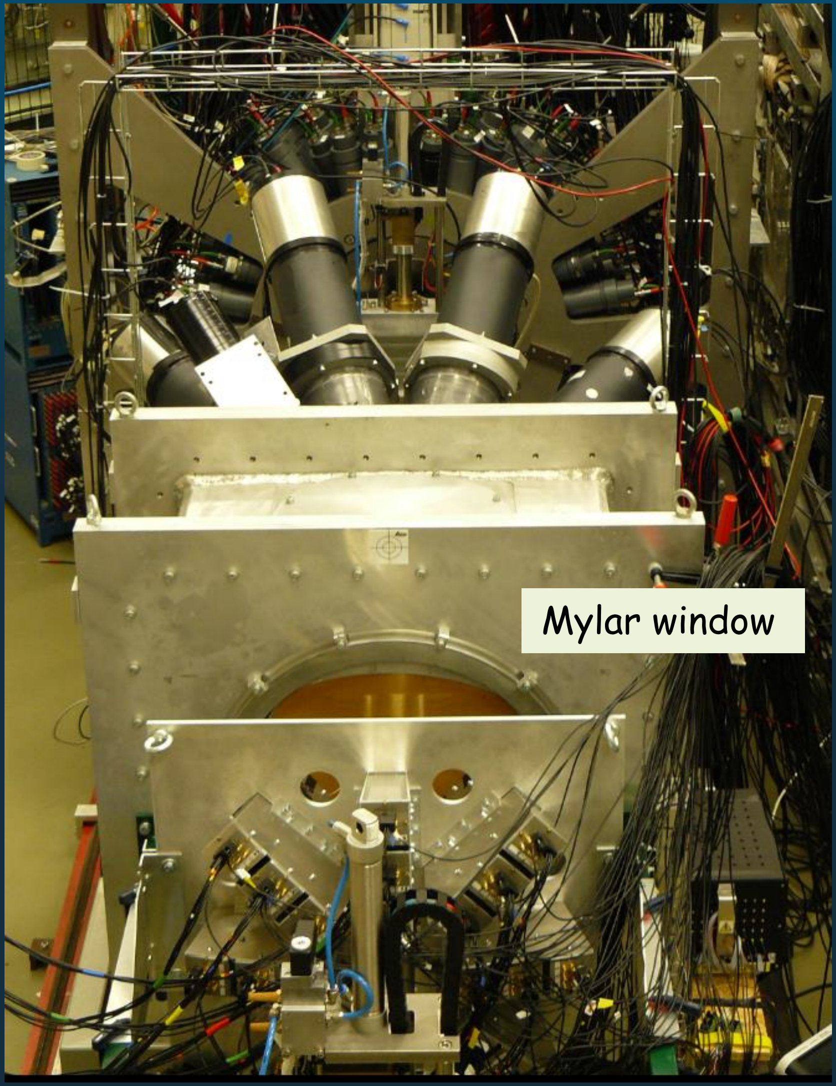
p @ 85 MeV on Pb
(0.2 mm) target - 2016

KRATTA with plastic scintillators

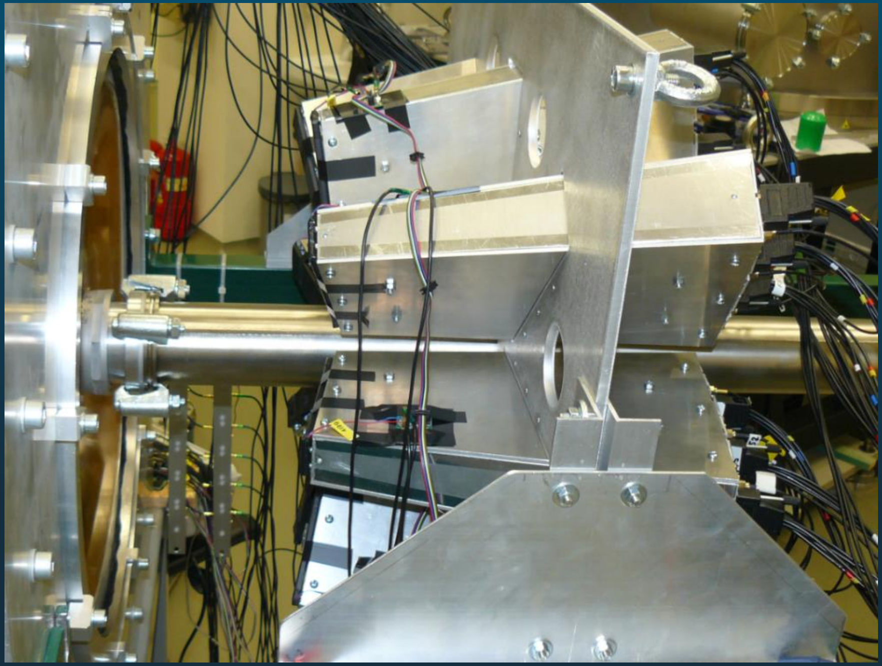


target in the air

Scattering chamber and KRATTA holder



small BINA chamber



KRATTA at angles 8.9° - 14.3°
with resolution 1.8°

plastic detectors
in the front
of every 3 KRATTA modules

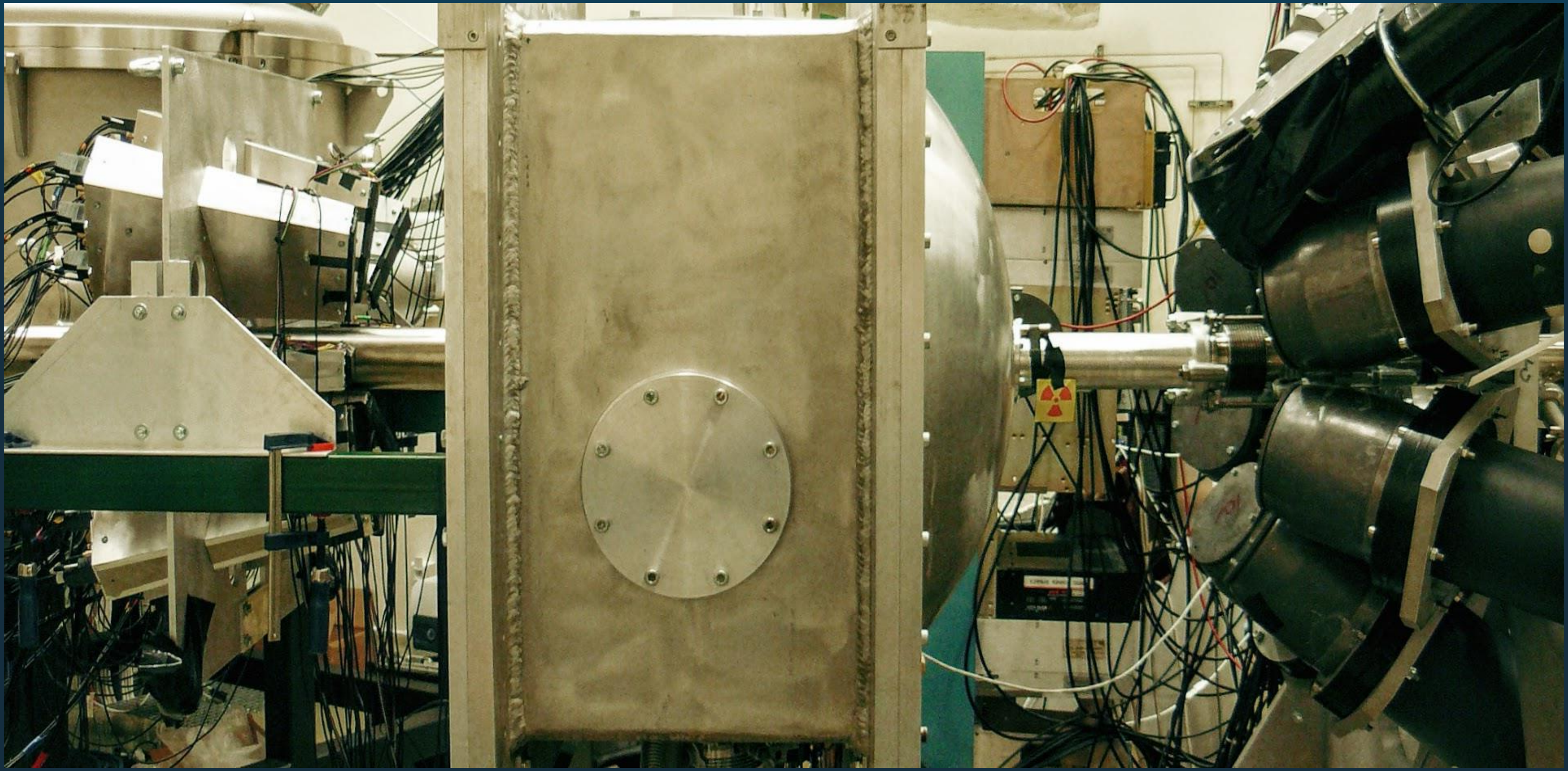
