Investigating the Pygmy Dipole Resonance in deformed nuclei

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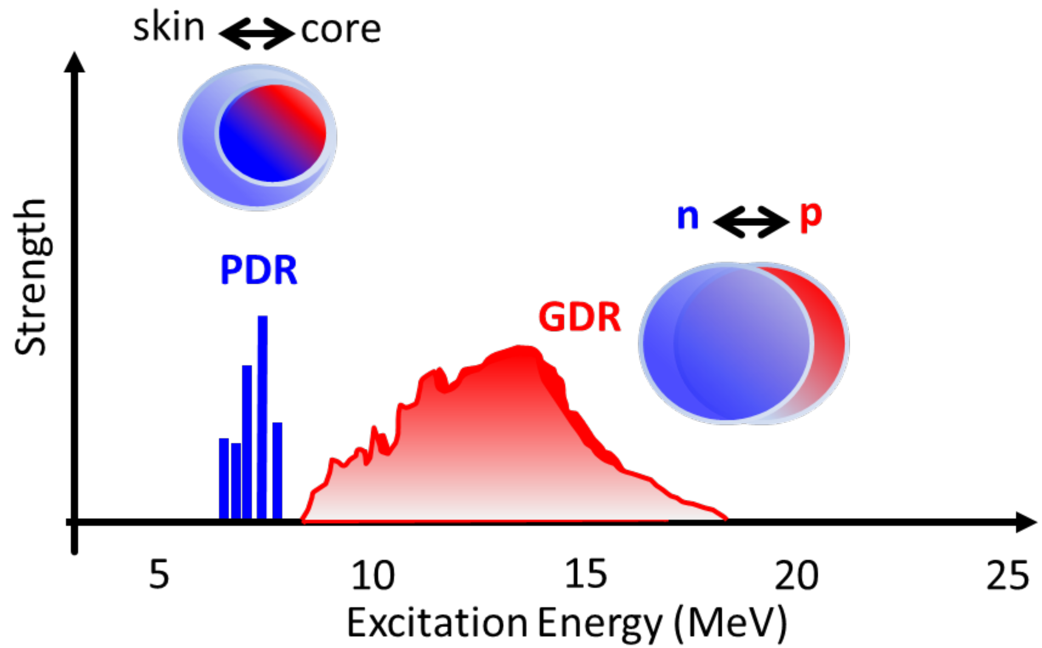
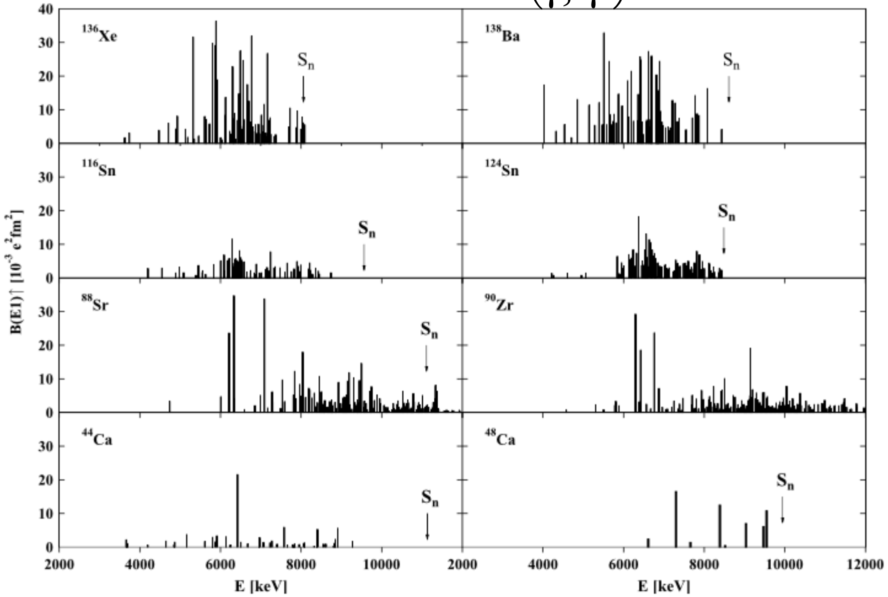
PYGMY DIPOLE RESONANCE



- 1950-60 – First observation in (n,γ) experiments of an **enhancement of the gamma ray strength around 5–7 MeV in many isotopes** (Bartholomew et al.)
- 1969 - Brzosko et al. used for the first time the notation "pigmy resonances" for this excitation mode.
- 1971 - First theoretical interpretation by R. Mohan et al. → **vibration of the excess neutrons against the core**
- Since 1969 – **PDR observed in several nuclei in different mass region**

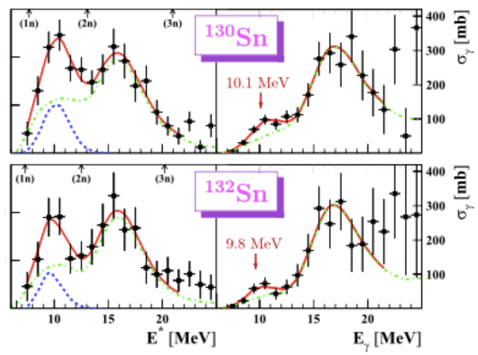
Experiments performed

STABLE NUCLEI – (γ, γ') and NRF

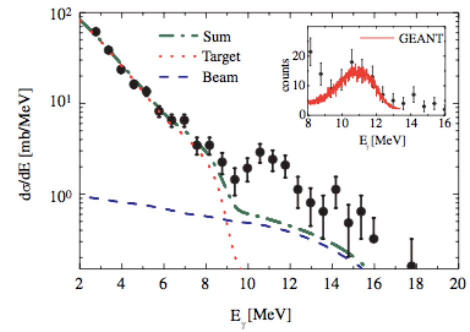


From D. Savran, T. Aumann, and A. Zilges Prog. Part. Nucl. Phys. 70 (2013) 210–245
And reference therein

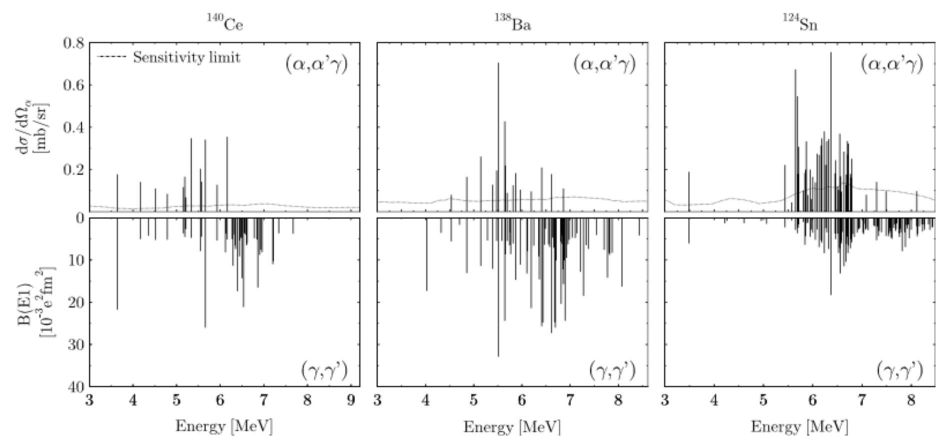
EXOTIC NUCLEI – COULEX



^{68}Ni



STABLE NUCLEI – (α, α' γ)

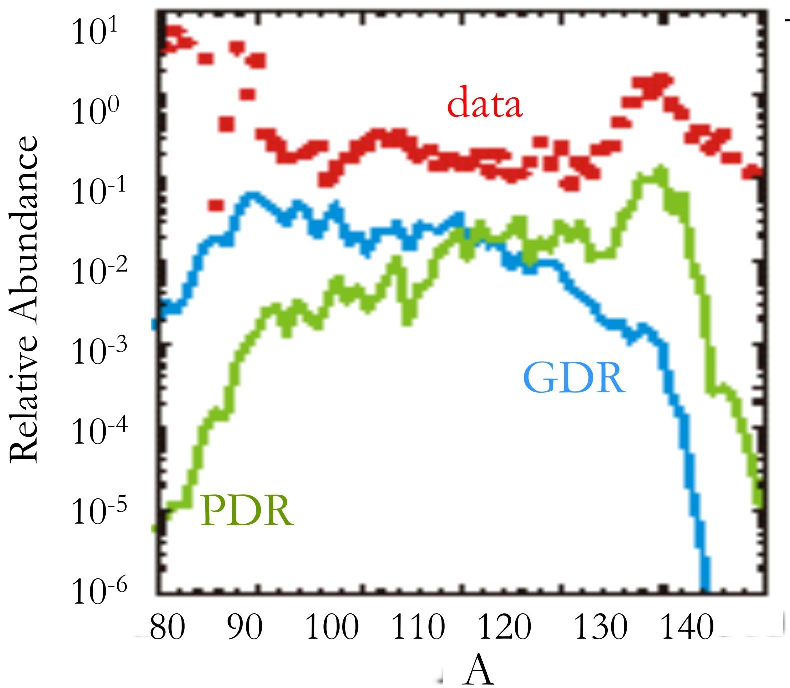


- **PDR strength** varies from close to 0% for the ^{40}Ca to about 5% for certain neutron-rich isotopes lying in different mass regions.
- **Splitting in the population of pygmy states**

Astrophysical implications

Interest in the PDR not only for the underlying nuclear structure → two important physical aspects related with the position and strength of the PDR in nuclei.

1) **Influence on reaction rates in the astrophysical r –process** → The relevant energy window for (γ,n) reactions in the stellar photon path is located in the vicinity of the PDR.



→ 2 different estimates of the neutron capture rates: the standard GDR component, and the PDR strength.

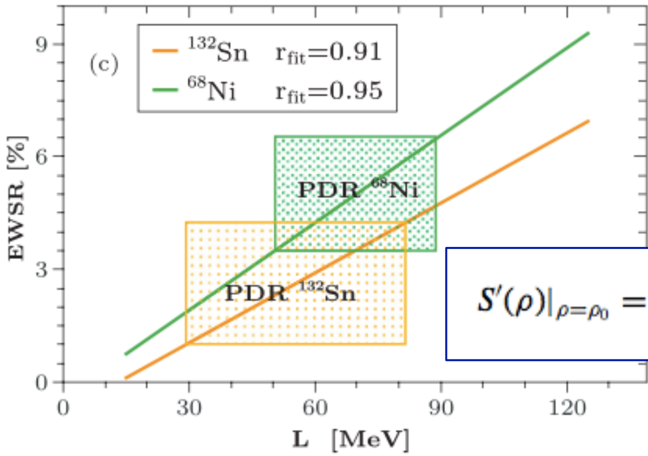
↓

While use of the GDR rates leads principally to the production of the *A*~90–110 r-elements, **the PDR effect tends to accelerate the neutron captures and enables the production of heavier nuclei (*A*~130).**

M. Thoennesen adapted from S. Goriely, Phys. Lett. B 436 (1998) 10

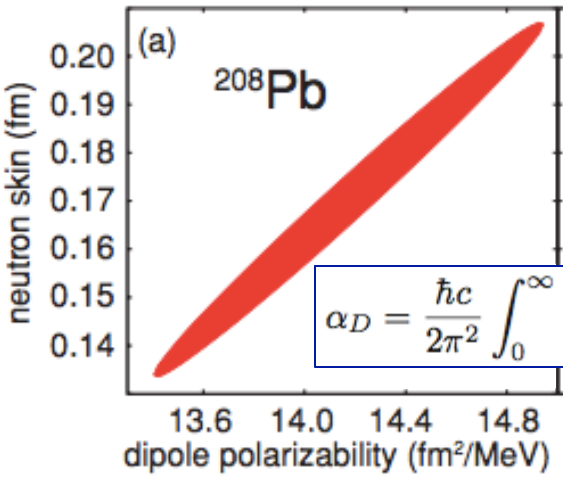
Astrophysical implications

2) Link of pygmy states to the equation of state (EOS) of neutron-rich matter and also to corresponding objects in the universe such as neutron stars.



