Giant Multipole Resonances: A Chapter in the History of Experimental Nuclear Physics

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Outline

- General features of Giant Resonances
- The IVGDR
- The ISGMR and Nuclear Incompressibility
- Dependence on Isospin
- The Brink-Axel Hypothesis
  - Multiphonon GRs
  - Hot GRs
- A Word of Conclusion

General Features of Giant Resonances

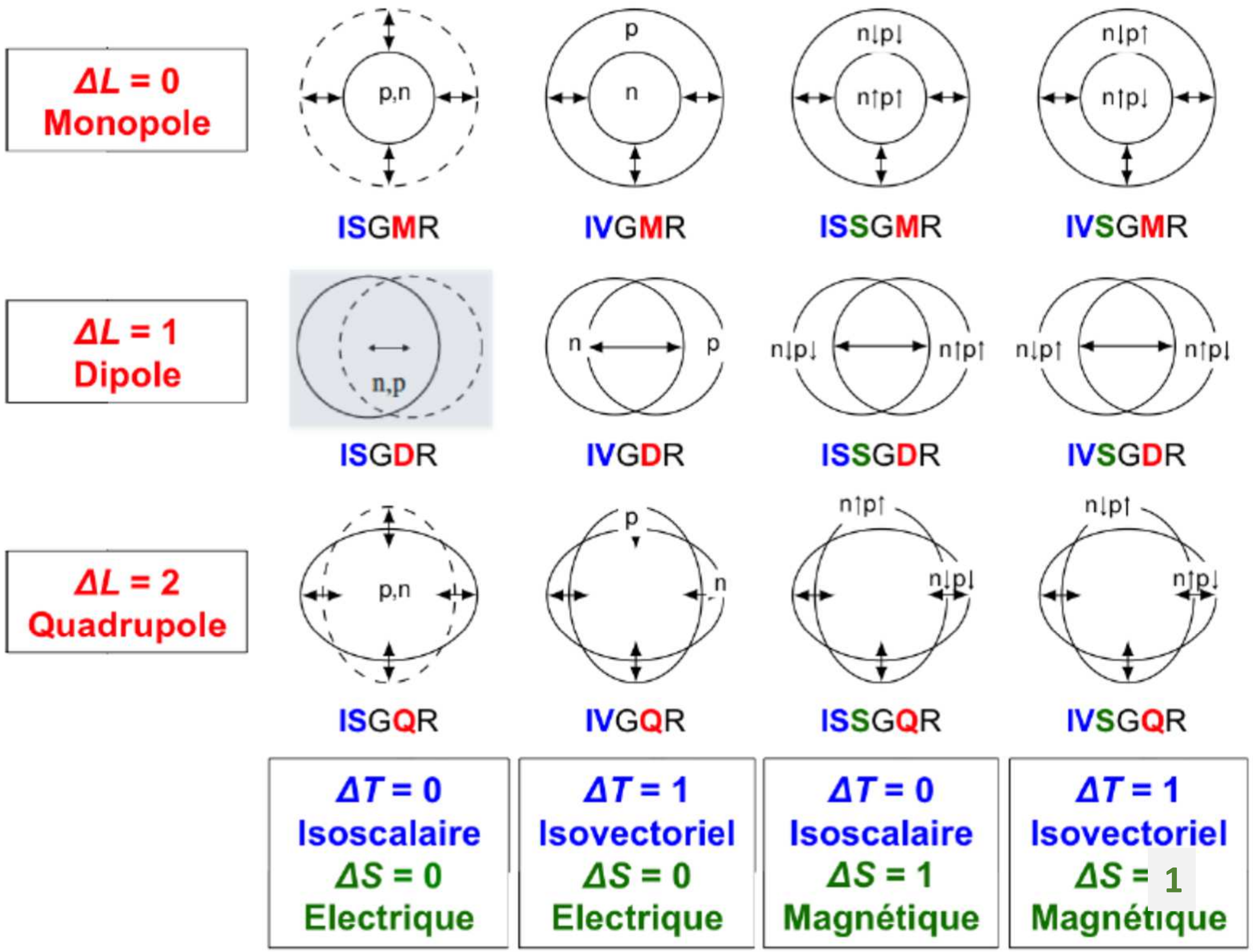
GRs are collective excitations involving a large fraction of nucleons of the nucleus.