Experiment

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

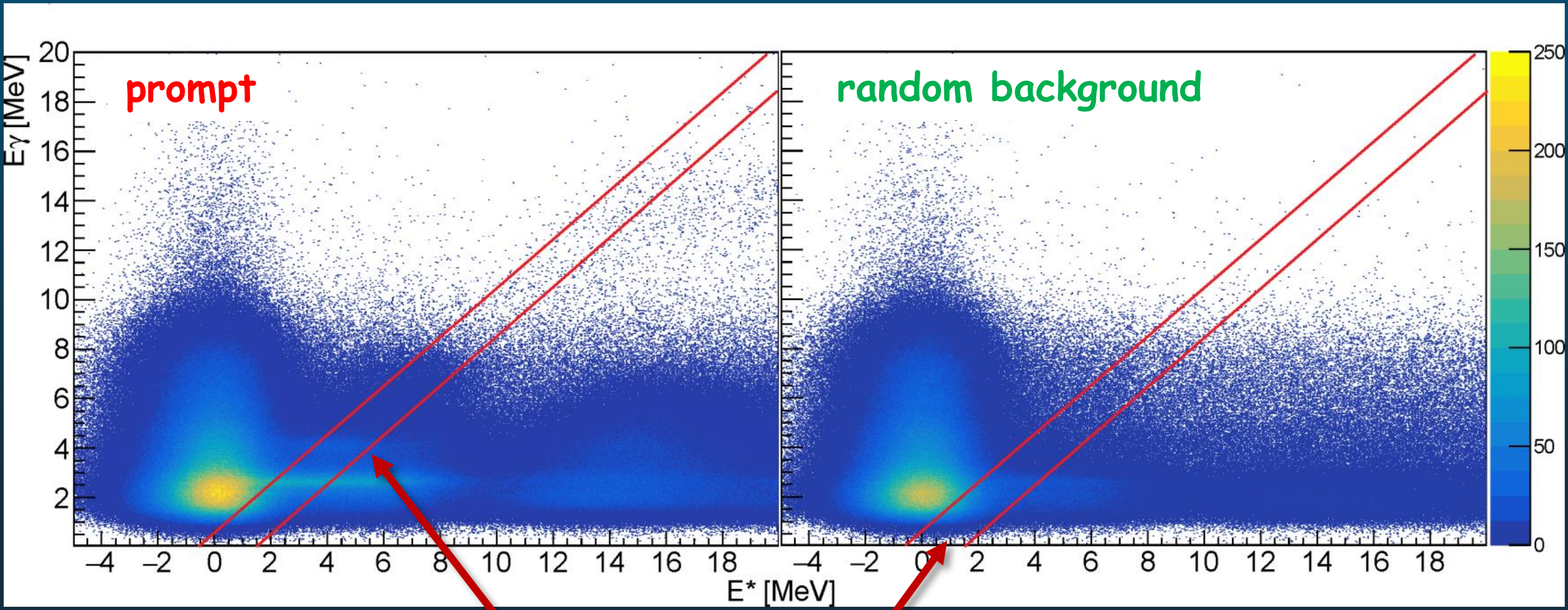
KRATTA (protons)

vacuum
scattering chamber

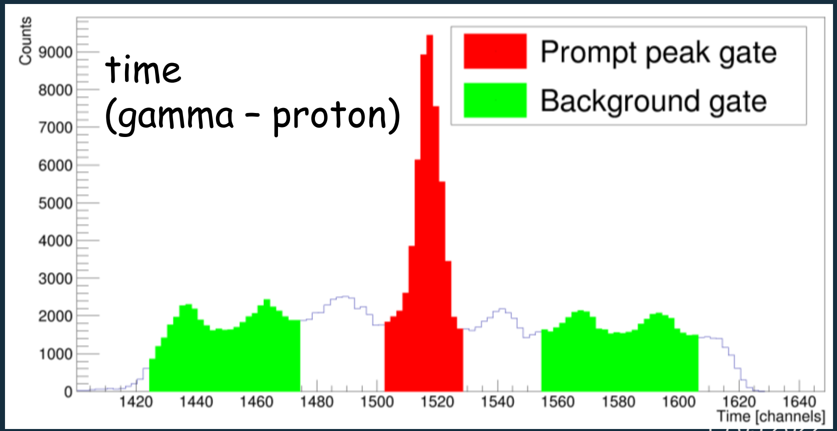
HECTOR + $LaBr_3$ + PARIS
(γ-rays)



γ-ray energy vs excitation energy



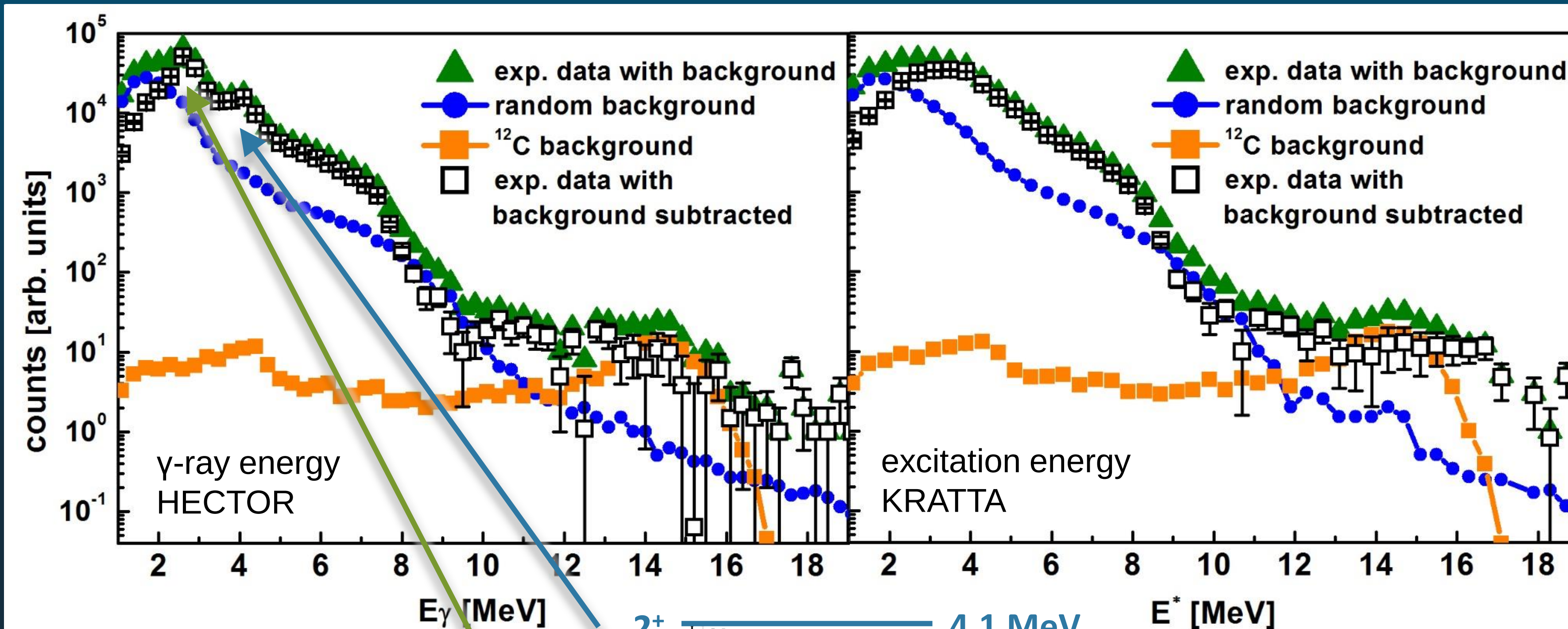
decay to the ground state ([Eγ+0.5-E*] ≤ 1 MeV)

