Isospin effects probed by the Electric Dipole Emission

Angela Bracco

Dipartimento di Fisica Università di Milano and INFN Milano
and
Centro Fermi -Roma

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
45th Course
Nuclei in the Laboratory and in Stars
Erice, Sicily, September 16-22, 2024

Directors of the school
Michael Buballa and Christian Fischer

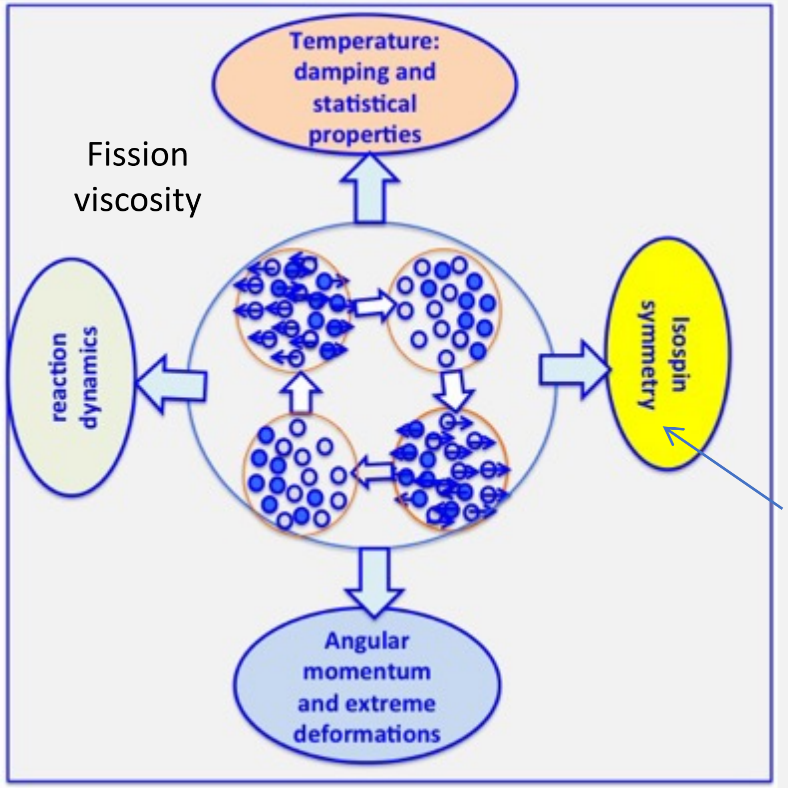
Gamma decay from dipole excitations in different conditions

3 MeV

1.5 MeV

0.5 - 1 MeV

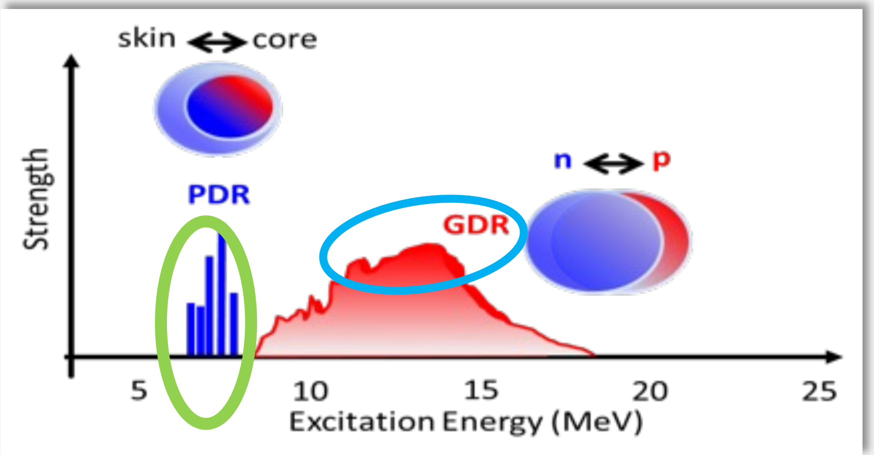
T= 0



Study of various aspects of nuclear structure via dipole oscillations

Isospin effects

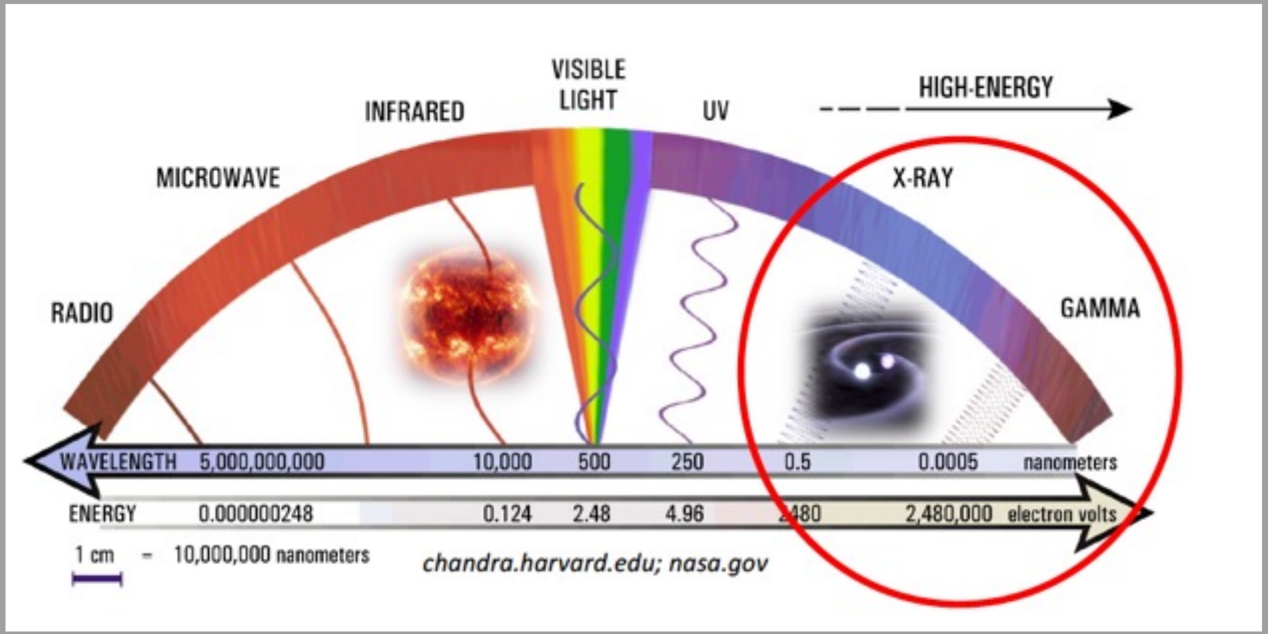
Isospin mixing



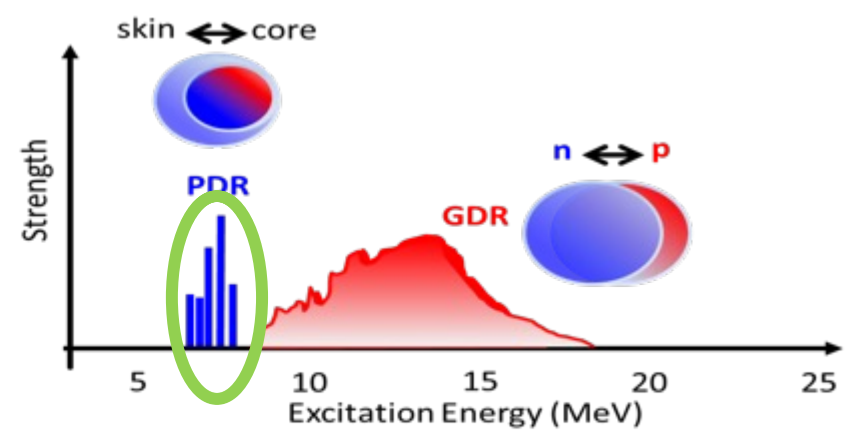
Isospin effects

- Nuclear equation of state
- Isospin effects

Why do we investigate the E1 strength, including the pygmy part?



- MeV-photons are abundant in the universe (Planck photon bath)
- The photon-nucleus interaction is dominated by the dipole response of atomic nuclei
- dipole response in the pygmy region is important for r-process modeling



For neutron rich nuclei the pygmy is mainly due to neutron excitations of the neutron skin and the latter is related to the properties of neutron matter (implications with the modeling of Neutron Stars)

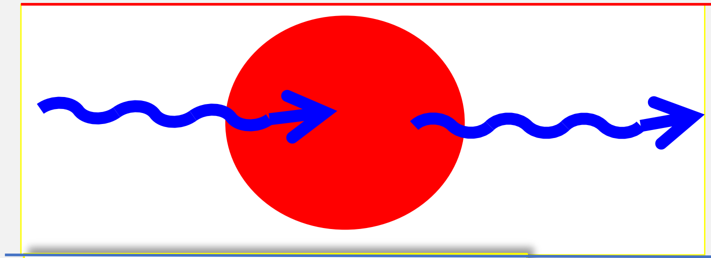
This talk addresses two issues :

1- Low lying dipole response (below binding Energy)
Its gamma decay to investigate isospin nature of the Pygmy strength

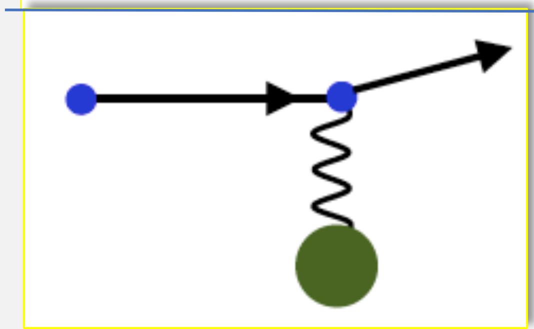
2. Gamma-decay from the GDR in hot rotating nuclei to deduce isospin mixing and possible restoration of isospin symmetry

Note that different reaction types are used

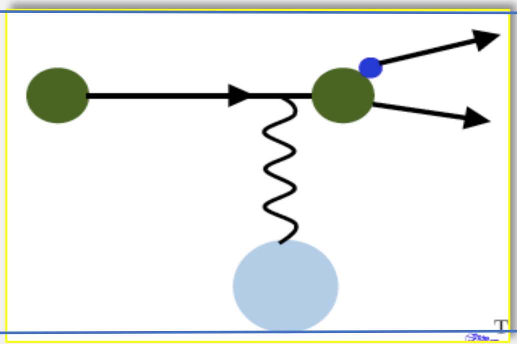
There is a need for a variety of experimental tools



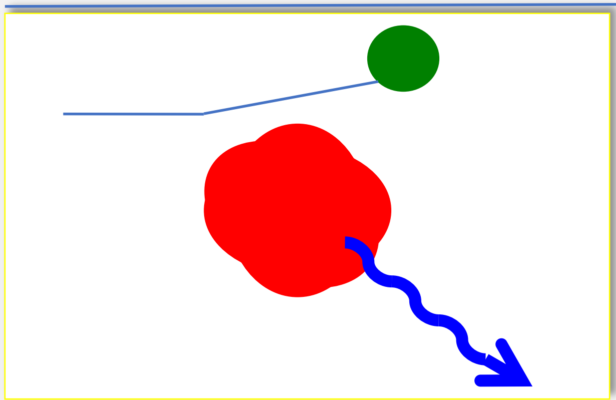
(γ,γ') real photons
on stable nuclei
Probing the entire nuclear volume



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

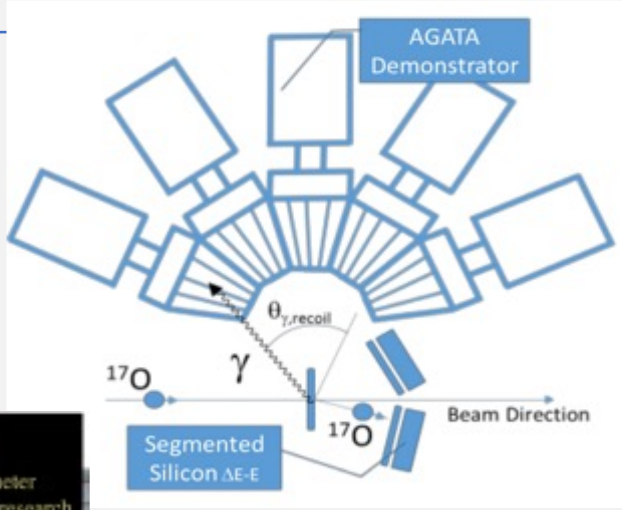


Coulomb excitation
with radioactive beams
virtual photons
Exotic nuclei

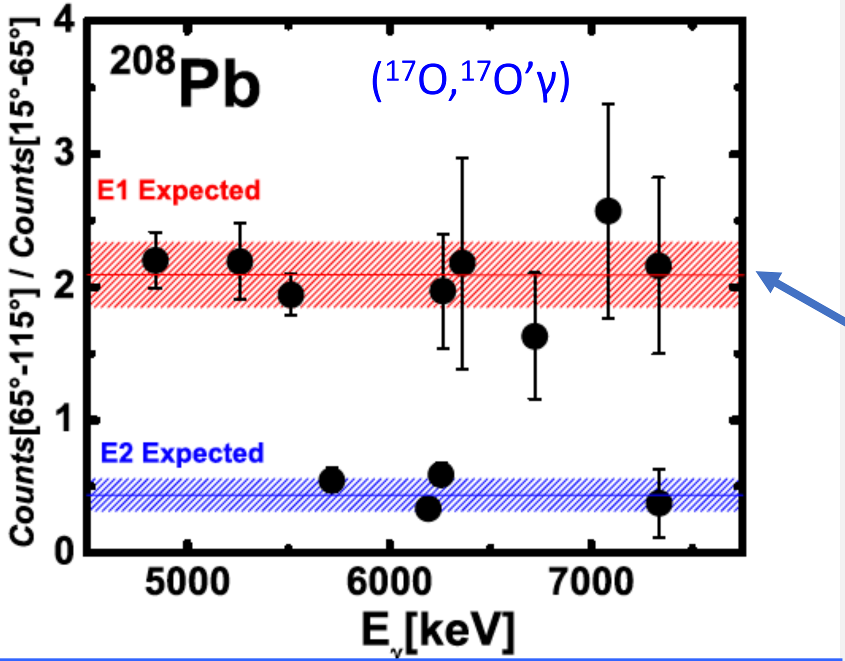


($\alpha,\alpha'\gamma$) or ($^{17}O,^{17}O'\gamma$) and ($p,p'\gamma$)

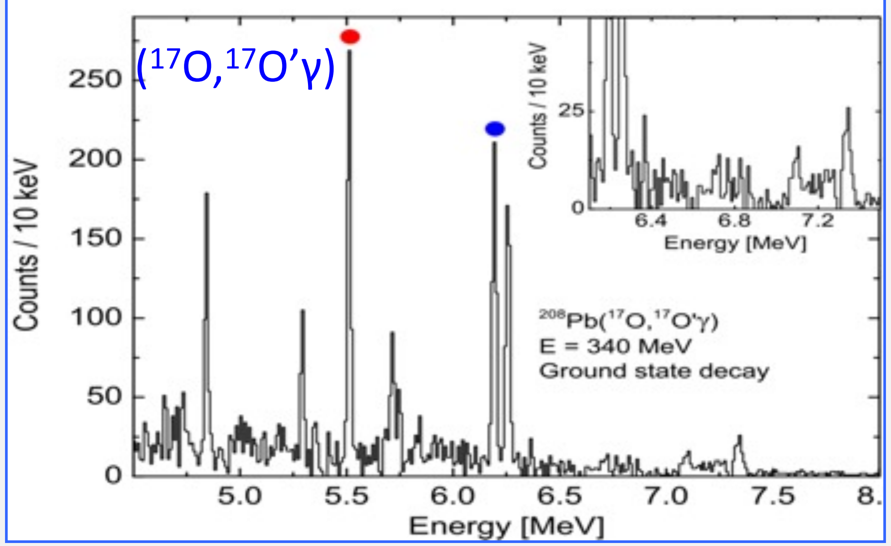
Probing the nuclear surface mainly
– short range nuclear forces and low-energy of the collision

