
Studi sperimentali delle
Risonanze Giganti nei nuclei atomici:
studio della struttura nucleare e applicazioni

Outline

Giant resonances : their classifications and physical issues addressed through their investigations

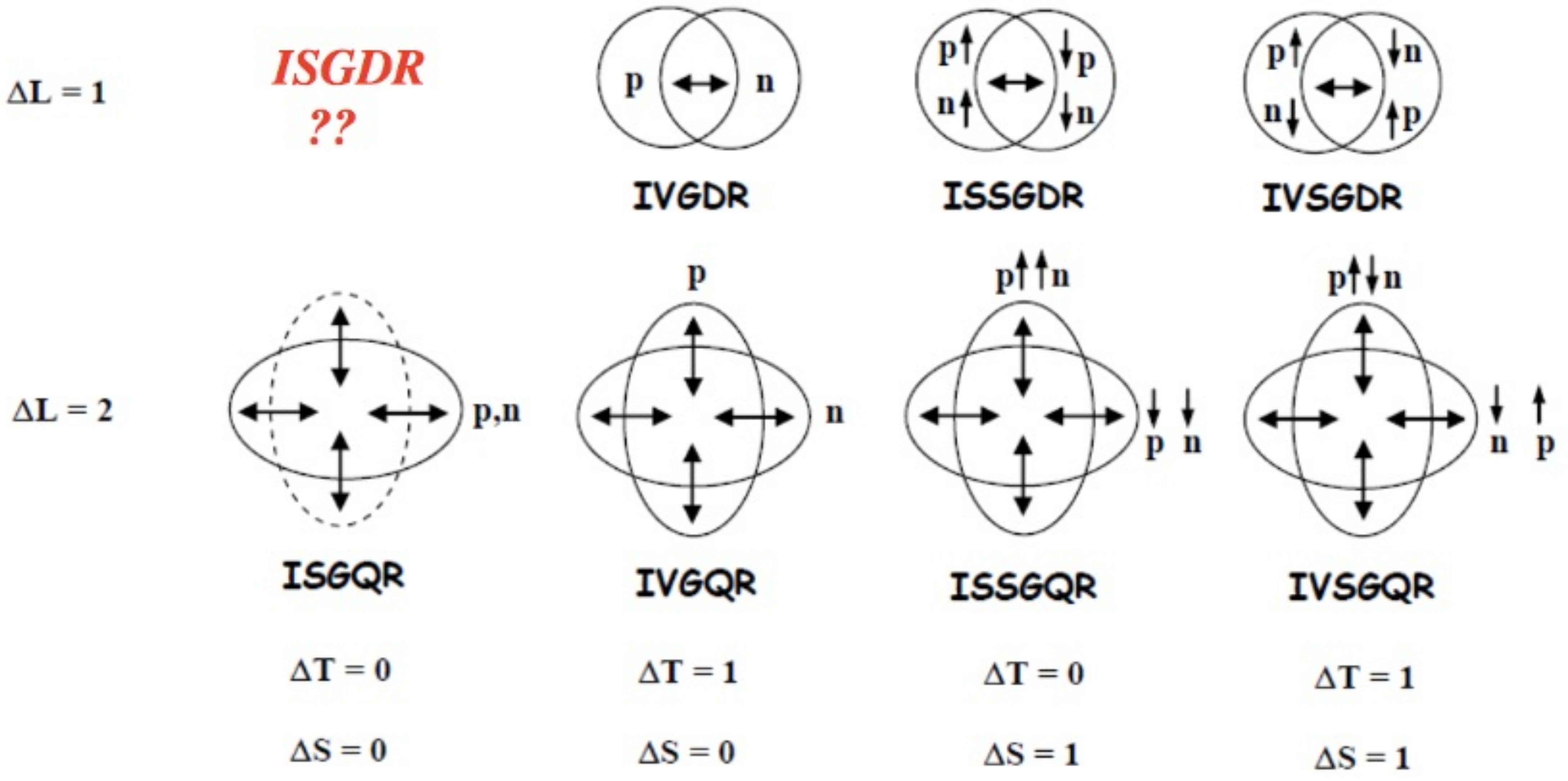
Compression modes – Monopole and Dipole

E1 response : why do we study it ?
what do we need to know?

E1 response in the low energy region :
Pygmy Dipole Resonance (in neutron rich nuclei)

stable nuclei and radioactive beams

Giant resonances: Fundamental modes of nuclear excitation



Microscopic picture: GRs are coherent (1p-1h) excitations induced by single-particle operators.

- **Excitation energy depends on**

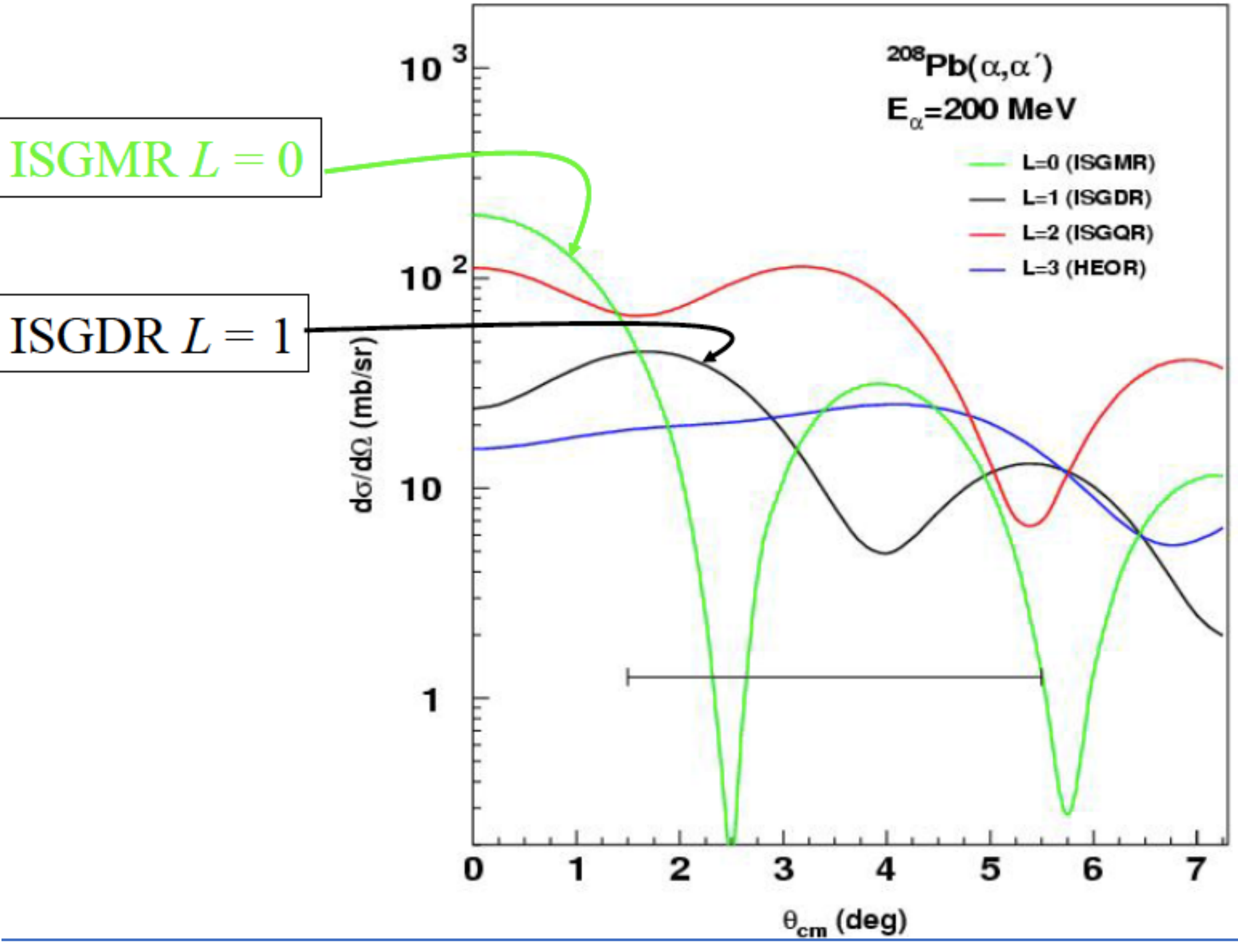
  ***i*) multipole *L* (*L*ħω, since radial operator ∝ r^L; except for ISGMR and ISGDR, 2ħω & 3ħω, respectively),**

  ***ii*) strength of effective interaction and**

  ***iii*) collectivity.**
- **Exhaust appreciable % of EWSR**
- **Acquire a width due to coupling to continuum and to underlying 2p-2h configurations.**

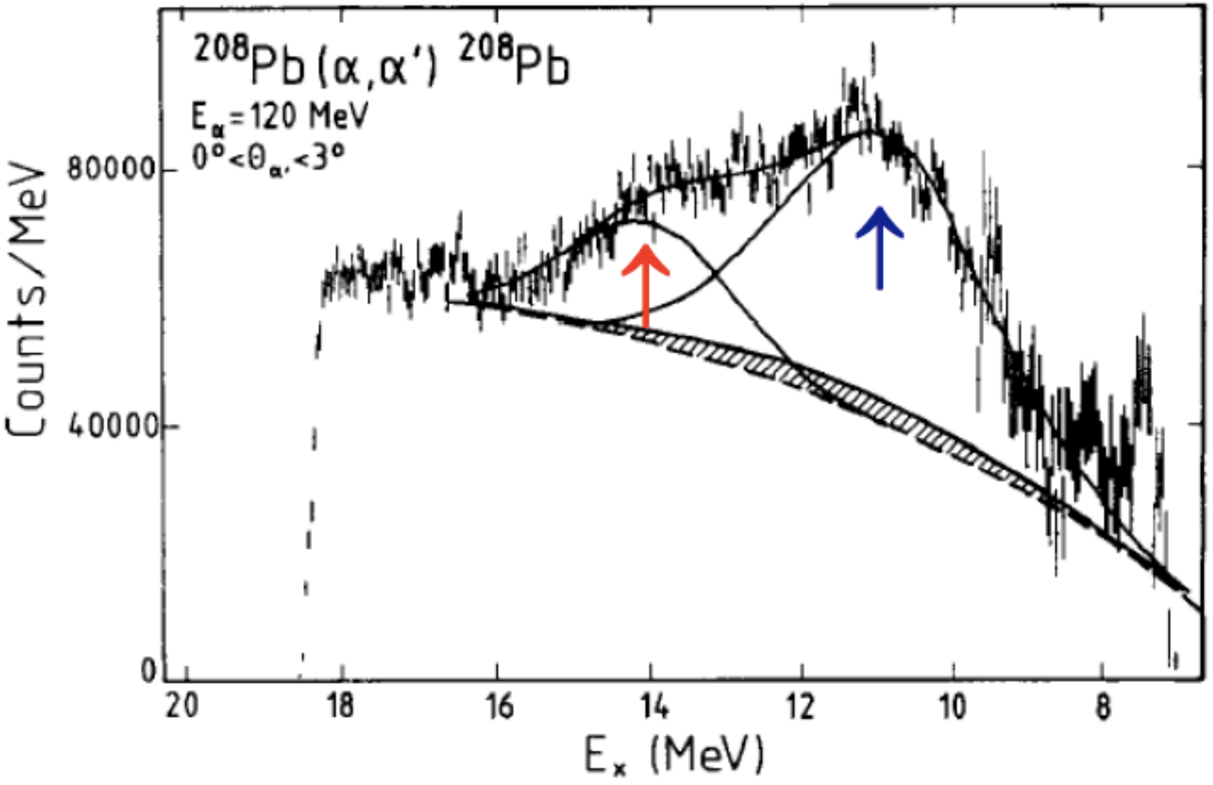
features

Angular distribution of
the population cross sections

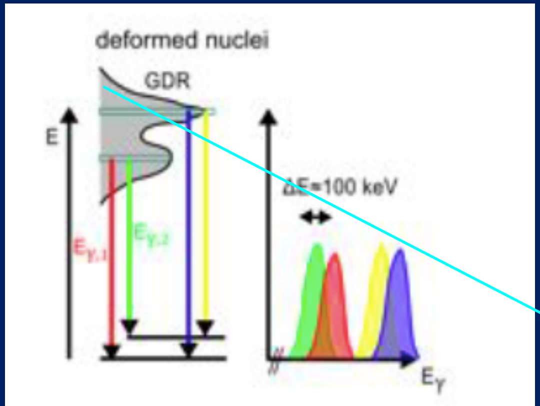


ISGQR at 10.9 MeV

ISGMR at 13.9 MeV

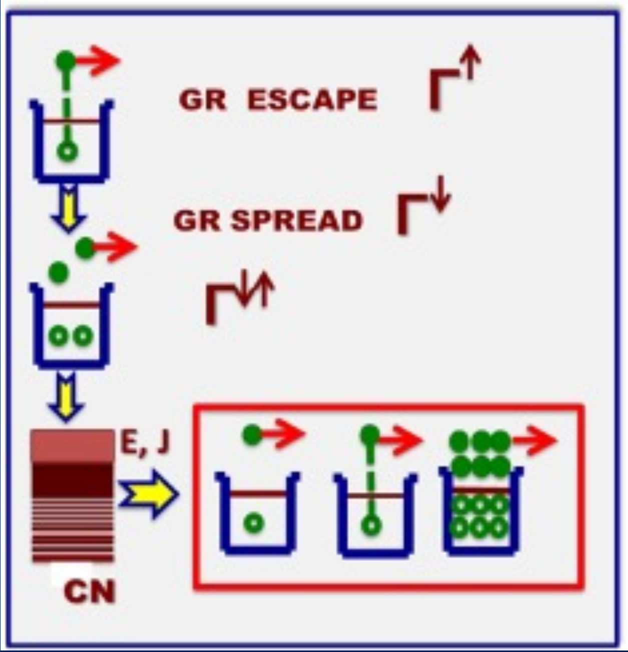


Damping of the giant dipole vibration in the nucleus

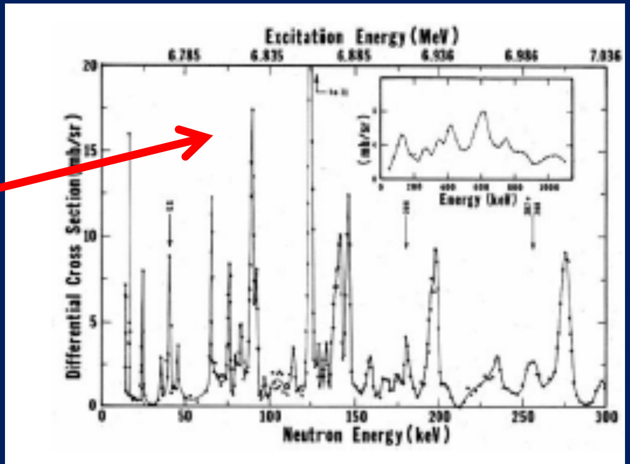


Exp. on gamma decay from GDR : why?

Damping mechanisms



- Ordered motion : dipole oscillation
- Coupling to complex states :
  Stringent test to theory
- Regime at which the
  nucleus is characterized by chaos :
  Compound nuclear system



Compund nuclear states n-resonances

Microscopic structure of ISGMR & ISGDR

Transition operators:

$$O^{L=0} = \sum_i r_i^0 Y_0^0 + \frac{1}{2}\sum_i r_i^2 Y_0^0 + \dots$$

Constant   Overtone

2ħω excitation

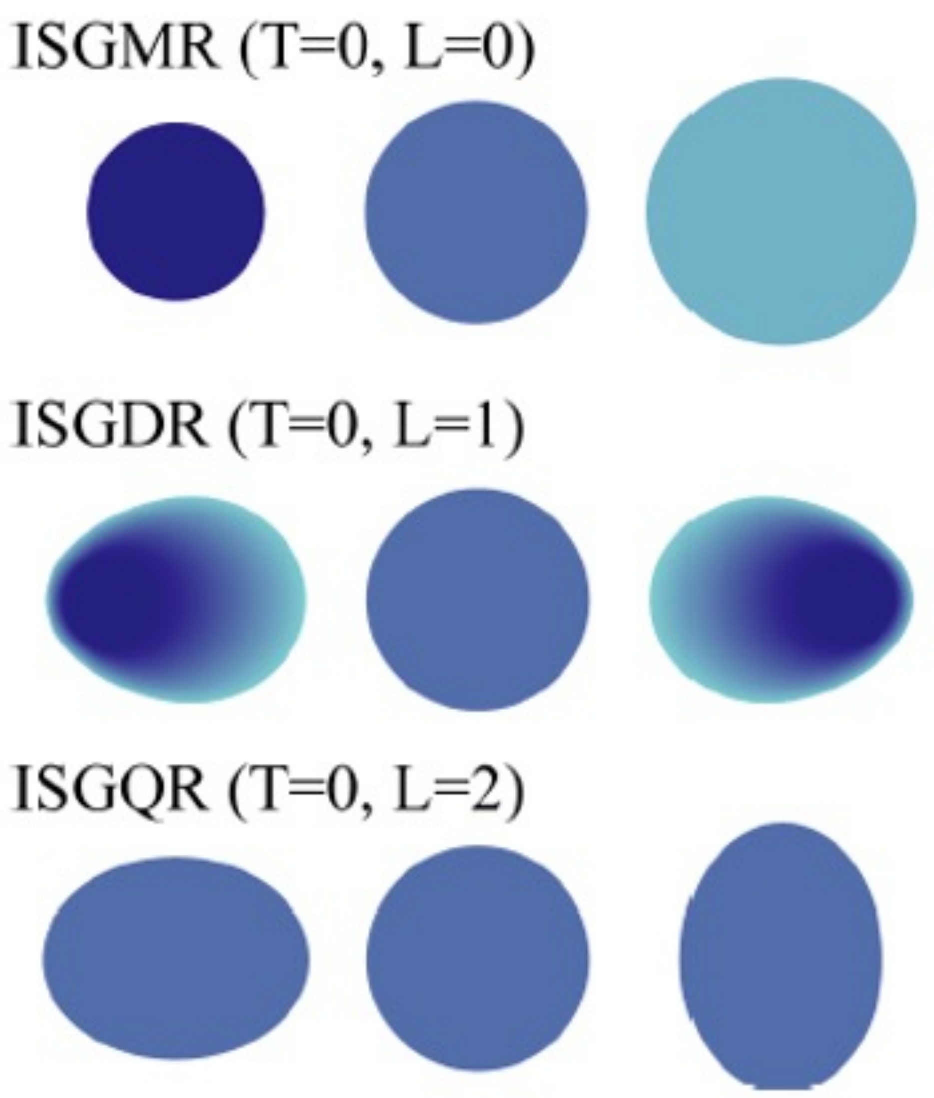
$$O^{L=1} = \sum_i r_i^1 Y_0^1 + \frac{1}{2}\sum_i r_i^3 Y_0^1 + \dots$$

Spurious c.o.m. motion   Overtone

3ħω excitation (overtone of c.o.m. motion)

Breathing mode

Squizing mode



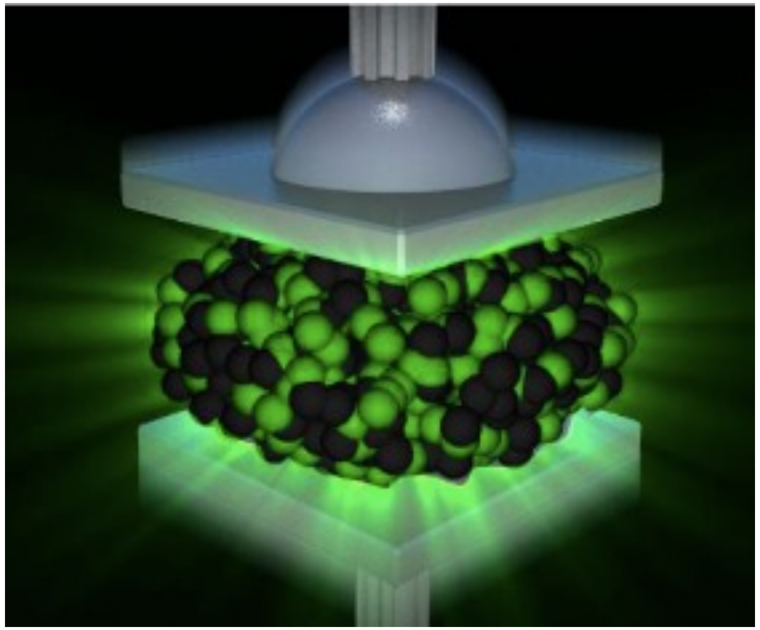
Microscopic picture: GRs are coherent (1p-1h) excitations induced by single-particle operators.