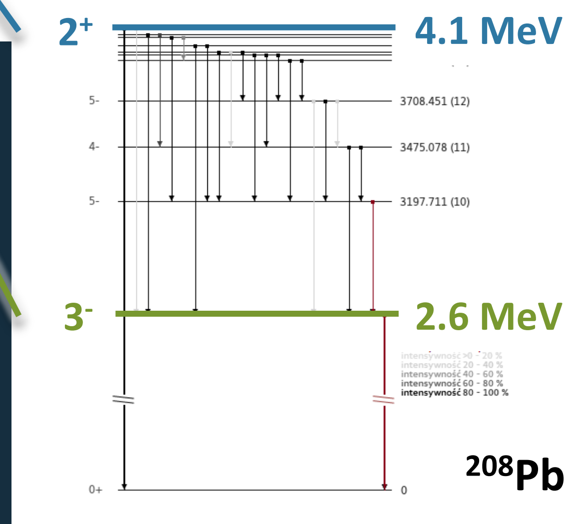


^{208}Pb S_n = 7.368 MeV

$E^* = E_{beam} - E_{scattered\ proton}$

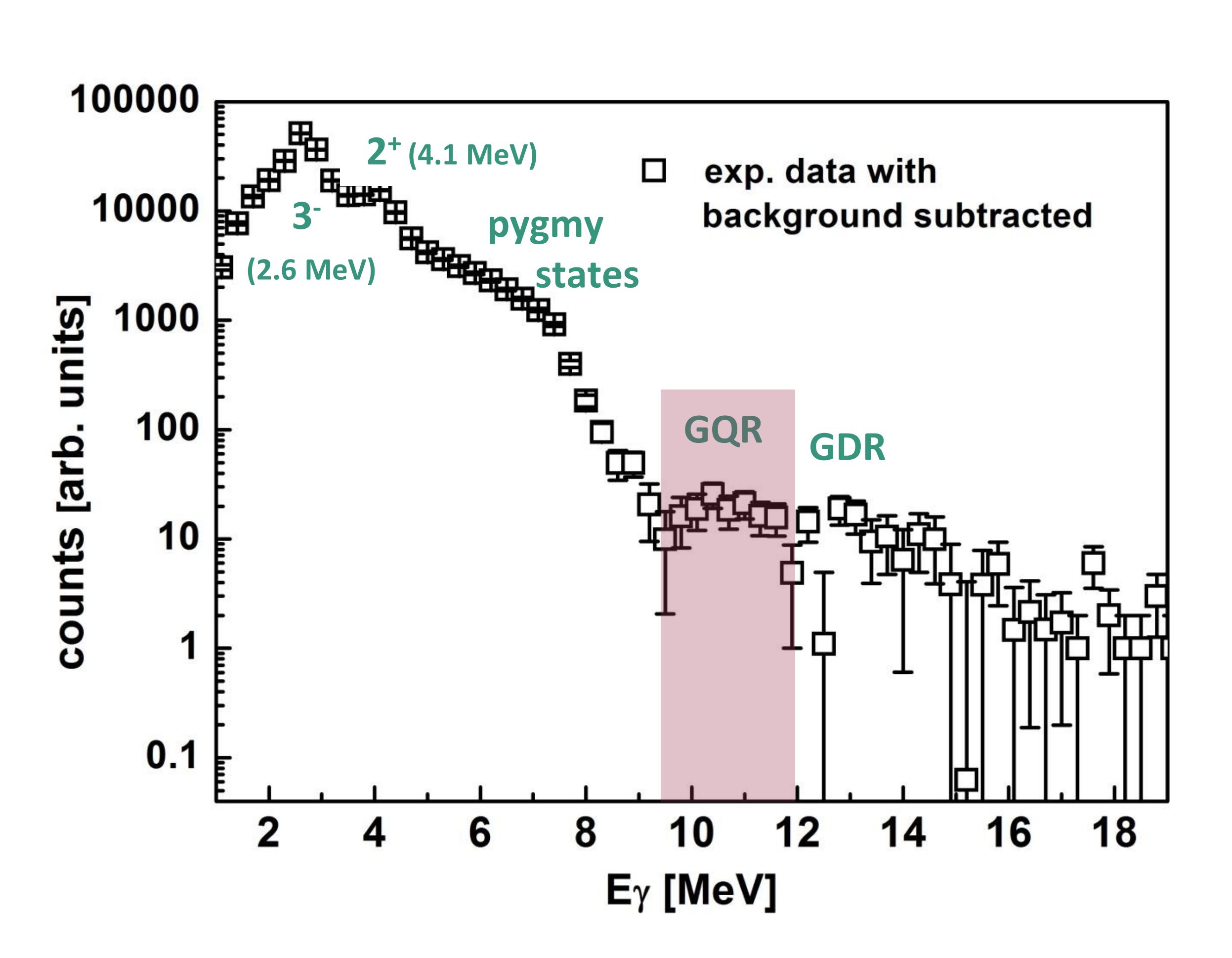
Background subtraction





^{12}C background ~ 0.1 % of exp. data

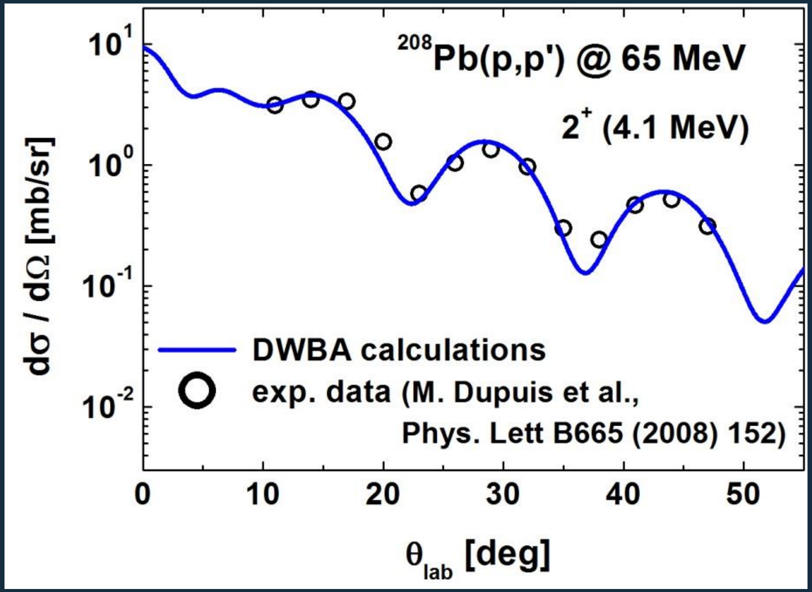
Background subtracted γ-ray spectrum



Method of analysis

- Calculations of cross sections for excitations in ^{208}Pb
- Extraction of γ–ray decay from GDR to the ground state
- Analysis of GQR part of γ–ray spectrum