They exist in all nuclei and their characteristics vary smoothly with mass.

A GR is defined by three characteristics:

- Energy
- Width
- Strength

GRs in a Hydrodynamical Representation



GRs in a Microscopic Representation

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

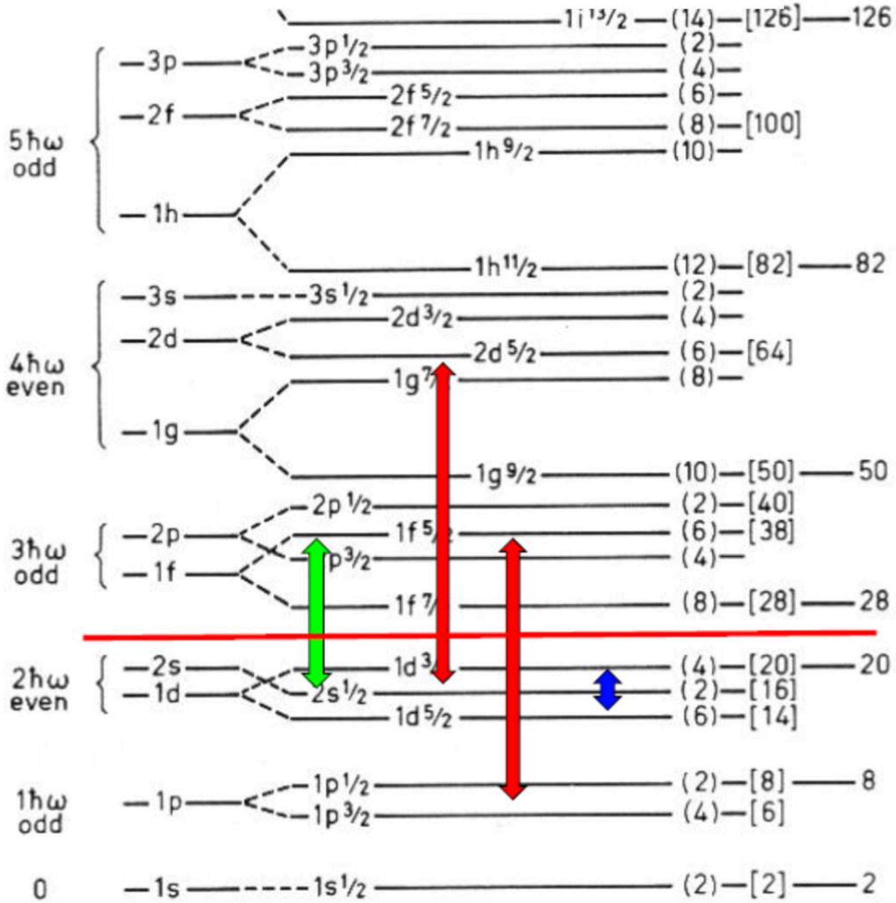
$\Delta N = 1$ **E1 (IVGDR)**

$\Delta N = 2$ **E2 (ISGQR)**

&

$\Delta N = 0$ **E0 (ISGMR)**

$$E \simeq \Delta N \times \hbar\omega = \Delta N \times 41 A^{-\frac{1}{3}}$$



Exhausted Sum Rule

Strength Distribution ➡ $S(E) = \sum_{\nu} \delta(E - E_{\nu}) \left|\langle \nu | O | 0 \rangle\right|^2$

Energy Weighted Sum Rule ➡ EWSR $= \int_0^{\infty} S(E)E \, \mathrm{d}E = \sum_{\nu} E_{\nu} \left|\langle \nu | O | 0 \rangle\right|^2$