Nucleus → **Many-body system with a finite size**

Vibrations → **Multipole expansion with** r, Y_{lm}, τ, σ

	ΔS=0, ΔT=0	ΔS=0, ΔT=1	ΔS=0, ΔT=1	ΔS=1, ΔT=1	ΔS=1, ΔT=1
L=0: Monopole	ISGMR $r^2 Y_0$	IAS τY_0	IVGMR $\tau r^2 Y_0$	GTR $\tau \sigma Y_0$	IVSGMR $\tau \sigma r^2 Y_0$
L=1: Dipole	ISGDR $r^3 Y_1$		IVGDR $\tau r Y_1$		IVSGDR $\tau \sigma r Y_1$
L=2: Quadrupole	ISGQR $r^2 Y_2$		IVGQR $\tau r^2 Y_2$		IVSGQR $\tau \sigma r^2 Y_2$
L=3: Octupole	LEOR, HEOR $r^3 Y_3$				

In fluid mechanics, **compressibility** is a measure of the relative volume change of a fluid as a response to a pressure change.



$$\beta = -\frac{1}{V}\frac{\partial V}{\partial P}$$

where P is pressure, V is volume.

Incompressibility or **bulk modulus** (K) is a measure of a substance's resistance to uniform compression and can be formally defined:

$$K = -V\frac{\partial P}{\partial V}$$

ISGMR (T=0, L=0)

ISGDR (T=0, L=1)

In Constrained and Scaling Models:

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

$$E_{ISGDR} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\varepsilon_F}{m\langle r^2\rangle}}$$

ε_F is the Fermi energy and the nucleus incompressibility:

$$K_A = \left[r^2(d^2(E/A)/dr^2)\right]_{r=R_0}$$

J.P. Blaizot, Phys. Rep. 64 (1980) 171

In HF+RPA calculations,

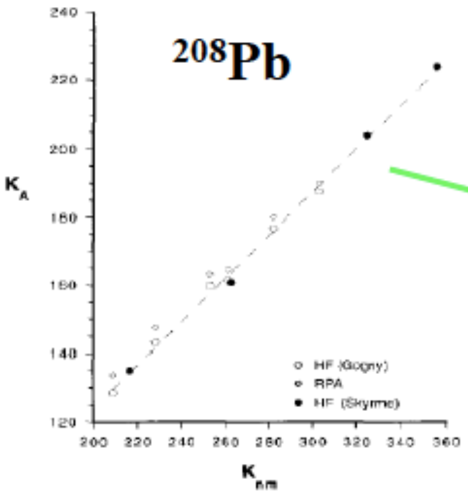
$$K_{nm} = \left[9\rho^2 \frac{d^2(E/A)}{d\rho^2}\right]_{\rho=\rho_0}$$

Nuclear matter

E/A: binding energy per nucleon **K_A: incompressibility**

ρ : nuclear density

ρ_0 : nuclear density at saturation



K_A is obtained from excitation energy of ISGMR & ISGDR

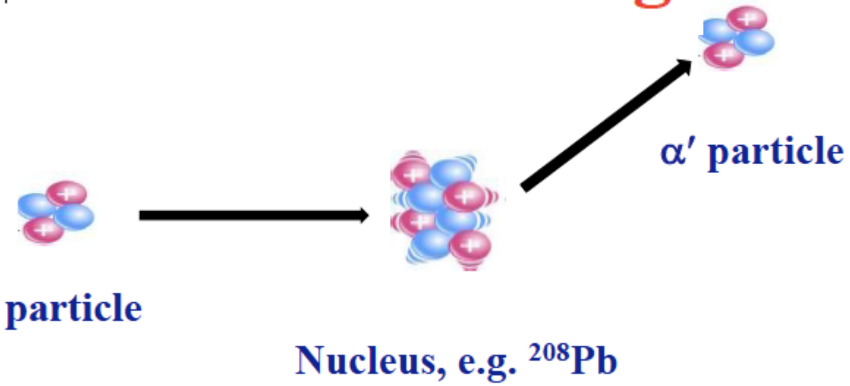
$K_A = 0.64K_{nm} - 3.5$

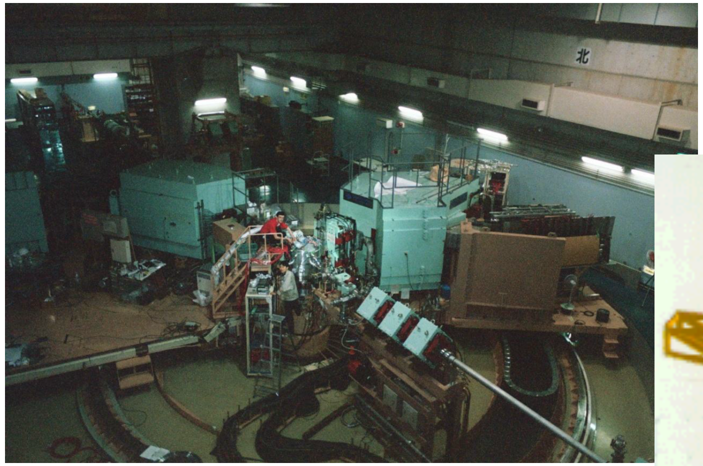
J.P. Blaizot, NPA591 (1995) 435

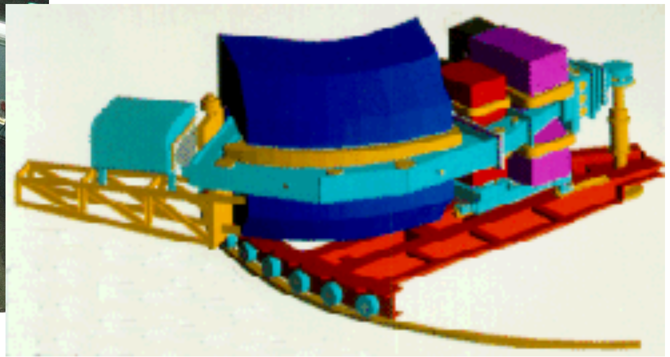
Difference Technique to isolate the GMR

Difference of spectra

Inelastic α scattering





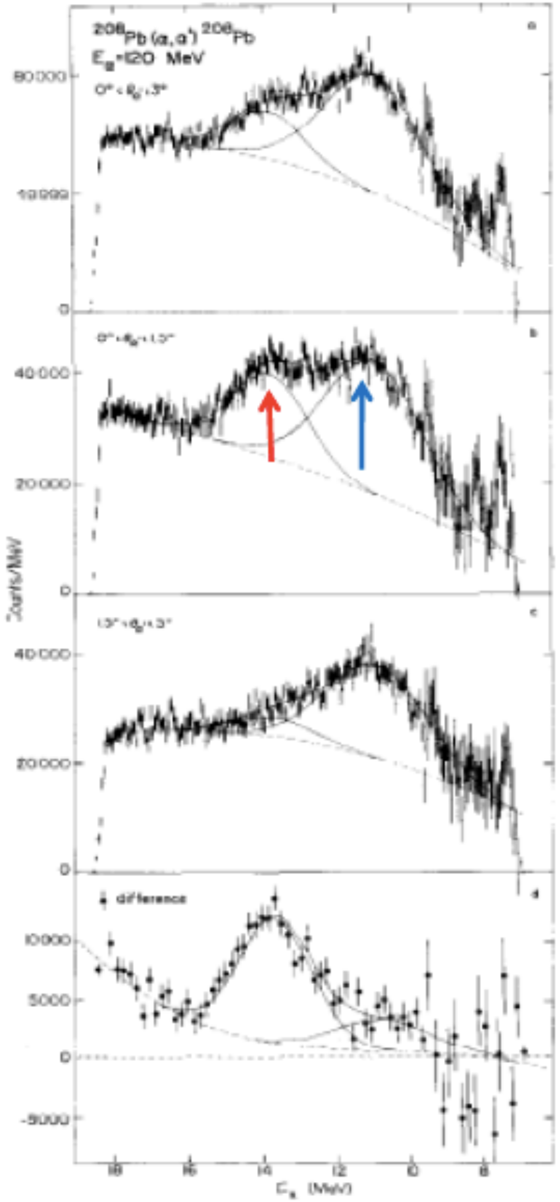


$0° < \theta_{\alpha'} < 3°$

$0° < \theta_{\alpha'} < 1.5°$

$1.5° < \theta_{\alpha'} < 3°$

Difference



Excitation of ISGDR in ^{208}Pb

From GMR data on ^{208}Pb and ^{90}Zr,

$K_\infty = 240 \pm 10$ MeV

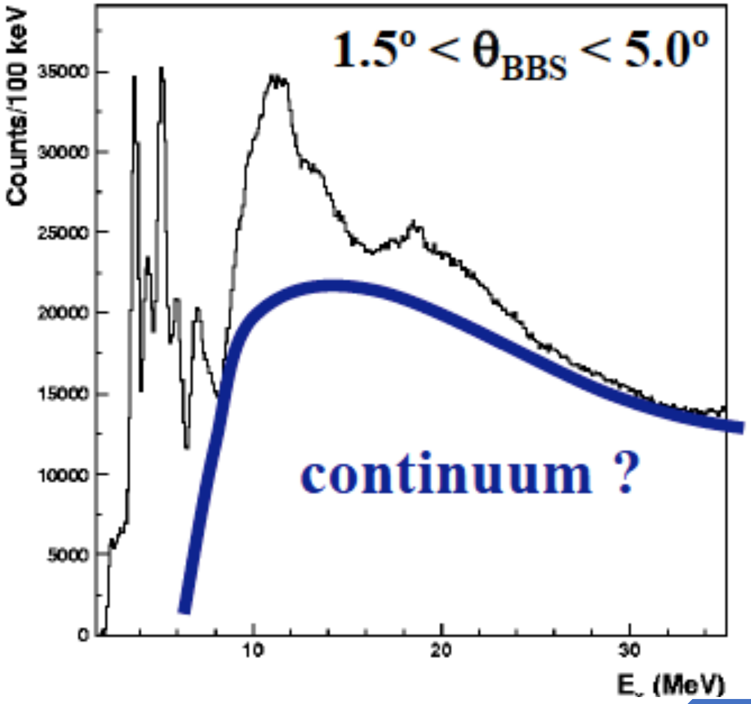
This number is consistent with both ISGMR and ISGDR Data

In ^{208}Pb located around 22 MeV and width of 4 MeV

L=1 angular distribution peaks close to a scattering angle of 0°

- Difficult to identify in nuclear continuum and rides on instrumental background

Singles ^{208}Pb(α,α′) 200 MeV ⇒



- There has been much progress in understanding ISGMR & ISGDR macroscopic properties

  Systematics: E_x, Γ, %EWSR

  $\Rightarrow K_{nm} \approx 240$ MeV

- Sn nuclei are softer than ^{208}Pb and ^{90}Zr.
- Recently, Microscopic Structure for a few nuclei

  CRPA has some success in ^{208}Pb & ^{58}Ni but fails badly in ^{116}Sn & ^{90}Zr.

- Possible observation quadrupole compression mode, i.e. overtone of ISGQR

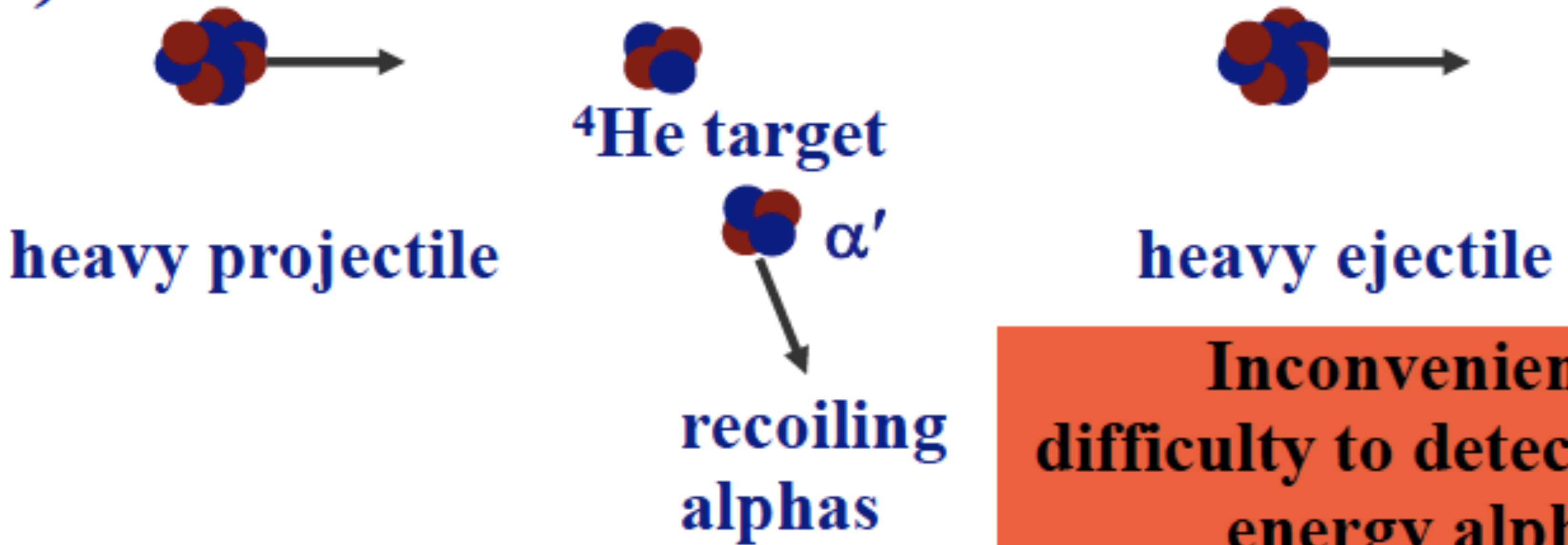
And in nuclei far from Stability?

GMR studies with radioactive beams

(beam energies of 50-100 MeV/u are needed!)

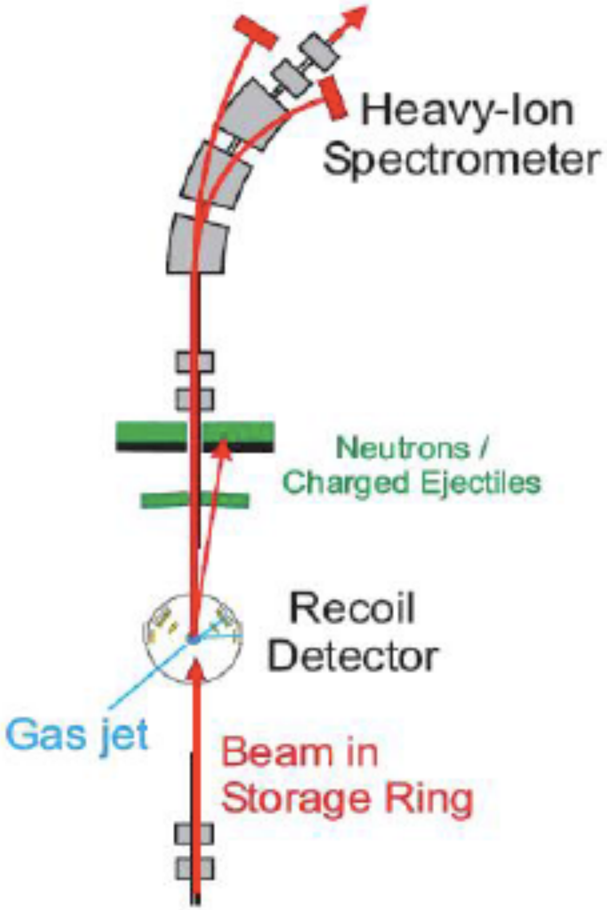
Approach (at FAIR): measure the recoiling alphas

(α,α')



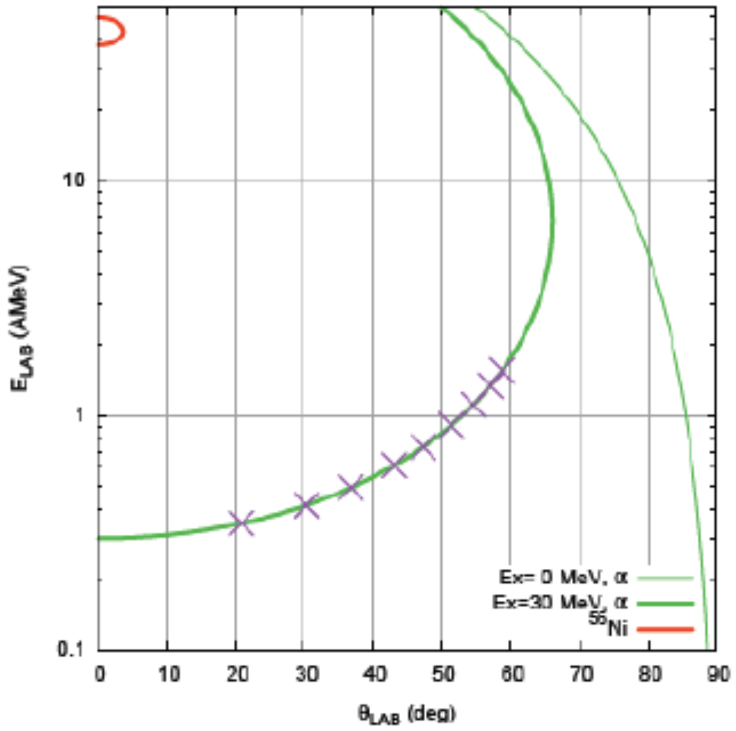
Inconvenience: difficulty to detect the low-energy alphas