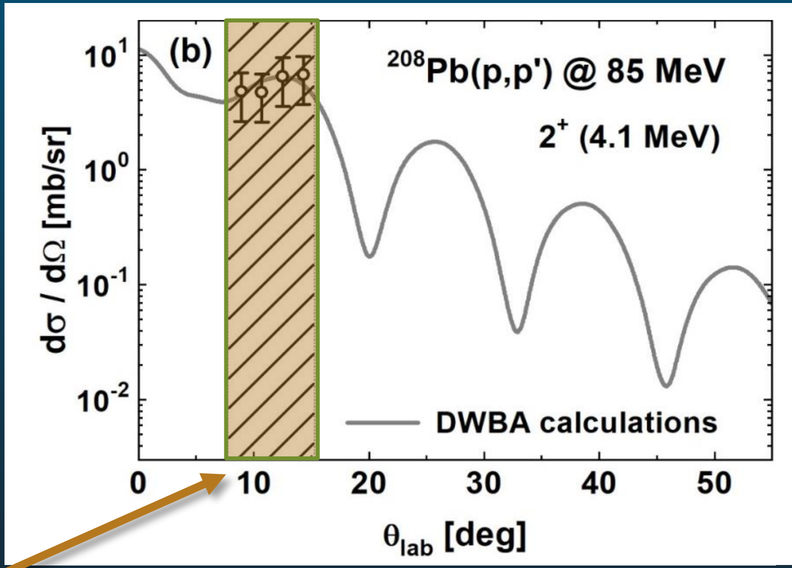
2^+ state cross section



DWBA code FRESCO

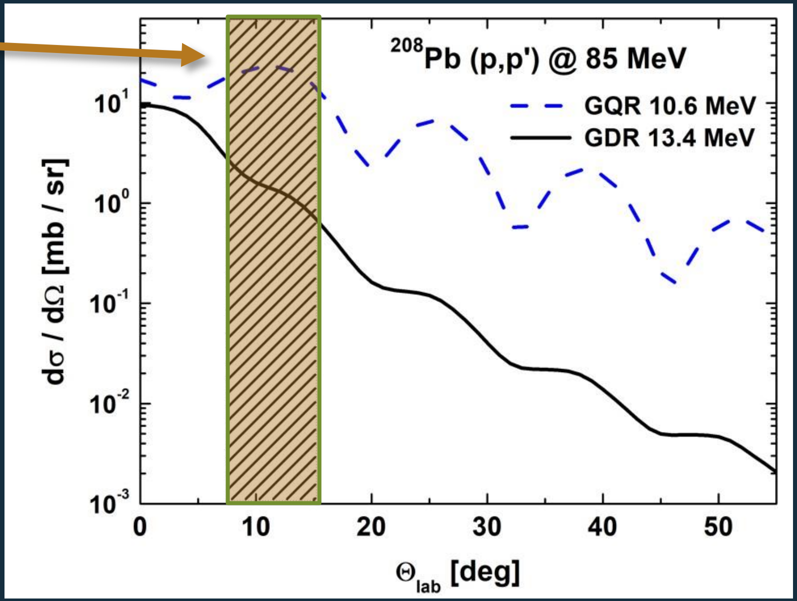
checking the model parameters

Cross sections for excitations in ^{208}Pb



2⁺ state

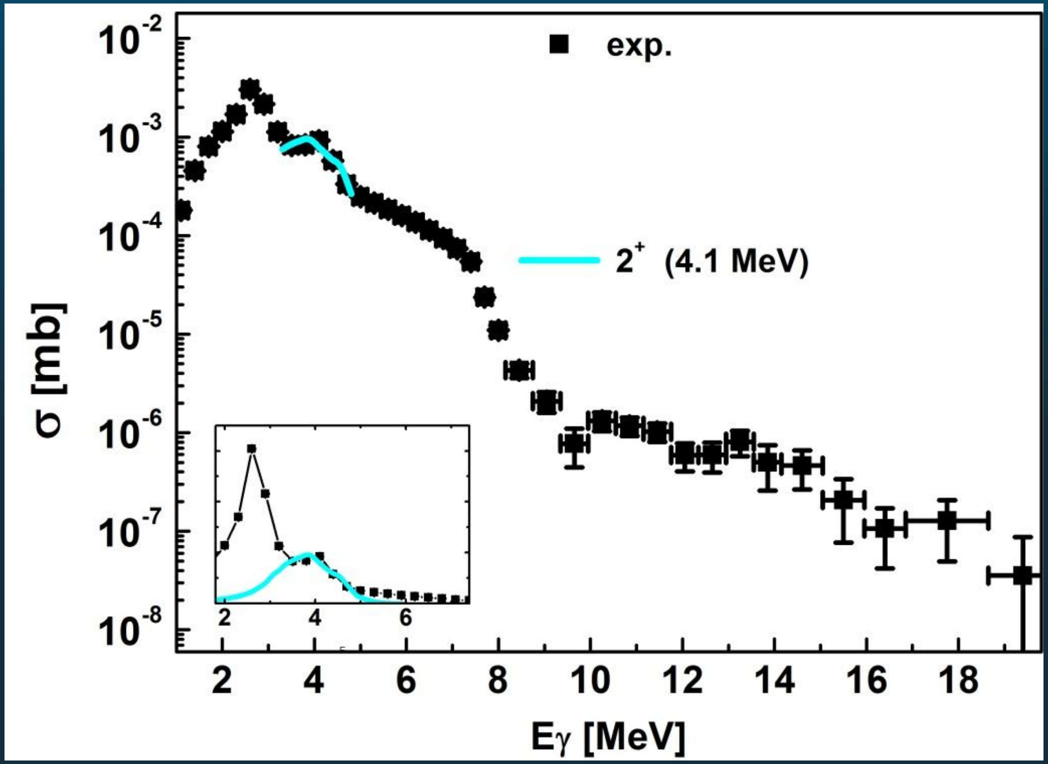
the angles covered by the experimental setup



GQR

GDR

gamma decay cross section



for 2^+ ^{208}Pb

$$\sigma_{p,p'} \approx \sigma_{p,p'\gamma}$$

calculated cross section folded with HECTOR response function

⬇

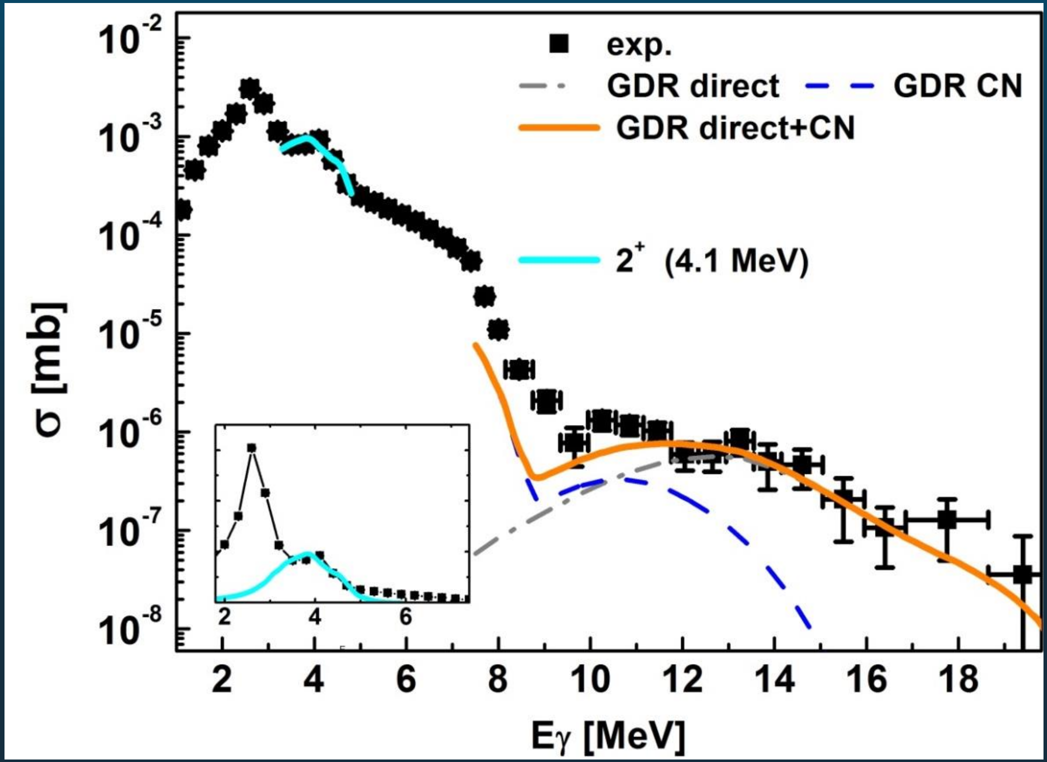
Normalization factor (taking into account the HECTOR and KRATTA efficiency)