$$\mathrm{EWSR}_{\mathrm{ISGMR}} = \frac{\hbar^2}{2m} A < r^2 >$$

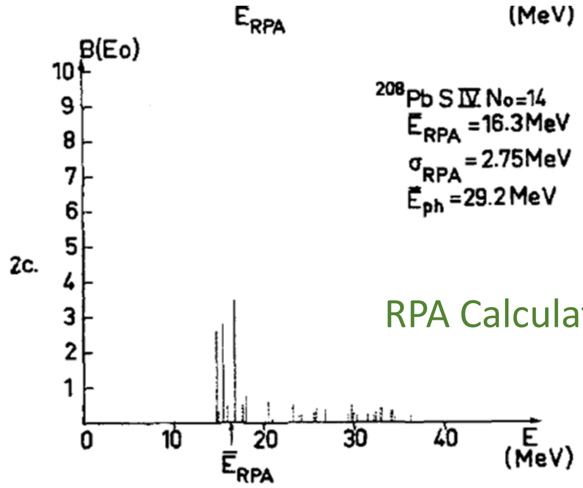
A resonance is considered Giant only if it exhausts a large fraction of the EWSR. Resonances which exhaust a small fraction of the EWSR are often called Pygmy (see Marine's talk)

Decay Processes and GR Width

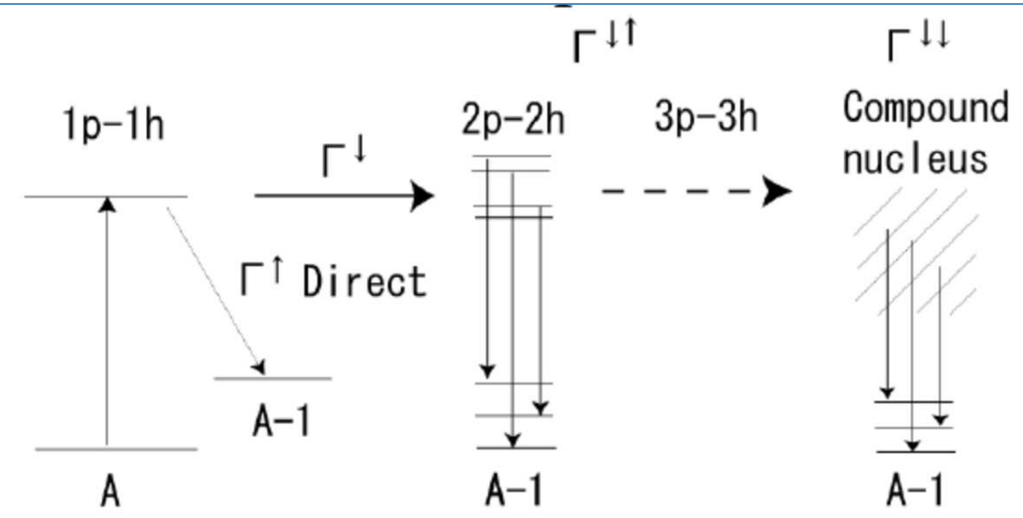
Γ^{Landau} : natural width (splitting)

$\Gamma^{\uparrow}$: escape width (direct decay)

$\Gamma^{\downarrow}$: spreading width (statistical decay)