$$S'(\rho)|_{\rho=\rho_0} = \frac{L}{3\rho_0}.$$

A. Carbone et al. PRC **81** (2010) 041301(R)



$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}\mathrm{d}E,$$

P.-G. Reinhard and W. Nazarewicz, PRC **81** (2010) 051303(R)
J. Piekarewicz et al., PRC **85** (2012) 041302(R)

The density dependence of the symmetry energy governs the neutron skin in nuclei as well as the radius of neutron stars

↓

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2.$$

Constraints on the EOS are highly desirable

Nuclear symmetry energy not an observable which can be directly measured → closely related observables

↓

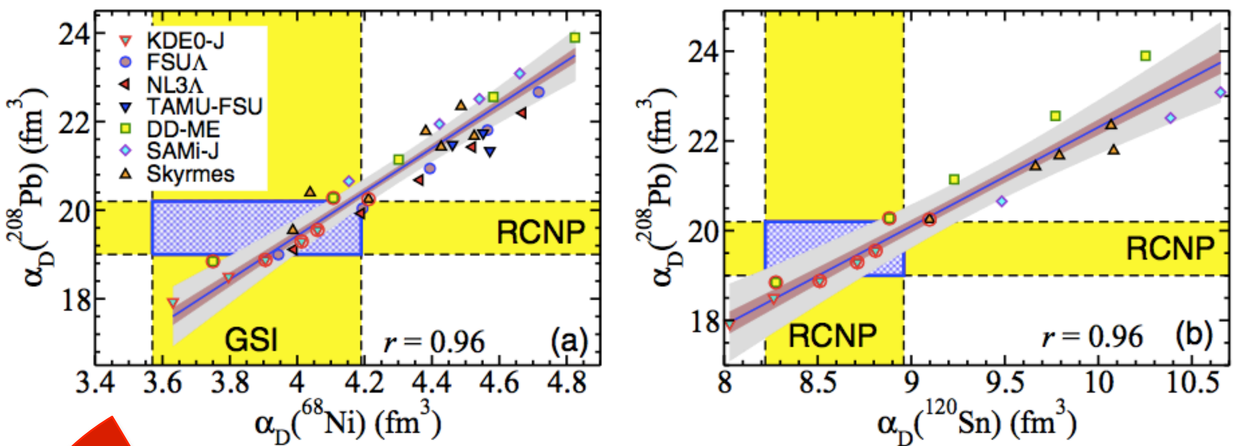
Several theoretical works suggest that the strength of the PDR and in particular the dipole polarizability are related to the size of the neutron skin.

These quantities can be experimentally measured and used as a constraint to the theory.

Astrophysical implications

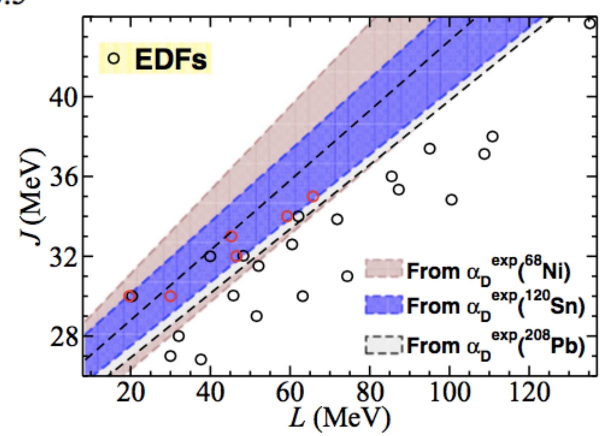
Strong correlation $\alpha_D J$-Δr_{np}

It is possible to **estimate the neutron skin thicknesses** of ^{68}Ni, ^{120}Sn, and ^{208}Pb **without invoking the empirical value of the symmetry energy coefficient J** (the symmetry energy at saturation $S(\rho_0)$) → Experimental values used to constrain the the EDFs



X. Roca-Maza et al. PRC **92** (2015) 064304

Nucleus	Δr_{np} (a)	Δr_{np} (b)	Δr_{np} (c)
^{68}Ni	0.15–0.19	0.18 ± 0.01	0.16 ± 0.04
^{120}Sn	0.12–0.16	0.14 ± 0.02	0.12 ± 0.04
^{208}Pb	0.13–0.19	0.16 ± 0.02	0.16 ± 0.03



Information on Δr_{np} and J - L by choosing the values predicted by the selected set of EDFs that reproduce the experiment in all three nuclei.

Theoretical description of PDR

Theoretical description of the PDR based on microscopic self-consistent mean field models:

SPHERICAL and CLOSED SHELL → HF+RPA

OPEN SHELL and DEFORMED NUCLEI → HFB + Quasi-Particle RPA

and more… ETFFS or Quasi-Particle Phonon Model (QPM) which take into account explicitly the coupling between nucleons and phonons.

also relativistic mean field theory, like Relativistic Quasi-Particle Time Blocking Approximation (RQTBA), have been used.

Calculations agree that

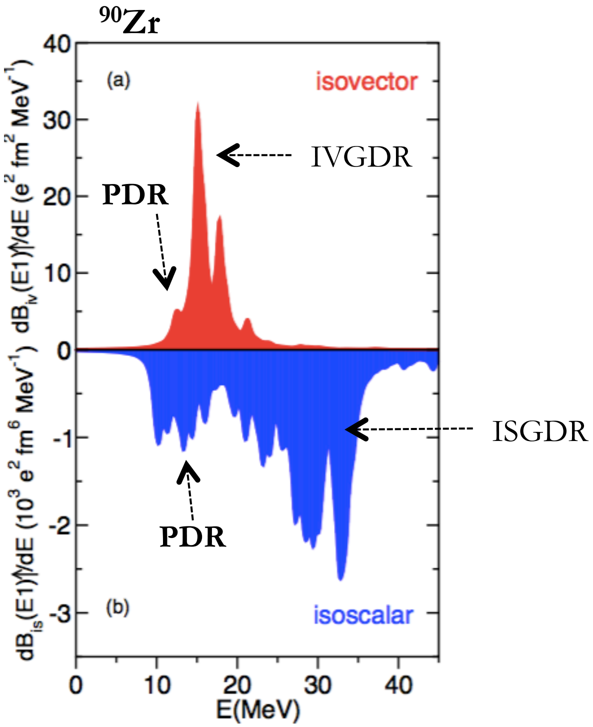
→ **PDR is observed in nuclei with N/Z > 1 due to the excitation of the neutron excess**

→ **Presence of a STRONG MIXING of the ISOVECTOR and ISOSCALAR character**

Calculations disagree on:

→ Collectivity

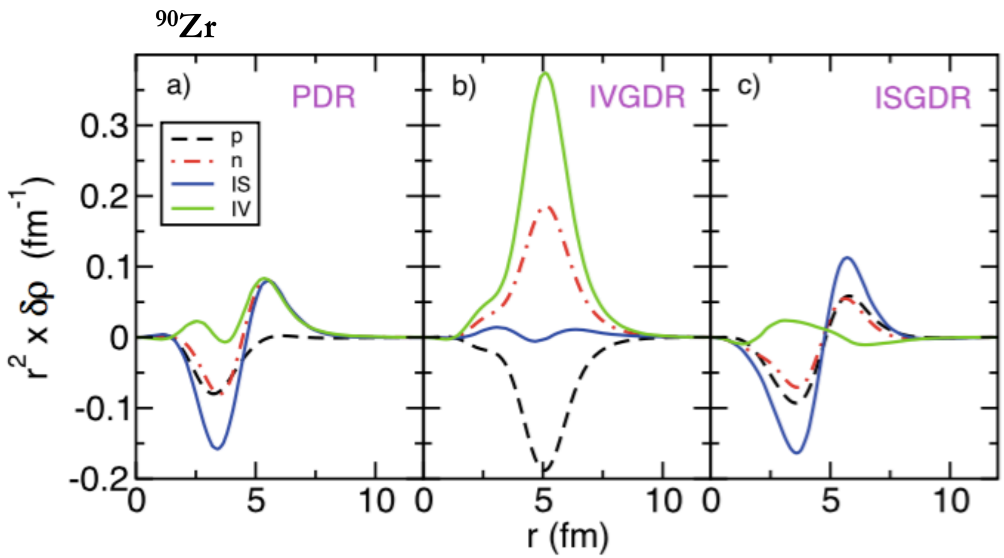
Isospin mixed character



A. Bracco, F.C.L. Crespi and E.G. Lanza, Eur. Phys. J A (2015) 51

Predicted dipole response to an ISOVECTOR (a) and ISOSCALAR (b) probe for ^{90}Zr nucleus:

- dominated by IVGDR and ISGDR
- presence of the PDR in the IV and IS response



Transition Densities(TD) of PDR, IVGDR and ISGDR

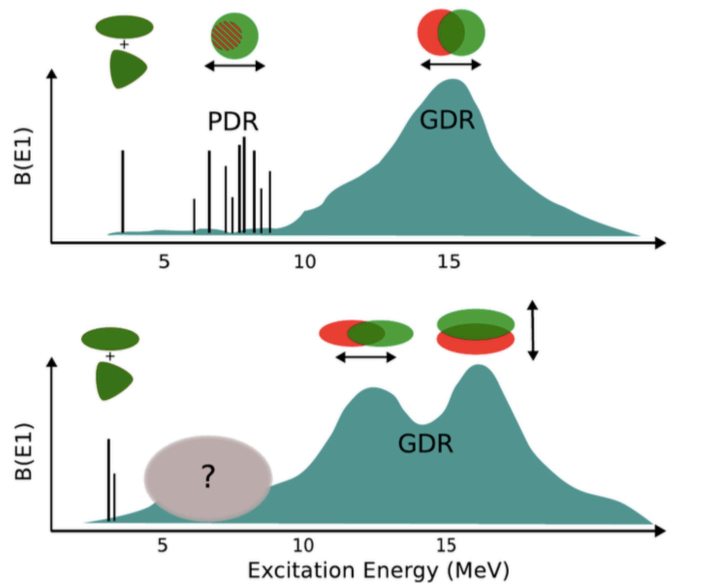
IVGDR: protons and neutrons TD out of phase → Strong isovector component

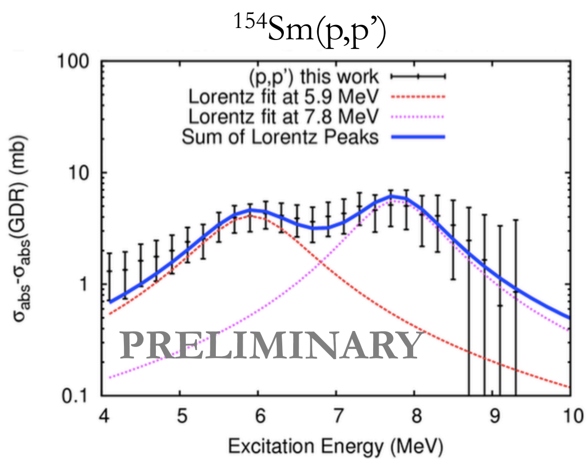
ISGDR: protons and neutrons TD in phase → Strong isoscalar component

PDR: neutrons and protons in phase inside and at the surface only neutron part survives → IS and IV components. ⟶ **Strong mixing allow the population with IS and IV probe**

Deformed nuclei

Only a **few measurements** on the PDR have been performed **in deformed nuclei**