GDR analysis

statistical model code ONESTEP

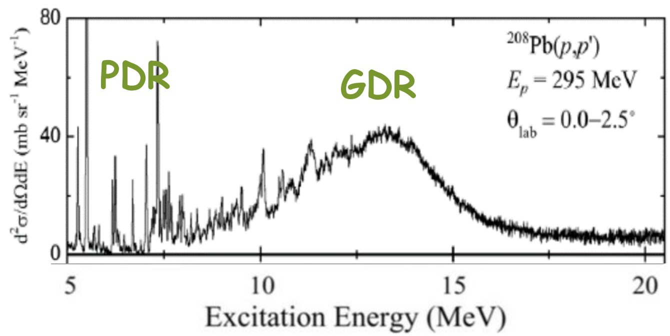
$$\sigma_{p,p'\gamma 0}(E) = \sigma_{p,p'}(E; B(E1)=1)\, b_{E1}(E)\left[\frac{\Gamma_{\gamma 0}}{\Gamma} + \frac{\Gamma\downarrow}{\Gamma} B_{CN}(E)\right] = \boldsymbol{\sigma_{direct}} + \boldsymbol{\sigma_{CN}}$$

direct decay — statistical (CN) decay



calculated for:
B(E1) for 111% EWSR;
E_{GDR} = 13.4 MeV;
Γ_{GDR} = 3.9 MeV

excitation cross section



A. Tamii et al., Phys. Rev. Lett. 107, 062502 (2011)

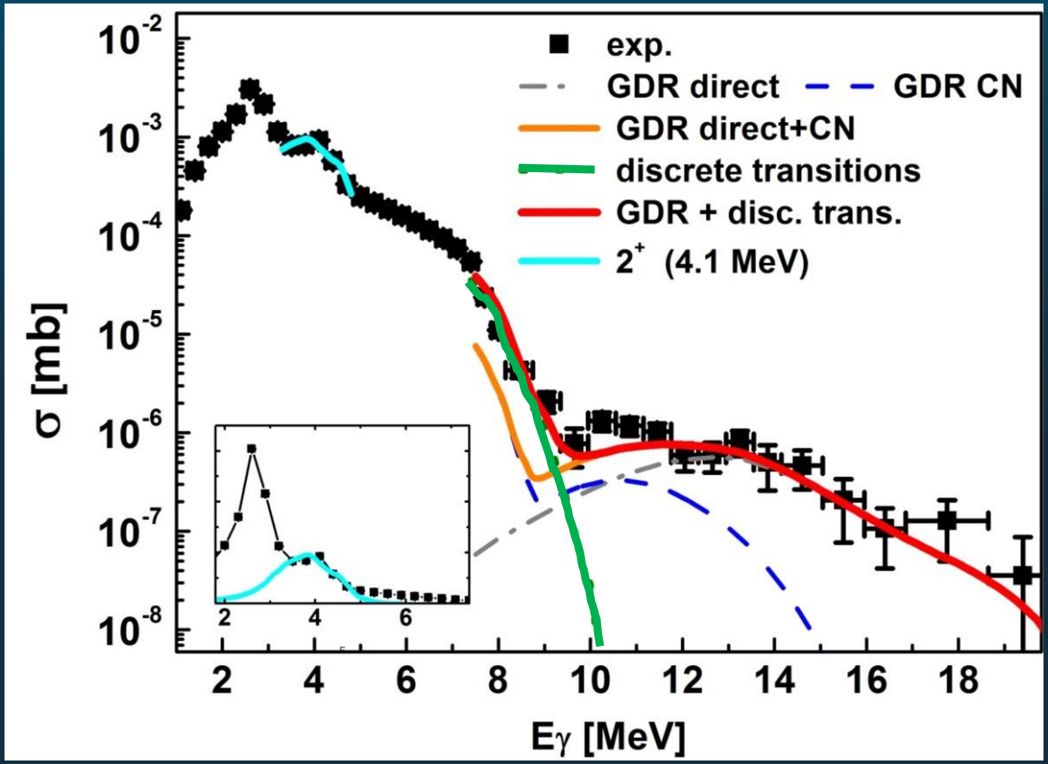
GDR γ-ray decay to the g.s. branching ratio:

$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GDR} = \sum_E \frac{\sigma_{p,p'\gamma 0}(E)}{\sigma_{p,p'}(E)}$$

$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GDR} = \mathbf{1.7\times 10^{-2} \pm 0.5\times 10^{-2}}$$

In agreement with published value

GDR + discrete transitions



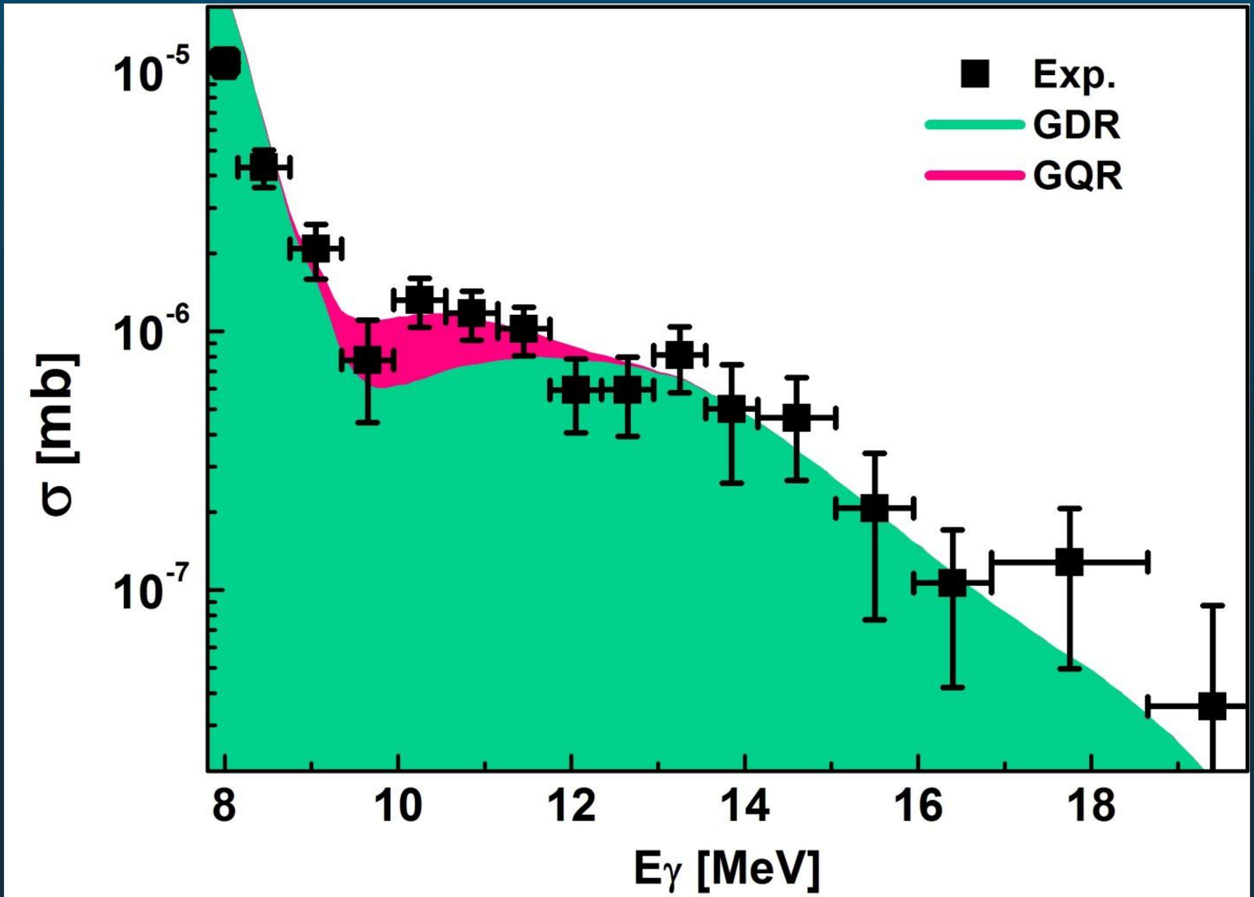
6.26 MeV; 8.37 MeV (1^-)