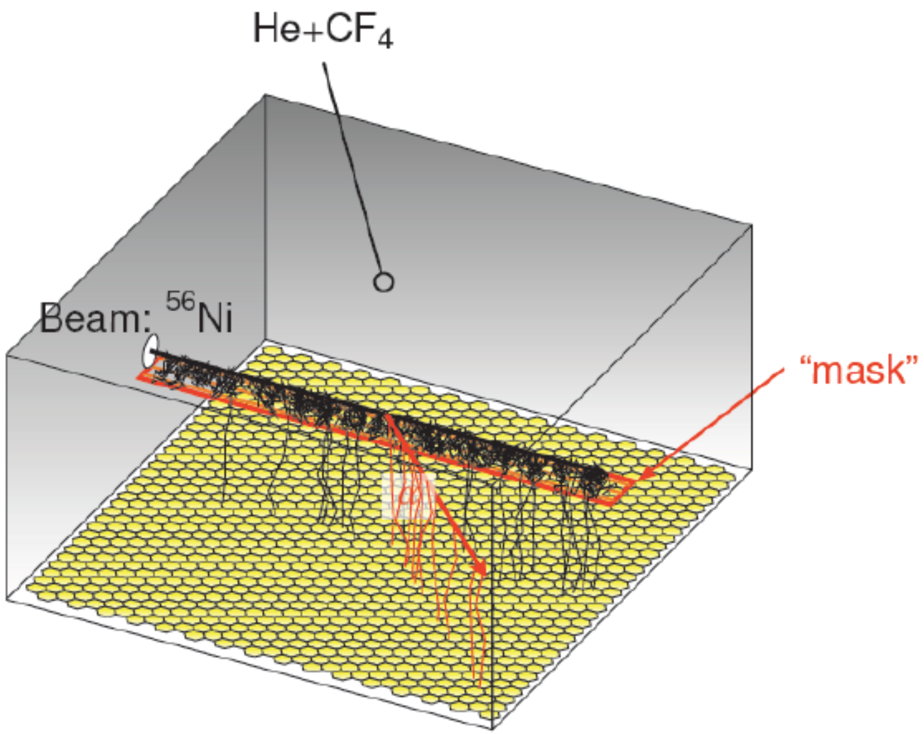
Two approaches



Storage ring

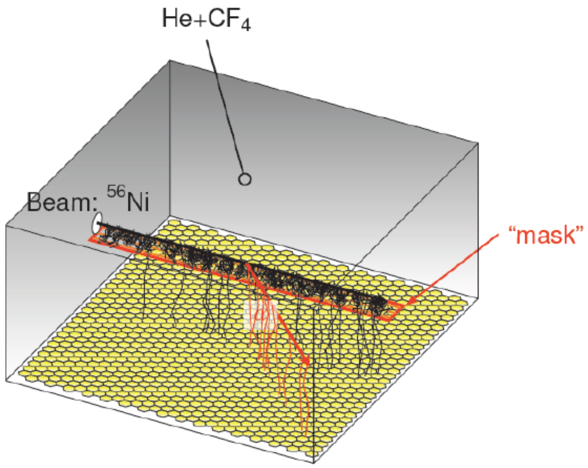
Measure angles and few hundreds keV alpha





Active target

results



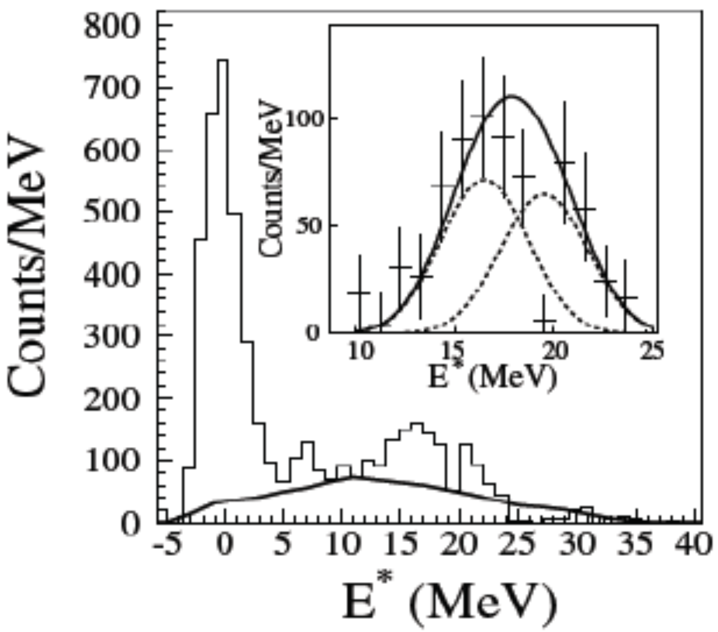
Experiments at GANIL

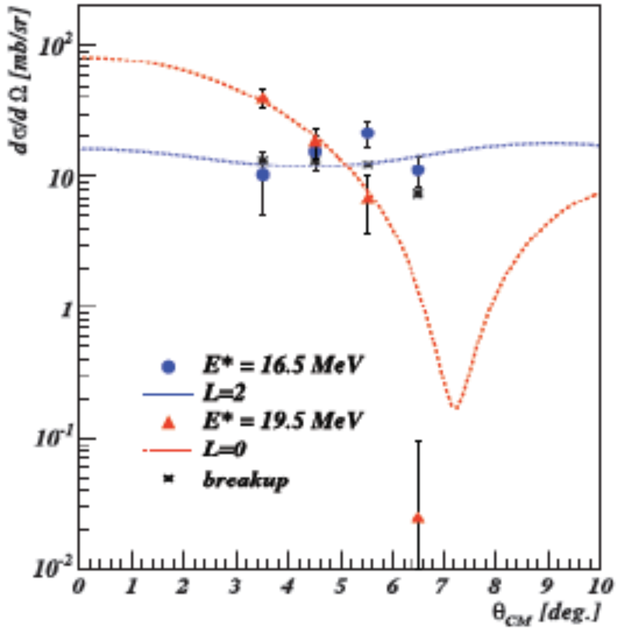
Phys. Rev. Lett. 100, 042501 (2008).

ISGMR in unstable nuclei

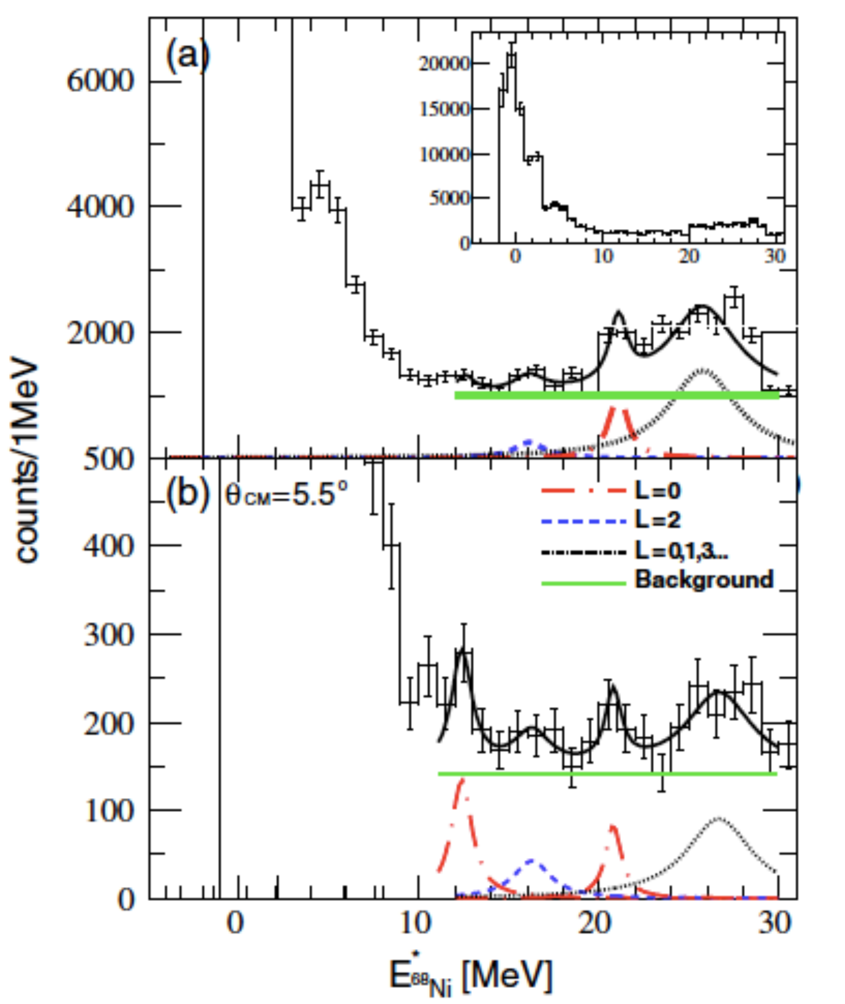
^{56}Ni: active target MAYA filled with deuterium gas bombarding energy of 50*A* MeV

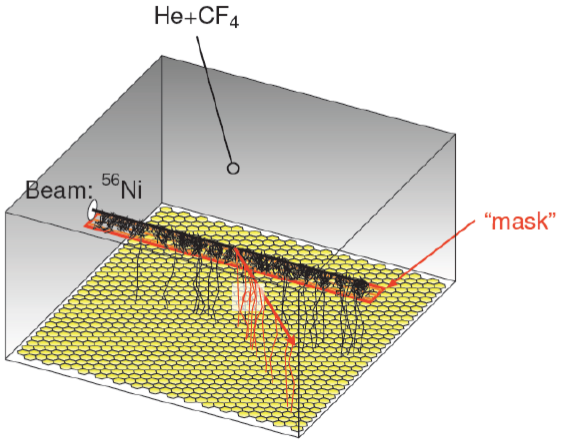
C. Monrozeau *et al.* @ GANIL





Results for GMR in ^{68}Ni

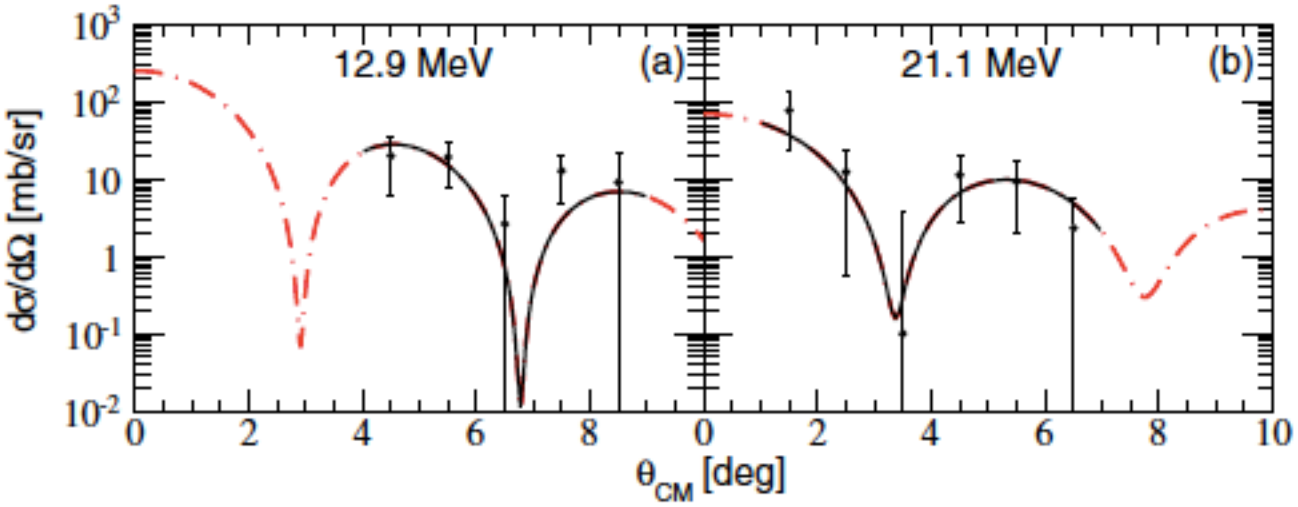




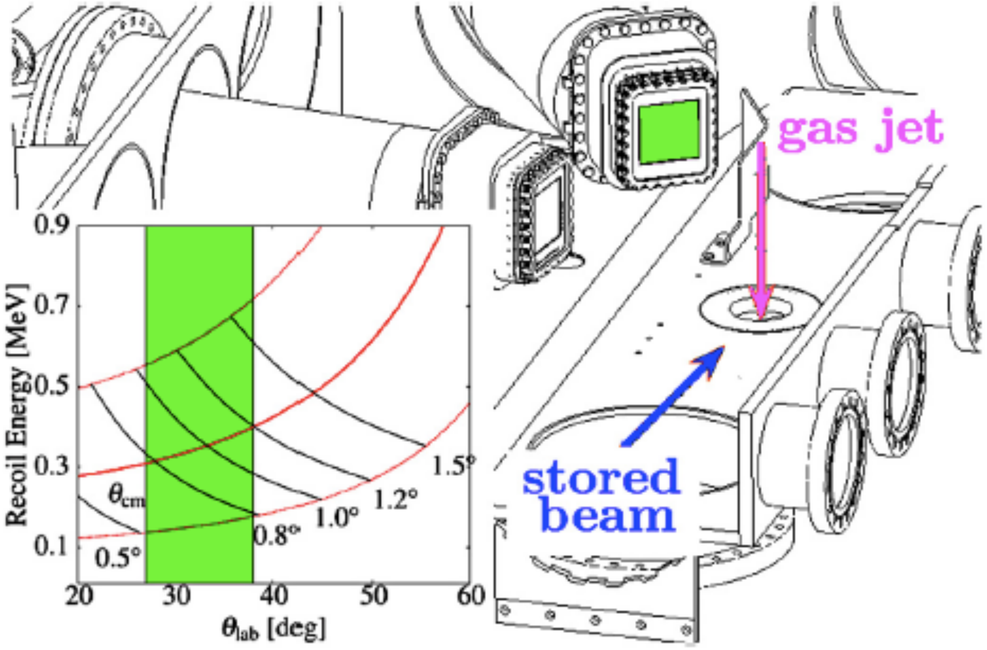
The isoscalar giant monopole resonance (ISGMR) centroid was determined to be

21.1 p/m 1.9 MeV
and indications for a soft monopole mode are provided for the first time at 12.9 p/m 1.0 MeV.

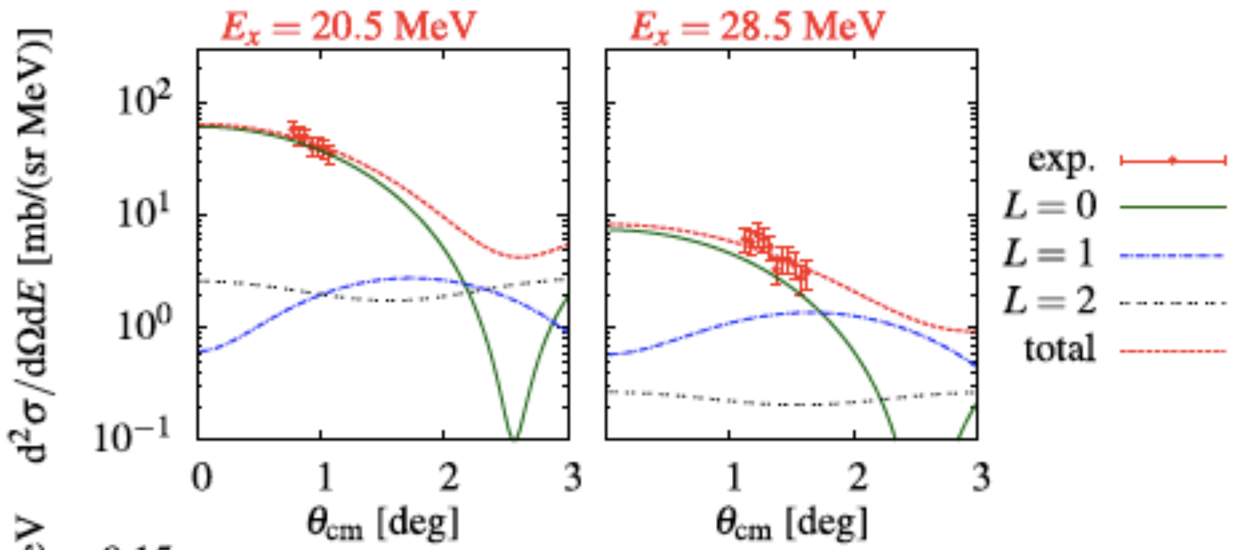
PRL 113, 032504 (2014)