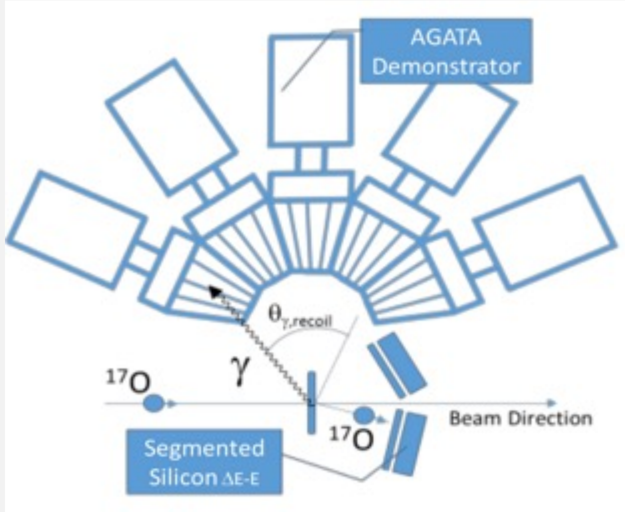


Angular distribution of the gamma rays-
In general one finds mostly 1⁻ states



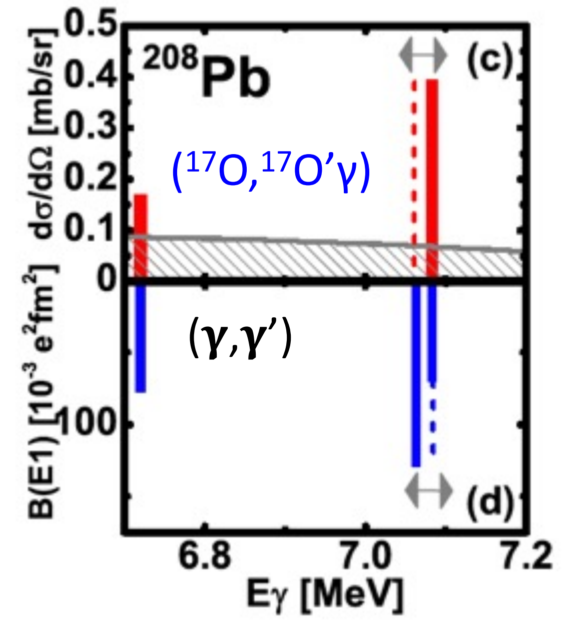
F.C.L. Crespi, et al., PRL113 (2014) 012501





Effect of isospin breaking

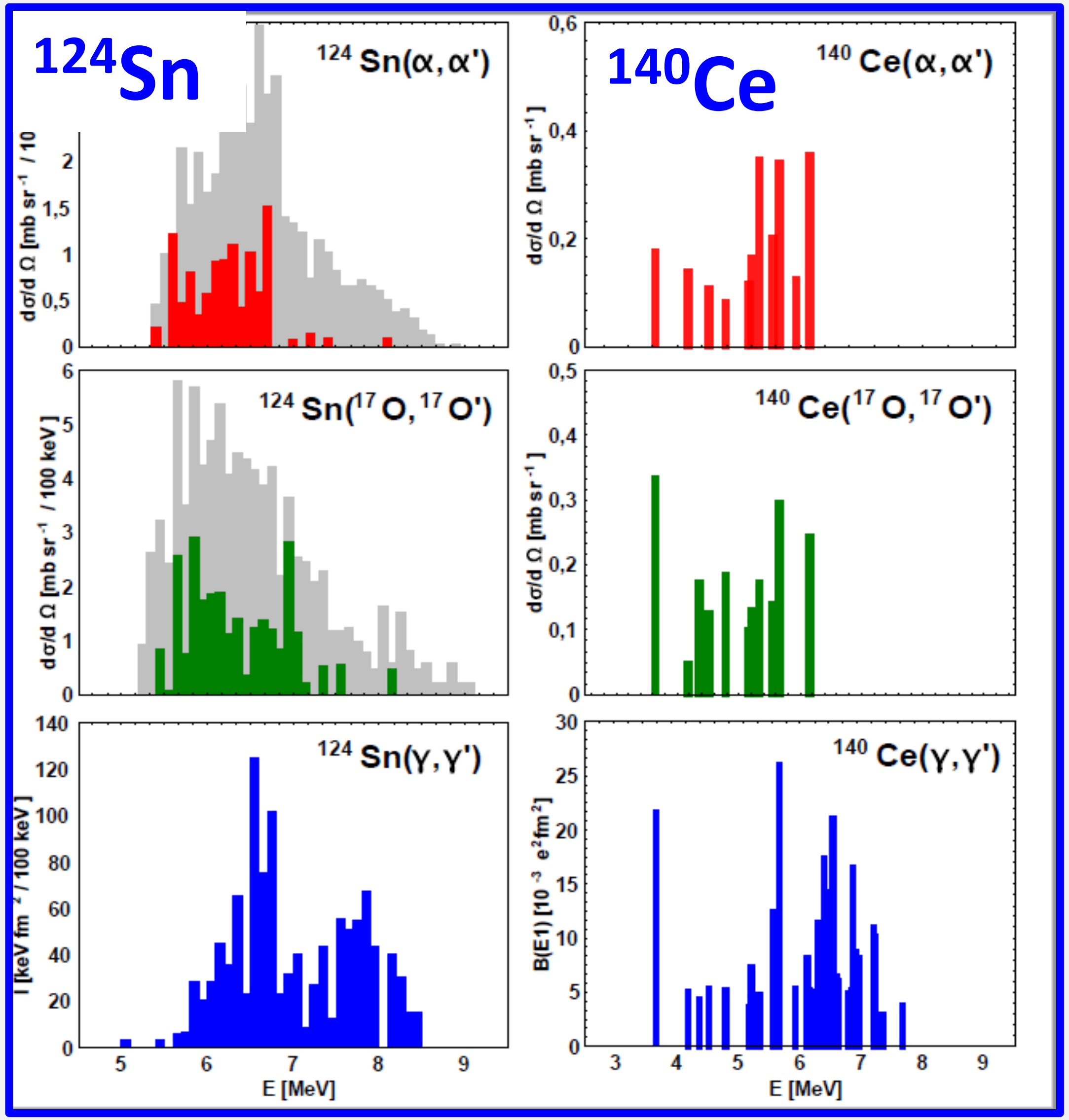
Isospin mixing allows E1 decay from isoscalar excitations



- Ground state decay select preferentially 1^- states
- Measurement of the angular distributions of the gamma-rays

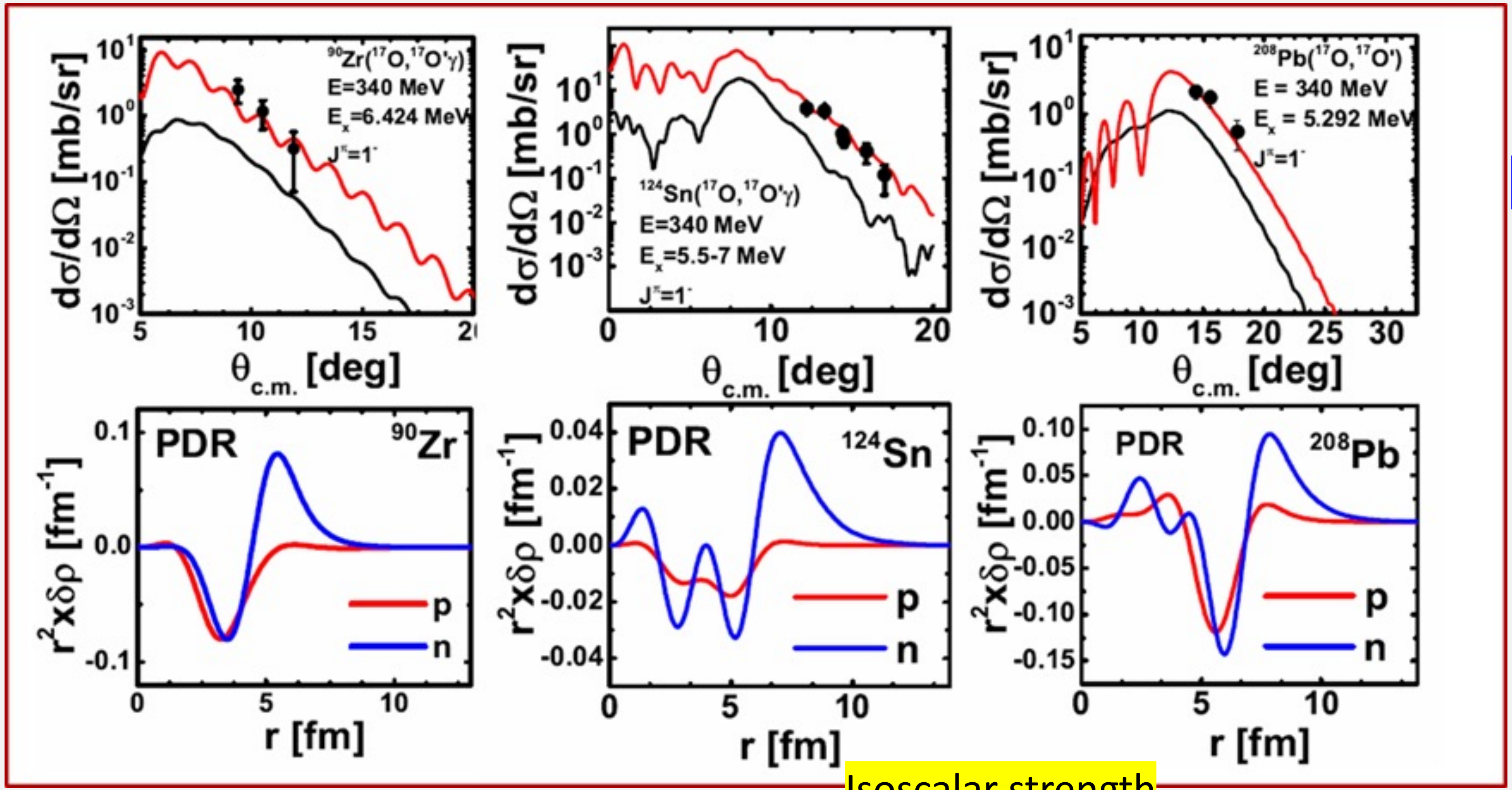
Main features of some existing results

Gamma -ray spectra



1^- excitation with :
^{17}O 20 MeV/u
and alpha scattering
at 130 MeV
and their comparison

In all cases only the region < 6-7 MeV is populated by all reactions



Heavy Ion Inelastic Scattering

DWBA calculation
(red solid lines)
with microscopic
form factors* based on
the transition density
associated to the E1 PDR states
very different
than that of the GDR

Isoscalar strength

Isotope	Selection	Energy range [MeV]	Isoscalar strength [10^4 e^2 fm^6/MeV]	Isoscalar EWSR [%]	B(E1)↑ [10^{-3} e^2 fm^2]
^{90}Zr	in peaks	6.3–6.9	4.6(0.7)	4.0(0.6)	87
^{124}Sn	in peaks	5.5–7.0	10.8(1.4)	1.5(0.2)	214
^{124}Sn	in peaks	5.5–9.0	11.9(1.6)	2.2(0.3)	228
^{124}Sn	unresolved	5.5–9.0	41.1(3.7)	7.8(0.7)	228
^{208}Pb	in peaks	4.8–7.3	8.9(1.5)	9.0(1.5)	1084

F.C.L. Crespi, et al., PRL113 (2014) 012501
L. Pellegri, et al., PLB738 (2014)519

F.C.L. Crespi et al, PRC 91 (2015) 024323

A. Bracco, F.C.L. Crespi and
B. E.G. Lanza, EPJA(2015)51:99

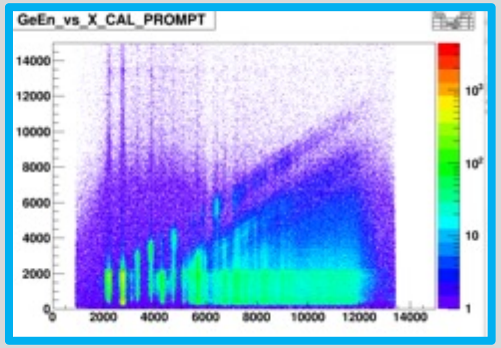
*E. G. Lanza et al., Phys. Rev. C 84 (2011) 064602

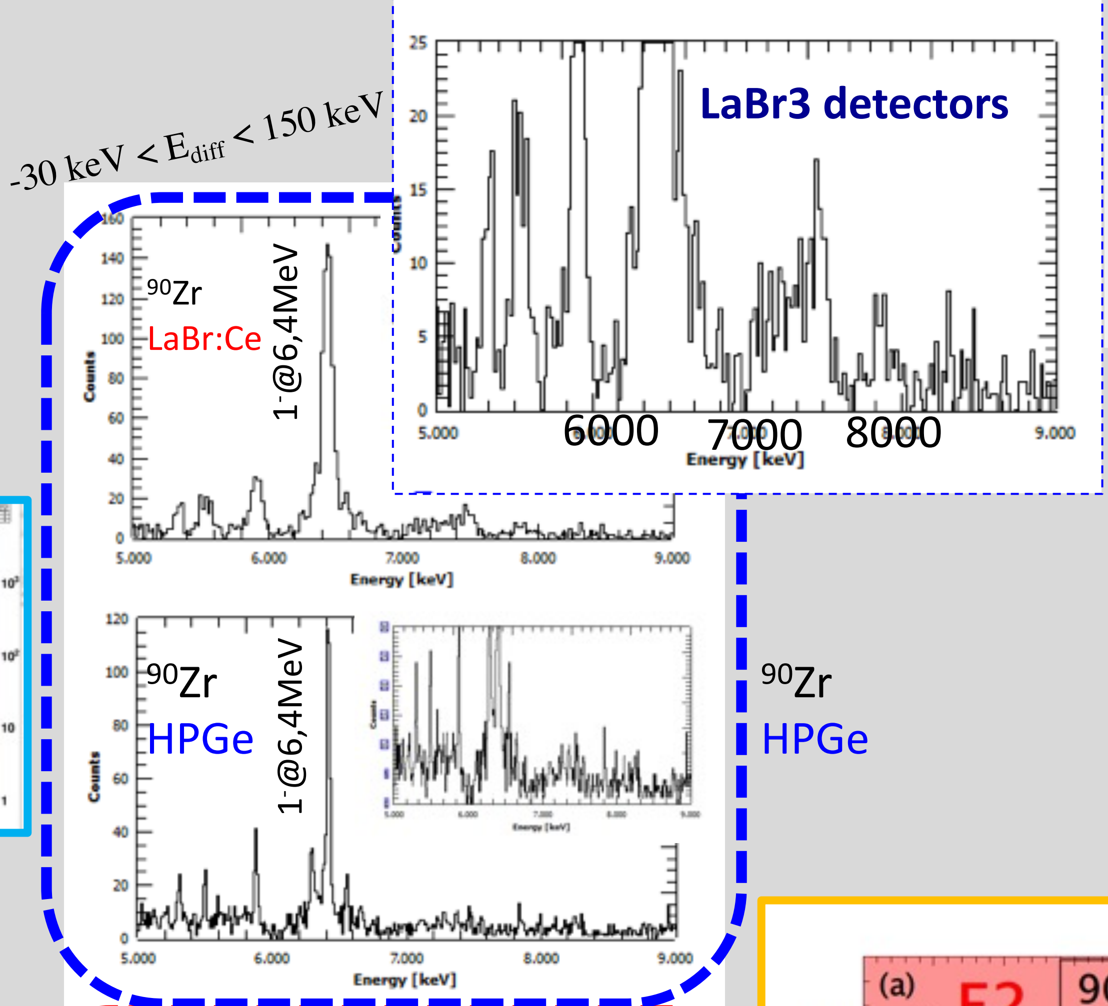
Data for ^{90}Zr (α,α'γ)

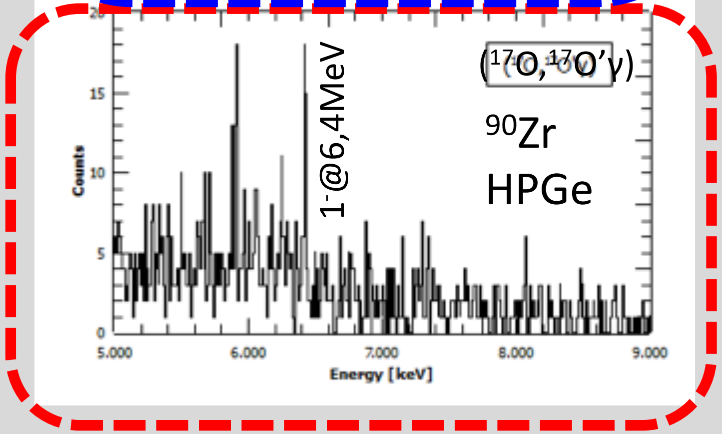
Several states at 7-9 MeV corresponding to ground state decay

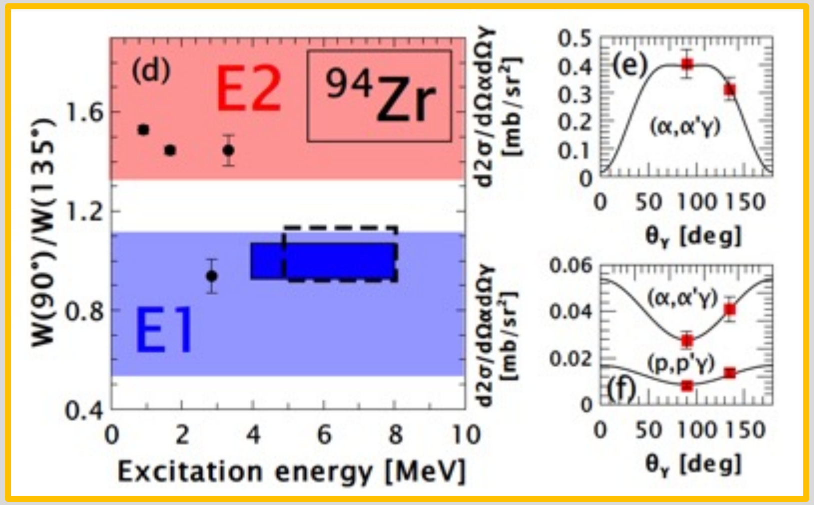
Alpha cross section larger than proton about a factor of 5