H. P. Morsch, P. Decowski, and W. Benenson, Nucl. Phys. A 297, 317 (1978)

7.36; 8.86; 9.34 (2^+)

F. E. Bertrand, et al., Phys. Rev. C 34, 45 (1986)

GQR region

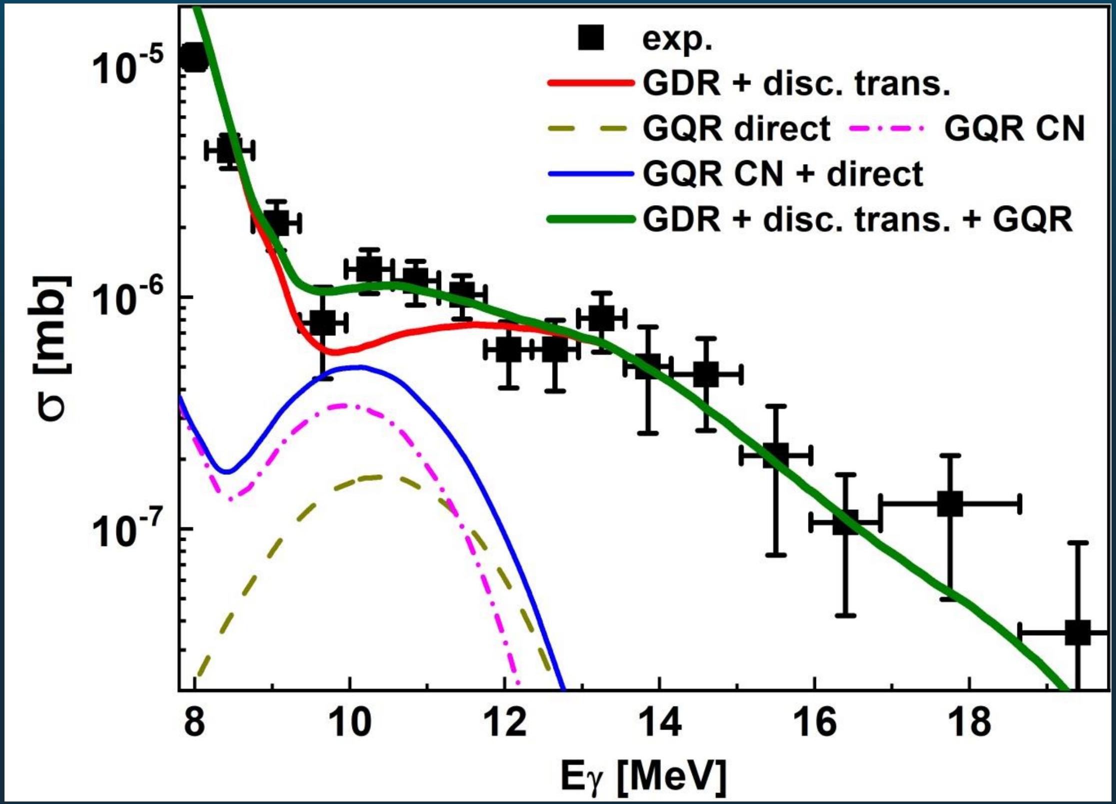


excess in the GQR region

GQR analysis

$$\sigma_{p,p'\gamma 0}(E) = \sigma_{p,p'}(E; B(E2) = 1) b_{E2}(E) \left[\frac{\Gamma_{\gamma 0}}{\Gamma} + \frac{\Gamma\downarrow}{\Gamma} B_{CN}(E)\right] = \boldsymbol{\sigma_{direct}} + \boldsymbol{\sigma_{CN}}$$

direct decay — statistical (CN) decay



calculated for
B(E2) for 112% ± 32% EWSR;
E_{GQR} = 10.6 MeV;
Γ_{GQR} = 2 MeV

GQR γ-ray decay to the g.s. branching ratio:

$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GQR} = \sum_E \frac{\sigma_{p,p'\gamma 0}(E)}{\sigma_{p,p'}(E)}$$

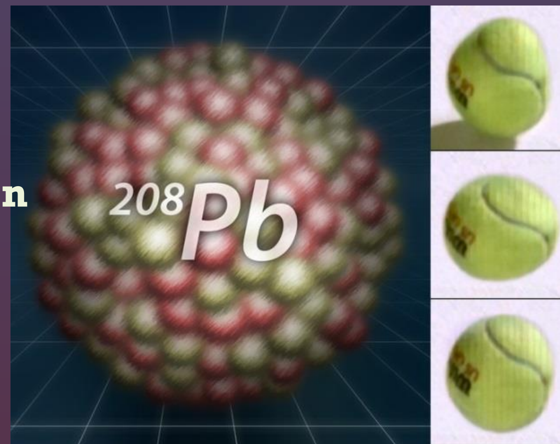
$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GQR} = 3\times 10^{-4} \pm 1\times 10^{-4}$$

GQR γ-decay to g.s. in ^{208}Pb

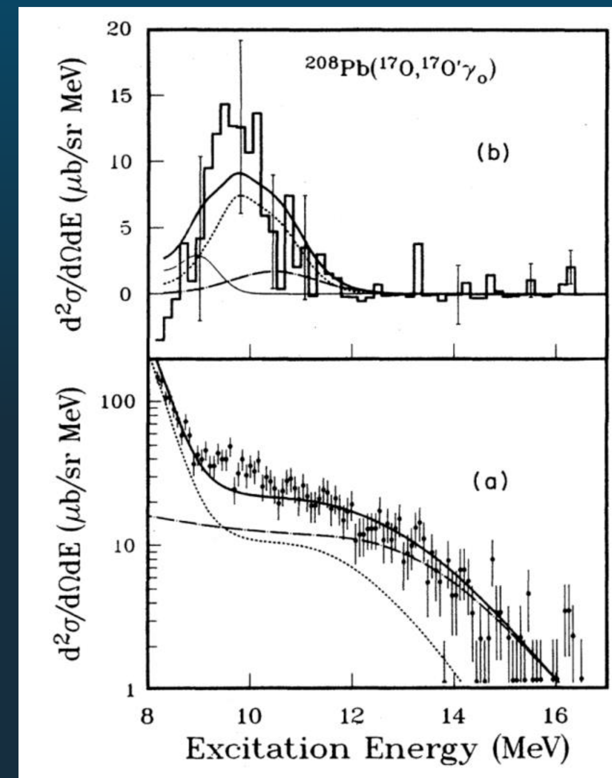
EurekAlert!:

News Release 17-Feb-2022

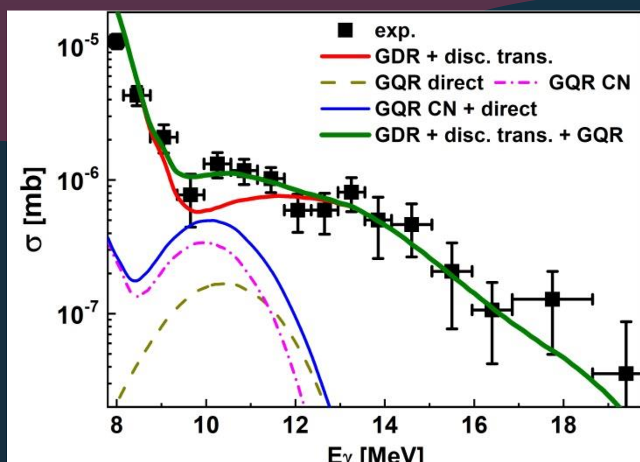
Extremely rare observation of 'tennis-like' vibrations of lead