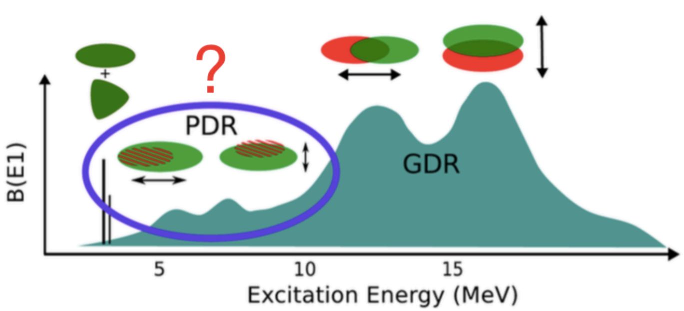




Krugmann A 2014 Ph.D. thesis

more details in Peter von Neumann-Cosel talk

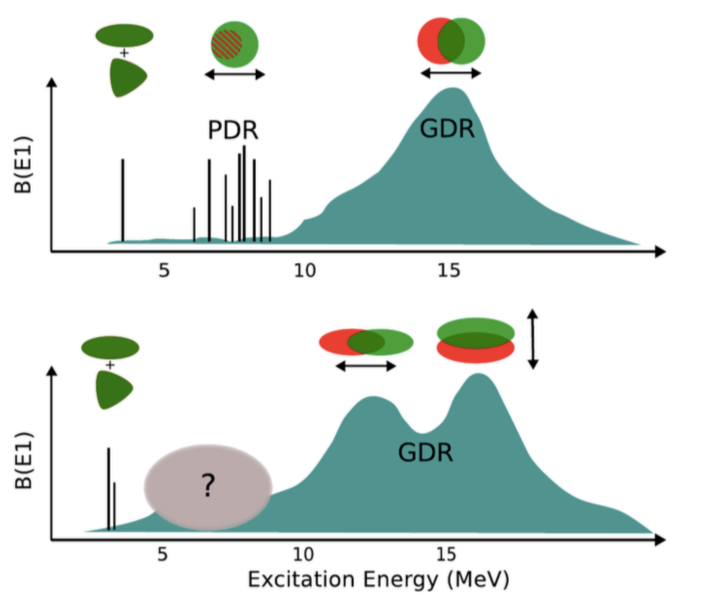
RCNP
^{154}Sm(p,p') @ 295MeV
Polarized beam

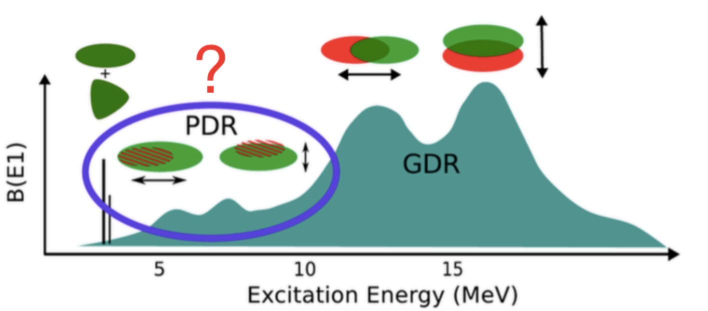


→ **Presence of a double-hump structure** of the PDR similar to the one observed in the GDR

Possible interpretation:
Deformed proton-neutron saturated core, oscillating against a neutron skin along two different axes

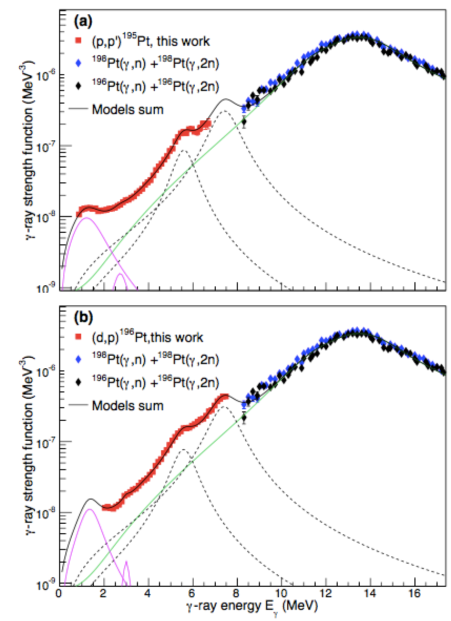
Only a **few measurements** on the PDR have been performed **in deformed nuclei**





OCL
^{195}Pt(d,p’) @ 11.3MeV
^{195}Pt(p,p’) @ 16.5 MeV

^{195}Pt(p,p) & ^{195}Pt(d,p’)



F. Giacoppo
arXiv:1402.2451v1 [nucl-ex] 11 Feb 2014

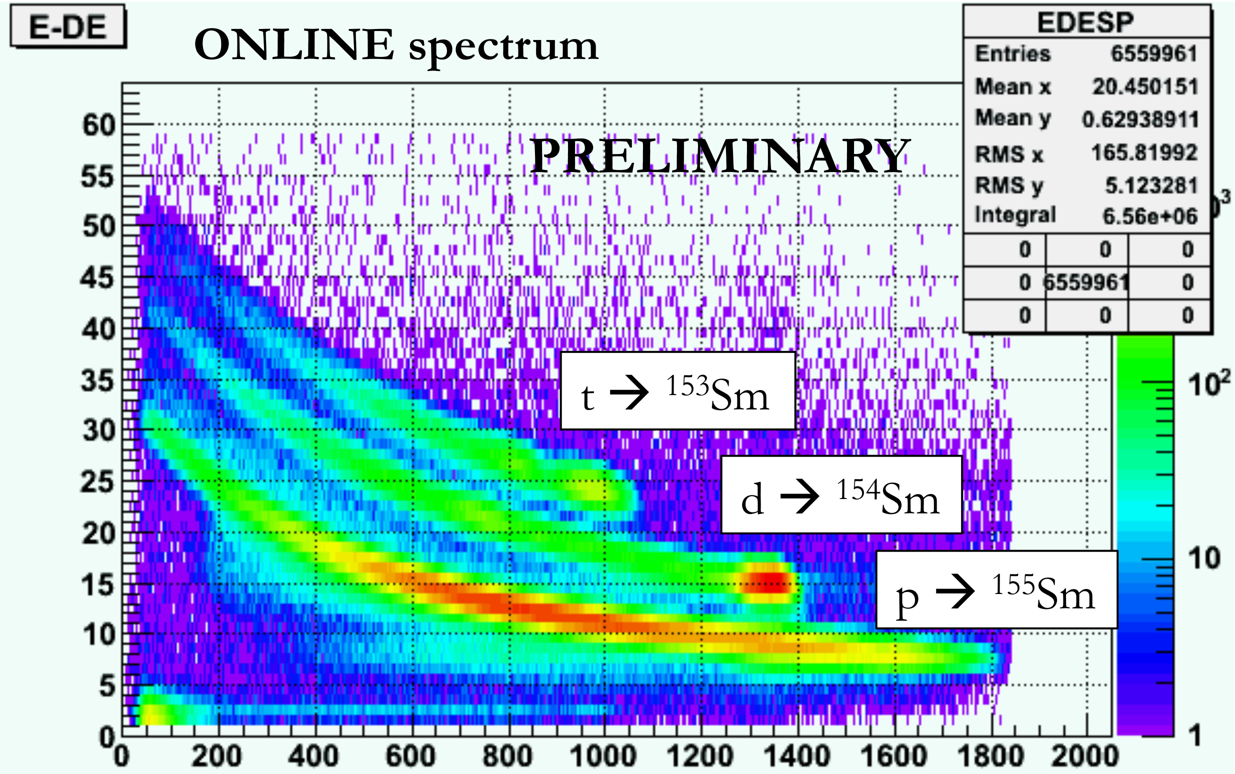
- **Double-hump structure assign to M1 and E1** strength based on previous experiment.
- Present experimental technique is **not sensitive to the electromagnetic character of the γ transitions.**

Other experiments on ^{154}Sm

Statistical Properties of highly deformed ^{154}Sm
K.L. Malatji et al. (iThemba LABS)

Aim: Study of Pygmy Dipole (PDR) and Scissors resonances (SR)
Experimental setup: CACTUS and SIRI arrays at the Oslo Cyclotron Laboratory.
Reactions used:

1. ^{154}Sm(d,d') @ 13 MeV → excitation energies of up to 8.5 MeV (Sn = 8 MeV)
2. ^{154}Sm(d,p) @ 10 MeV → excitation energies of up to 9 MeV (Sn = 5.8 MeV)



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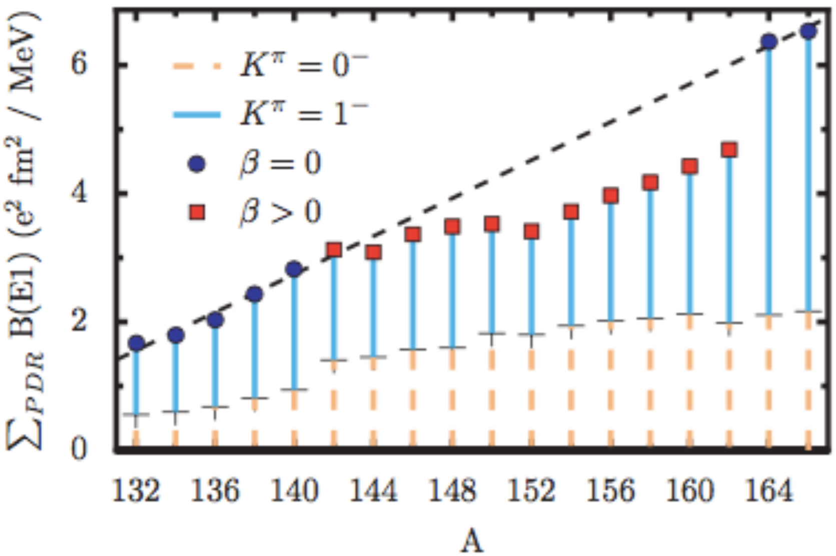
COMPLEMENTARY information to the (p,p') and (α, α' γ) data on PDR

RQRPA calculations

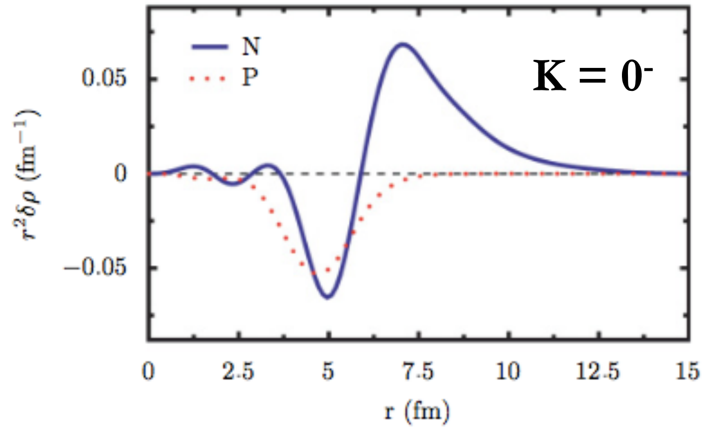
E1 strength studied in Tin chain ($^{132-162}$Sn)