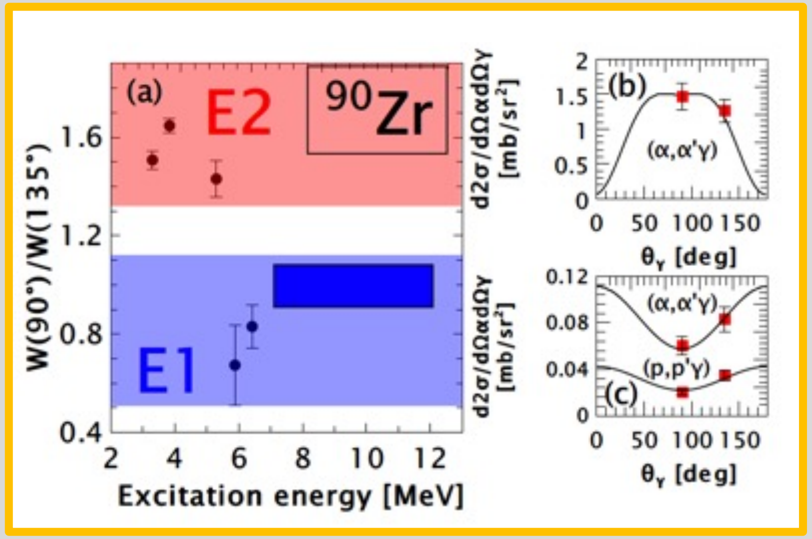
Alpha angle = 4.5
Proton angle = 6

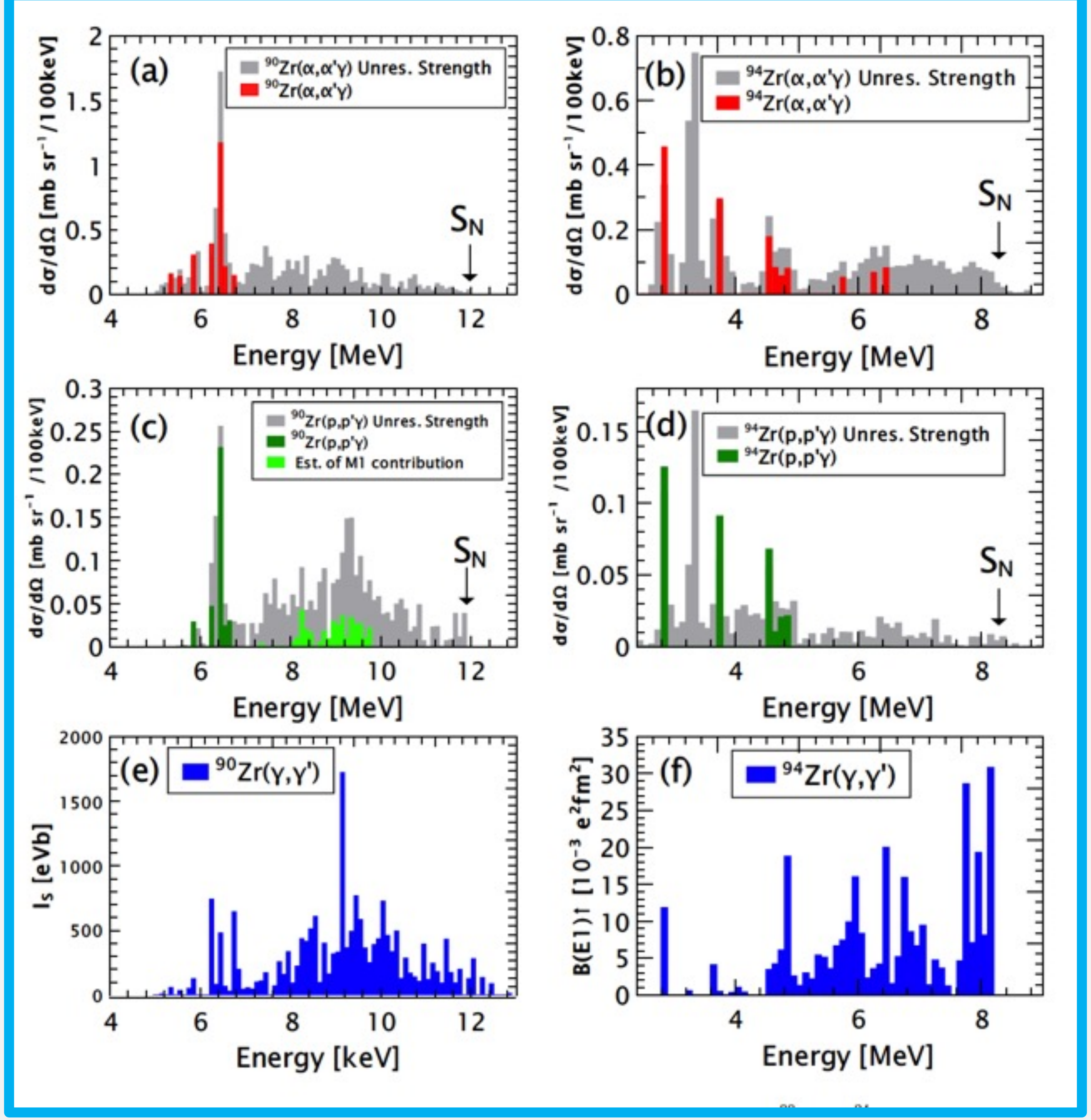












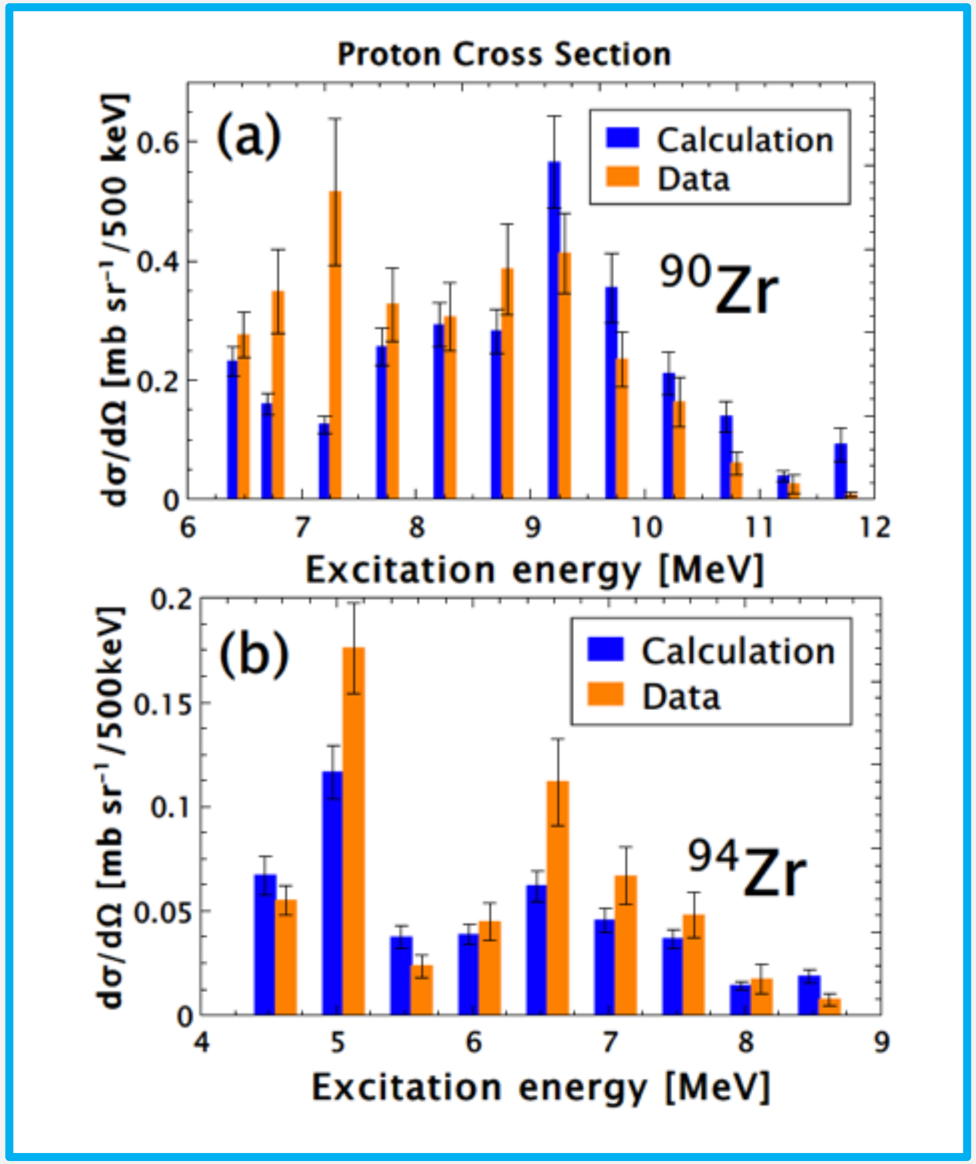
Comparison of cross section data for proton and alpha Inelastic Scattering on the ^{90,94}Z target nuclei

There is a region where only (γ,γ') populate states

Colored bars denote descrete transitions

However the (p.p') is less peaked on the surface as compared with alpha scattering

Proton cross section is 5 times smaller



F. Crespi et al Physics Letters B 816 (2021) 136210
Calculations error bars because we used the isoscalar strength deduced from alpha scattering data with their errors

Comparison of data with calculations for proton Inelastic Scattering on the ^{90,94}Z target nuclei

Cross section calculated with the DWBA approach with:

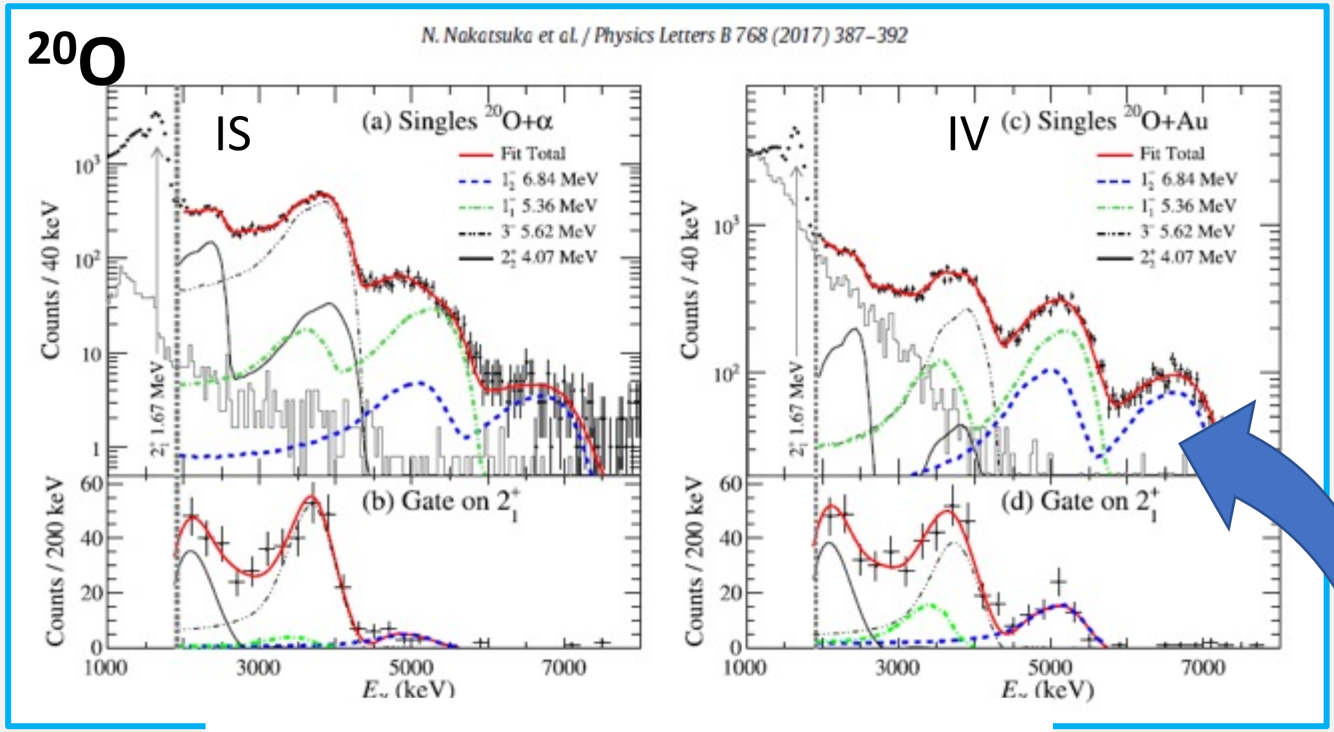
- The choice of form factor for which the normalization was about 0.9 for the discrete peaks
- Value of the ISEWSR deduced from fit to the alpha data

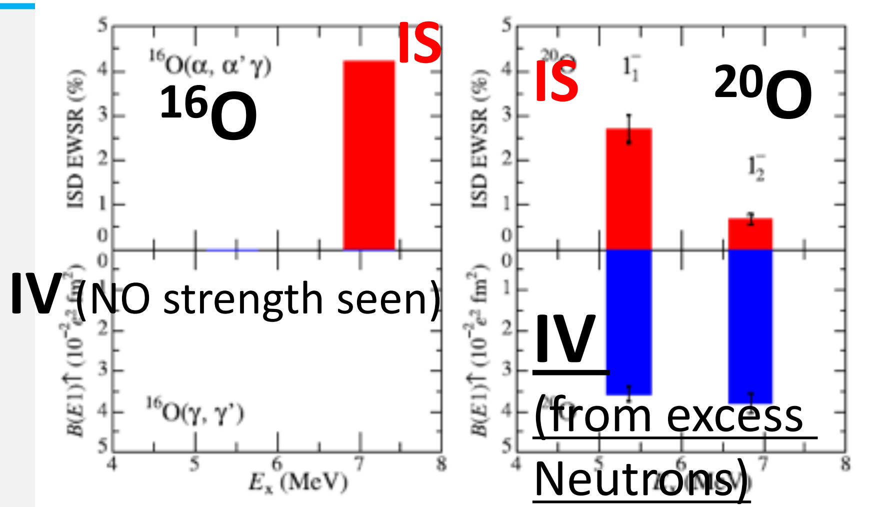
Only in some cases discrepancies out of the error bars (indicating that these states are not strongly surface peaking)

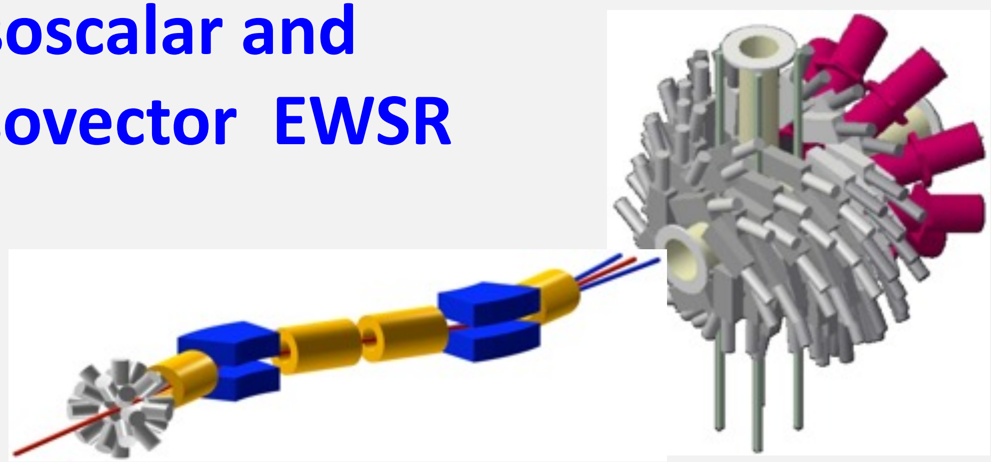
……with radioactive beams

Comparison of data for Coulomb excitation and alpha Inelastic Scattering on the ^{20}O beam nuclei