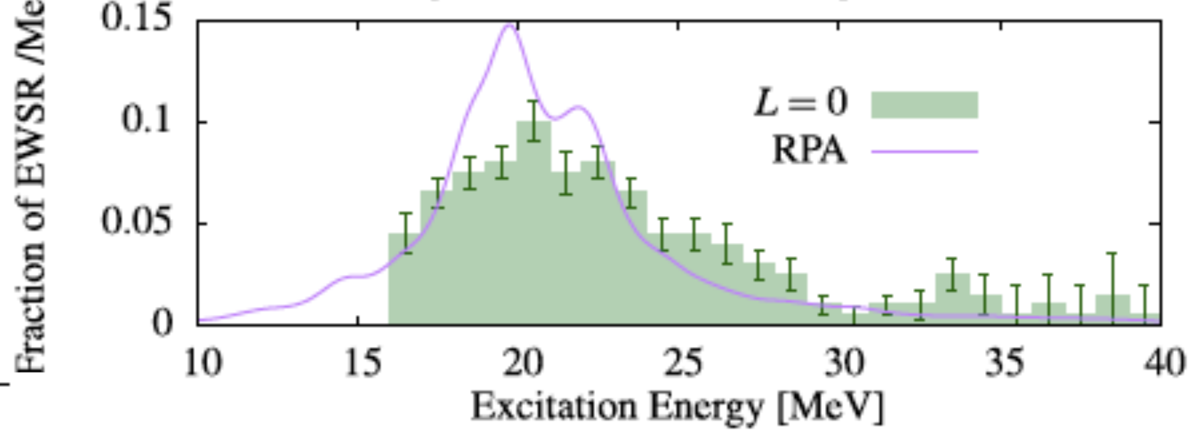


The feasibility study using the ^{58}Ni stable nucleus beam



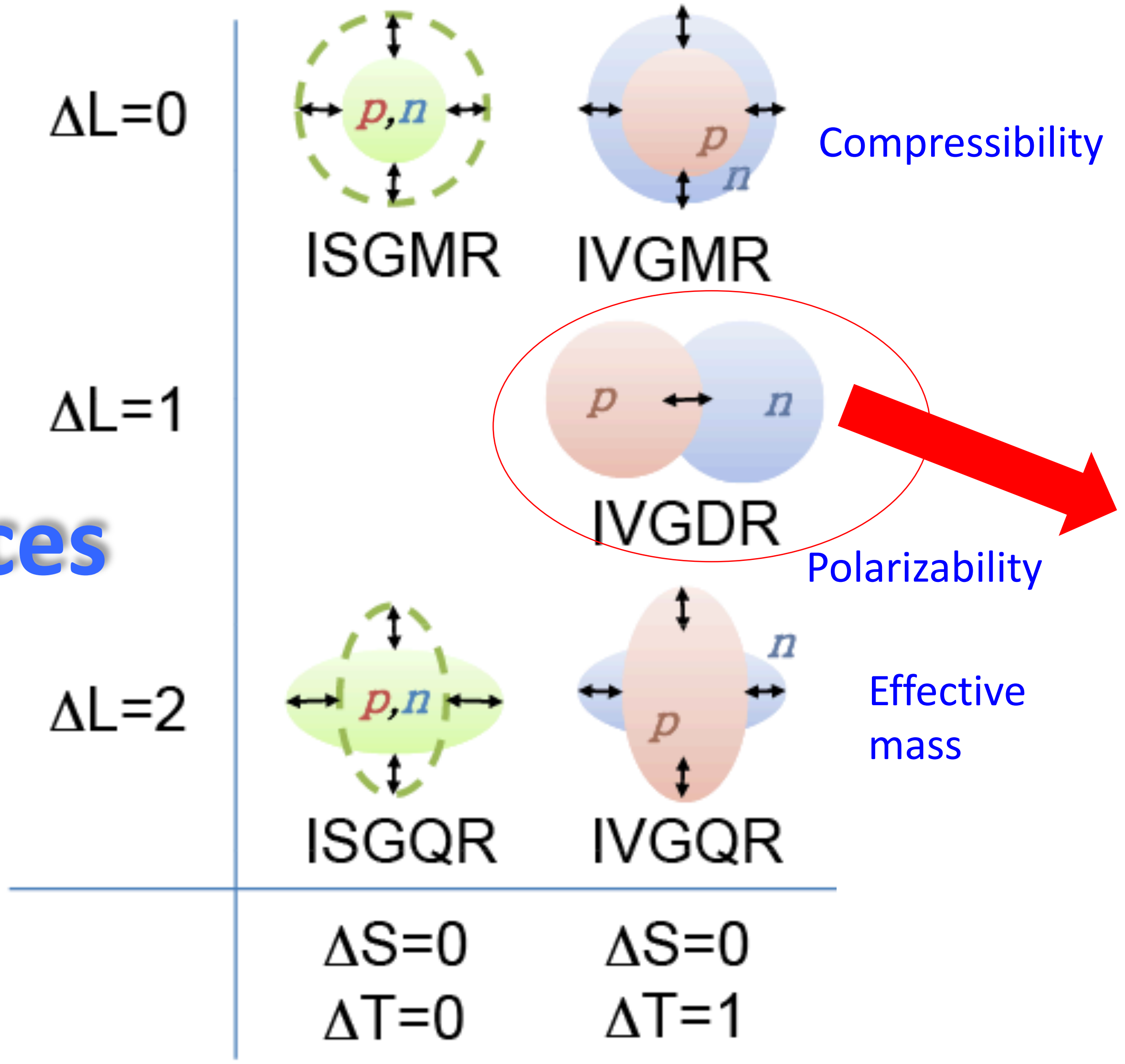
Reference	Centroid [MeV]	$Width_{RMS}$ [MeV]	EWSR [%]
this work	20.5(6)	4.6(6)	79^{+12}_{-11}
[9]	$19.20^{+0.44}_{-0.19}$	$4.89^{+1.05}_{-0.31}$	85^{+13}_{-10}
[32]	$20.30^{+1.69}_{-0.14}$	$4.25^{+0.69}_{-0.23}$	74^{+22}_{-12}
[26]	$19.9^{+0.7}_{-0.8}$	–	92^{+4}_{-3}





The collective response of nuclei

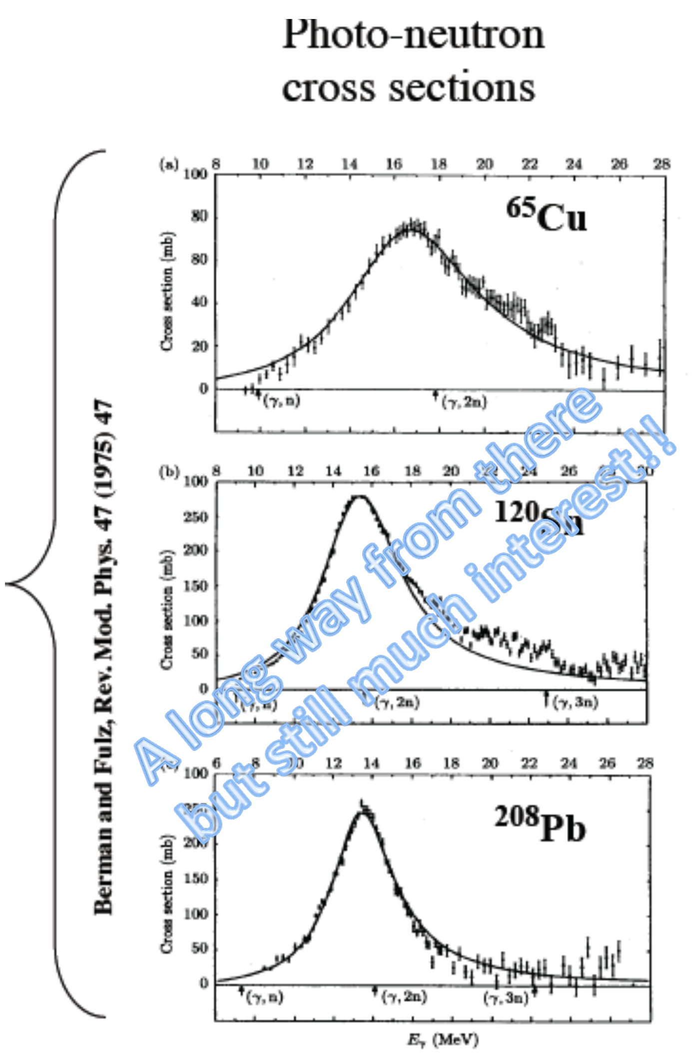
Electric Giant Resonances



Compressibility

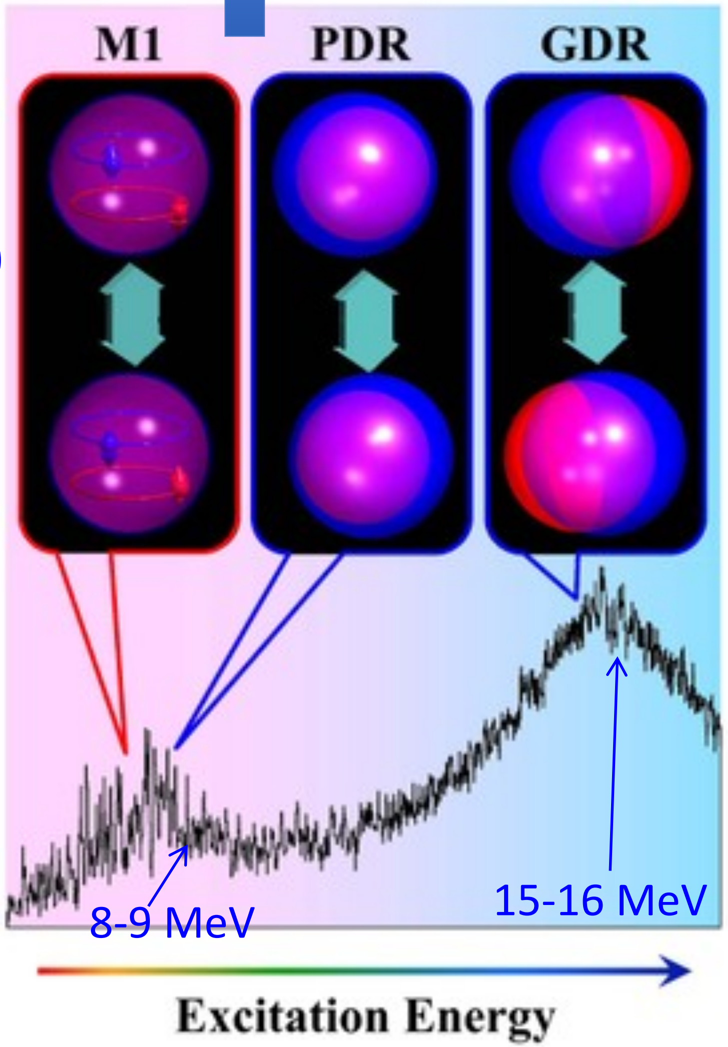
Polarizability

Effective mass



The collective dipole response of nuclei: the details

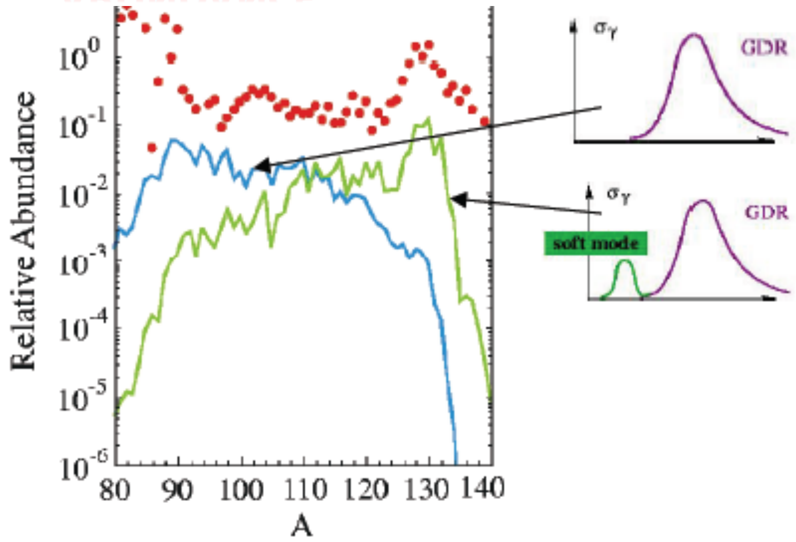
Dipole strength at low energy below the particle binding energy (pygmy)



PDR (Pygmy) : Much work is being made (exp –and theory) to understand its structure

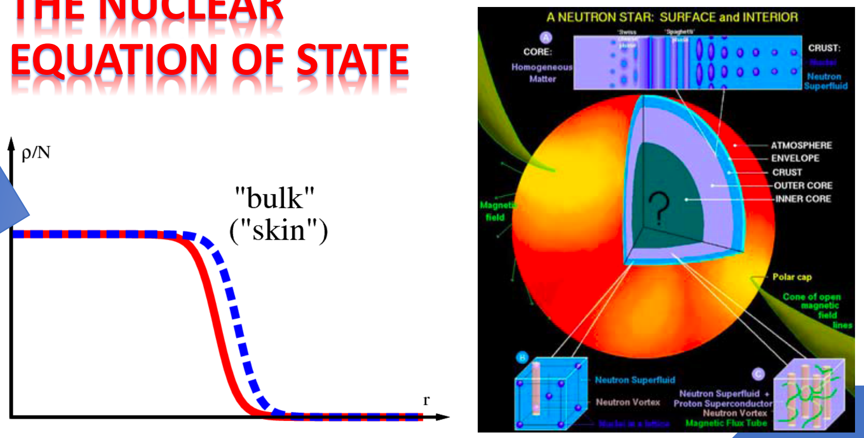
The E1 around binding affects r-process

THE R-PROCESS ABUNDANCE



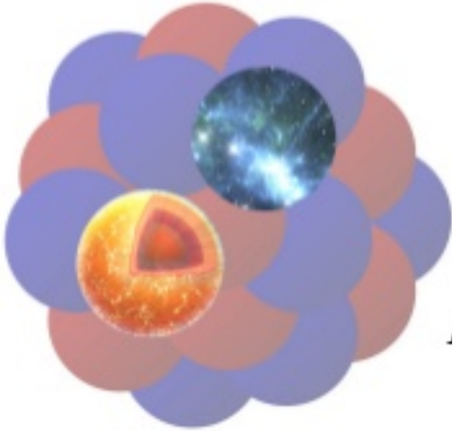
In neutron rich (with a neutron skin) the pygmy is seen of a properties of the nucleus skin

THE NUCLEAR EQUATION OF STATE



THE GDR AND THE NUCLEAR EQUATION OF STATE (EOS)

A function of nuclear density and asymmetry



EOS for Energy per nucleon

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

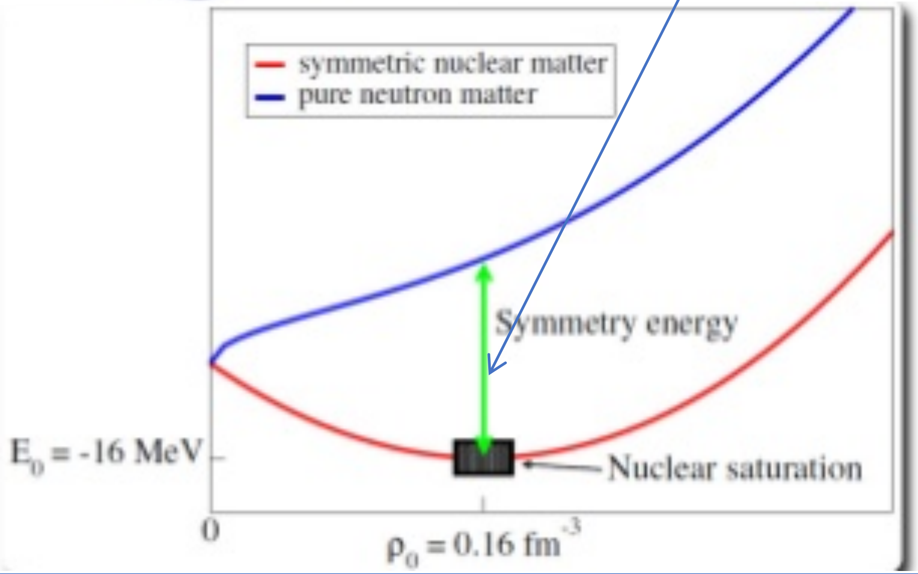
$$\rho(r)=\rho_n(r)+\rho_p(r)$$

$$\delta(r)=\frac{\rho_n(r)-\rho_p(r)}{\rho_n(r)+\rho_p(r)}$$

Saturation Density
~0.16 fm^{-3}
ρ_0 :

symmetry energy

$$S(\rho)=J+\frac{L}{3\rho_0}(\rho-\rho_0)+\frac{K_{sym}}{18\rho_0^2}(\rho-\rho_0)^2+\ldots$$



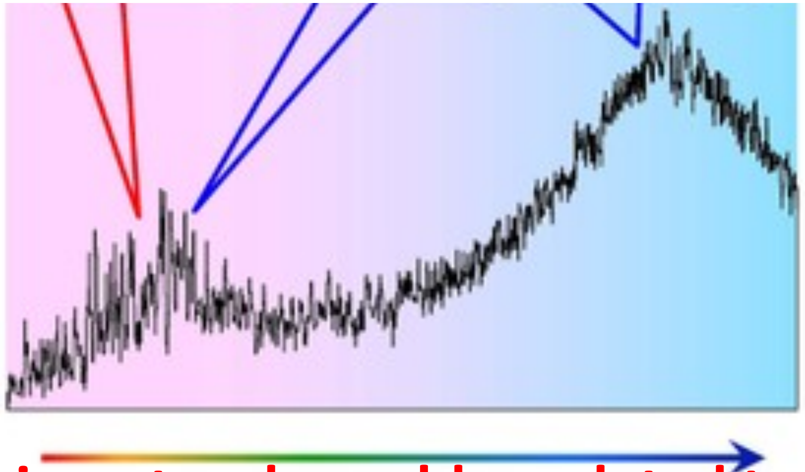
Expansion in series- L is the first derivative of an energy and this is a pressure…

$$L \propto P \propto R_{n-star}^4$$

(Baryonic Pressure)

P = pressure

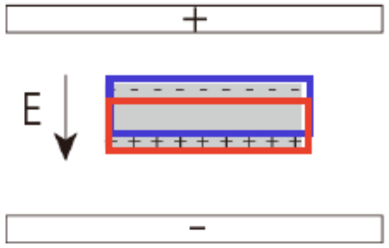
THE GDR AND THE NUCLEAR EQUATION OF STATE (EOS)



Experiments: observables related to the electric dipole response

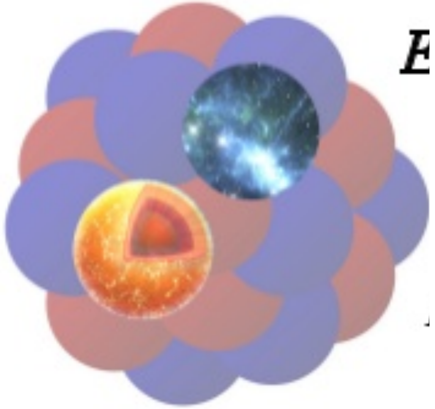
- The position and intensity of the low energy part (Pygmy)
- Polarizability (the pygmy part plays a role!)