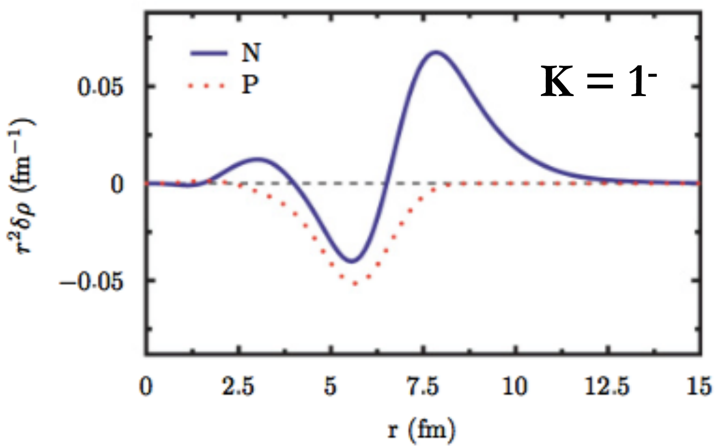
- Evolution of the low-lying strength in deformed nuclei determined by **isospin asymmetry and deformation → greater neutron excess increases the total strength while deformation hinders and spread it.**

D. Peña Arteaga, E. Khan, and P. Ring PRC 79, 034311 (2009)



^{150}Sn



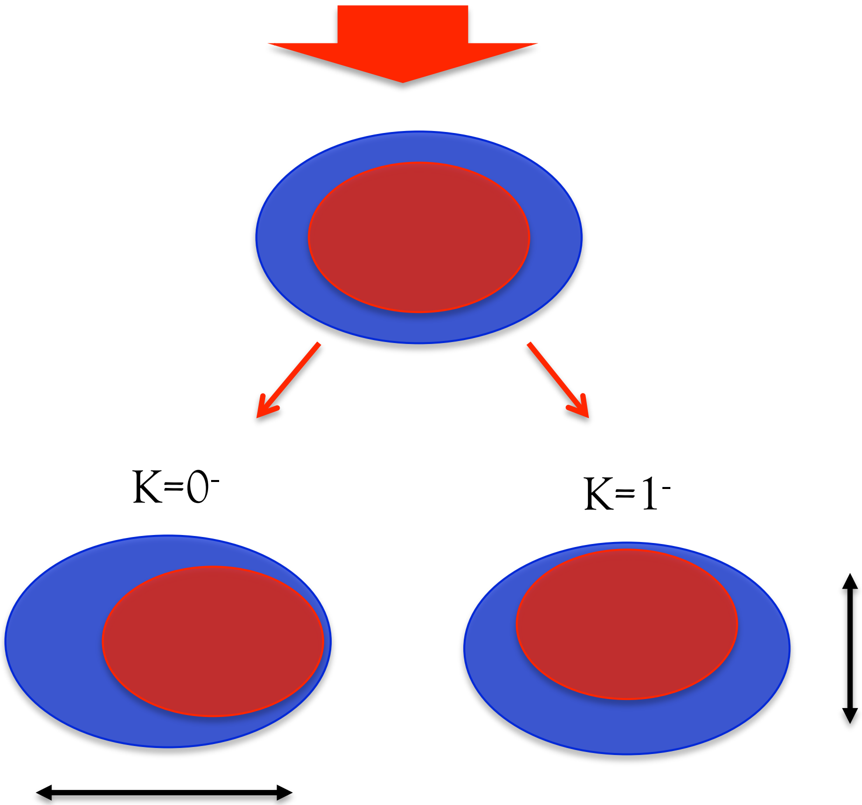


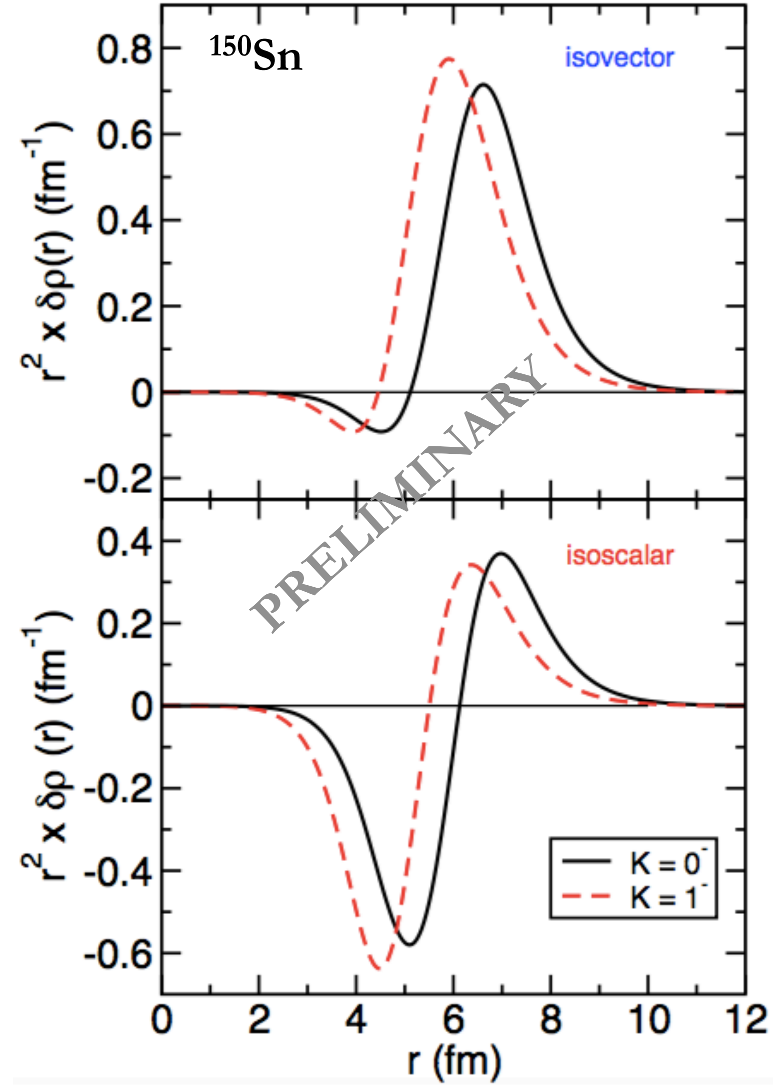
Deformation does not either destroy the excitation pattern or the collectivity of the PDR but merely splits the response into different peaks for the different K^π modes.

Liquid-drop model calculations

The PDR can be described by three liquid drops:

- Protons Z
- Core Neutrons N^c
- Valence Neutrons N^v





M. Faccioli, J.A. Lay, A. Vitturi, M.V. Andrés, E.G. Lanza – to be published

Strong contribution of the isoscalar transition density at the nuclear surface

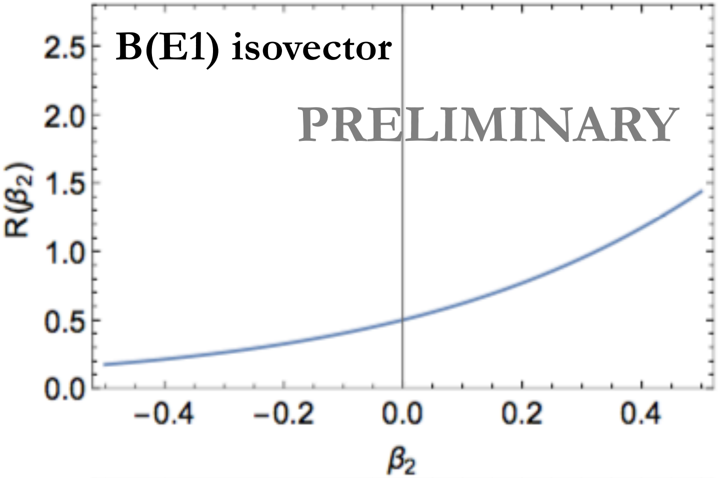
Liquid-drop model calculations

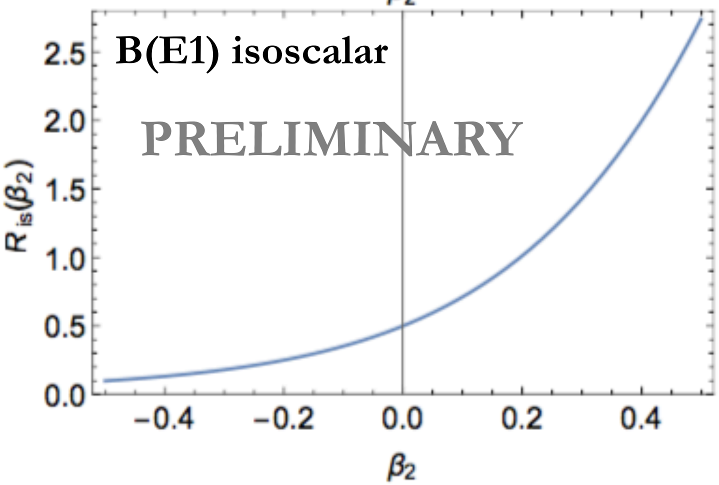
M. Faccioli, J.A. Lay, A. Vitturi, M.V. Andrés, E.G. Lanza – to be published

Ratio between the transition probability of K=0 and K=1 for the isovector and iscoscalar component:

$$R(\beta) = \frac{B(E1)^{IV}_{K=0^-}}{B(E1)^{IV}_{K=1^-}}$$

$$R(\beta) = \frac{B(E1)^{IS}_{K=0^-}}{B(E1)^{IS}_{K=1^-}}$$





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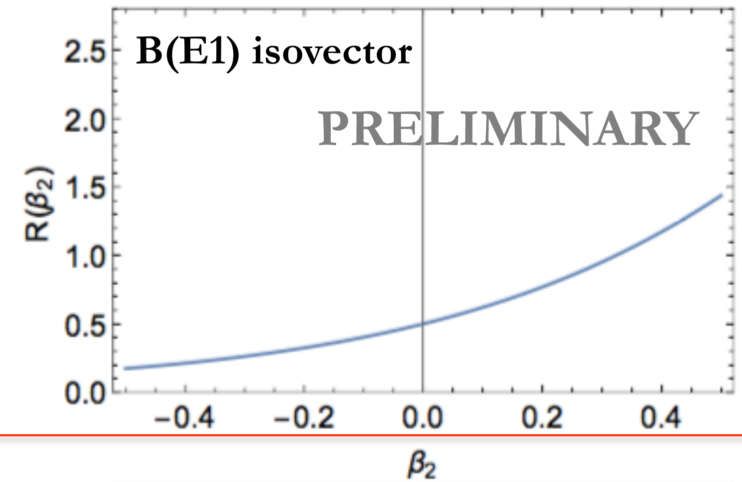

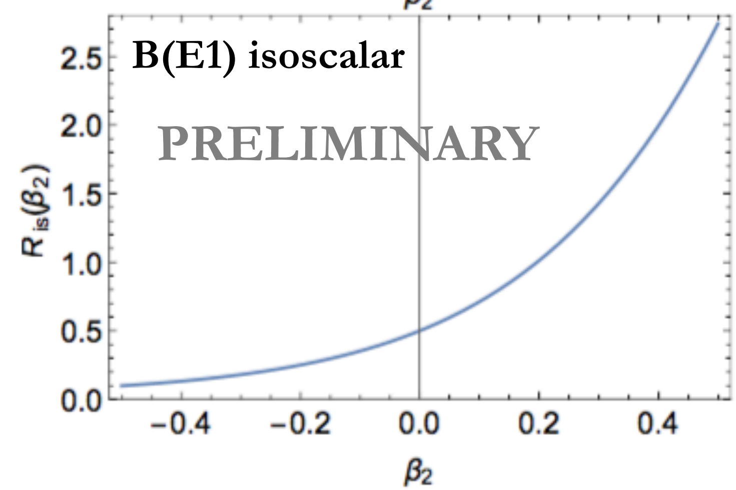

the variation of the ratio for the isoscalar case is stronger
→ Different population of the PDR for different probe