Spectral shape is very different Isoscalar and isovector EWSR





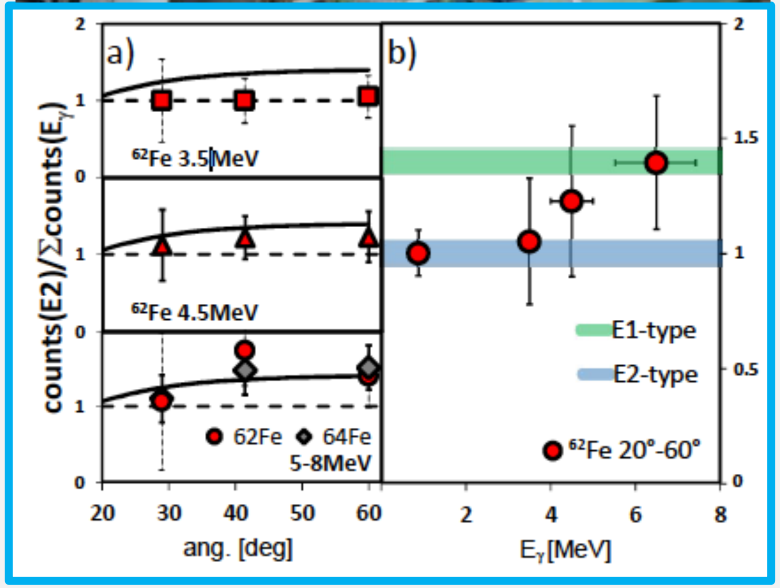


N. Nakatsuka et al., PLB 768 (2017) 387

Courtesy H.Baba, N. Nakatsuka

^{64,62}Fe nuclei

PYGMY measurement @ GSI Coulomb excitation - AGATA for the gamma rays



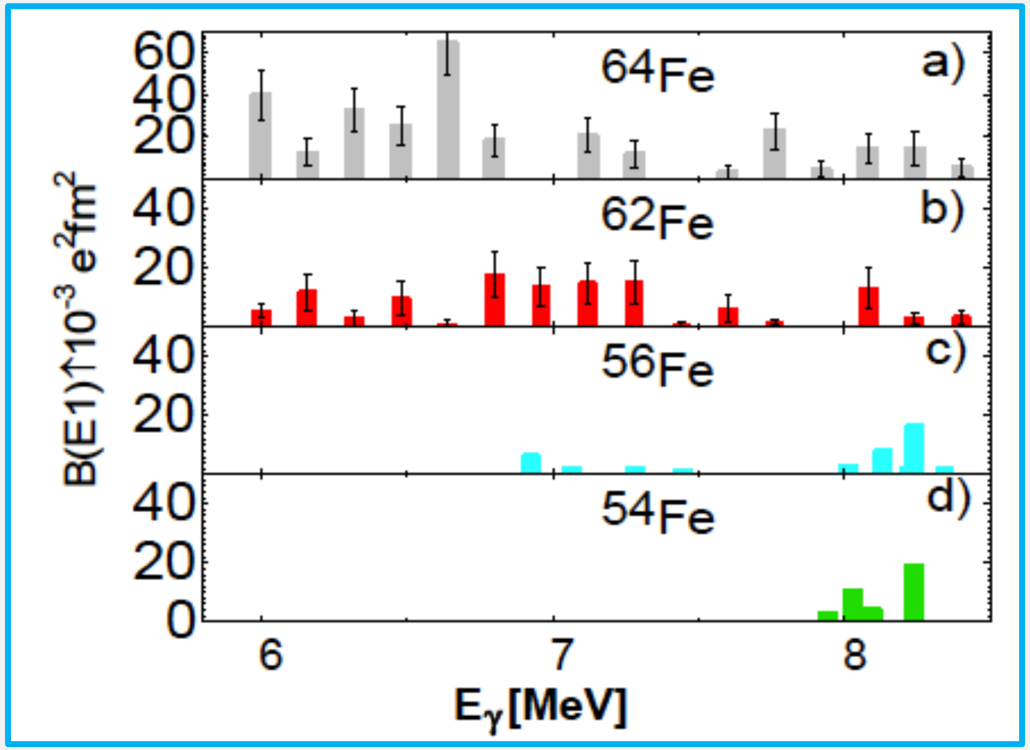
Ratio with counts in the first 2^+ excited states

More E1 strengh in the region 5.5-7.5 MeV

There is an increase with neutron number and thus could be attributed to neutron excitations

In the future measurements with alpha and proton scattering would give insight into the nature of the states

Comparison of data of Coulomb Excitation in unstable nuclei ^{64,62}Fe and gamma scattering on stable targets

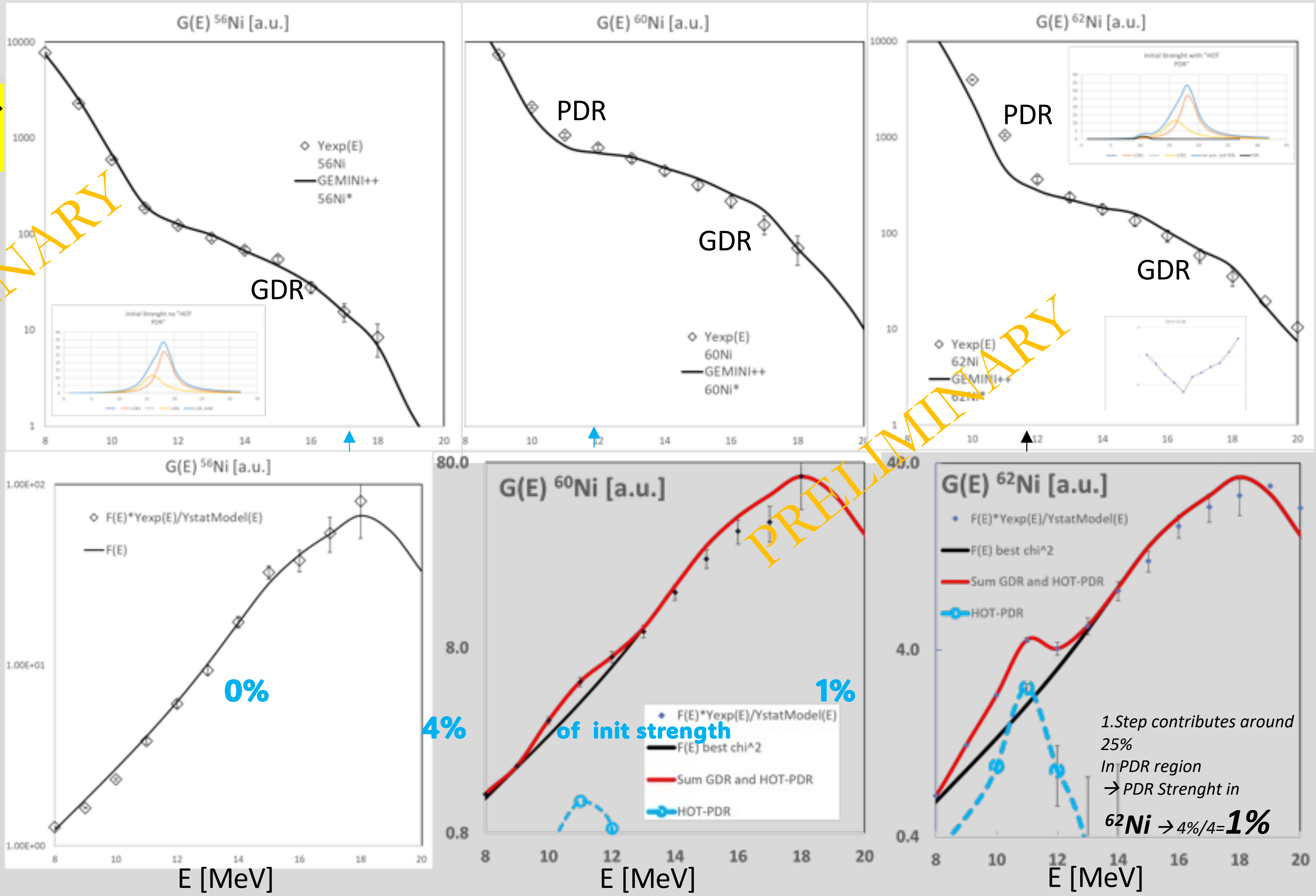


Measured spectra of continuum type
R. Avigo et al., Phys. Lett. B 811, 135951 (2020).

OPEN PROBLEM: SEARCH for PIGMY in neutron rich nuclei at finite T

- **Analysis 2022**

Time gated γ-spectra → and stat. model



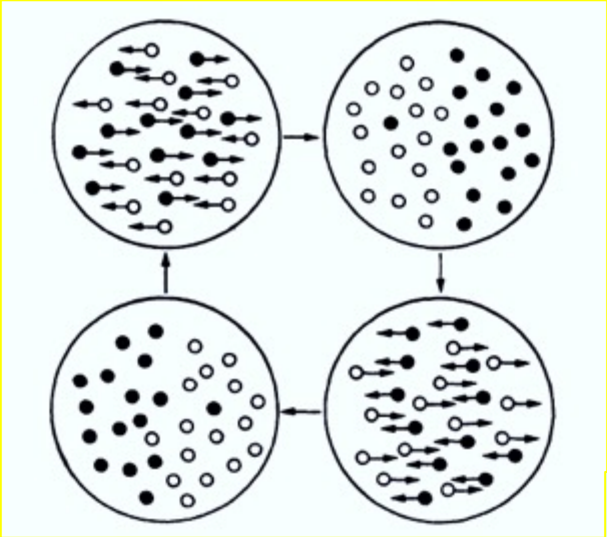
REMARK: To reproduce the lower extra yield effect by deformation (angular momentum) an unphysical one is needed and additionally the GDR part will not be reproduced anymore

1- Low lying dipole response (below binding Energy)
Its gamma decay to investigate isospin nature of the Pygmy strength

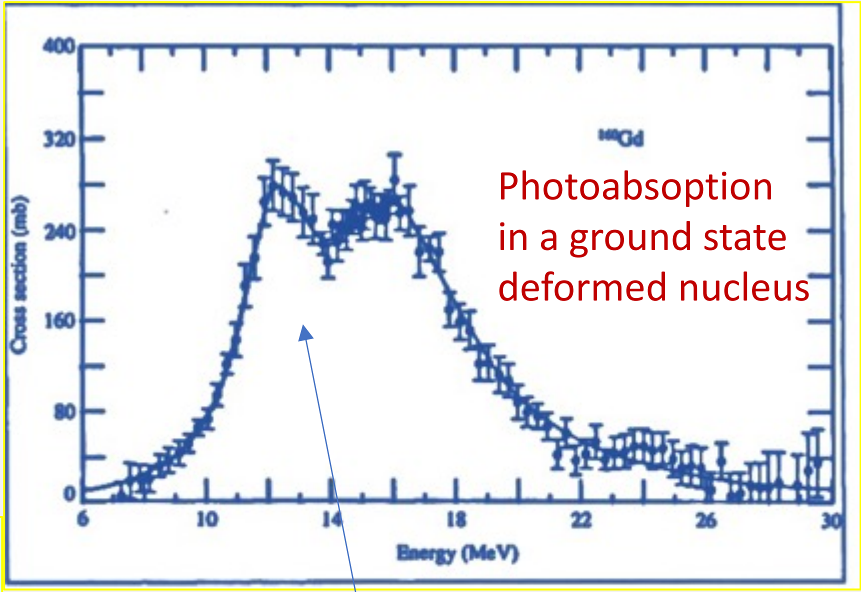
2. Gamma-decay from the GDR in hot rotating nuclei to deduce isospin mixing and possible restoration of isospin symmetry

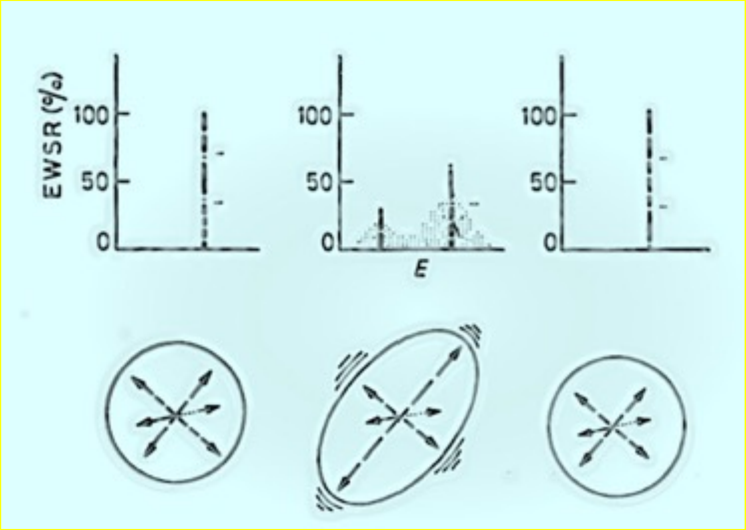
Note that different reaction types are used

The basic concepts for the GDR



GDR frequency of the vibration depends on the nuclear axis on which the vibration takes place





Centroid at around 15 MeV and width 4-5 MeV (due to mixing to other states)

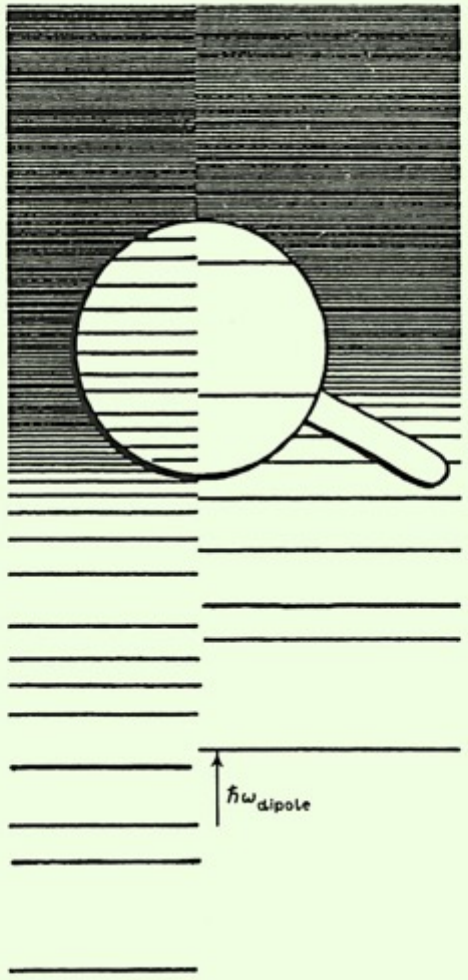
Pictures from : P. F. Bortignon, A. Bracco, and R. A. Broglia,1998 Giant Resonances: Nuclear Structure at Finite Temperature, Harwood Academic Publishers (Australia)

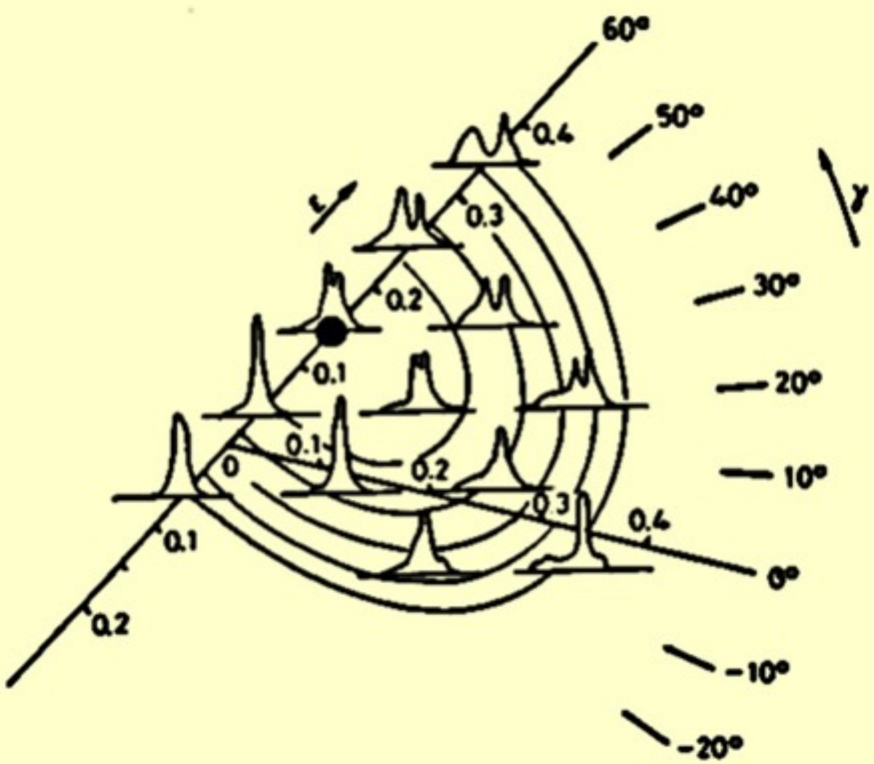
The basic concepts for the GDR at finite T

GDR is built on any excited nuclear state

Brink-Axel (1955)

At Finite Temerature and angular momentum the nucleus samples an ensamble of shape





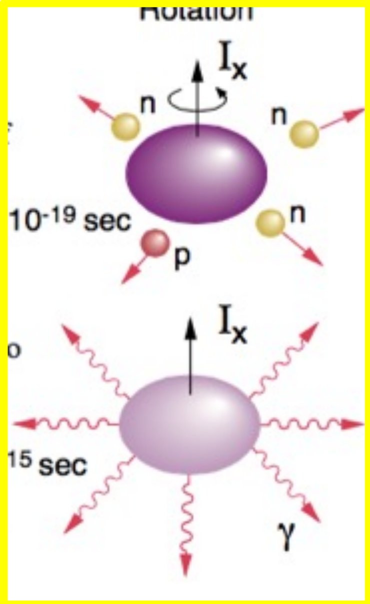
A simple ordered collective mode exists in the CN system characterized by a chaotic behavior