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int \frac{\sigma_{abs}}{\omega^2}\, d\omega$$



Electric Dipole Polarization

$\mathbf{P} = \alpha \mathbf{E}$



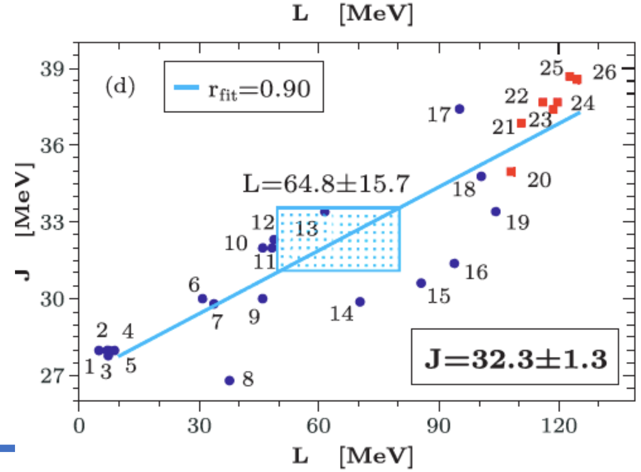
Theoretical predictions

Correlations between different quantities

L -→ related to Pygmy and polarizability

L → related to the neutron skin (difference of the matter and electromagnetic radii)

L and J are related

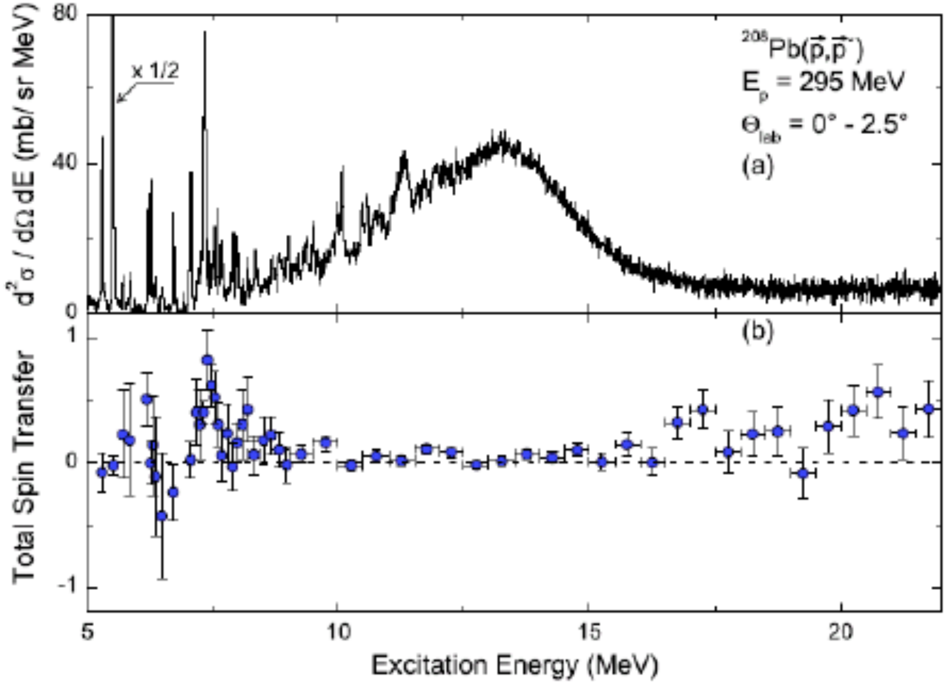


SOME RESULTS FOR ^{208}PB

- Polarization observables at 0° → spinflip / non-spinflip separation
  model-independent
  T. Suzuki, PTP 103 (2000) 859

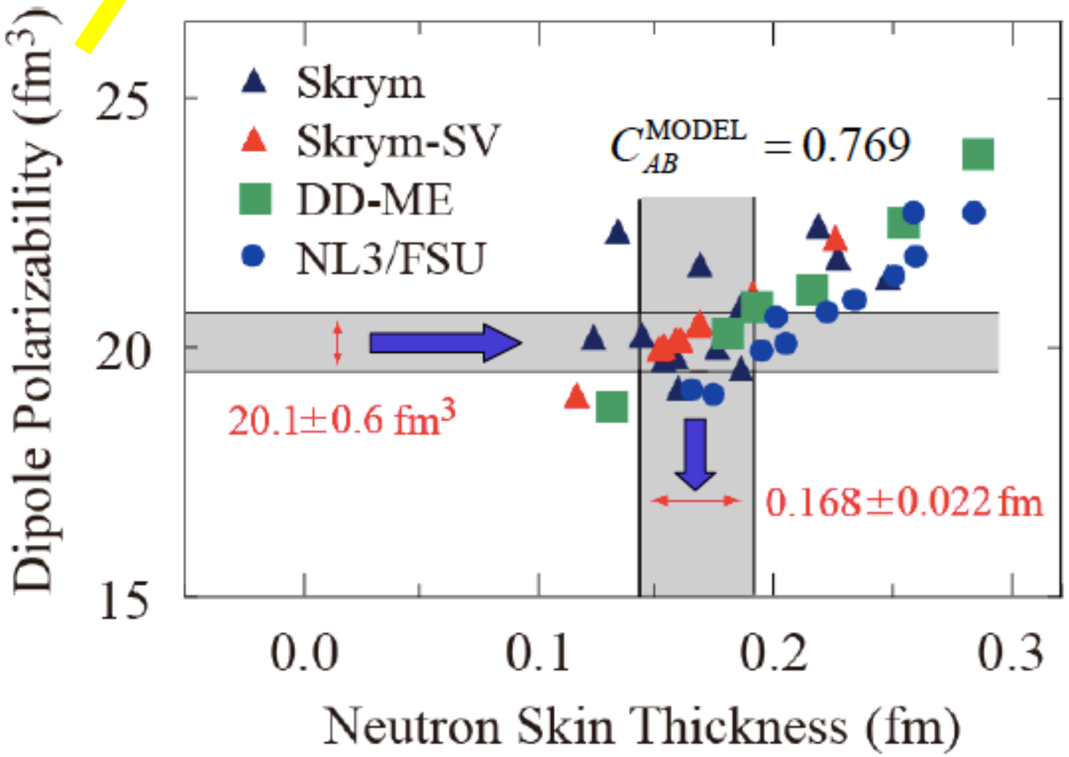
E1 and M1 decomposition

$$\text{Total Spin Transfer } \Sigma \equiv \frac{3-(2D_{SS}+D_{LL})}{4} = \begin{cases} 1 \text{ for } \Delta S = 1 & \text{M1} \\ 0 \text{ for } \Delta S = 0 & \text{E1} \end{cases}$$



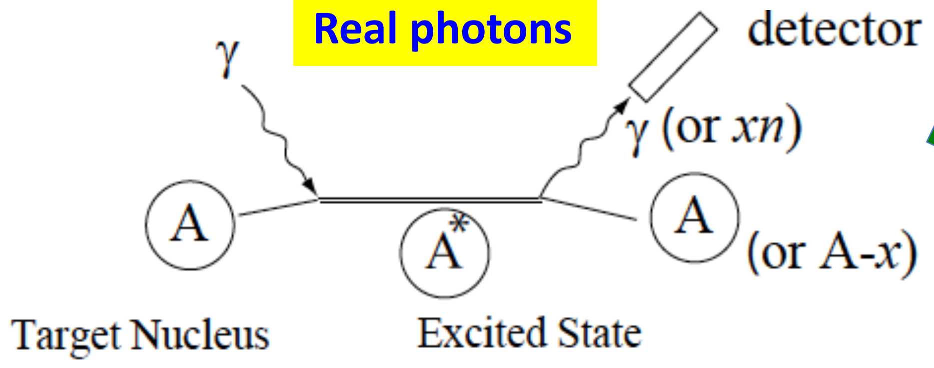
Inelastic scattering of polarized protons at 295 MeV

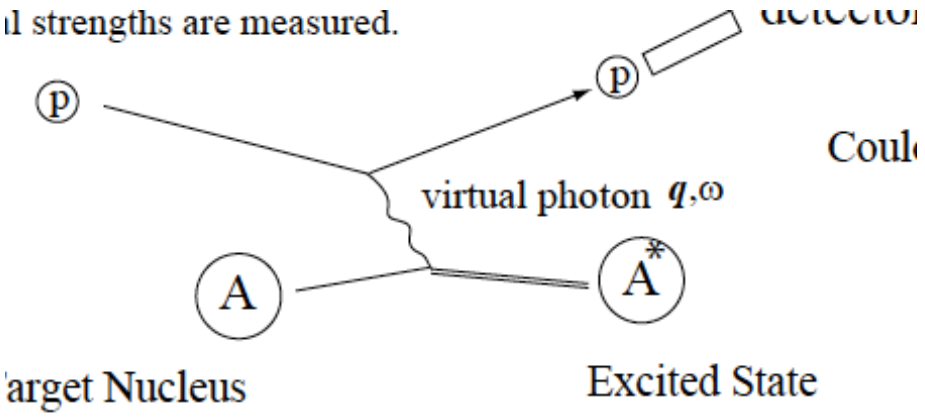
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{abs}}{\omega^2} d\omega$$



SOME RESULTS FOR ^{208}PB

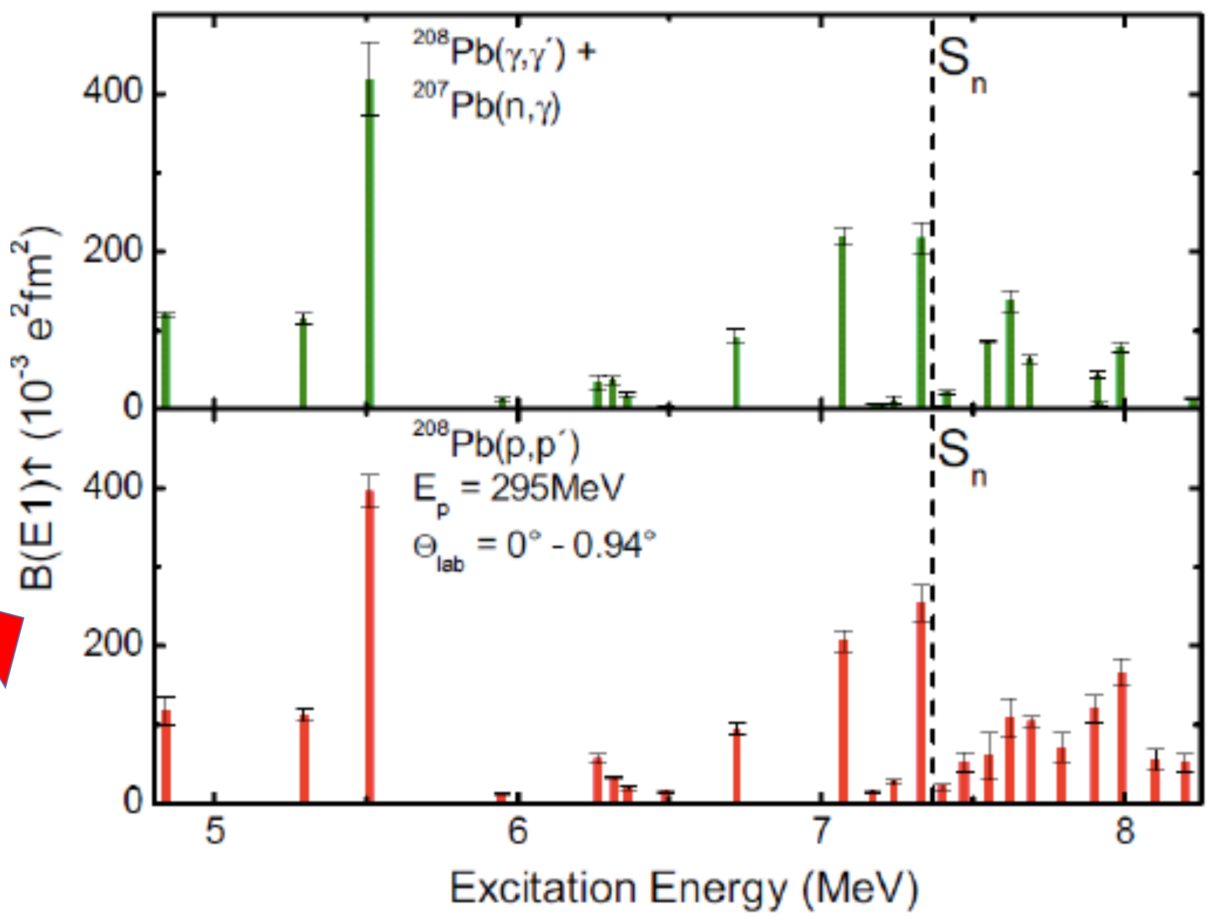
Real photons





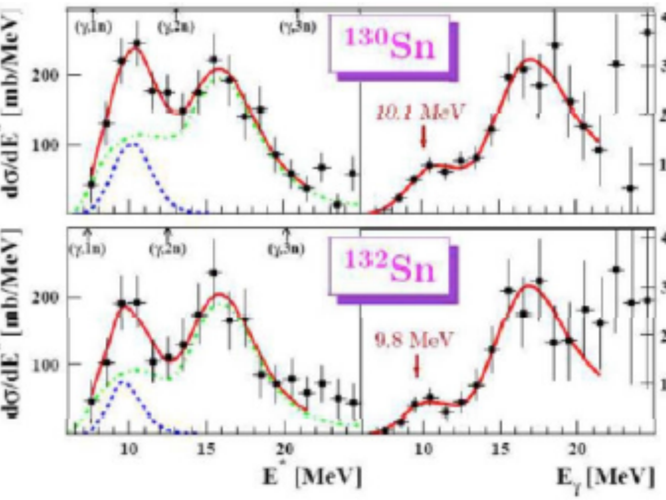
Virtual photons

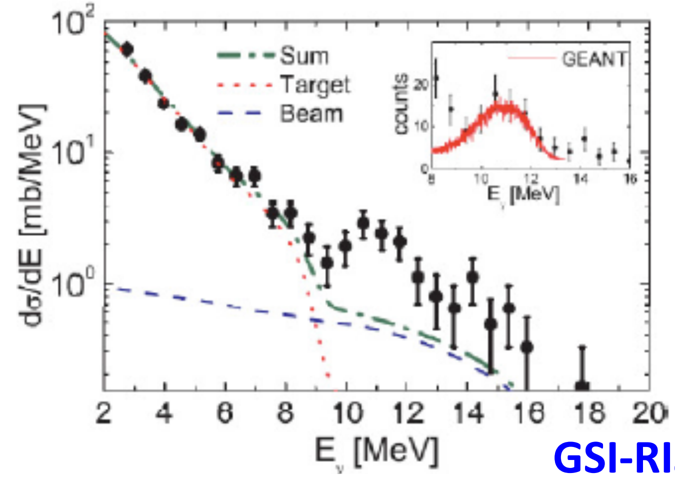
B(E1): low-lying discrete states



Pygmy – via Coulomb excitation on exotic nuclei -$^{130-132}$Sn and ^{68}Ni

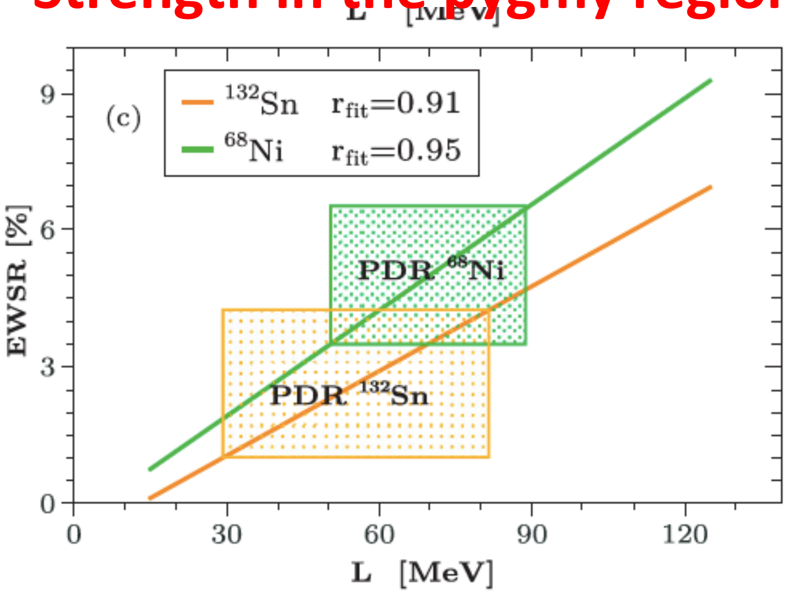
GSI- LAND





GSI-RISING

Strength in the pygmy region



From the deduced L the corresponding neutron skin is

0. 200 p/m 0. 015 fm for ^{68}Ni

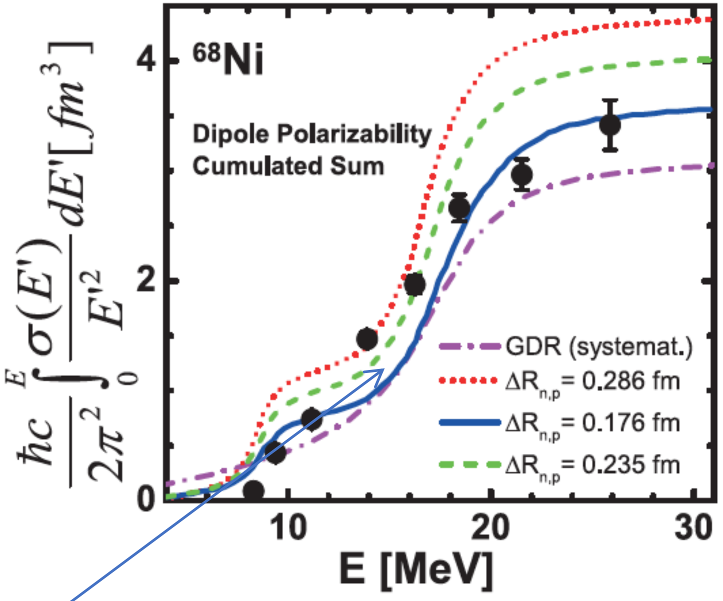
0. 258 p/m 0. 024 fm ^{132}Sn

0. 194 p/m 0. 024 for ^{208} Pb

Polarizabolity – via Coulomb Exc. on exotic ^{68}Ni

Polarizability

GSI- LAND

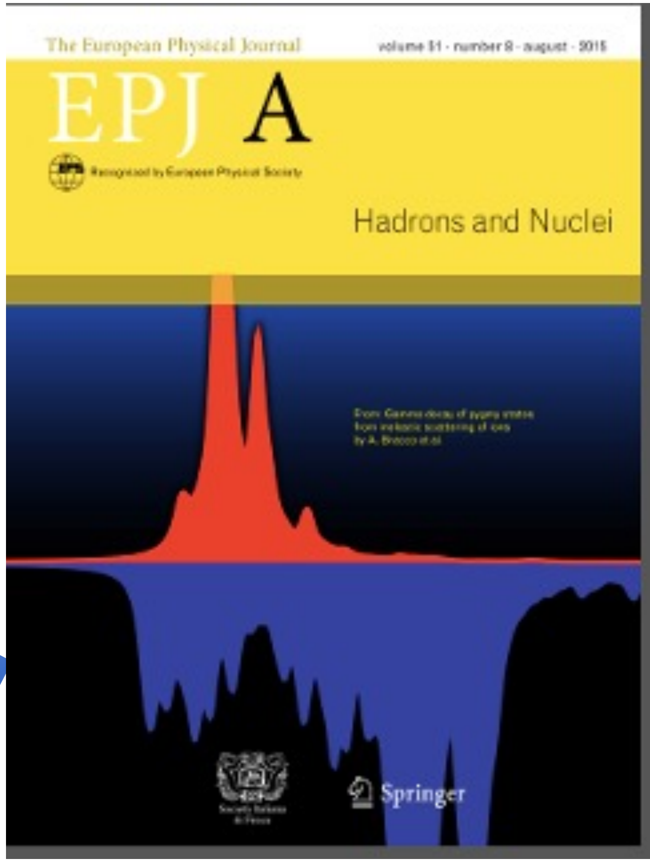


0. 176 fm for ^{68}Ni

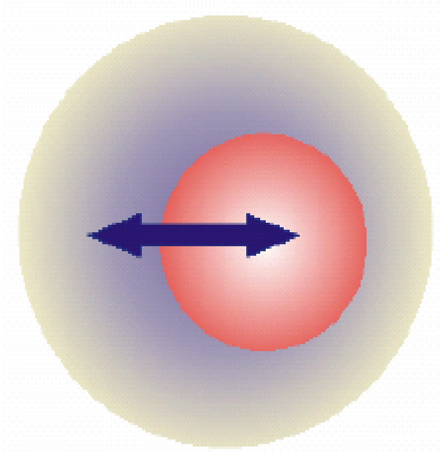
0.17 fm

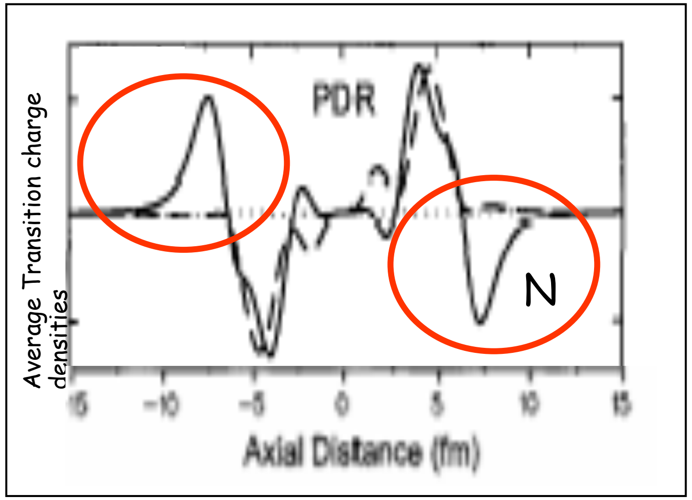
STUDY OF PYGMY STATES

- NATURE OF THE STATE
- CONSTRAIN BETTER THE CALCULATIONS
- GET INFORMATION ON THE WAVE-FUNCTION



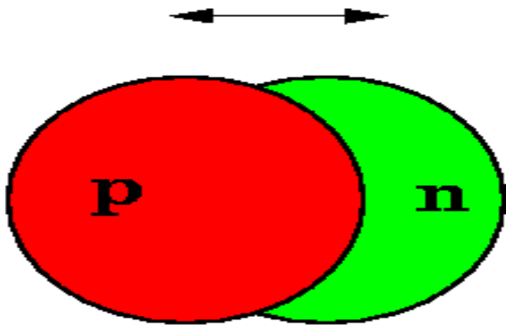
We need to understand the structure of the low lying E1 strength !