J.Beene et al., PRC39(1989)1307



Our work:
B.Wasilewska et al., PRC105(2022)014310



γ-ray energy

$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GQR} = 3 \times 10^{-4} \pm 1 \times 10^{-4}$$

excitation energy measured in coincidence with γ-rays

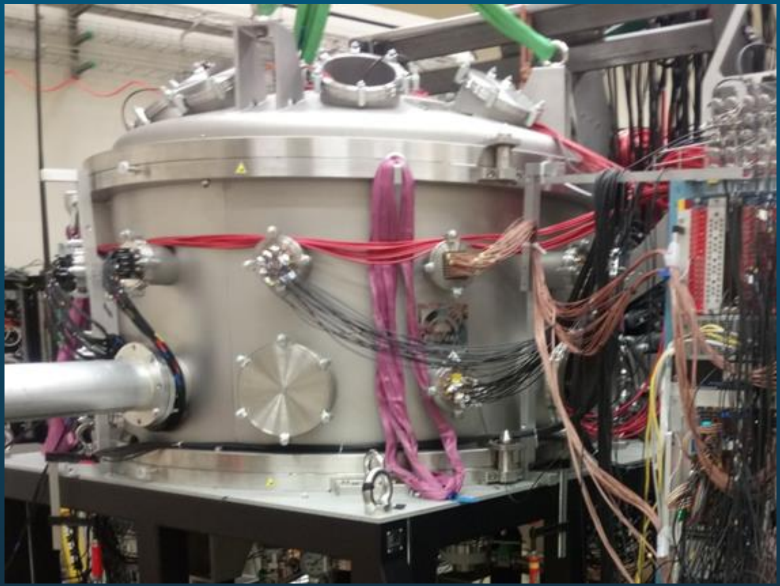
$$\left(\frac{\Gamma_{\gamma 0}}{\Gamma}\right)_{GQR} = 4 \times 10^{-4} \pm 1 \times 10^{-4}$$

Our „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.

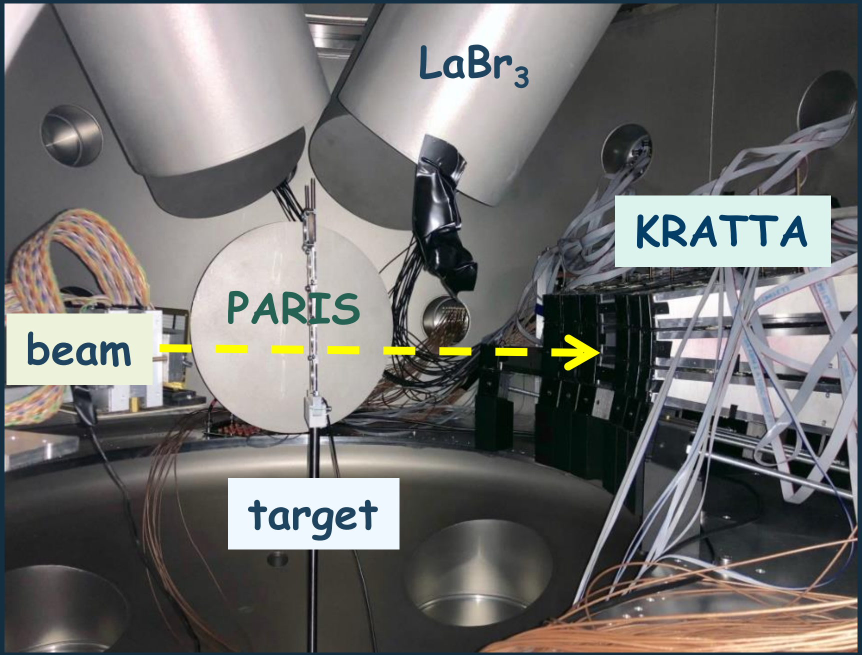
Continuation

upgraded setup

big scattering chamber

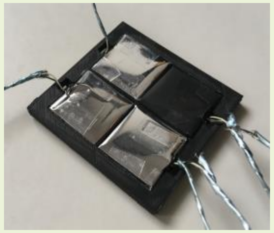


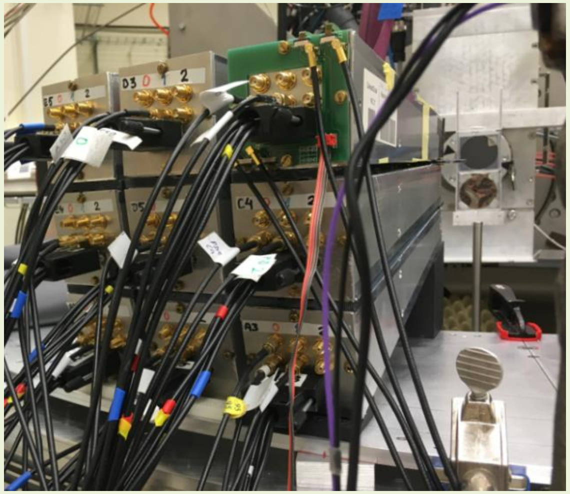
KRATTA inside the chamber – in the vacuum
gamma detectors outside
mounted using holders / cylindrical pockets

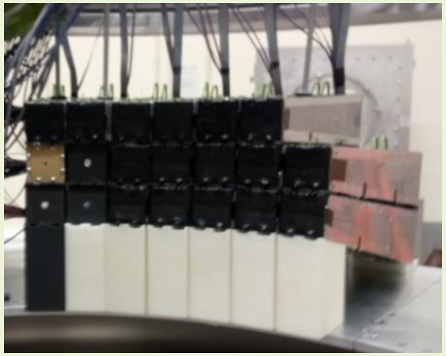


Setup upgrade

4 plastic scintillators
for each KRATTA module
mounted in the front







40 cm from the target

possible angles ~ 4° - 45° (with PARIS in the setup)
resolution ~ 2° (with plastic scintillators)

4 large volume **$LaBr_3$** (3.5"x8") detectors and

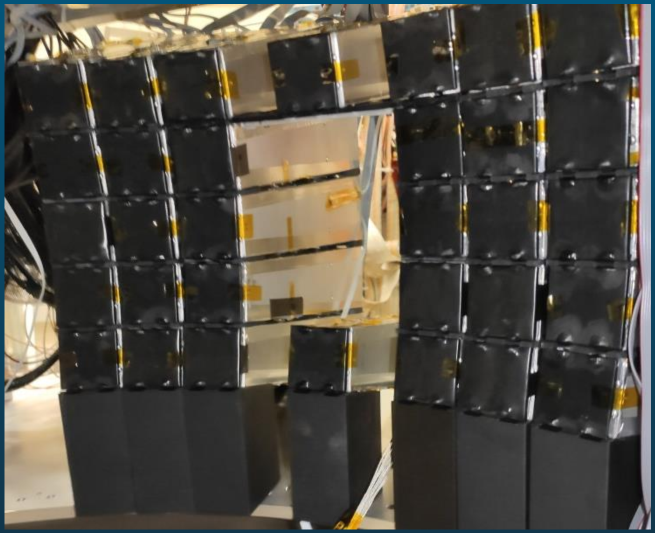
2 **PARIS** clusters:
9 $LaBr_3$+NaI
9 $CeBr_3$+NaI
phoswiches