PDR study at iThemba LABS

Inelastic scattering of alpha particles + subsequent gamma decay

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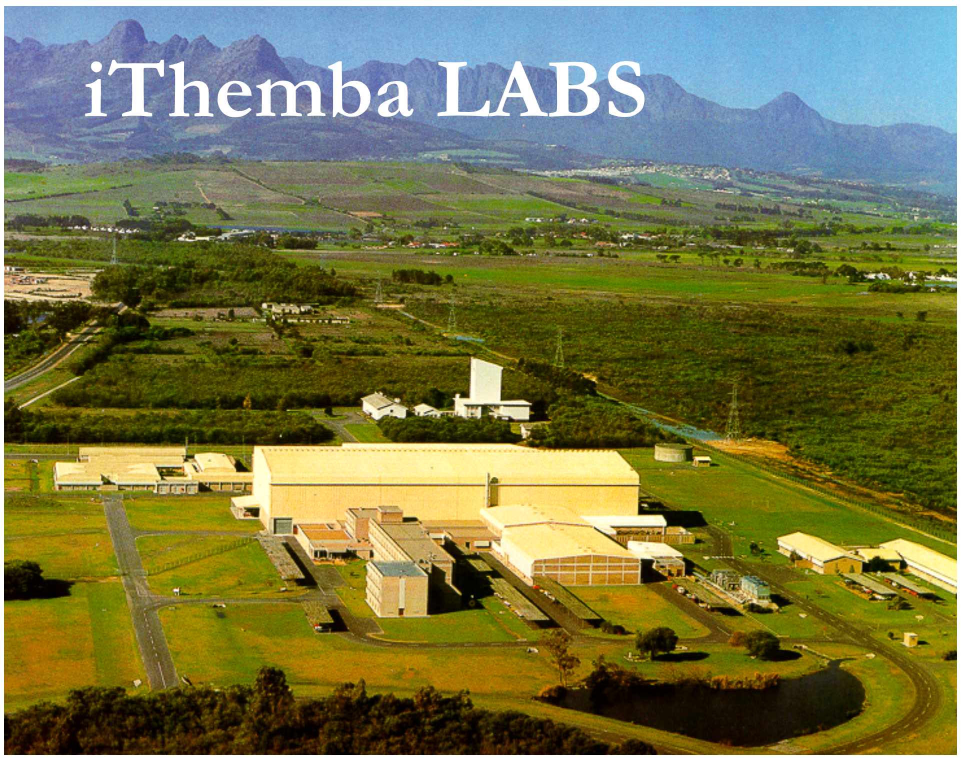
First time coupling of

K600 spectrometer to a gamma detector array (BaGeL)

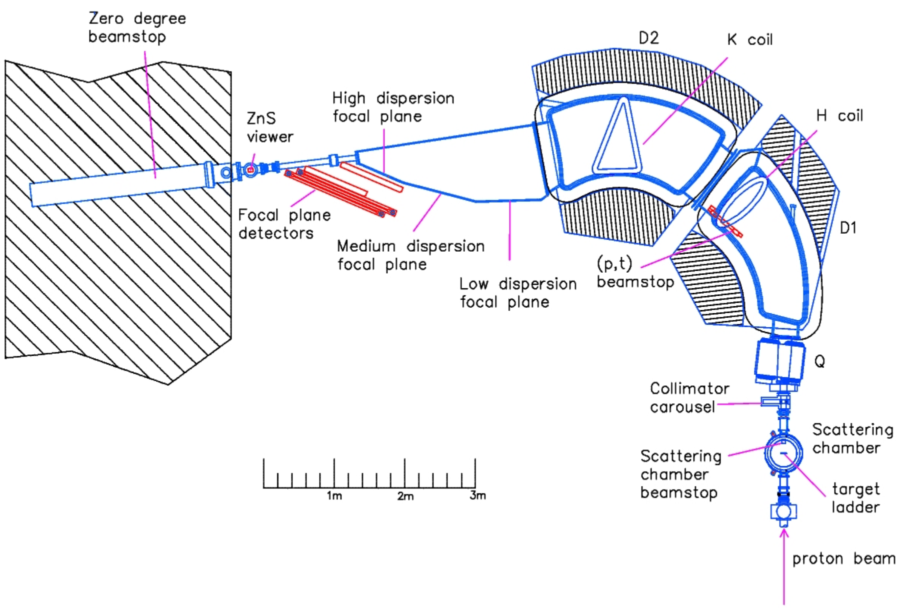


$^{154}Sm(\alpha, \alpha' \gamma)$ @ 120MeV

- iThemba LABS is one of the unique facilities that can perform this kind of experiment
- Only place with a high resolution magnetic spectrometer and a permanent array of HPGe Clover detectors

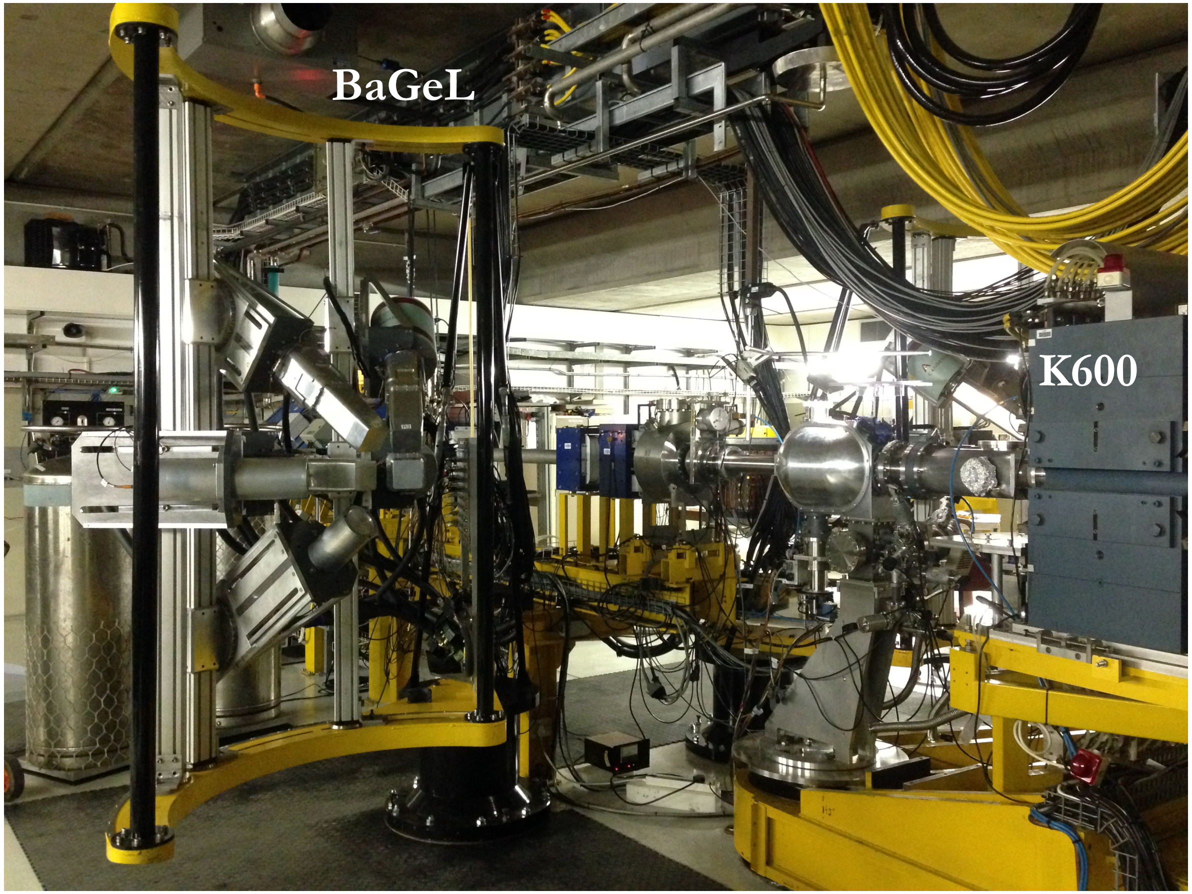
K600 magnetic spectrometer

The K600 is **one of only two facilities** in operation worldwide capable of **high energy resolution** (≤100 keV FWHM) measurements **at zero degrees**, with a **low background contribution** to the measured spectrum, for **medium energy** (E~50-200 MeV/A) **light ions** (p,d,t,α).



- Detection system: two vertical drift chambers (position and angle measurements), two plastic scintillation detectors (trigger and particle identification)
- **In this experiment** the accessible excitation-energy range was **4-16 MeV**
- Full solid angle is 3.5 msr and K600 efficiency 80%
- **K600 energy resolution: ~**120 keV due to the 4.8 mg/cm^2 thick target

BaGeL – Ball of Germanium and LaBr



BaGeL – 8 HPGe Clover (from the AFRODITE array) + 2 large volume LaBr3:Ce

→ Possibility to allocate 14 detectors at backward angles and 3 at forward angles

→ 8 Clovers efficiency ~ 0.5-0.6% @ 6 MeV and 20cm from the scattering chamber

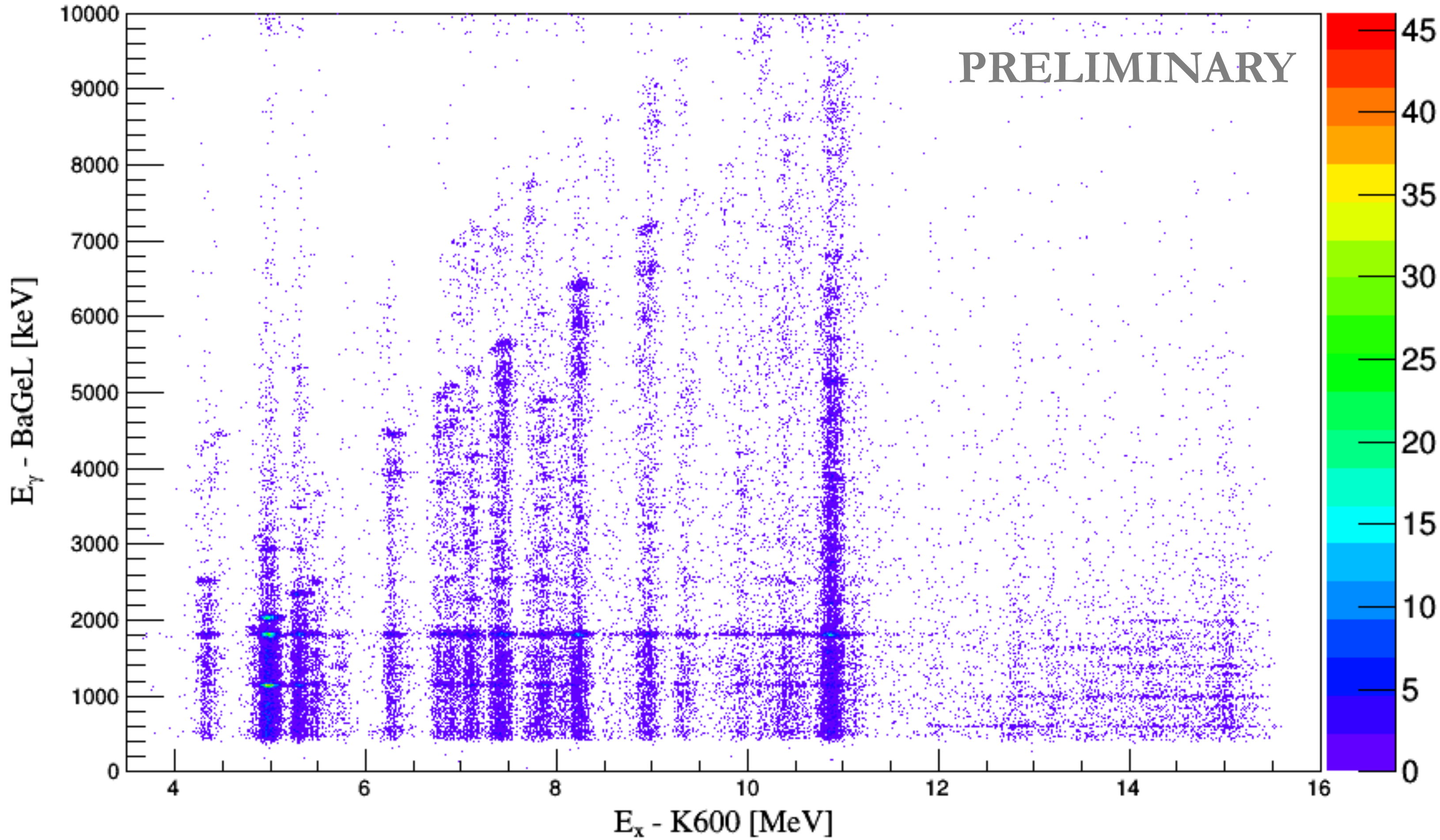
→ 2 $LaBr_3$:Ce efficiency ~ 0.3% @ 6 MeV and 20cm from the scattering chamber