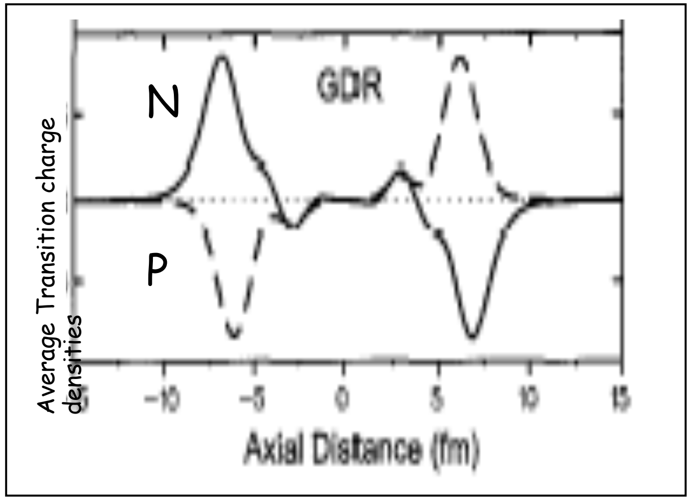




Typical transition density of protons and neutrons for 1^- states at excitation energy in the region of the tail of the GDR

There are regions in which only neutrons contribute

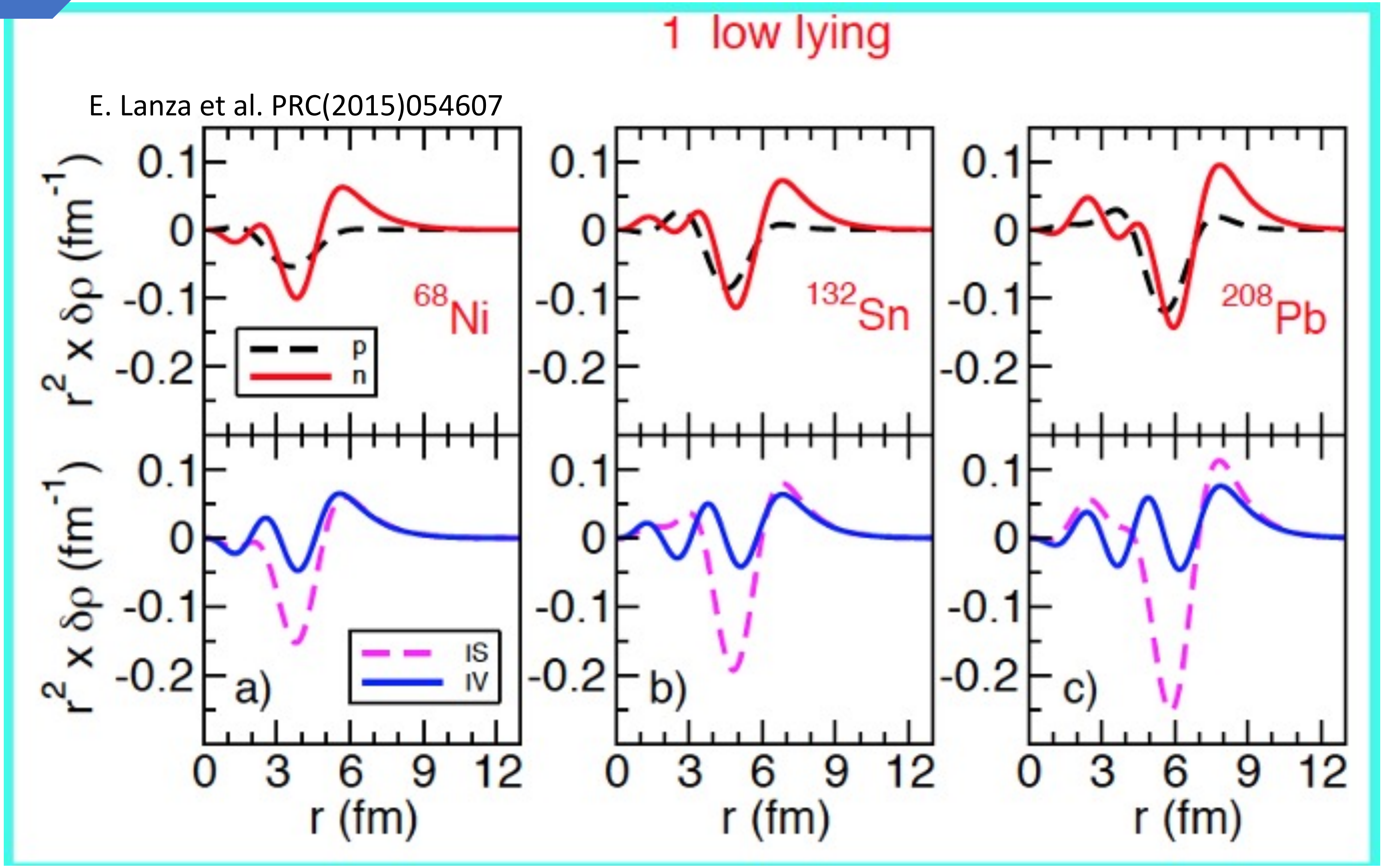




Typical transition density of protons and neutrons for 1^- states at excitation energy in the region of the GDR centroid

Neutron and proton contributions extend in the same spatial regions and proton and neutron oscillations are out of phase!

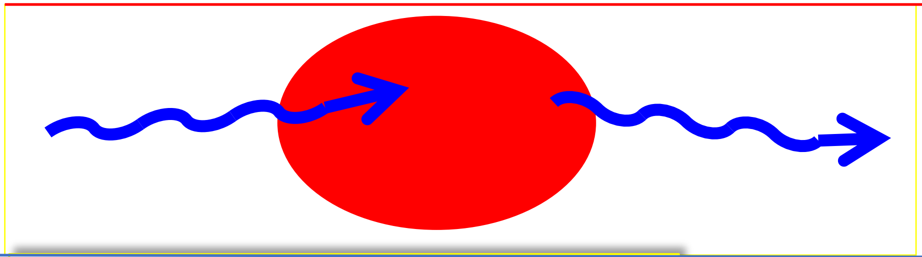
The structure of the low lying 1^- states : Isovector and Isoscalar components



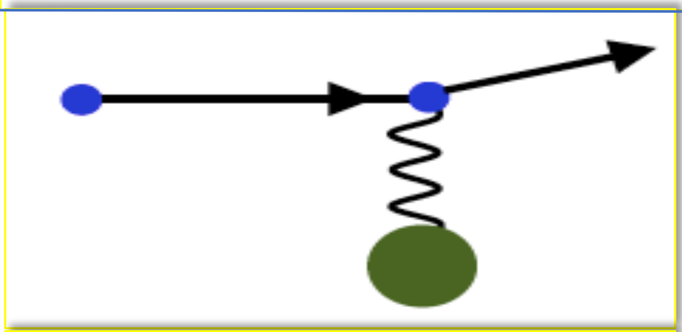
Transition densities of protons and neutrons for 1^- states in the PDR region : similar features for different

Isoscalar and isovector components of the transition densities

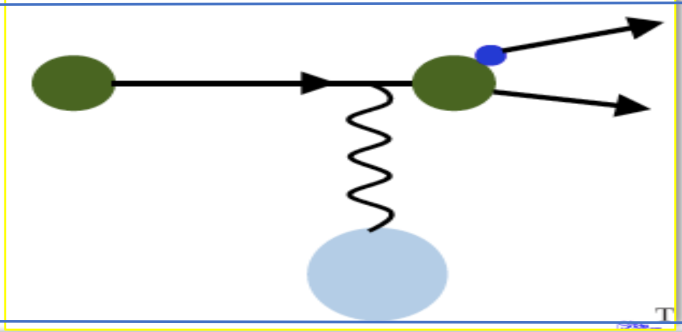
There is a need for a variety of experimental tools



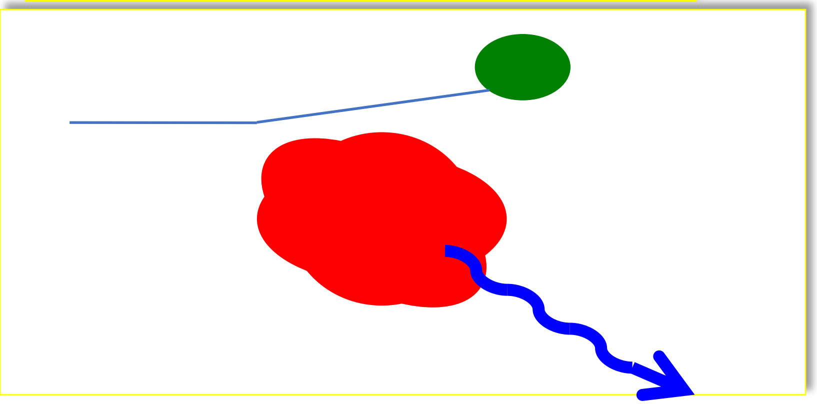
(γ,γ') real photons
on stable nuclei
Probing the entire nuclear volume



(p,p') virtual photons at E_{beam}> 200 MeV
on stable nuclei
Probing the entire nuclear volume
Work at Osaka RCNP



Coulomb excitation with radioactive beams virtual photons
Exotic nuclei
E1 excitation at high energy (GSI, MSU) with particle and gamma decay from the projectile



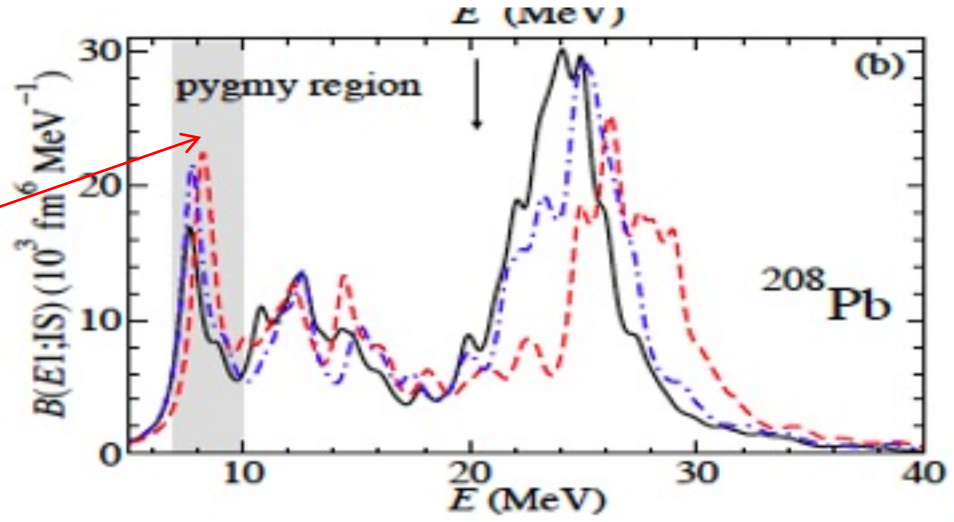
(α,α'γ) or (^{17}O,^{17}O'γ)
on stable nuclei
Probing the nuclear surface mainly

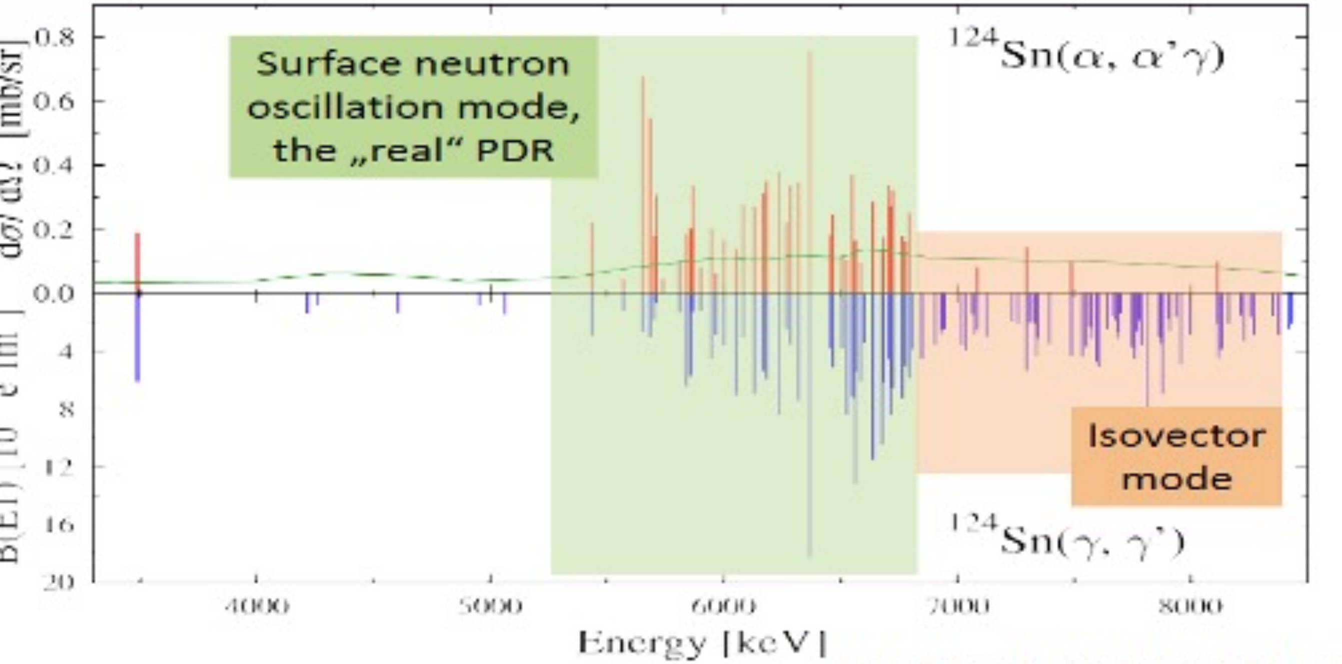
KVI and LNL

Do we need different probes ?

Isoscalar or isovector?

In ^{208}Pb
4.3-5.5 % IS EWSR strength
at 9 MeV
Theory from Rocha-Maza, Colo'





Janis Endres et al., PRL 105 (2010) 11250
Janis Endres et al., PRC 85 (2012) 064331

IS nature of the PDR due to outermost nucleons (neutrons in a neutron-rich nucleus).
The r_{np} is correlated with J and L.

Interesting to study the properties of the neutron skin

First work on (α,α'γ) – PLB278, 423 (1992).

Recent measurements with ^{17}O

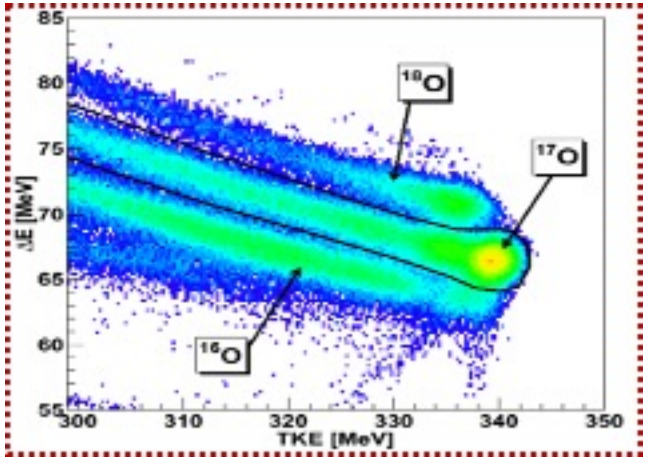
Using AGATA at LNL

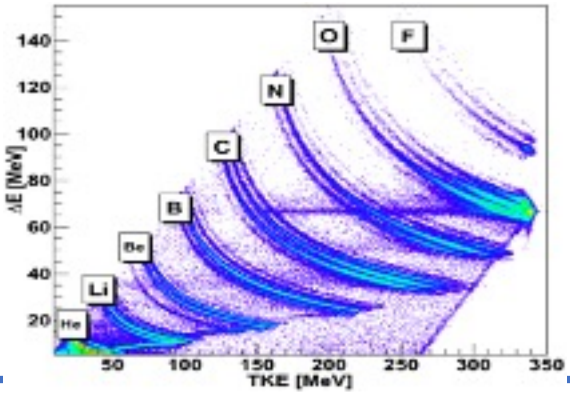
The AGATA experiments

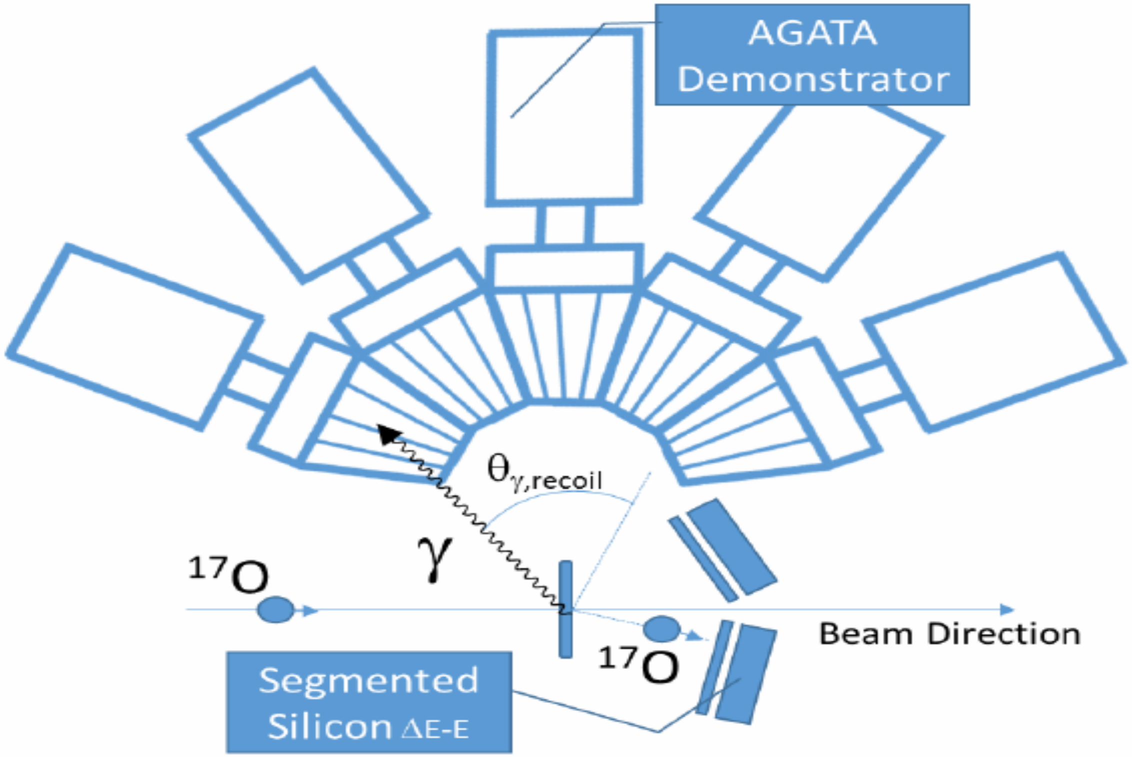
- Large cross-section for the population of the giant resonance region
- ^{17}O is loosely bound (S_n = 4.1 MeV)
- Clean removal of projectile excitation