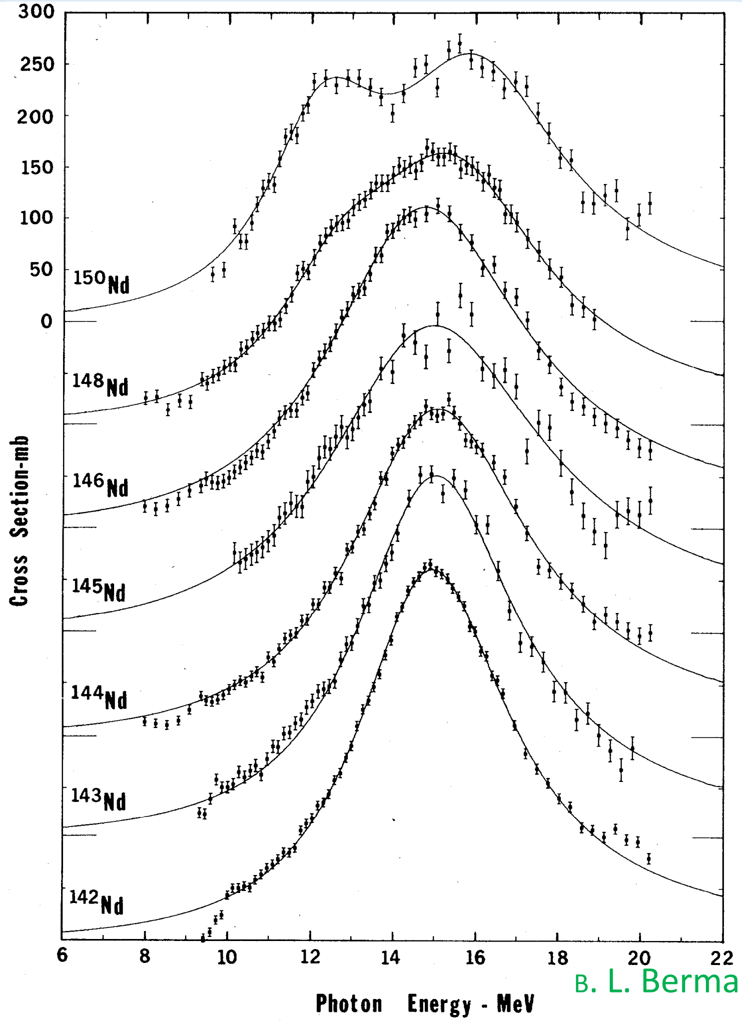


RPA Calculation



Small γ branch from 10^{-2} for the IVGDR to $10^{-4 \text{ or } 5}$ for isoscalar resonances.

The First Giant Resonance: Isovector Giant Dipole Resonance



- First inferred in 1937 by Bothe and Gentner. Systematic study by Baldwin and Klaiber started in 1947 through (γ,n) reactions. Comprehensive review: B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975)
- Occurs in all nuclei
- Lorentzian shape: $$\sigma(E) = \frac{\sigma_m \Gamma_m^2 E^2}{(E^2 - E_m^2)^2 + \Gamma_m^2 E^2}$$
- Mean energy: $$E_x = 31.2\, A^{-1/3} + 20.6\, A^{-1/6}\ \mathrm{MeV}$$
- Width from 5 MeV for light nuclei to 2.5 MeV for heavy nuclei
- Exhausts large fraction of the Thomas-Reiche-Kuhn sum rule:

$$\int_{E_{min}}^{E_{max}} \sigma_\gamma^{abs} dE = \frac{60NZ}{A}(1+\kappa)\ \mathrm{MeV\ mb}$$

- Splits into 2 Lorentzians for axially symmetric deformed nuclei

B. L. Berman and S. C. Fultz, Rev. Mod. Phys. **47**, 713 (1975)

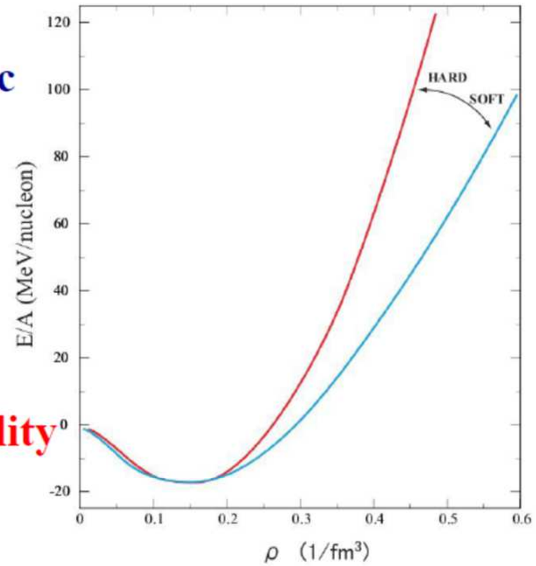
Some Basic facts about the GMR

For the equation of state of symmetric nuclear matter at saturation nuclear density:

$$\left[\frac{d(E/A)}{d\rho}\right]_{\rho=\rho_0} = 0$$

and one can derive the incompressibility of nuclear matter:

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



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

***ρ* : nuclear density**

***ρ₀* : nuclear density at saturation**

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

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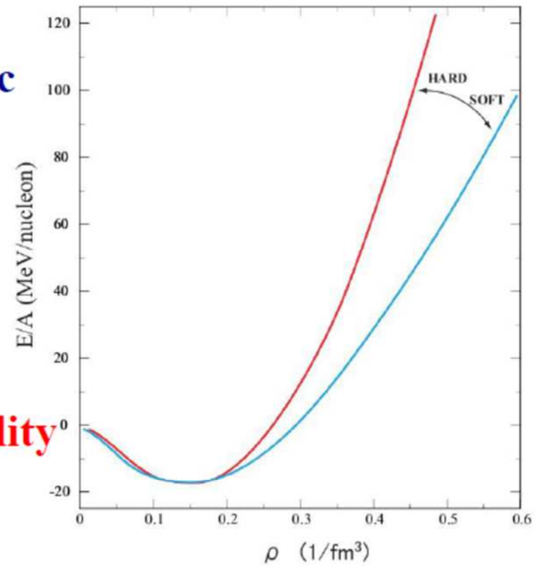


J.P. Blaizot, Phys. Rep. 64 (1980) 171

Some Basic facts (continued)

The compressibility of a nucleus A, K_A , is related to the energy of the GMR by

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}} \quad \text{with} \quad K_A = \left[r^2(d^2(E/A)/dr^2)\right]_{r=R_0}$$

The GMR (like every GR) is defined by E_{ISGMR}, Γ and %EWSR
To define precisely E_{ISGMR} one needs to observe a large %EWSR
To obtain experimentally the %EWSR one compares data with a reaction model (DWBA) which includes the transition density (scaling model):

ISGMR Satchler, Nucl. Phys. A472 (1987) 215

$$\delta\rho_0(r,E) = -\alpha_0[3 + r\frac{d}{dr}]\rho_0(r)$$

$$\alpha_0^2 = \frac{2\pi\hbar^2}{mA < r^2 > E}$$

The experimental error on E_{ISGMR} comes mainly from high energy strength difficult to observe and for which the transition density may not follow the above formula and from uncertainties on the experimental background (see later)