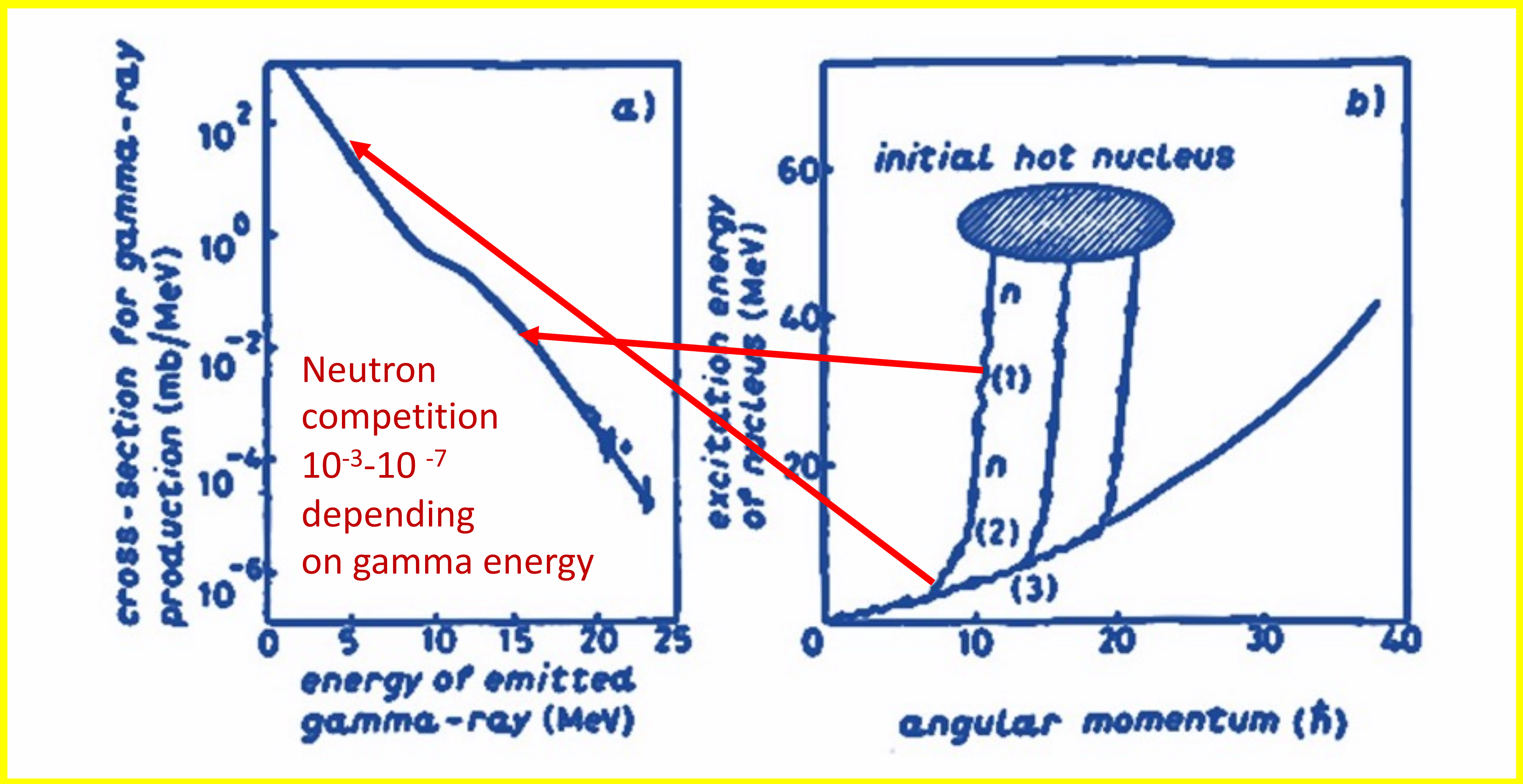
The GDR width is strongly affected by the distribution of shapes

original Models developed by P.F. Bortignon, R.A Broglia, E. Ormand, Y. Alhassid

Angela Bracco

The basic concepts for the experimental investigation



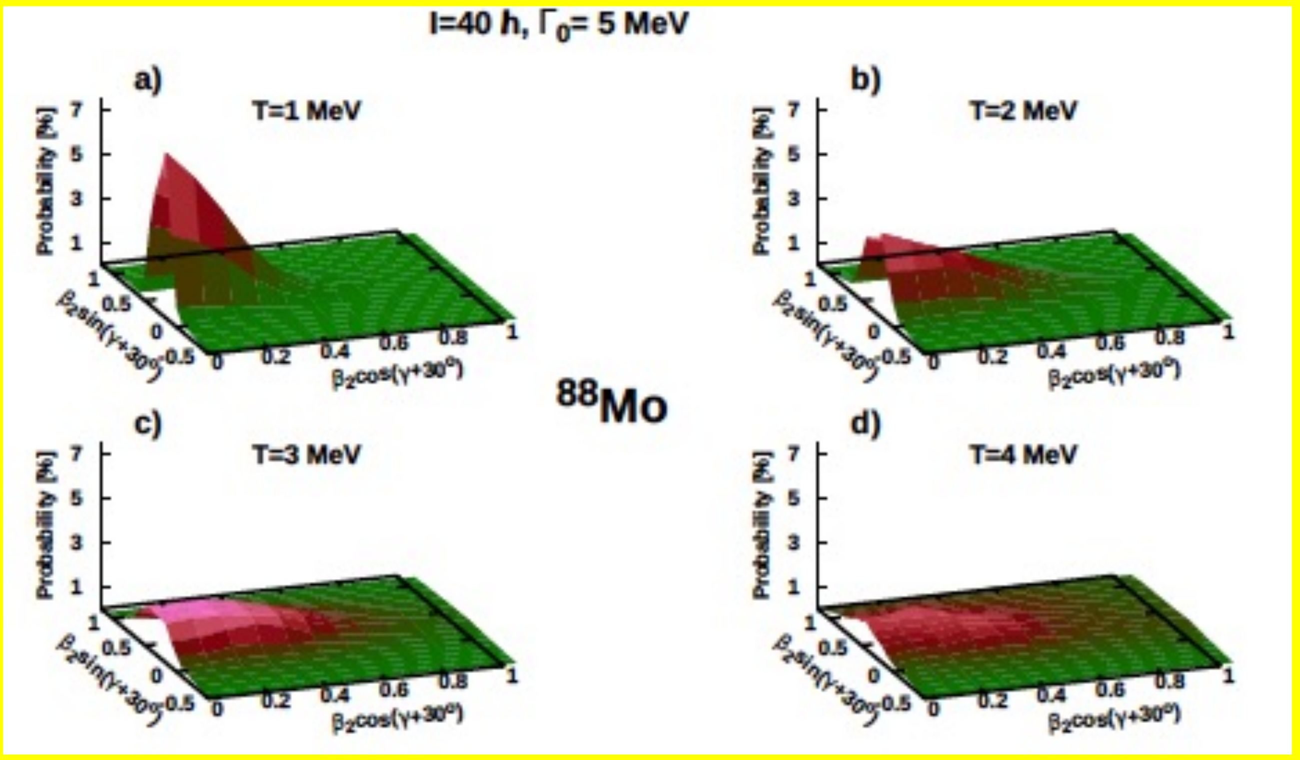


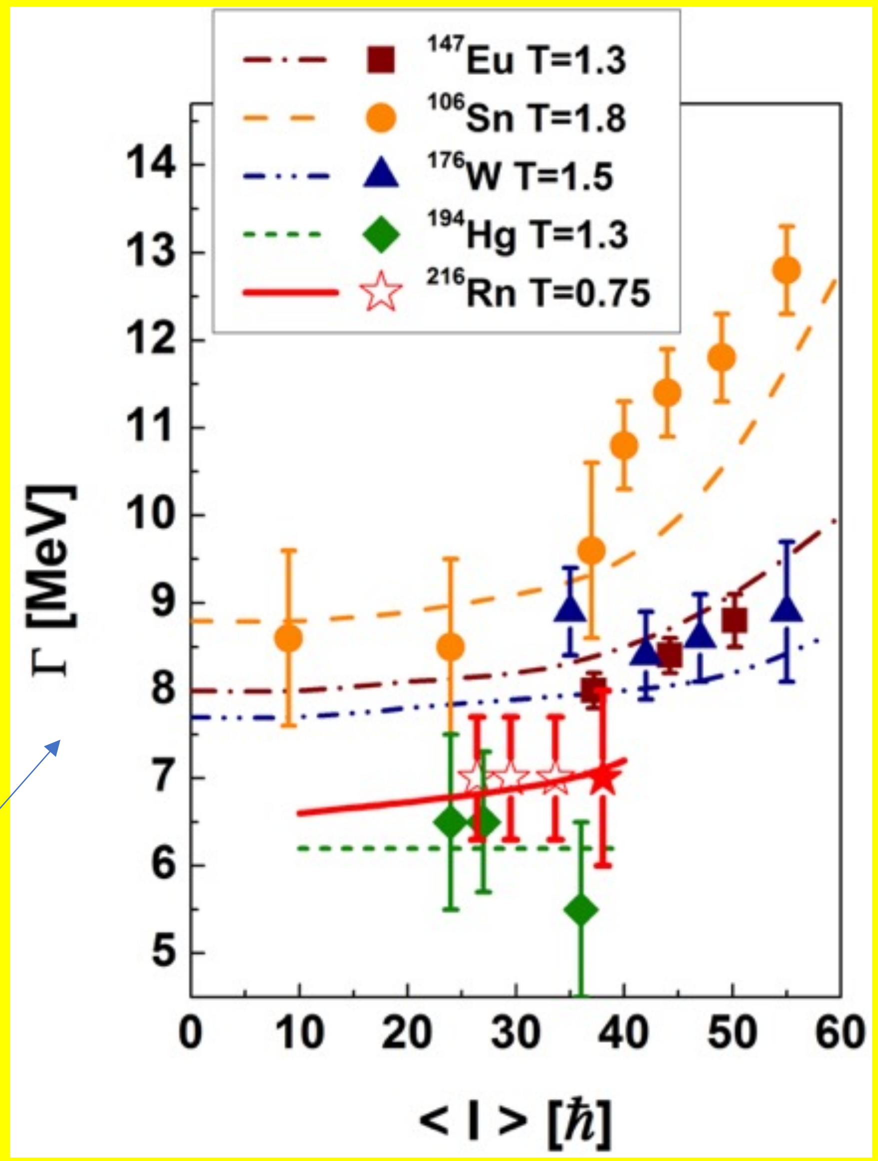
Reactions leading to CN

Observation of Giant Dipole Resonances Built on States of High Energy and Spin
J. O. Newton, B. Herskind, R. M. Diamond, E. L. Dines, J. E. Draper, K. H. Lindenberger, C. Schück, S. Shih, and F. S. Stephens - Phys. Rev. Lett. **46**, 1383 (1981)

Angela Bracco

Why does the GDR width increase?





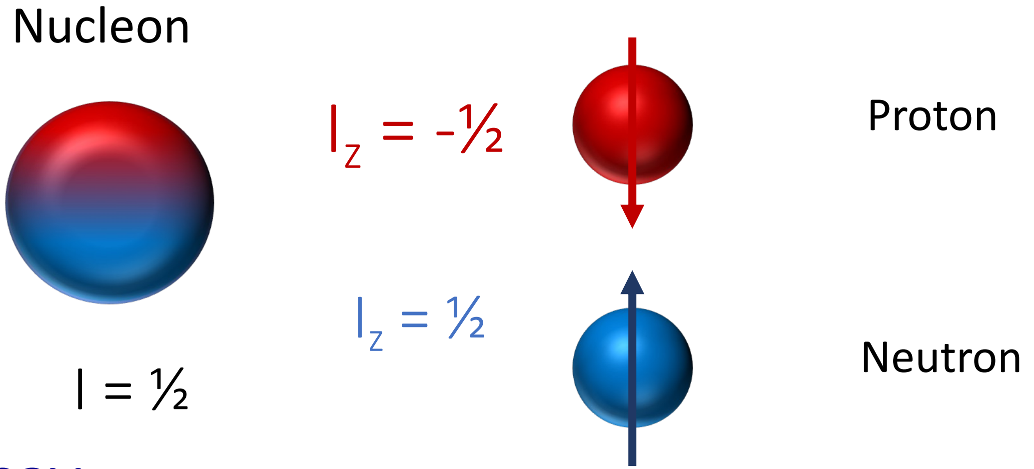
The shape distribution becomes broader with increasing Temperature !

Calculations of A. Maj and Dudek

At **fixed temperature** the most probable deformation increases in size with angular momentum

Angela Bracco

Isospin symmetry at finite temperature



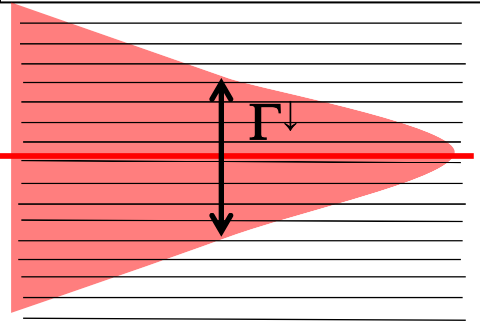
- **Isospin symmetry in nuclei**
- Measurements of isospin mixing via E1 decay
- Isospin mixing at finite temperature
- Use of the GDR decay in compound nuclei with N=Z
- Experiments in the mass region 60-80
- Isospin mixing correction to extract the CKM matrix in beta decay

Angela Bracco

Isospin symmetry in nuclei

Definitions: i_z=-1/2 for a proton; i_z =+1/2 for a neutron; I_z =(N-Z)/2 for a nucleus
(Heisenberg, 1932)

$$|\psi\rangle = |I, I_z\rangle = |0,0\rangle$$

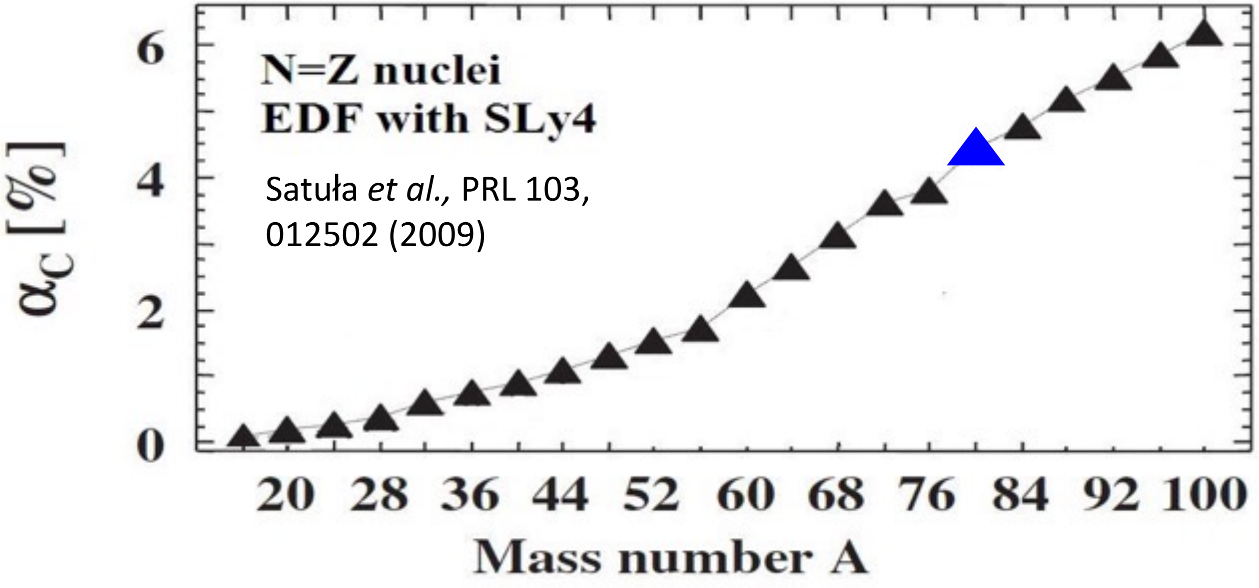


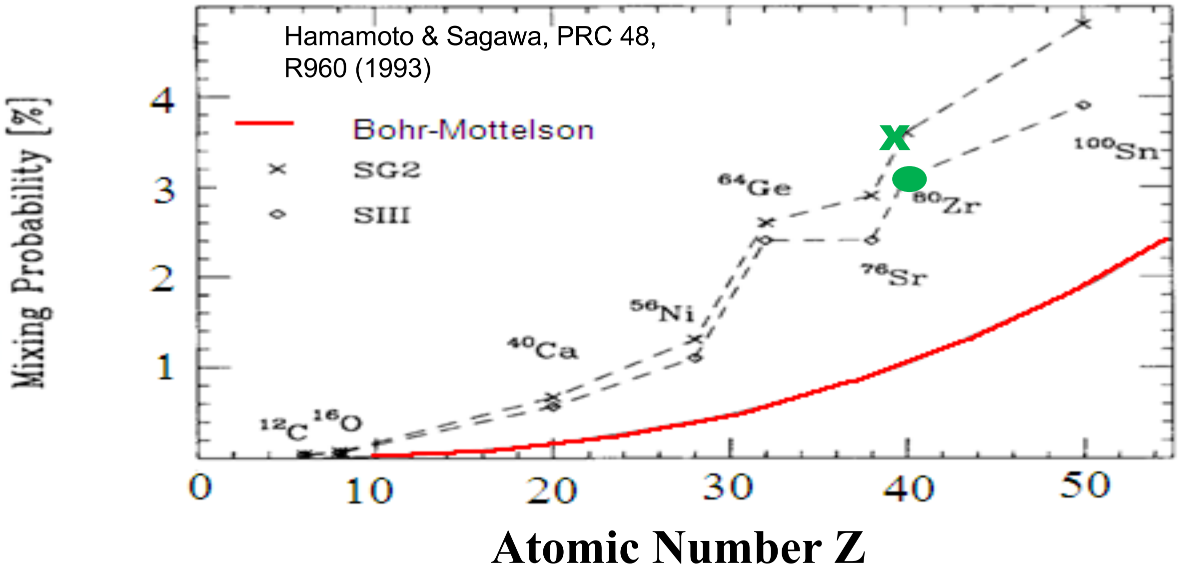
I=1

I=0 $$|\tilde{\psi}\rangle = (1-\alpha^2)|I, I_z\rangle + \alpha^2 |I+1, I_z\rangle = (1-\alpha^2)|0,0\rangle + \alpha^2|1,0\rangle$$