^{17}O @ 20 MeV/u on different targets

+ γ-rays in coincidence



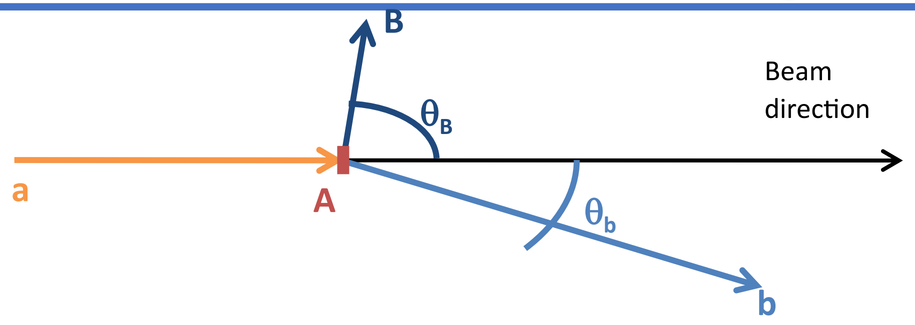




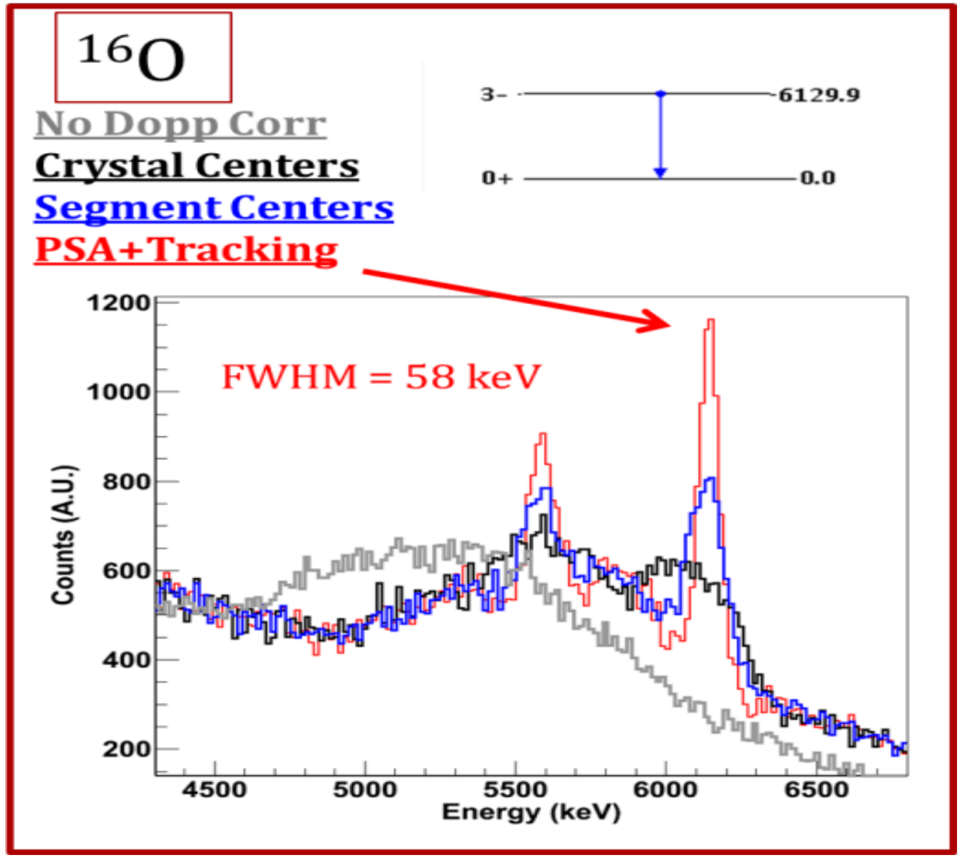
Silicon Detectors, D. Mengoni NIMA 764(2014)241

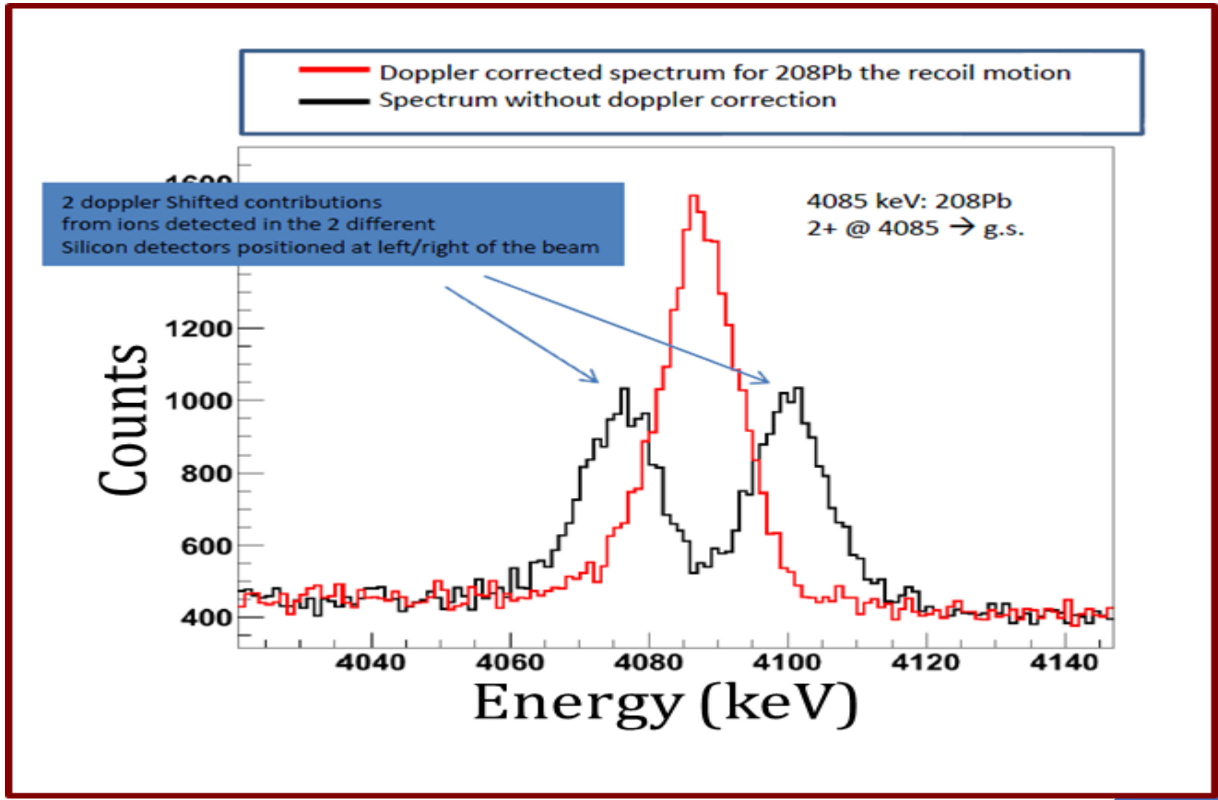
Doppler correction…..AGATA performances

Projectile-like (^{16}O, v/c ~20%)
- > 500 keV @ 5 MeV

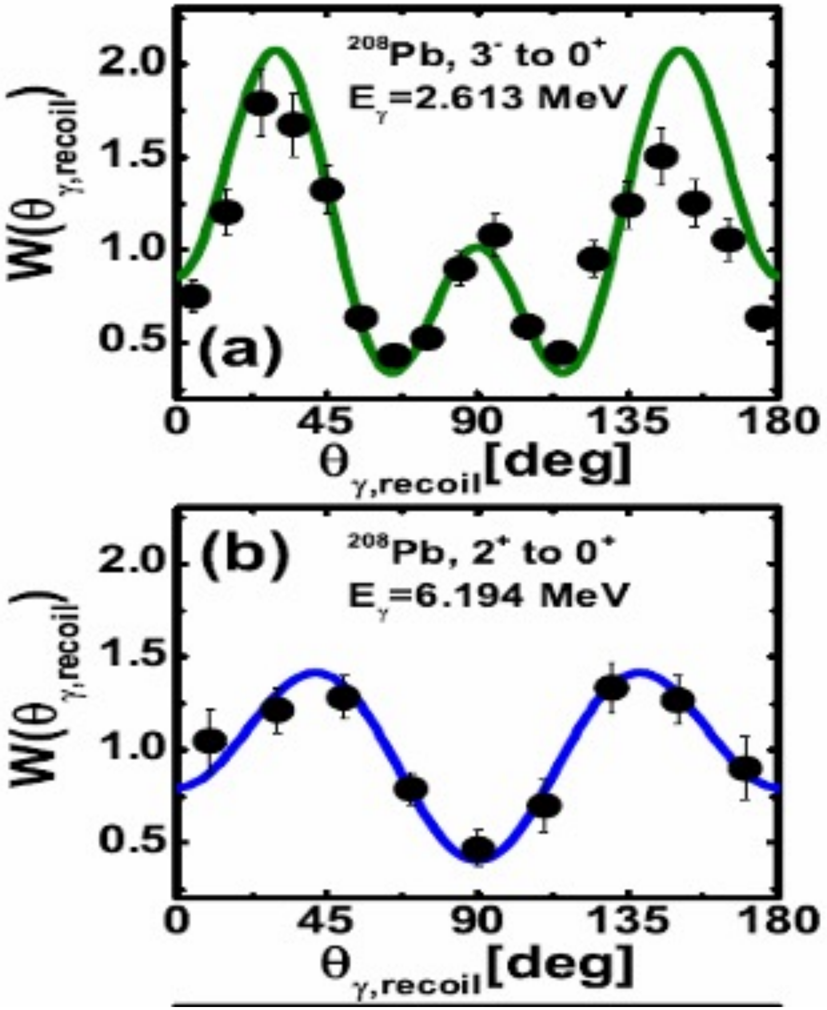


Target-like recoils (v/c ~0.5%)
- ~25 keV @ 5 MeV



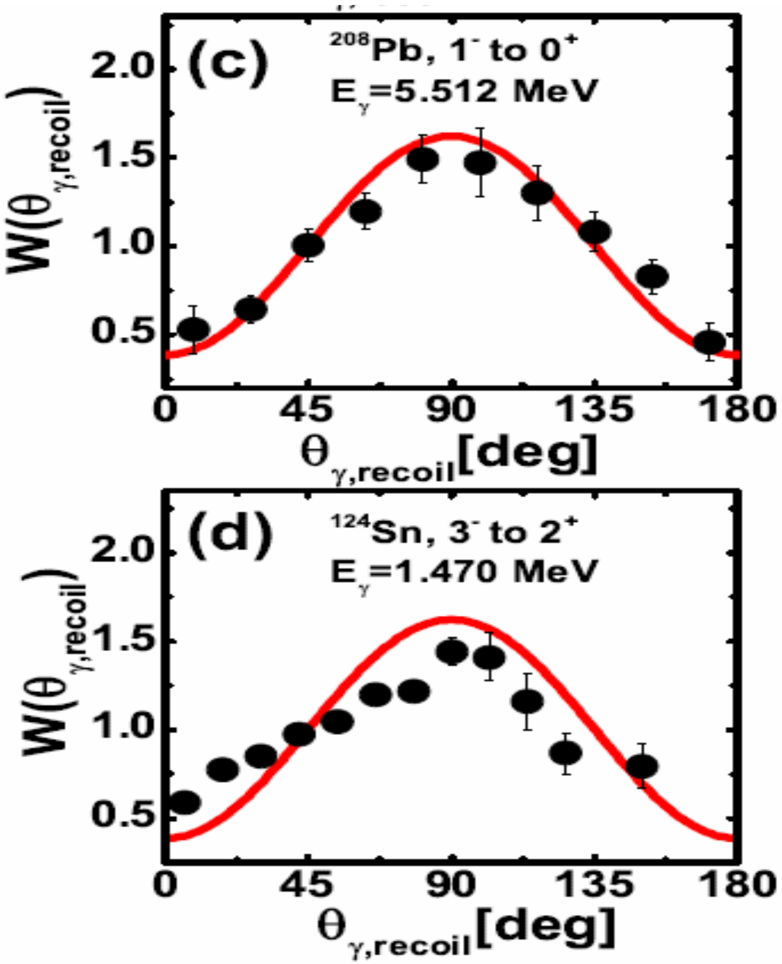


Angular distribution of γ-rays ---Some data on ^{208}Pb



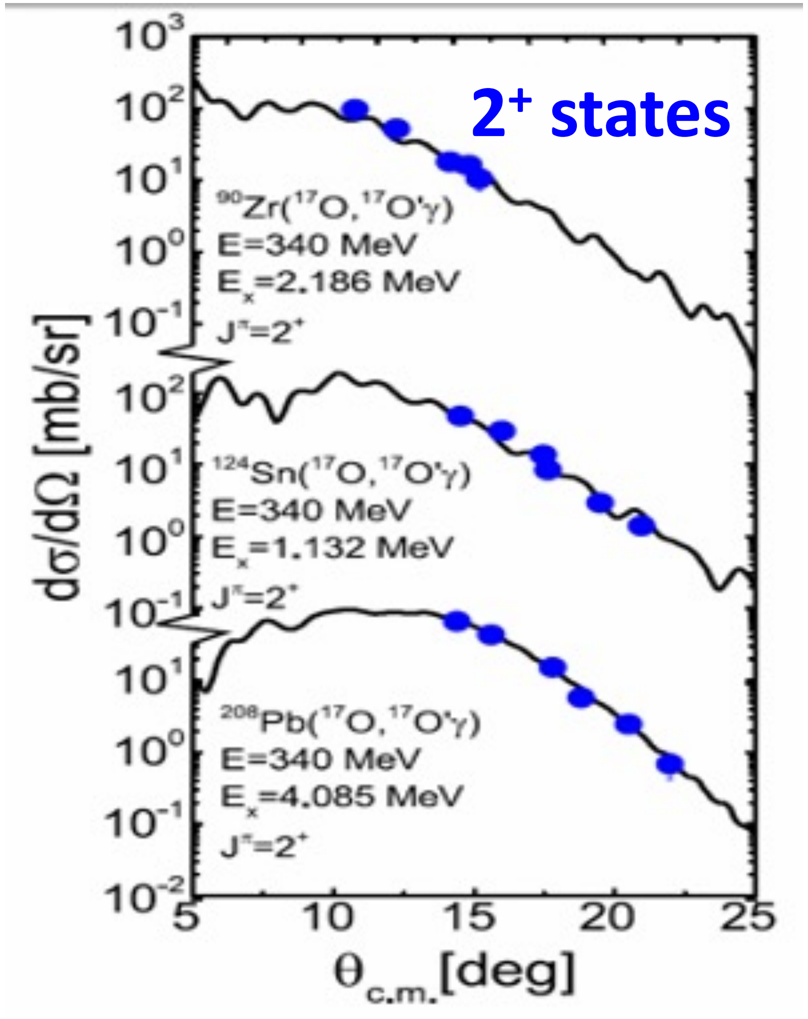
Angular Distribution
of γ's

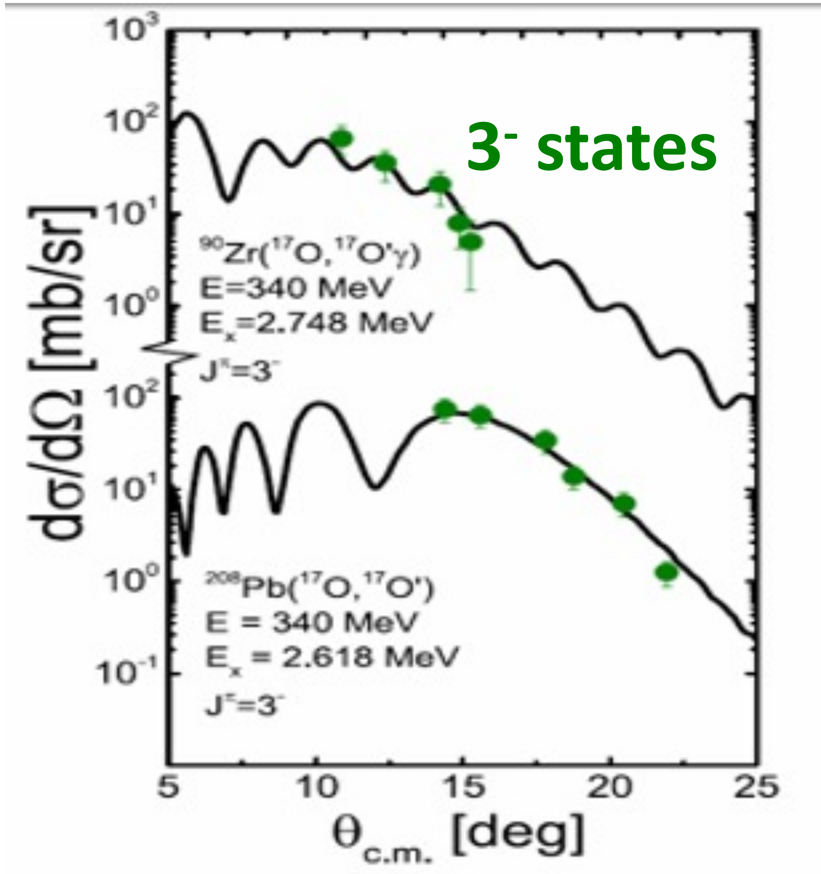
position sensitivity
of AGATA
and E-ΔE Si
telescopes (pixel type)



Excitation of the 2^+ and 3^- states in ^{90}Zr, ^{124}Sn, ^{208}Pb

- The B(E2) and B(E3) known from other works*
- Calculations assumed pure isoscalar excitation namely the p and n matrix element are related by
  $M_n / M_p = N/Z$