Combined use of K600 spectrometer and BaGeL is a powerful tool to study the PDR and in general the gamma decay from GR

$^{26}Mg(\alpha, \alpha' \gamma)$

Offline analysis

One LaBr3:Ce detector

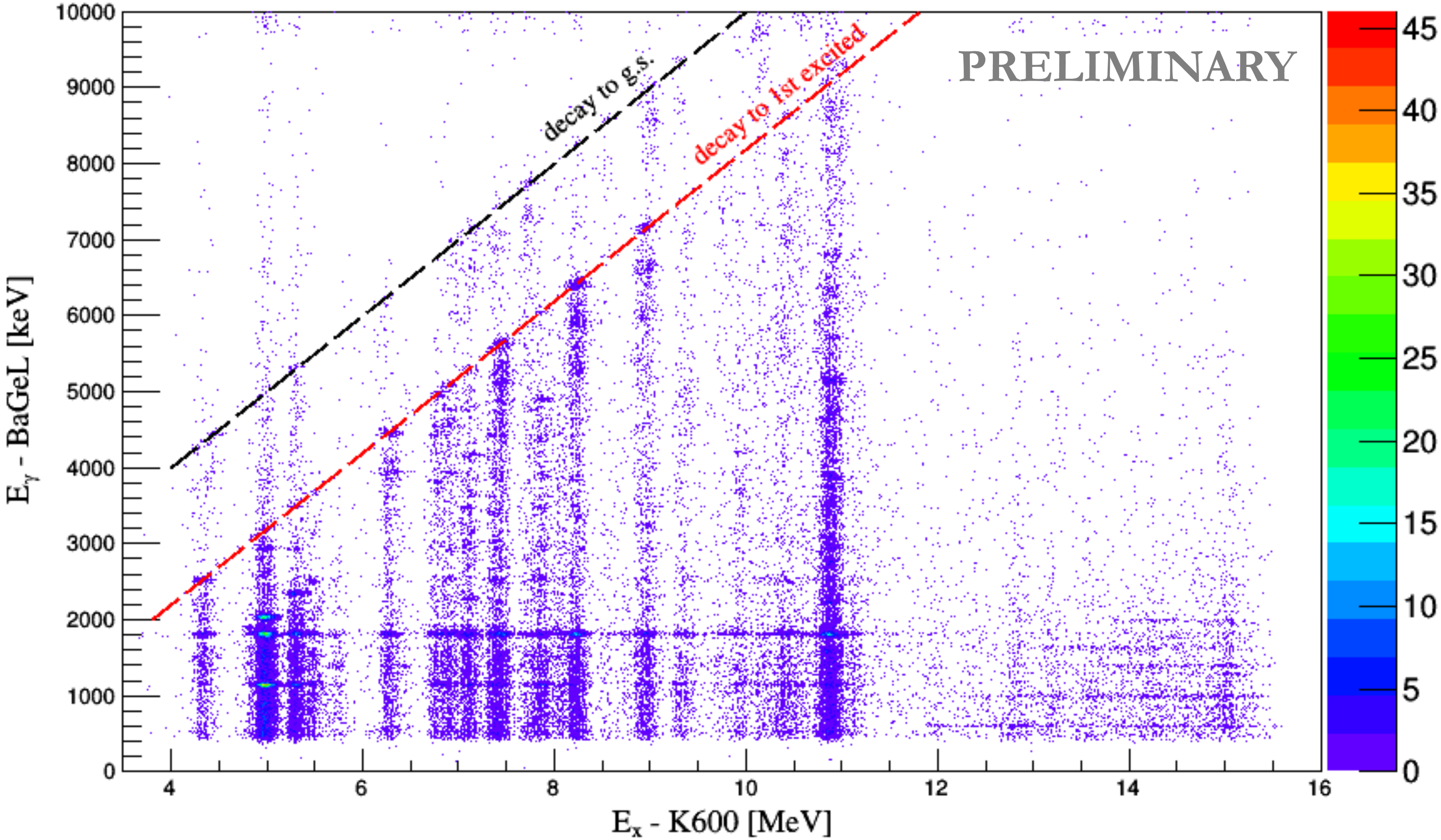


GATES: PID & Y1 plane & GammaTime

$^{26}Mg(\alpha, \alpha' \gamma)$

Offline analysis

One LaBr3:Ce detector



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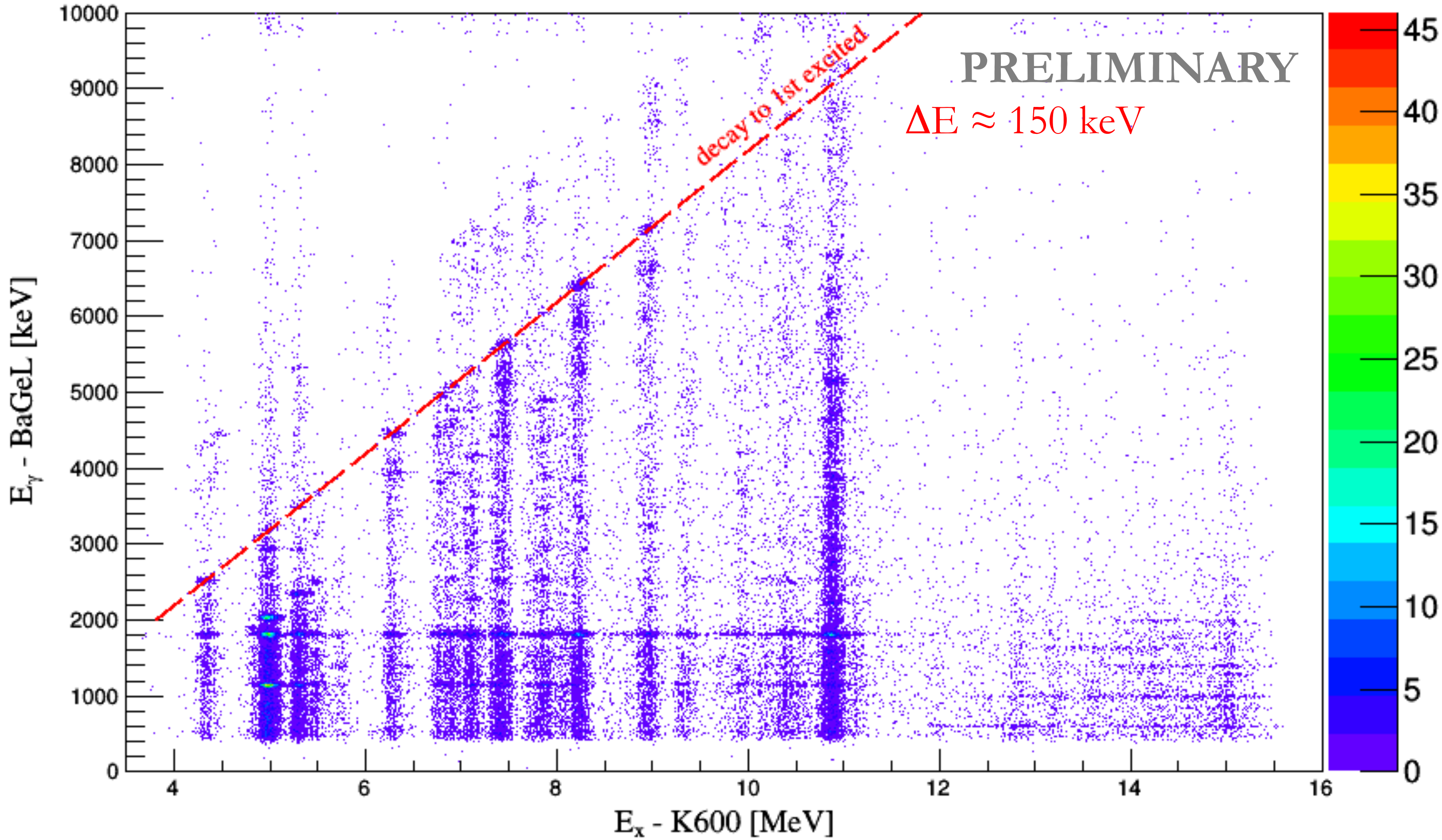