Coulomb spreading width $$\Gamma^{\downarrow} = 2\pi \langle 1,0|H_c|0,0\rangle \rho(1)$$

$$\alpha^2 \simeq \frac{\Gamma^{\downarrow}}{\Gamma_{CN}} \simeq \frac{\tau_{CN}}{\tau_{MIX}}$$





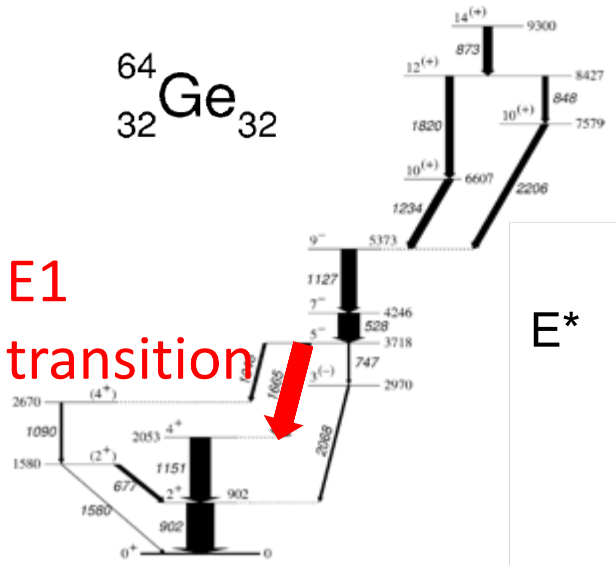
Angela Bracco
September 2024

Measurements of isospin mixing via E1 decay

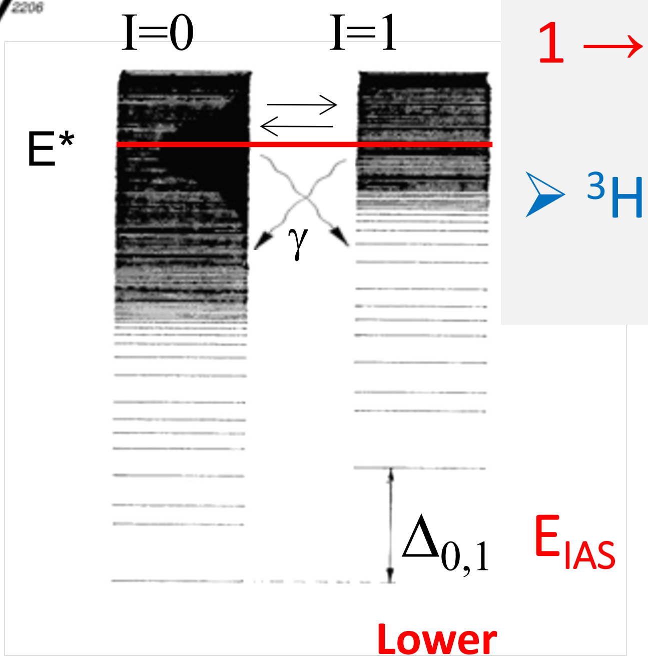
E1-γ decay from I=0 nuclei forbidden by selection rules

- $\Delta I = 0, \pm 1$
- $0 \rightarrow 0$ forbidden

Small E1 Strength T=0 → temperature → T>0 100% of E1 Strength

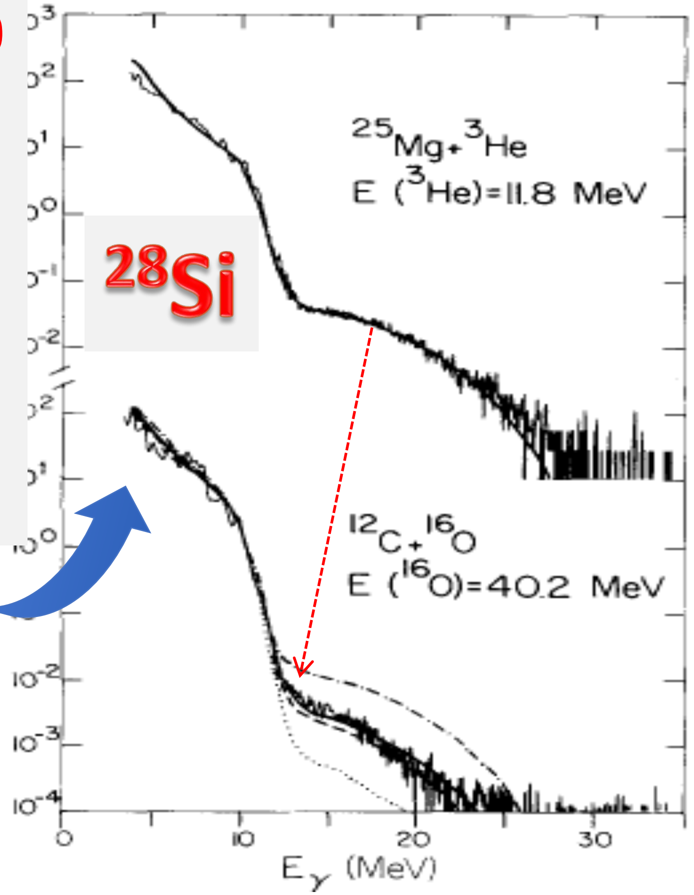


E.Farnea *et al.*, PLB 551 (2003), 56



Lower density of states

- $^{12}C+^{16}O \rightarrow {}^{28}Si$ Isospin = 0
  - $0 \rightarrow 0$ forbidden
  - $0 \rightarrow 1$ allowed but $\rho(1) \ll \rho(0)$
  - $1 \rightarrow 0$ via isospin mixing
- $^{3}He+^{25}Mg \rightarrow {}^{28}Si$ I = 1 allowed

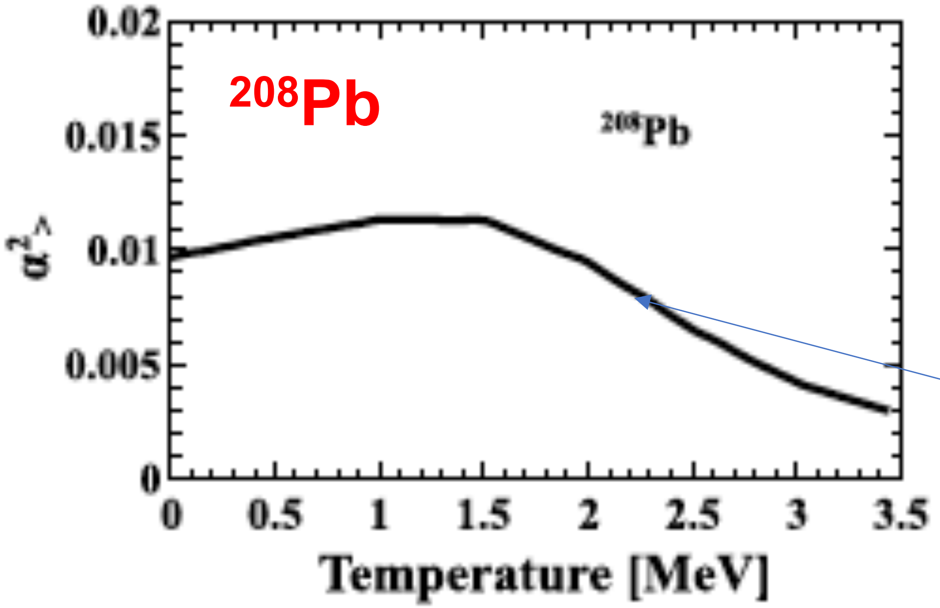


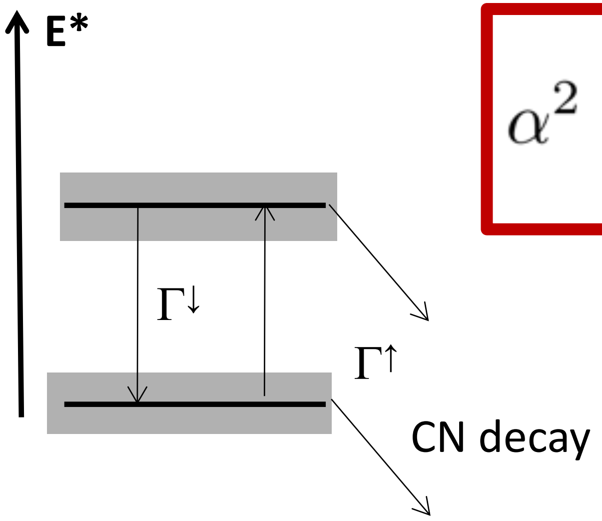
Angela Bracco
September 2024

Isospin mixing at finite temperature

Finite lifetime of excited states (compound nucleus) does not allow to achieve full mixing: restoration of isospin symmetr (Wilkinson, 1956)

$$\alpha^2_{I_0+1}(\mathrm{T}) \approx \frac{\Gamma^{\downarrow}_{IAS}}{\Gamma^{\uparrow}{}_{CN}\,(T) + \Gamma_{IVM}\,(E_{IAS})}$$





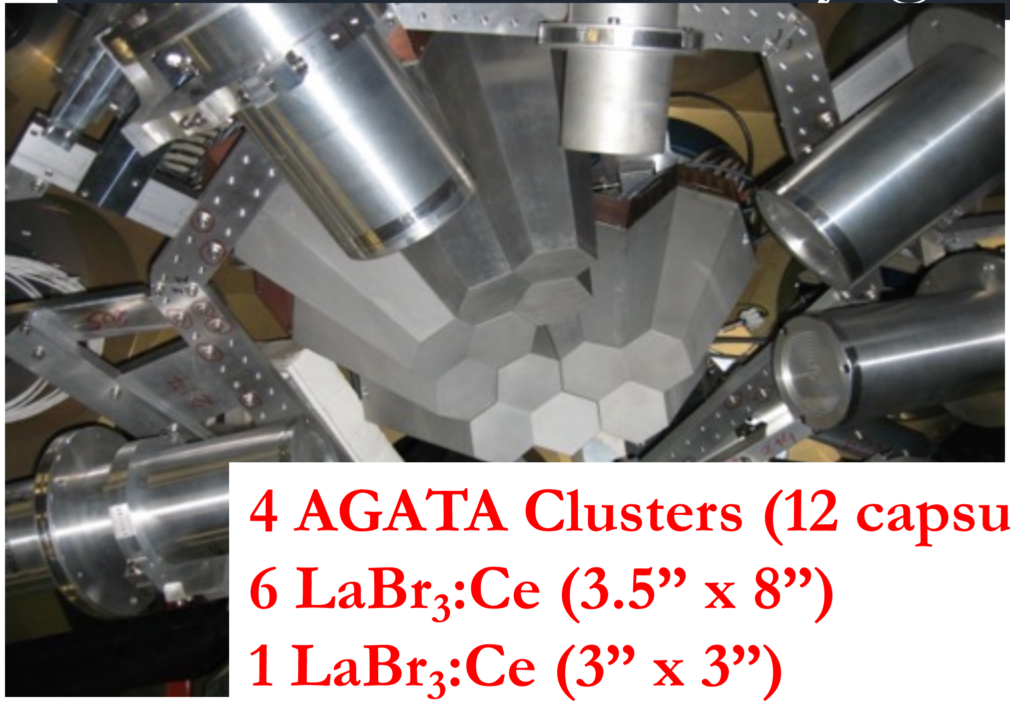
$$\alpha^2 \simeq \frac{\Gamma^{\downarrow}}{\Gamma_{CN}} \simeq \frac{\tau_{CN}}{\tau_{MIX}}$$

The mixing decreases with T because of the increase of the width of the CN (inverse of the lifetime)

Sagawa, Bortignon, Colò PLB 444 (1998), 1

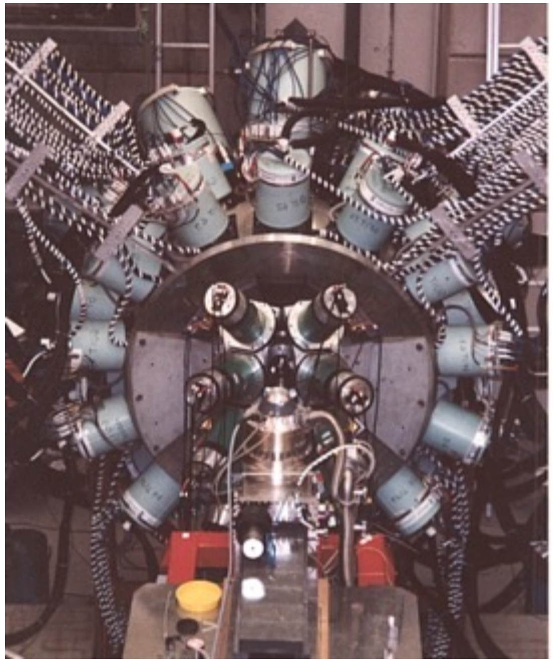
Experimental setups to measure Isospin Mixing at Finite T A=60-80