- (e,e') and (γ,γ') experiments, see e.g.: http://www.nndc.bnl.gov/ensdf/

**for the case of ^{208}Pb:
D.J. Horen et al. PRC44(1991)128

Agreement with measurements at similar beam energy**

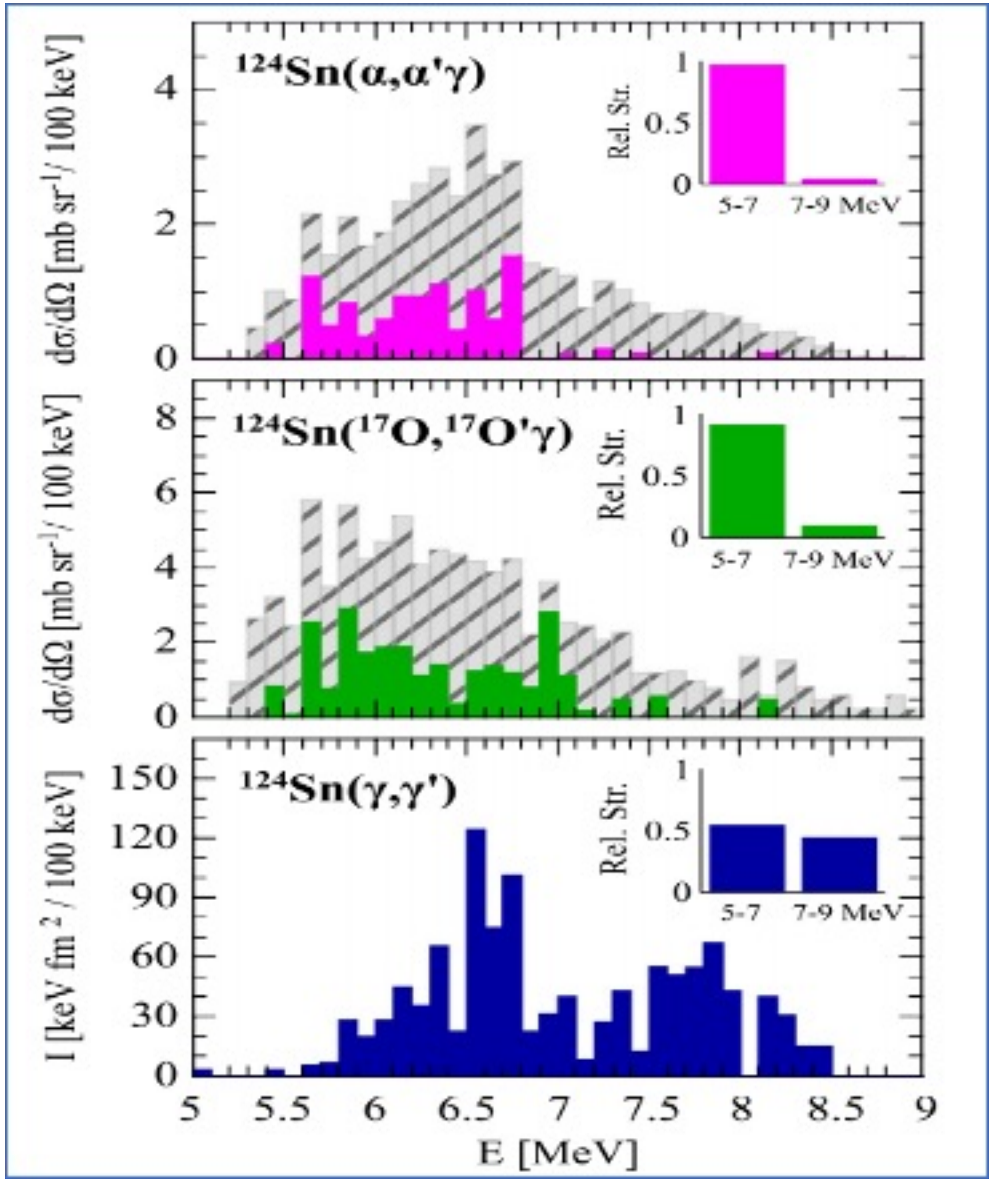
A. Bracco , F.C.L. Crespi and E.G. Lanza, EPJ**A51**(2015)99

Results for ^{124}Sn and comparison with other probes

1^- excitation with ^{17}O
20 MeV/u

Comparison with alpha and Gamma scattering

In all cases only the region below 7 MeV is populated by all reactions

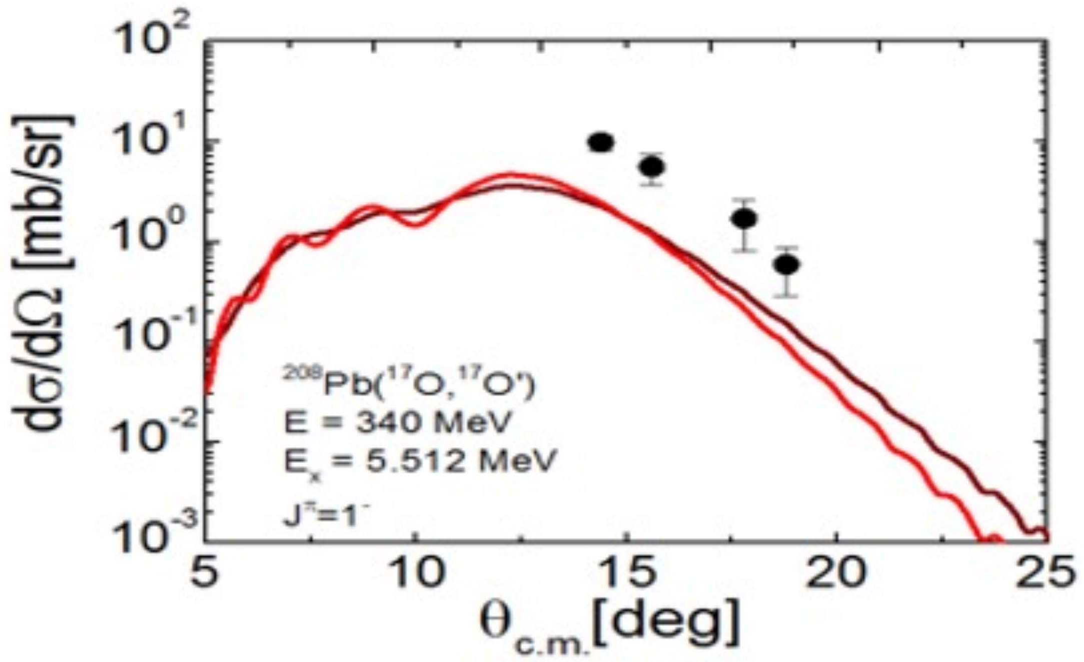


(**) J. Endres et al., PRL105, 212503 (2010)

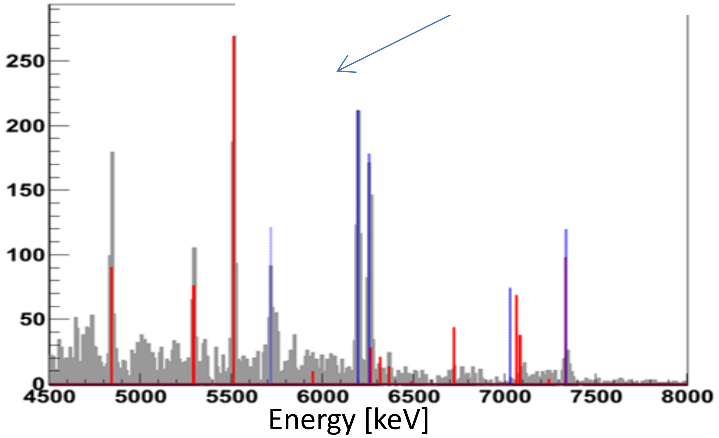
L. Pellegri, et al., PLB738 (2014)519

1^- states in ^{208}Pb

The calculation accounts only for a fraction of the measured yield



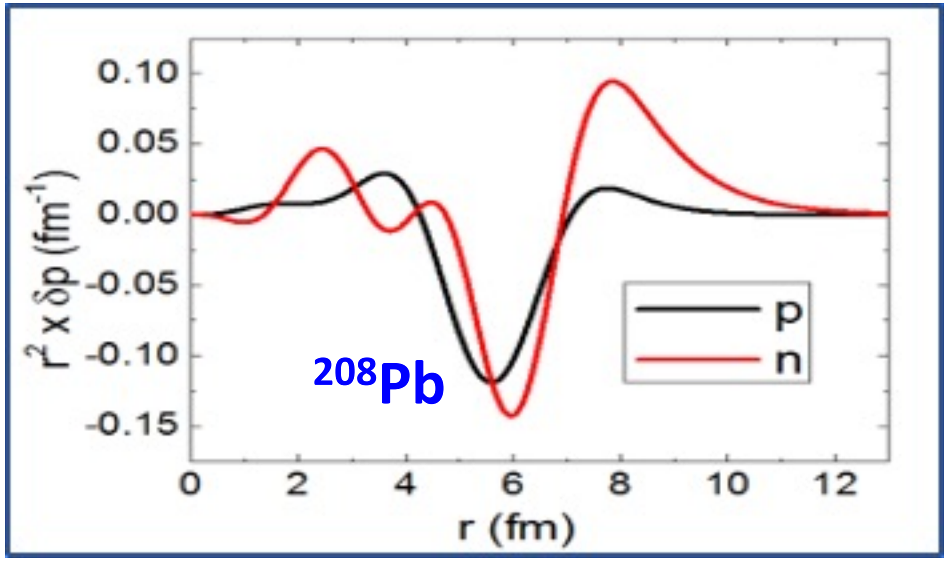
Why?
Calculations obtained using a standard form factor are found to be very similar to the Coulomb excitation alone

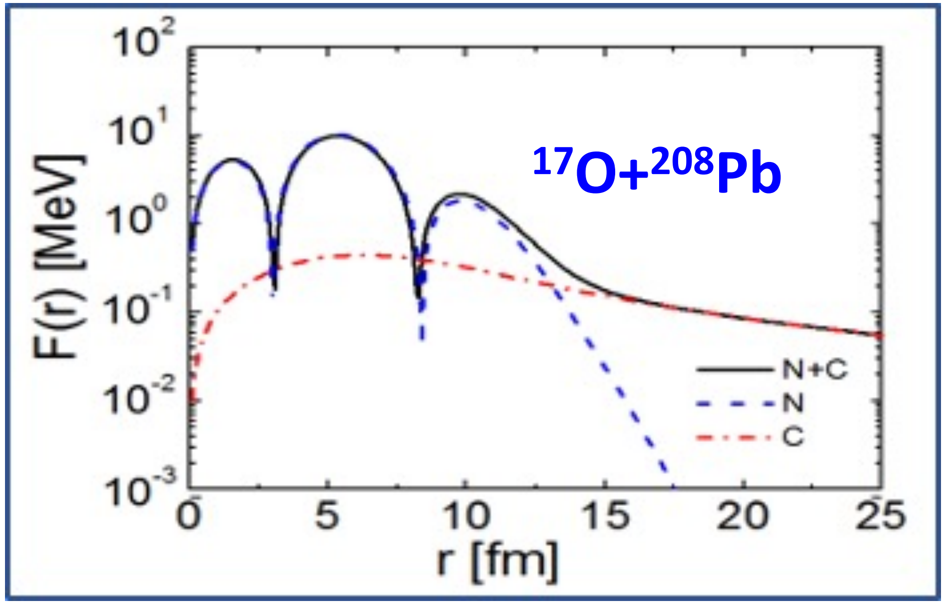


B(E1)↑ values known from (γ,γ)**

** photon scattering experiments:
N. Ryezayeva et. al PRL89(2002)272502,
T. Shizuma et al. PRC78(2008)061303

Use a microscopic form factor

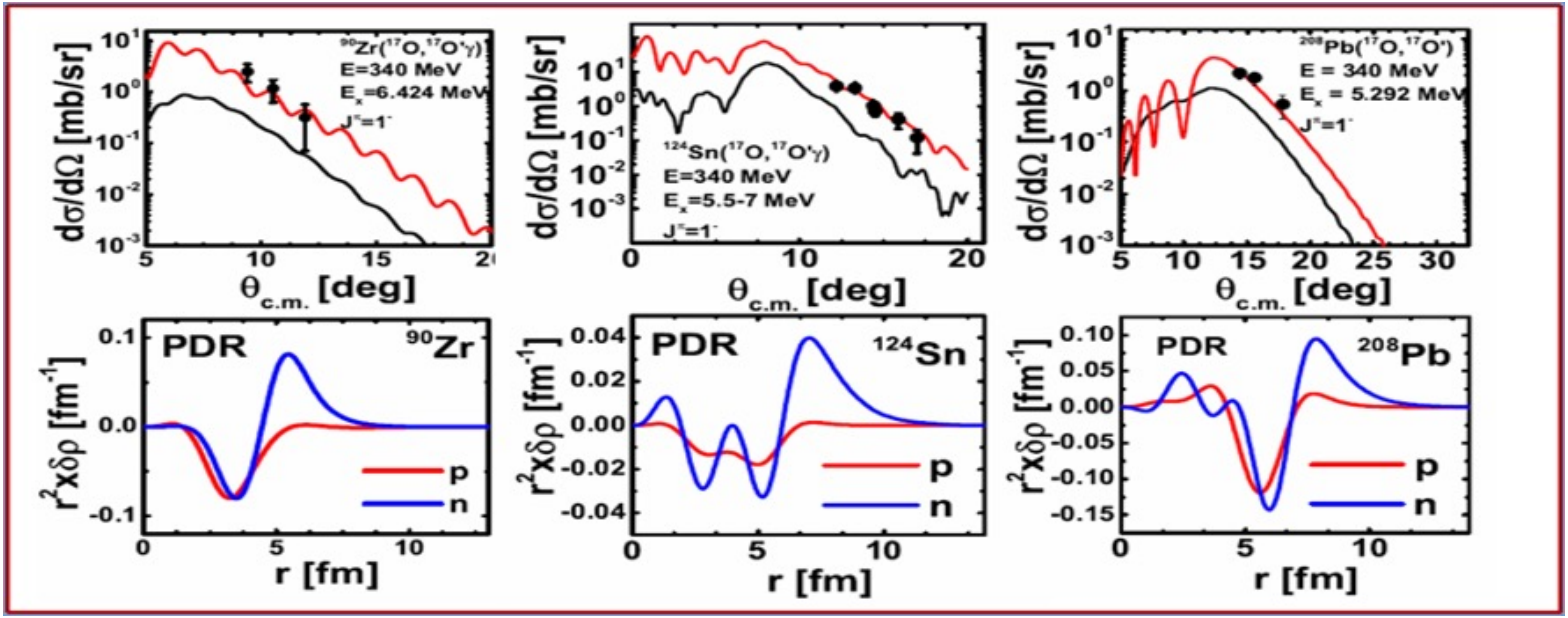




Scattering of ^{17}O at these energies is probing mainly the nuclear surface!!

*E. G. Lanza et al., Phys. Rev. C 79 (2009) 054615
**E. G. Lanza et al., Phys. Rev. C 84 (2011) 064602
***E. G. Lanza et al., PRC 89 (2014) 041601

Some results for selected 1^- in ^{90}Zr, ^{124}Sn and ^{208}Pb

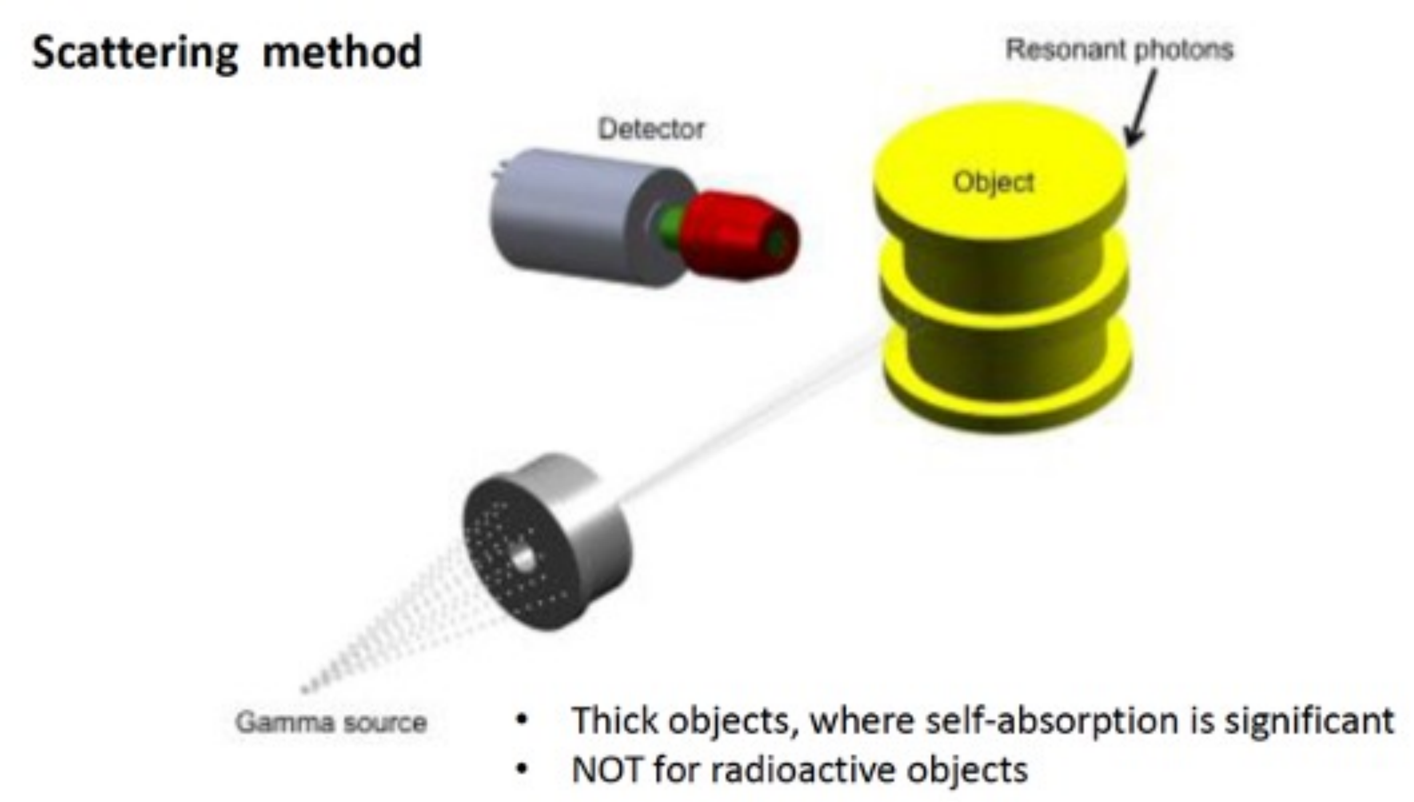


Calculated transition densities:

*(for 124Sn)E. Litvinova, et al., PRC 78 (2008)014312, **E.G. Lanza, et al.,PRC 89 (2014) 041601

Industrial tomography

material inspection nuclear waste- food contaminations



Conclusions and perspectives

- GMR and isoscalar GDR information on nuclear compressibility

- GDR and Pygmy at T=0 Information on the neutron Skin- related to the Radius of the neutron stars- Information for the r-process
more work on deformed nuclei and on exotic nuclei with radioactive beams

- Finite temperature : extreme deformations
Isospin mixing measurements in other mass regions