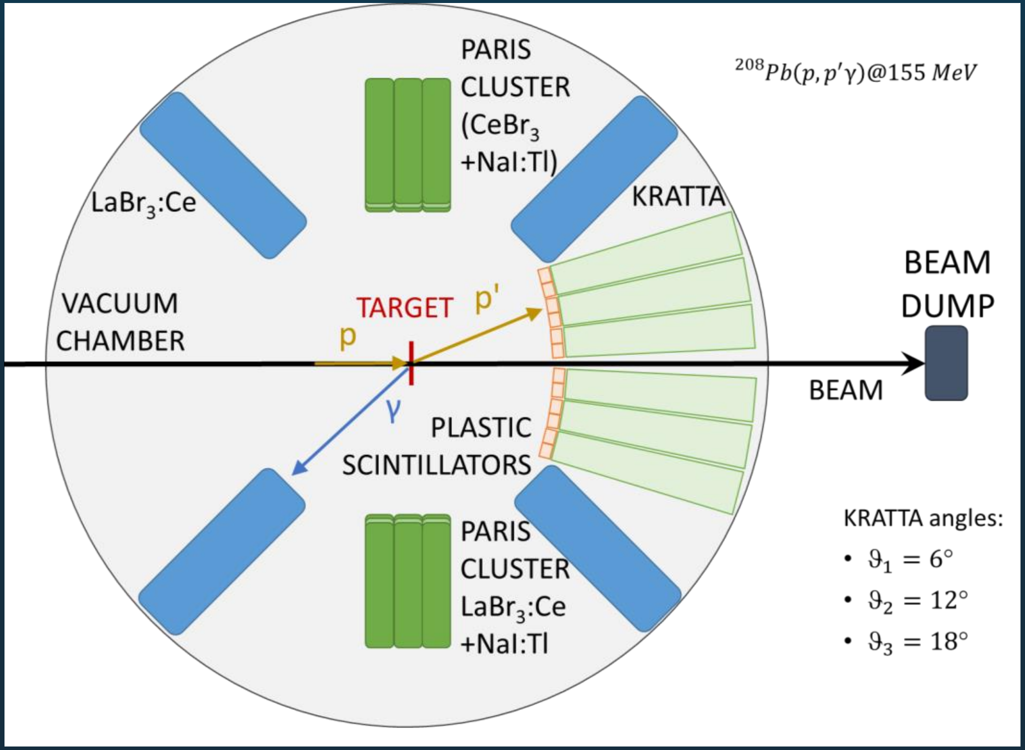
better resolution

New experiments performed

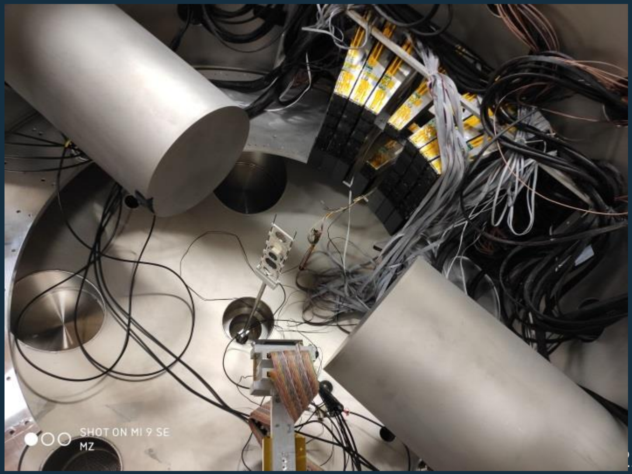
(p,p'γ) on ^{208}Pb @ ~155 MeV

(p,p'γ) on ^{120}Sn @ ~200 MeV





- 4 large volume LaBr3 (3.5"x8") at top
- 2 PARIS clusters: (9 LaBr$_3$+NaI and 9 CeBr$_3$+NaI) at 90°
- KRATTA covering angles from ~8° to ~24°

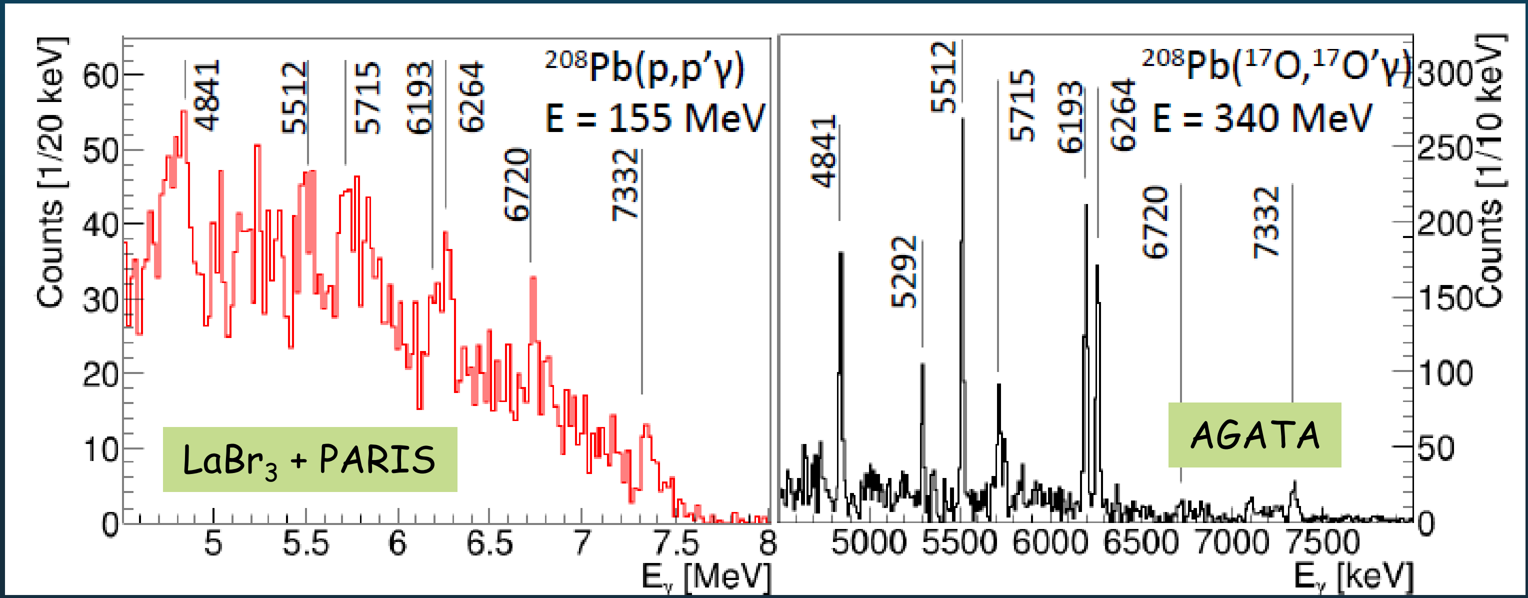


Pygmy states region

good energy resolution
of PARIS and $LaBr_3$ detectors

comparison to AGATA data
HpGe array

B. Wasilewska et al., Acta Phys. Pol. B (2020) 677



F.C.L. Crespi et al., PRL113 (2014) 012501

- ❑ similar transitions
- ❑ more detailed studies needed

Future plans

Study of the gamma decay of the GQR in

- various mass nuclei
- deformed nuclei

Study of the gamma decay of the Pygmy Dipole Resonances - PDR

Complementary investigations to the planned at LNL Legnaro with the use of heavy ion beams

Summary

- experimental campaign to study γ-decay from states excited using proton beam has been performed at Cyclotron Center Bronowice IFJ PAN in Krakow
- gamma decay of giant quadrupole resonance (GQR) have been observed for ^{208}Pb in inelastic proton scattering (p,p'γ), confirming the only one result published previously
- recently measurements have been done for ^{208}Pb with higher energy of proton beam (155 MeV) and for ^{120}Sn
- similar investigations are planned for other nuclei

Thanks to:

P. Bednarczyk, M. Ciemała, I. Ciepał, N. Cieplicka-Oryńczak, B. Fornal, J. Grębosz, Ł. W. Iskra, M. Jeżabek, M. Krzysiek, P. Lasko, J. Łukasik, A. Maj, M. Matejska-Minda, K. Mazurek, W. Parol, P. Pawłowski, B. Sowicki, A. Szperłak, B. Wasilewska, M. Ziębliński

The CCB staff

NCN Grants No. 2015/17/N/ST2/04034 and No. 2015/17/B/ST2/01534

ENSAR2 *„This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654002"*