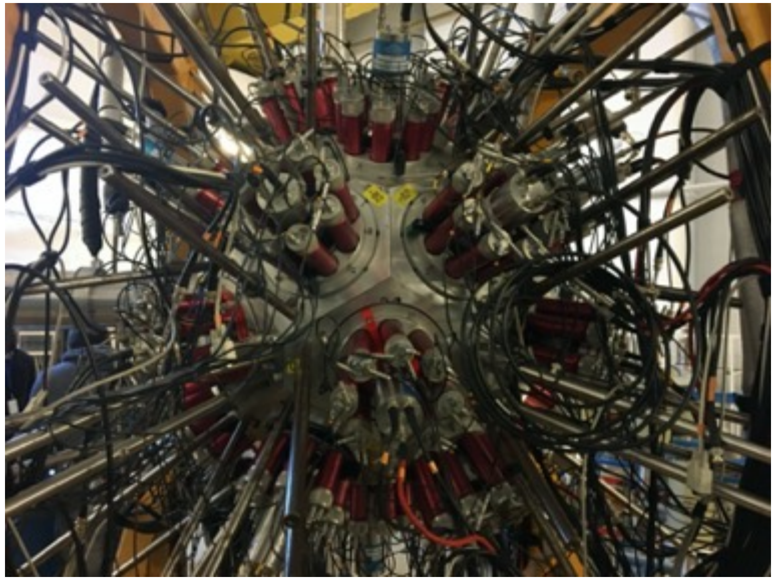
AGATA – HECTOR+ array @ LNL



4 AGATA Clusters (12 capsules)
6 $LaBr_3$:Ce (3.5" x 8")
1 $LaBr_3$:Ce (3" x 3")

At LNL with GALILEO



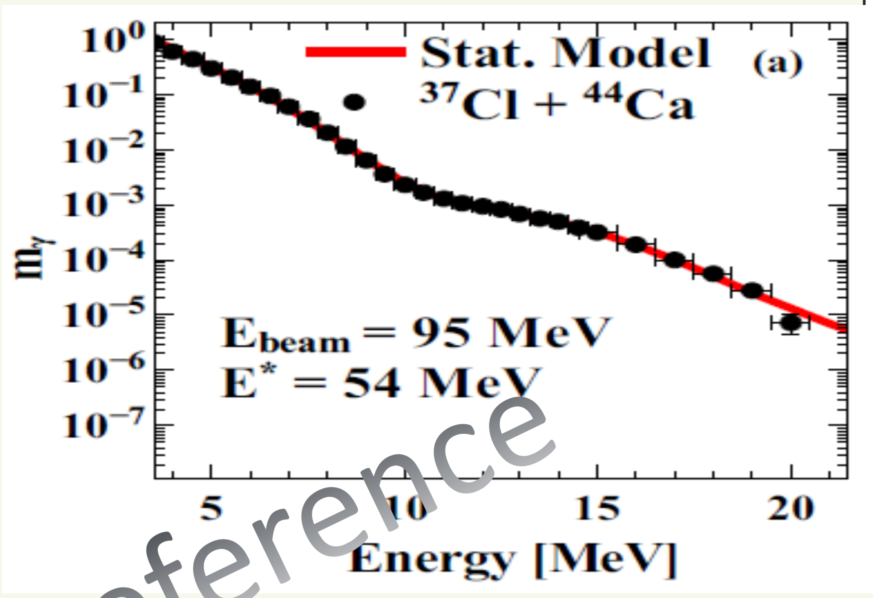


at Bucharest ELIFANT-GG@IFIN

The lowest T Measurement with the smallest cross-section

Isospin mixing experiment in ^{80}Zr

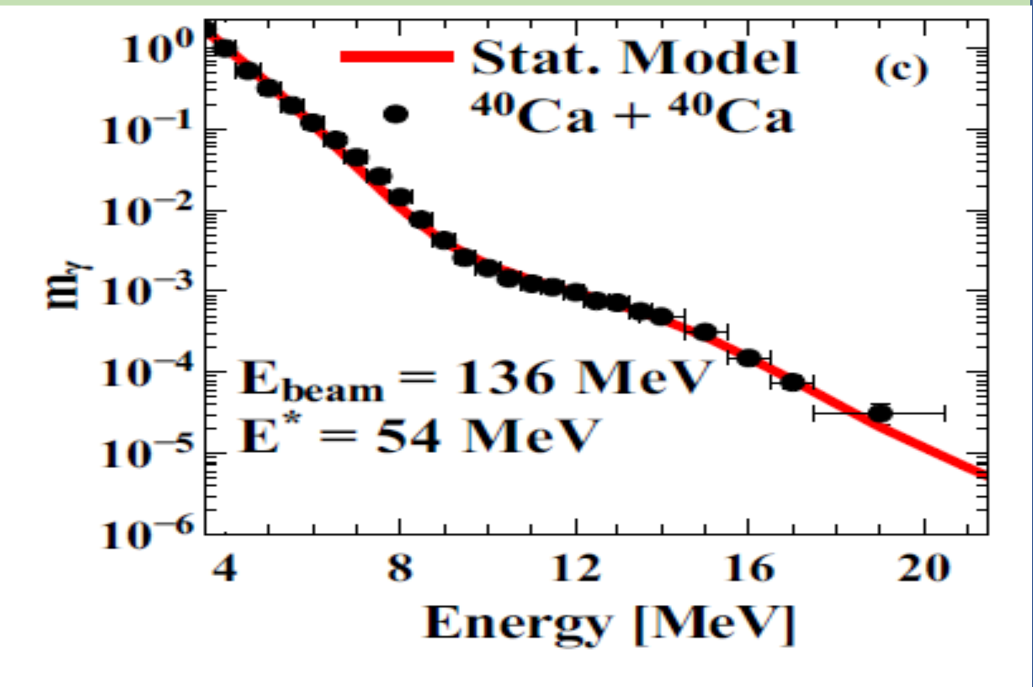
^{81}Rb–HECTOR^{+}

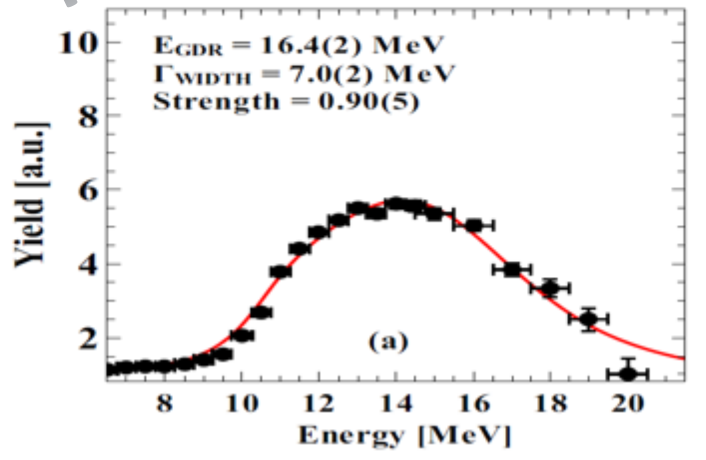


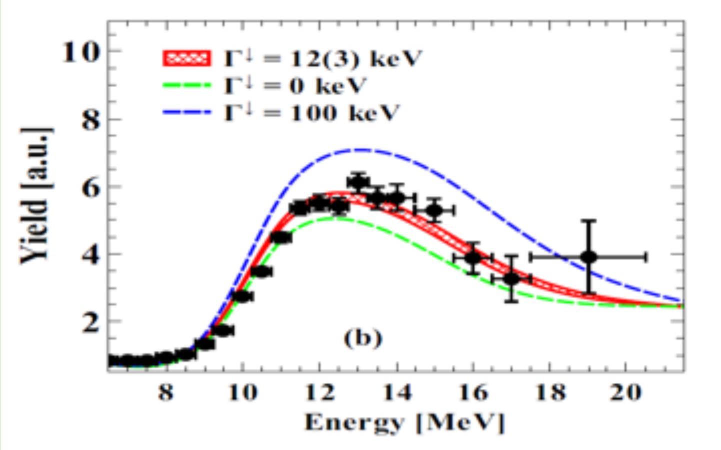
E_{GDR} = 16.4 ± 0.2 MeV
Γ_{GDR}= 7.0 ± 0.4 MeV
S_{GDR} (%)= 90 ± 5

GDR parameters consistent with those at E* = 84 MeV

^{80}Zr–HECTOR^{+}



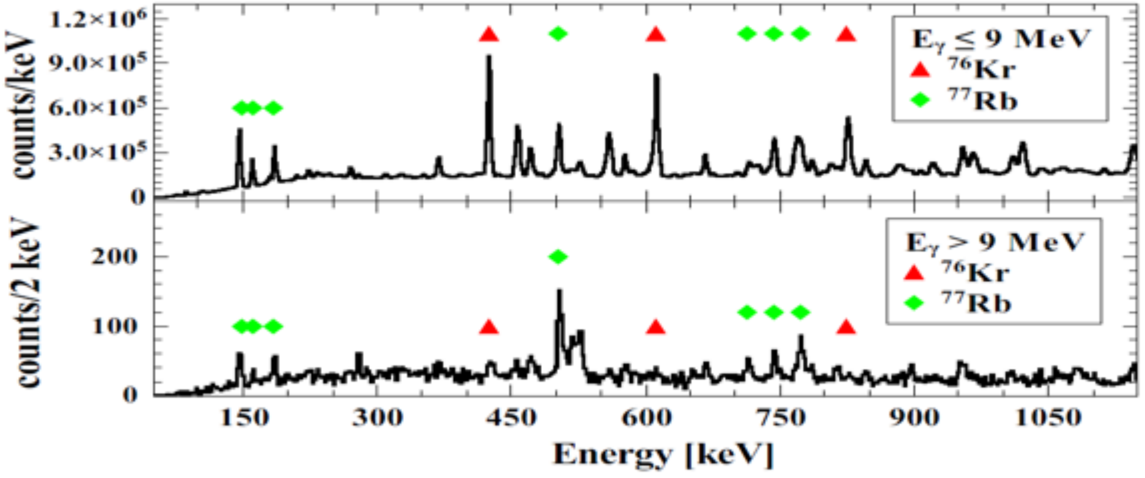


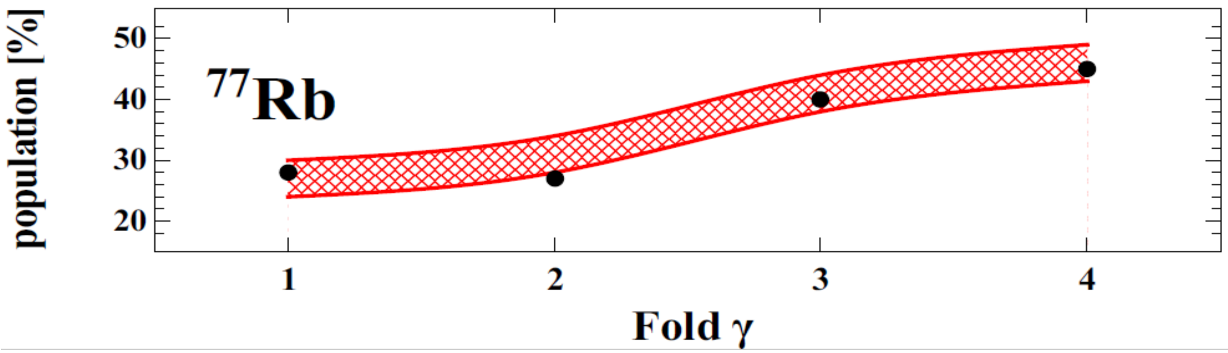


$\Gamma^{\downarrow}$=12±3 keV, α^2=0.046±0.007

$\Gamma^{\downarrow}$ does not change with T
α^2 is larger at lower T

Measurements and Analysis- Isospin mixing (residues of CN)



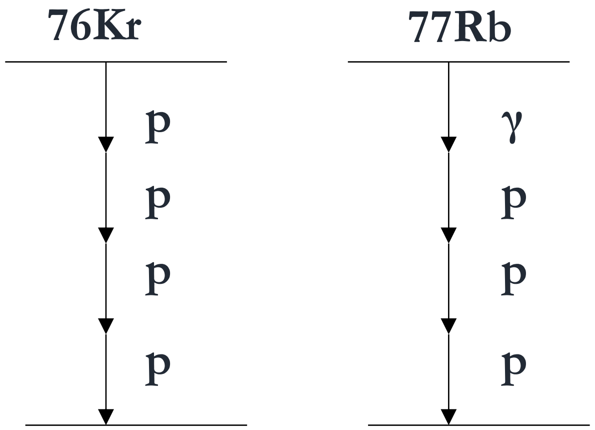


Identification of the residual nuclei

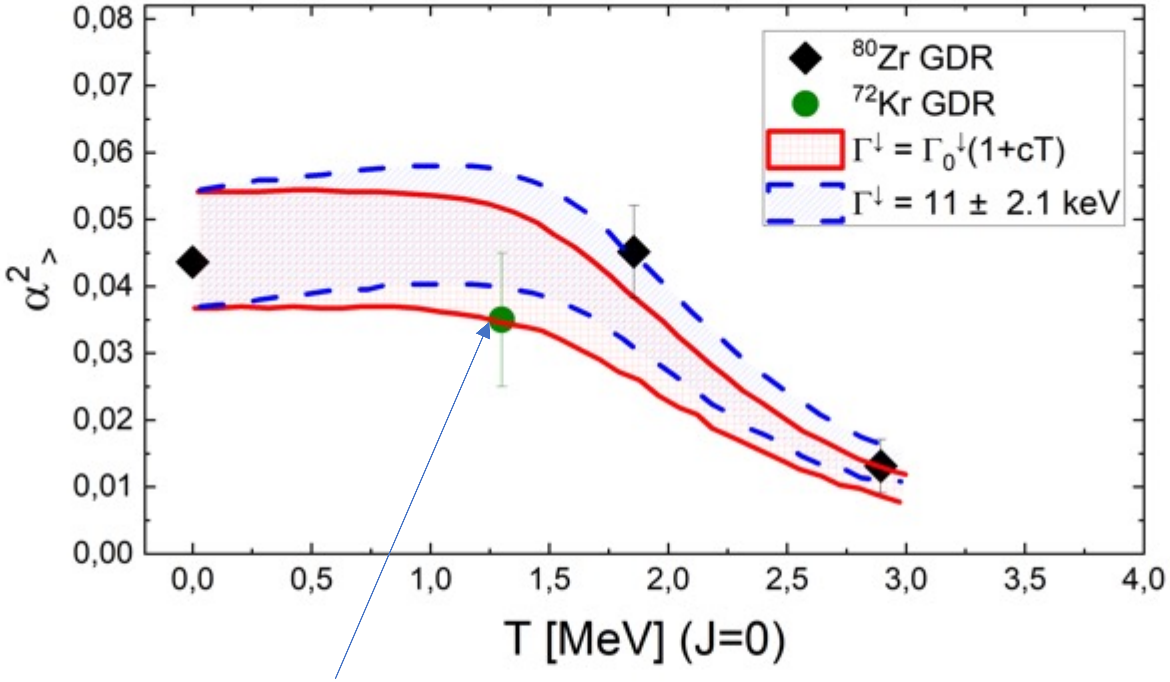
The statistical model reproduces well the reaction

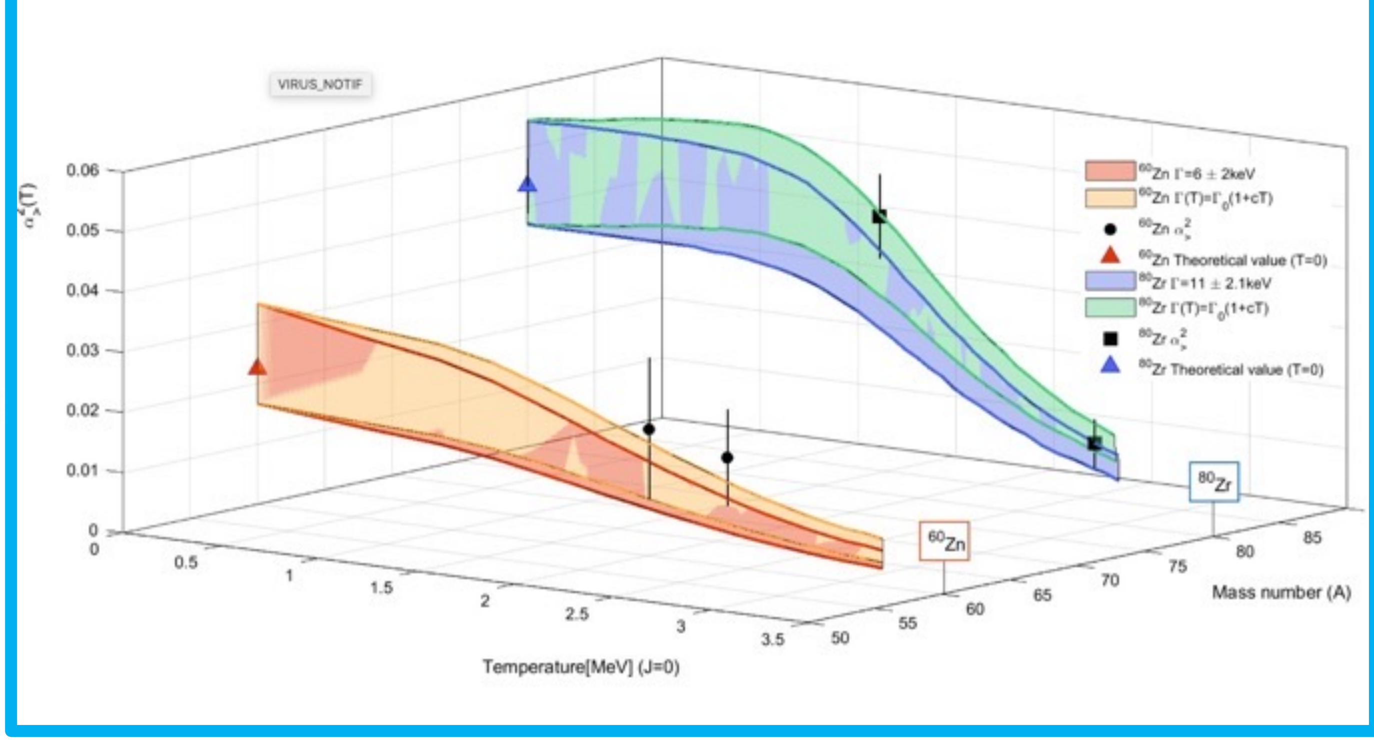
The gating condition changes the phase space available for particle emission

77Rb = 3p
76Kr = 4p



Results - Isospin mixing experiment ^{60}Zn and ^{80}Zr





New datum in ^{72}Kr **to be published** obtained at the Tandem Laboratory in Bucharest

Satuła *et al.,* PRL 103, 012502 (2009)

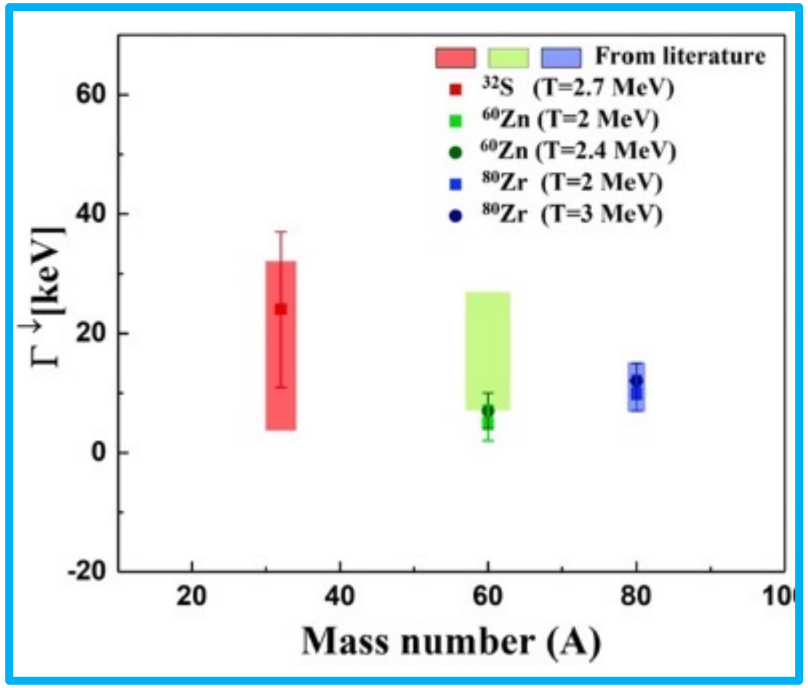
A.Corsi et al. PRC 84, 041304(R) (2011)