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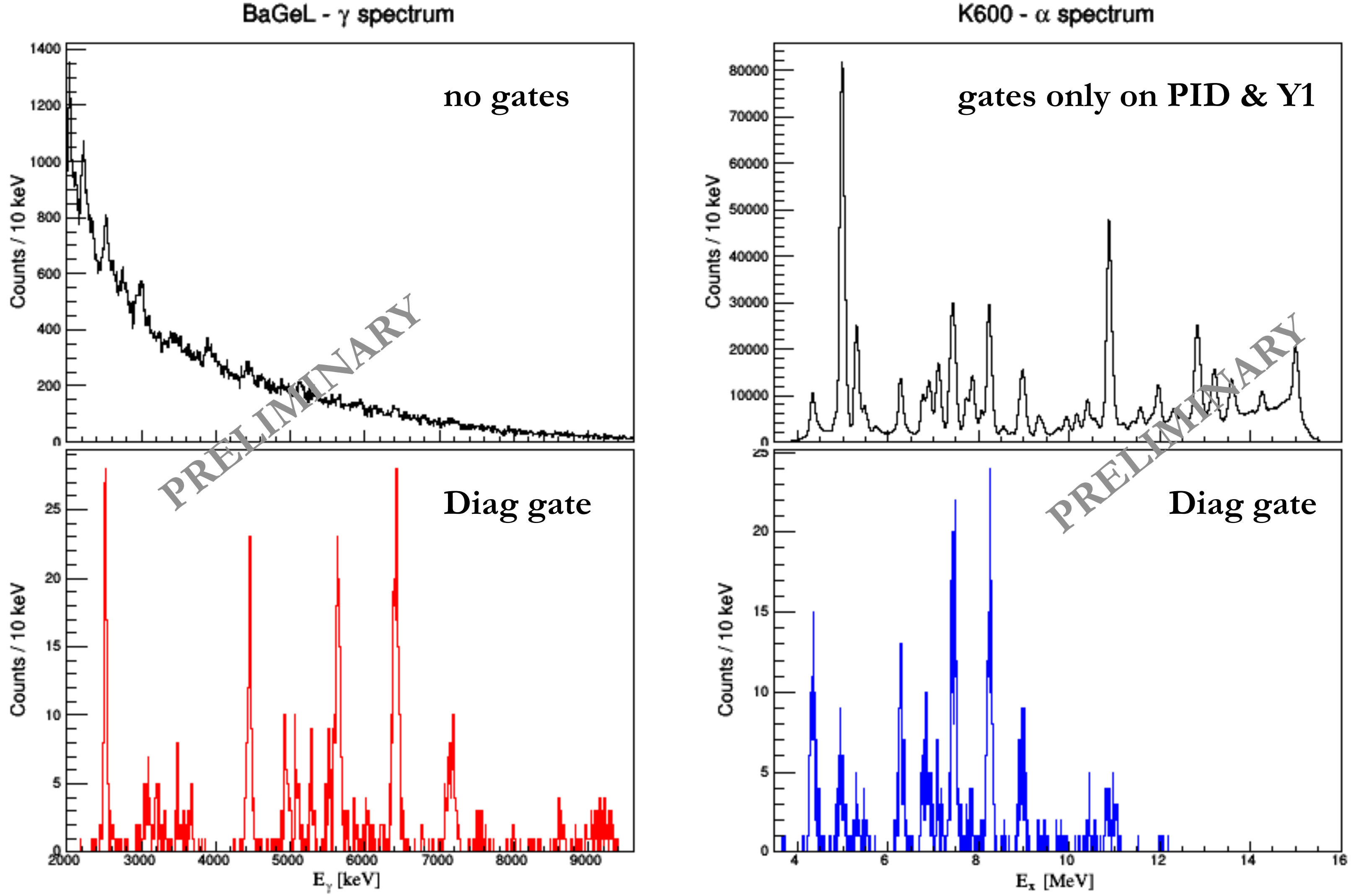
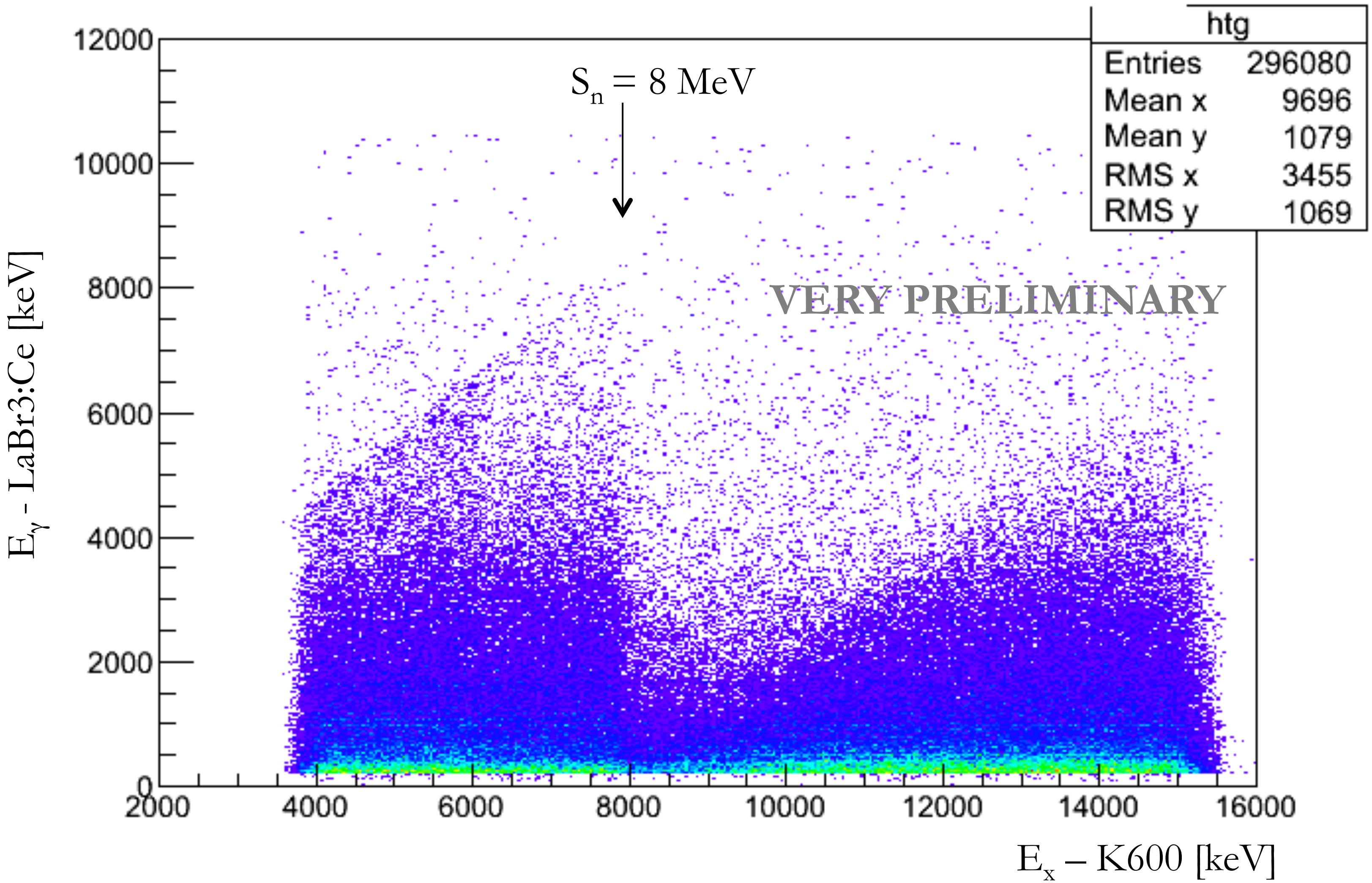


Only the peaks that decay to the 1st excited states are selected

$^{154}Sm(\alpha, \alpha' \gamma)$ – online data

VERY VERY VERY PRELIMINARY → Online data extracted from a subset of runs



GATES: PID & Y1 plane & GammaTime

$^{154}Sm(\alpha, \alpha' \gamma)$ – online data

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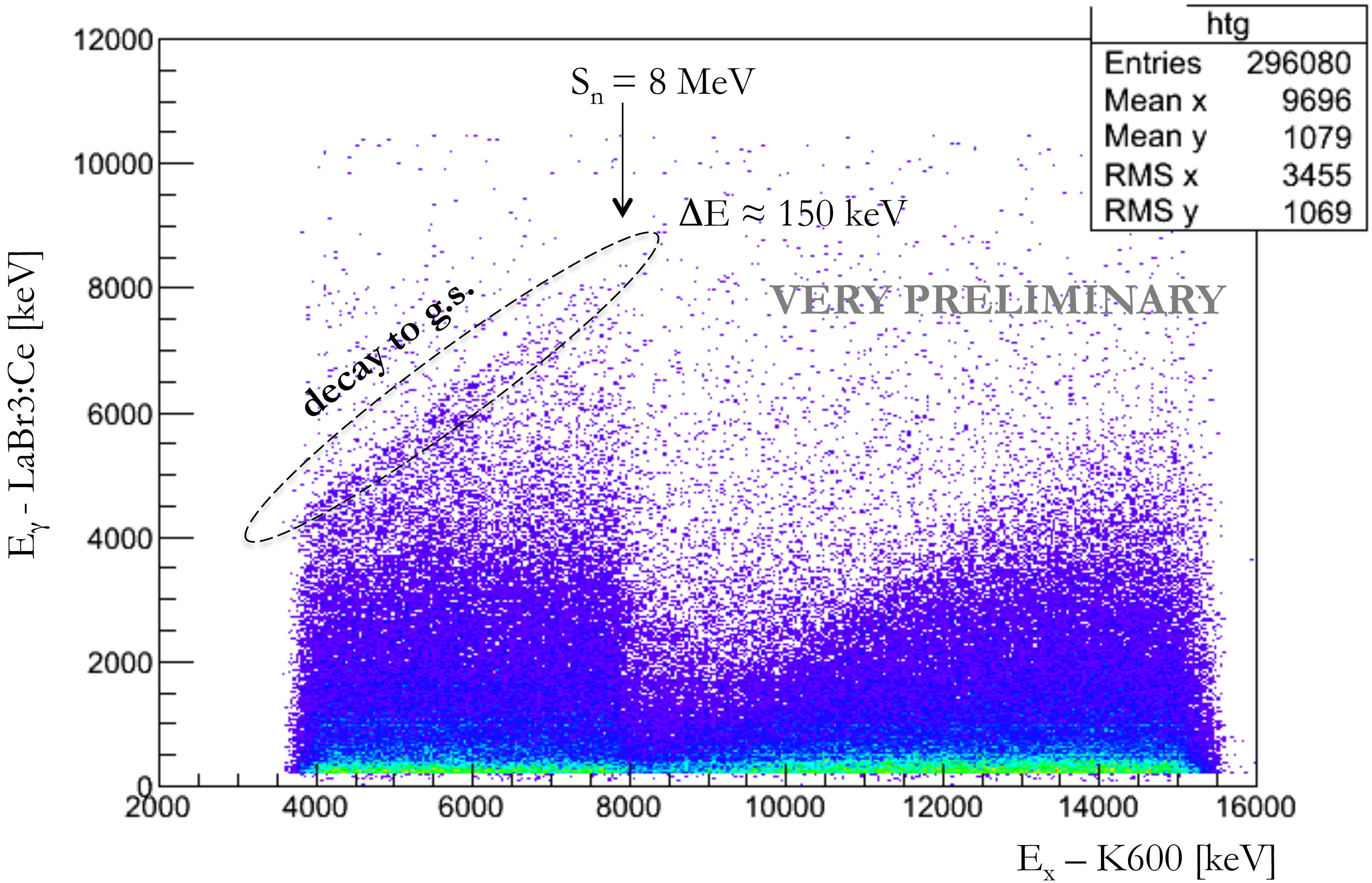
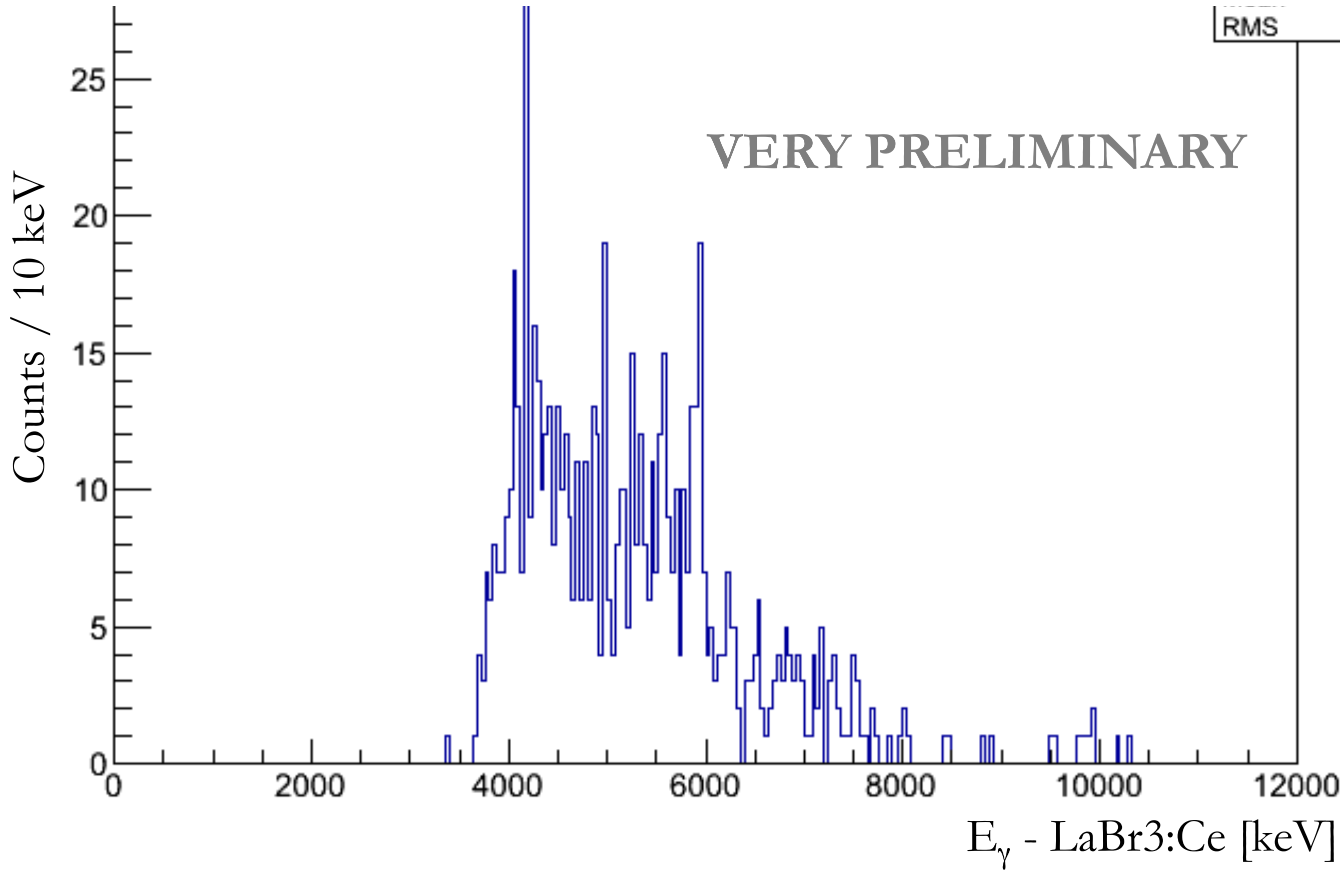


GATES: PID & Y1 plane & GammaTime

^{154}Sm(α, α' γ) – online data

VERY VERY VERY PRELIMINAR → Online data extracted from a subset of runs

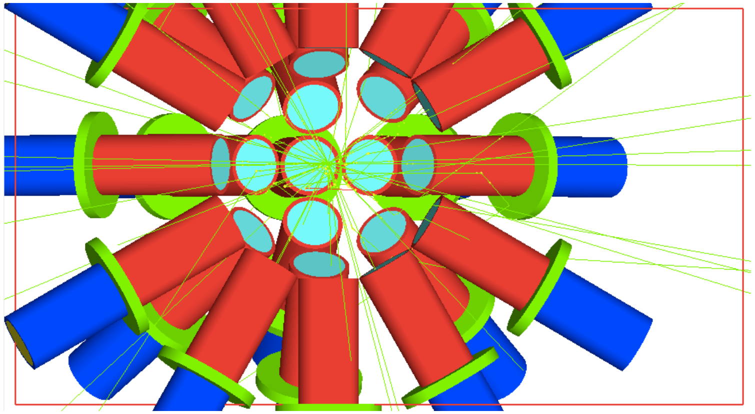
Rough calibration for K600 and LaBr3:Ce used **GATES: PID & Y1 plane & GammaTime**

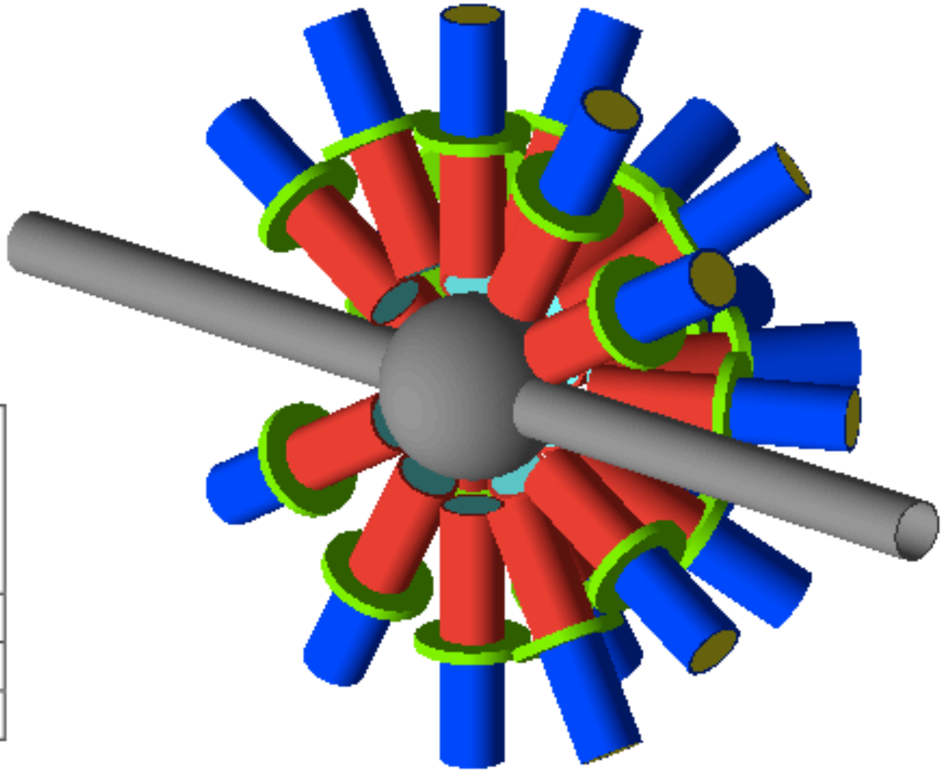


- **Region of interest populated**
- **Low energy region mainly excited → Isoscalar component enhanced**

ALBA – African LaBr3:Ce Array

ALBA will be composed by 23 large volume LaBr3:Ce





Gamma-Ray Energy (MeV)	Efficiency for 6 LaBr3:Ce detectors (%)	Efficiency for 23 LaBr3:Ce detectors (%)
1.3	2.28	8.74
6	0.96	3.68
10	0.60	2.30

This unique experimental setup would pioneer a new generation of studies where the γ-decay probability is too low to be investigated with the current arrays located worldwide.

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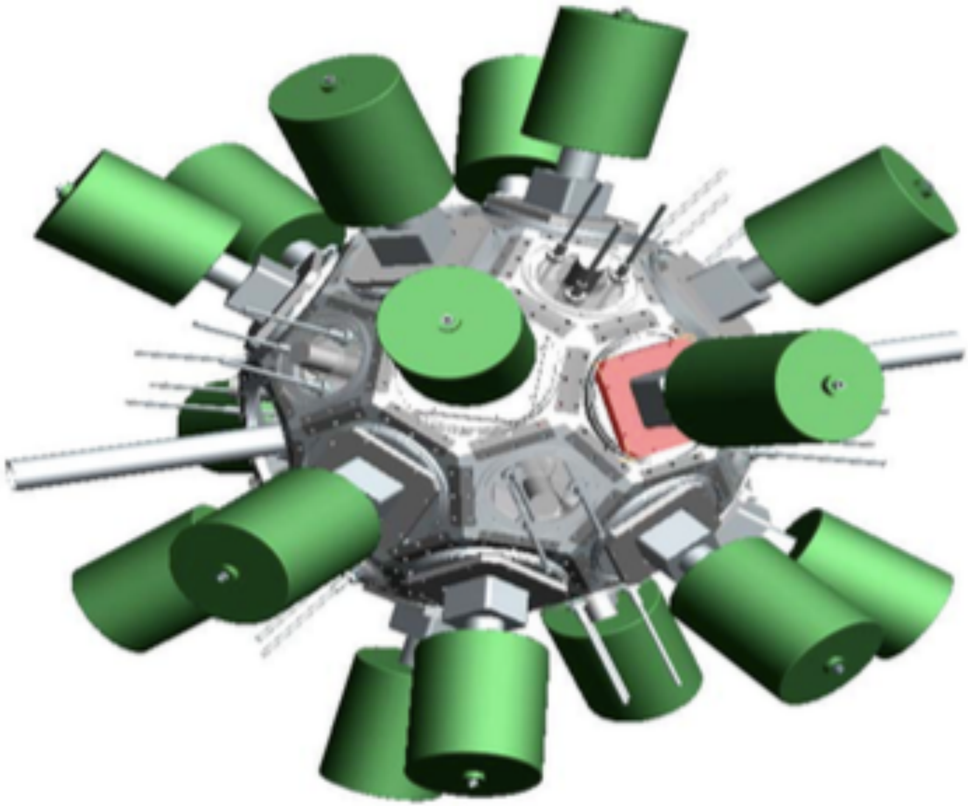

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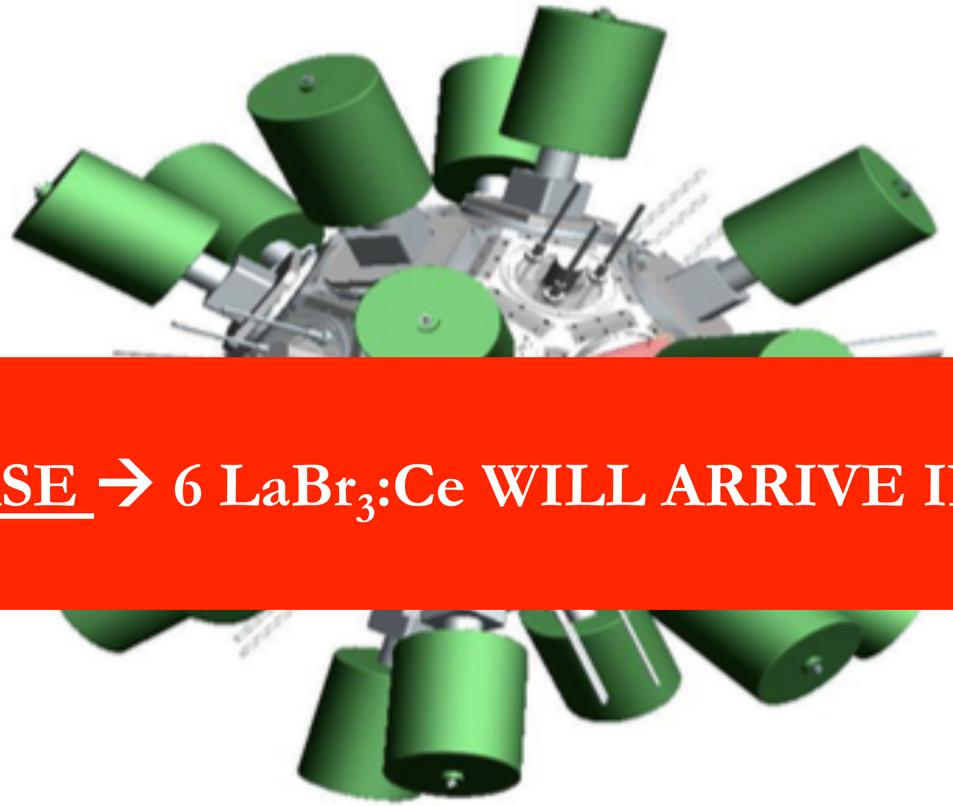

<u>FIRST PHASE</u> → 6 $LaBr_3$:Ce WILL ARRIVE IN AUGUST

This unique experimental setup would pioneer a new generation of studies where the γ-decay probability is too low to be investigated with the current arrays located worldwide.

CONCLUSIONS

Pygmy Dipole Resonance:

- Intensively studied in the past 20 years
- **Important astrophysics implications**: nucleosynthesis and Equation of State (EoS)
- Experiments performed in different mass region and with different probes
- **PDR present in neutron-rich nuclei**
- **Isovector and Isoscalar nature but still disagreement on collectivity**

PDR in deformed nuclei:

- Few studies up to now
- **Deformation does not destroy the excitation pattern but splits the response into different peaks for the different K^{π} modes.**
- **Isoscalar channel enhanced**

iThemba LABS:

- New experiment performed at iThemba LABS: ^{154}**Sm(α,α'γ)**
- **First time coupling of K600 spectrometer to a gamma detector array (BaGeL)**
- Preliminary results
- **ALBA** – African LaBr3:Ce Array

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Thanks for the attention