S. Ceruti, et al., Phys. Rev. Lett. 115, 222502 (2015).

^{60}Zn data: G. Gosta et al..Phys. Rev. C 103, L041302 (2021) -

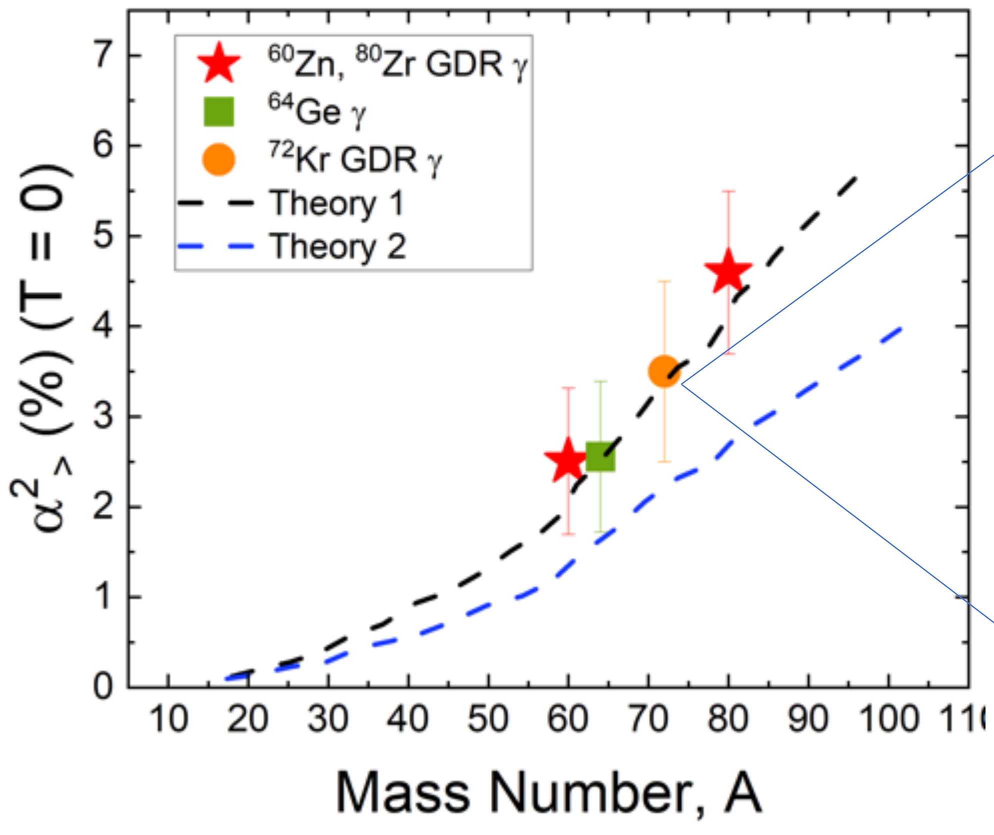
GDR used as a probe to study Isospin Mixing

The Coulomb Spreading width – no T dependence

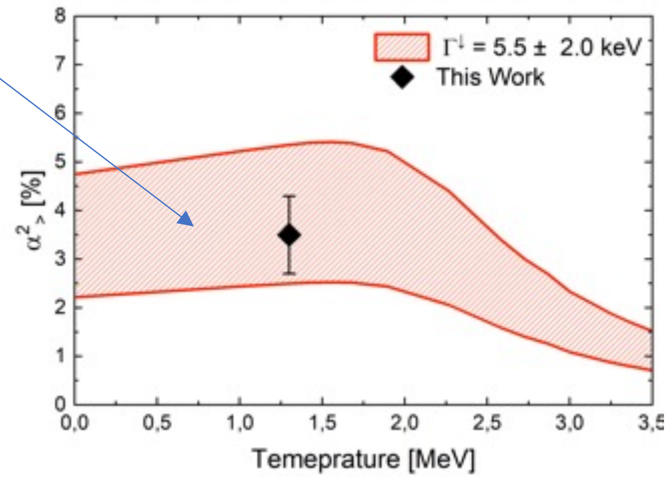


$$\alpha^2 \simeq \frac{\Gamma^{\downarrow}}{\Gamma_{CN}} \simeq \frac{\tau_{CN}}{\tau_{MIX}}$$

Isospin mixing from GDR in the medium mass region



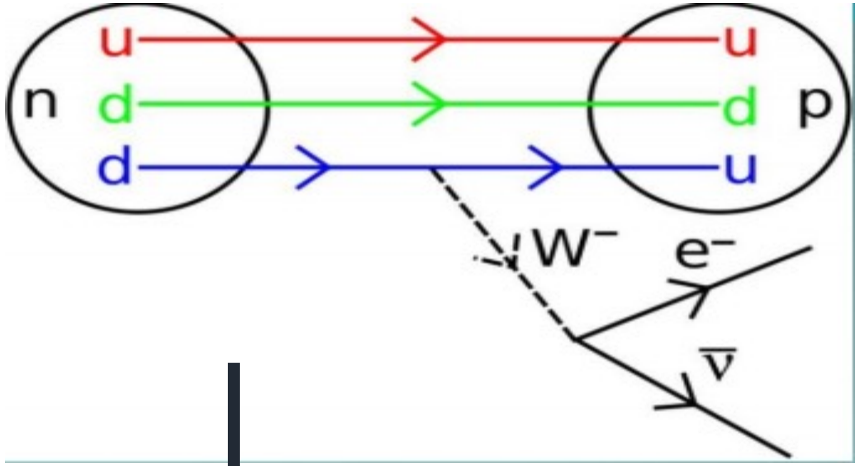
Datum from
The experiment
In Bucharest
It is at the lowest
temperature

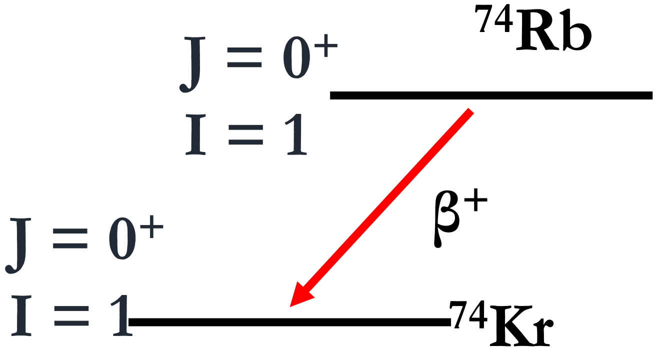


Theory: W. Satu la, J. Dobaczewski, W. Nazarewicz, and M. Rafalski, Phys. Rev. Lett. 106, 132502 (2011).
Theory1: after performing a rediagonalization on the isospin basis.

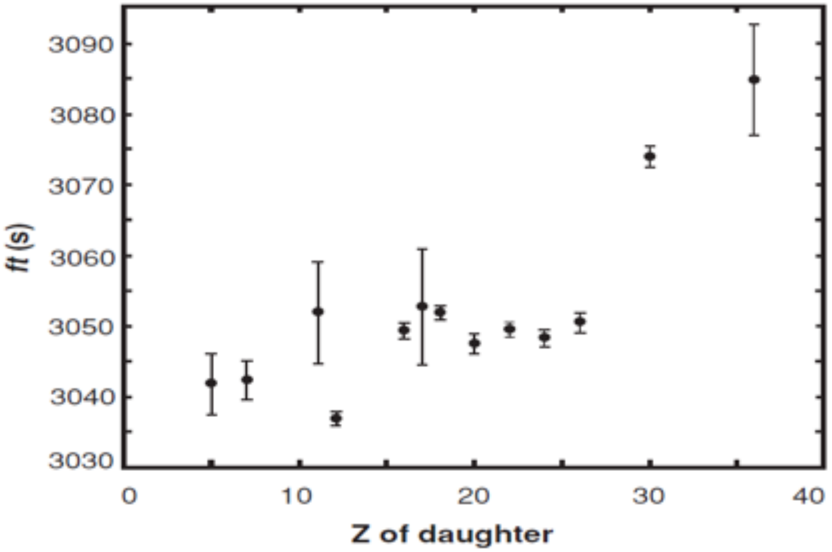
Beyond nuclear structure: CKM matrix

Superallowed Fermi



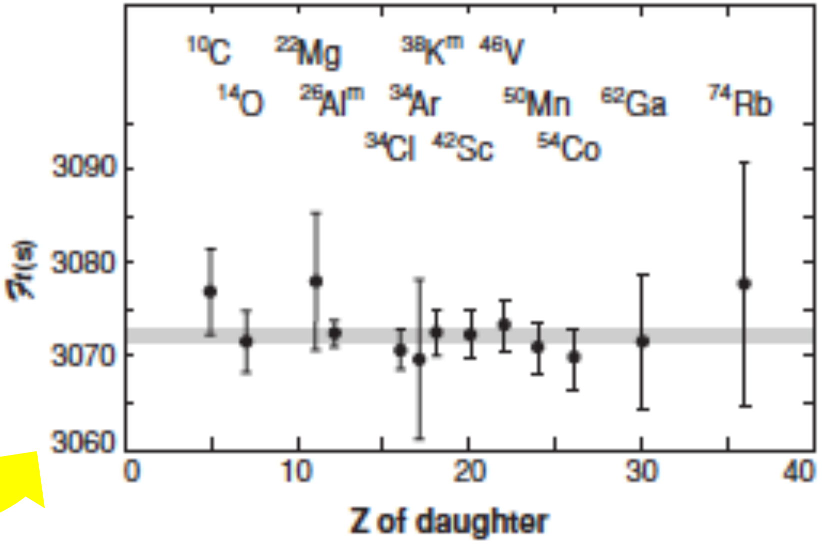


$$0^+ \rightarrow 0^+, \Delta I = 0$$



$$ft = \frac{K}{|M_F|^2 G_V^2} = \frac{K}{|M_F|^2 G_F^2 V_{ud}^2}$$

$$Ft \equiv ft(1 + \delta_R)(1 - \delta_C)$$



ft depends only on universal quantity.
It **should** be independent on the nuclear mass.

Beyond nuclear structure: CKM matrix

$$Ft \equiv ft(1+\delta_R)(1-\delta_C)$$

Many parametrizations are present in literature to describe $\boldsymbol{\delta_C}$ behaviour.
Auerbach proposed:

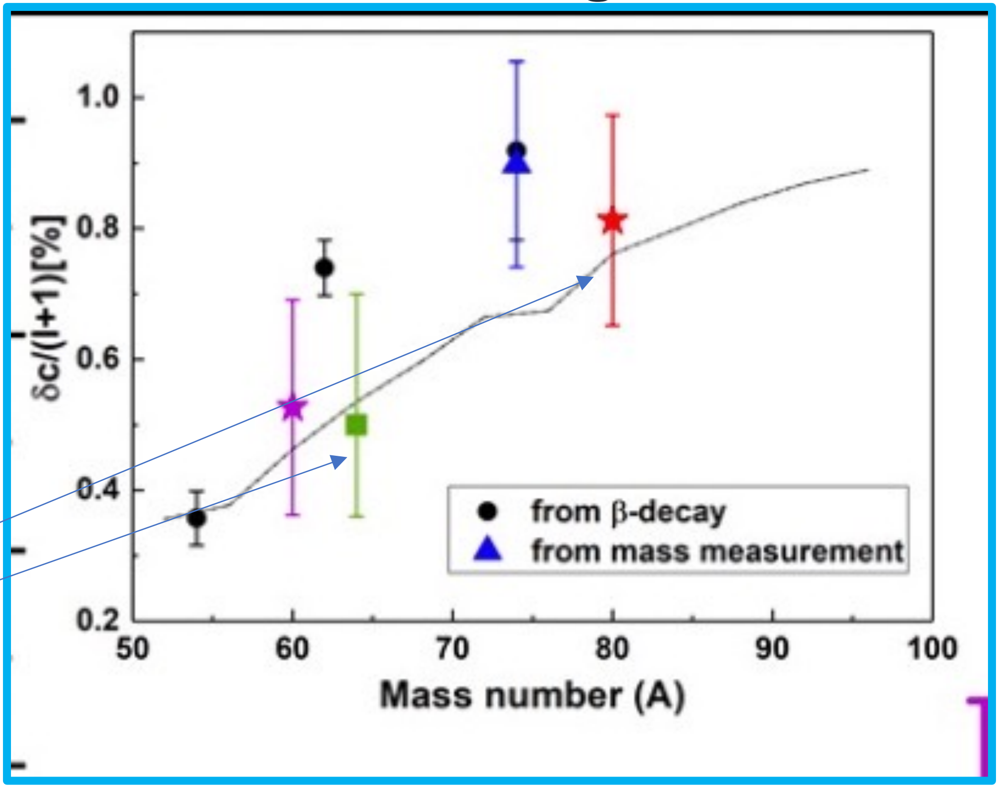
$$\delta_C = 4(I+1)\frac{V_1}{41\xi A^{2/3}}\alpha^2$$

Isospin mixing

Conclusion

- **Isospin mixing in a region not measured with other techniques**
- **Verify data obtained with other techiniques**

From GDR decay

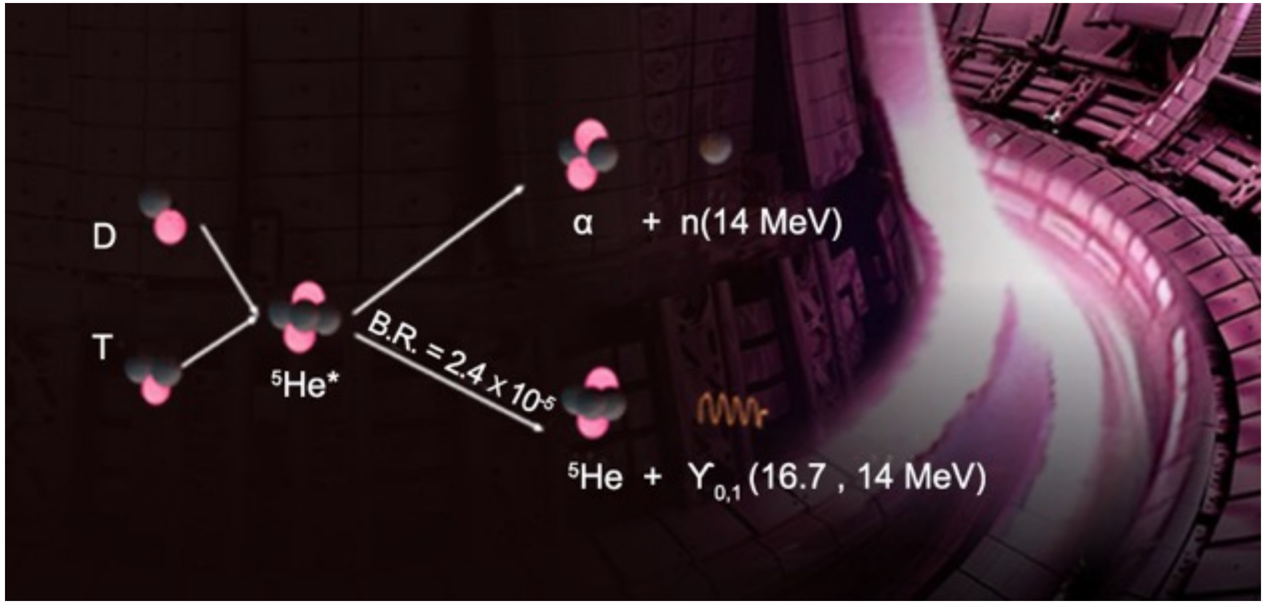


I.S. Towner and J.C. Hardy PRC 82, 065501 (2010)

Are the techniques developed to address fundamental questions in nuclei useful for applications?

To master techniques to measure Gamma-rays with energy 10-20 MeV emitted with small branching ratios has impact on applications!

SIF prima pagina
SOCIETÀ ITALIANA DI FISICA



Cnr-Istp in collaboration with Milano-Bicocca and Milano Statale, ENEA Frascati, and other institutions in the project “GETART”

Measurement at JET Tokamak in UK

nuclear fusion: a new method to measure the reactor power with gamma-rays

A.Dal Molin et al., PRL133,055102 (2024), and M. Rebay Rev. C 110, 014625 (2024)

The accurate evaluation of the deuterium-tritium $BR_{\gamma/n}$ branching ratio 2.4+/- 0.3 10^{-5} important for the nuclear fusion field, an independent way to measure the fusion power in magnetic confinement devices.

Summary

PYGMY STATES and identification of the isoscalar nature of part of the strength

- E1 strengh of the PDR increses with N and Z asymmetry (also in nuclei far from stability)

- Efforts are presently made to obtain insight into the nature of the pygmy states : are they related to neutron skin excitations ? Which type?

- Search the survival of Pygmy states at finite T

- Electromagnetic response but also Hadronic probes are important to have additional information about isospin/single-particle structure (transfer reactions).

ISOSPIN MIXING

- Isospin mixing in a region not measured with other techniques

- Verify data obtained with other techiniques