Hadron Inelastic Scattering

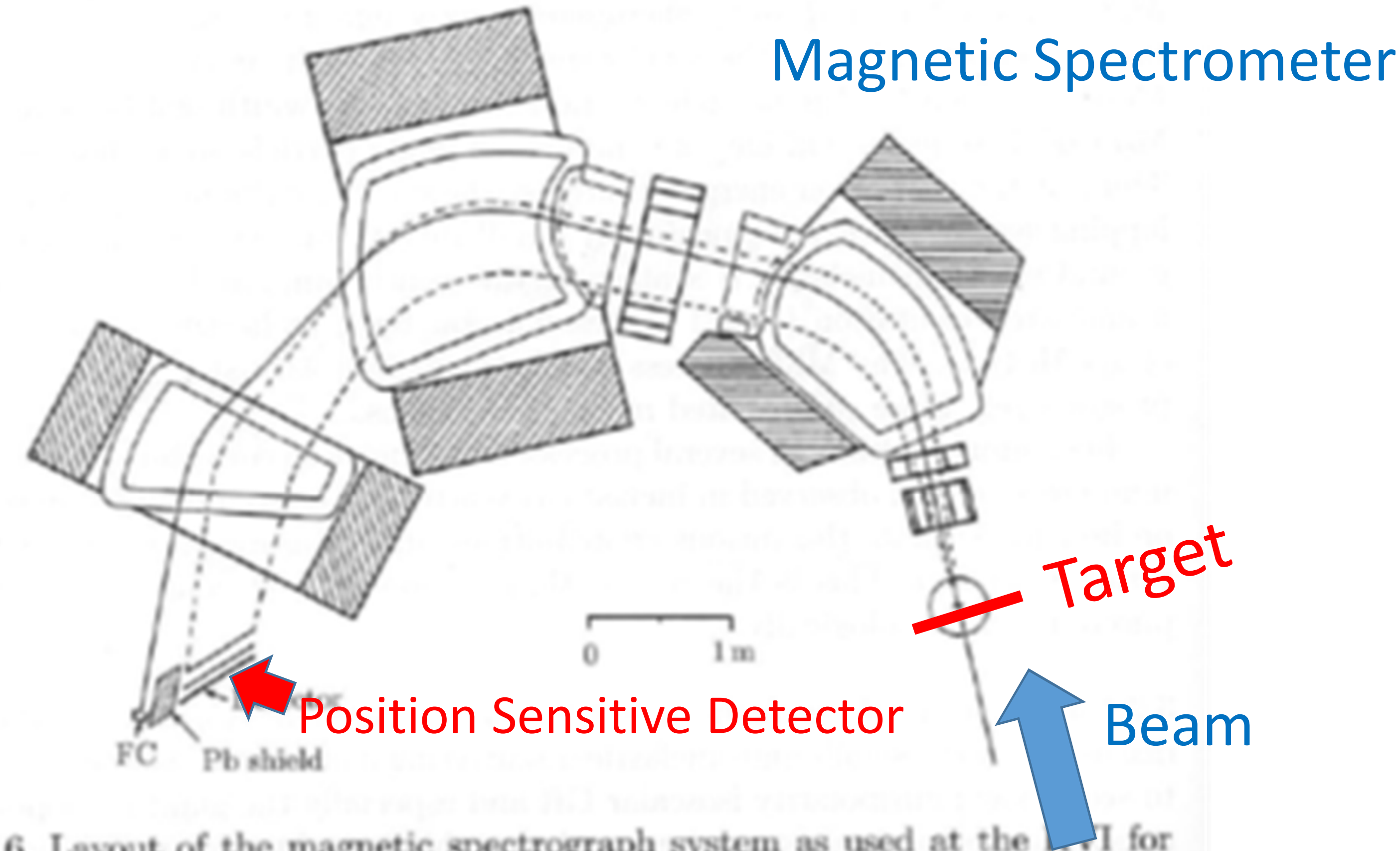
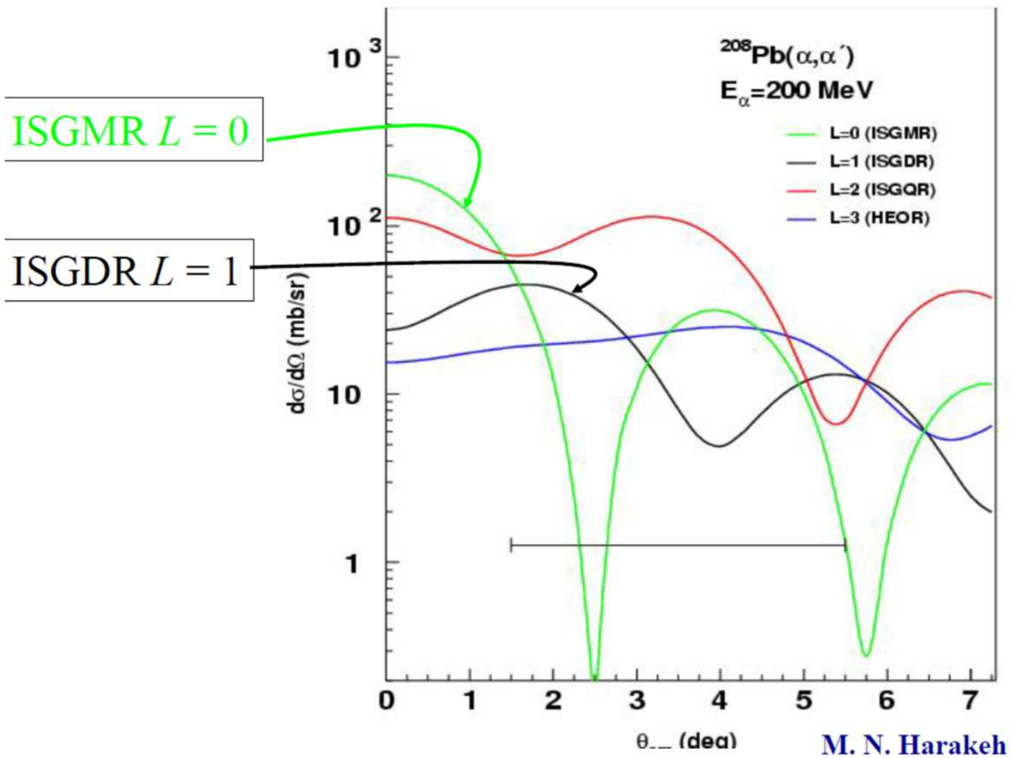
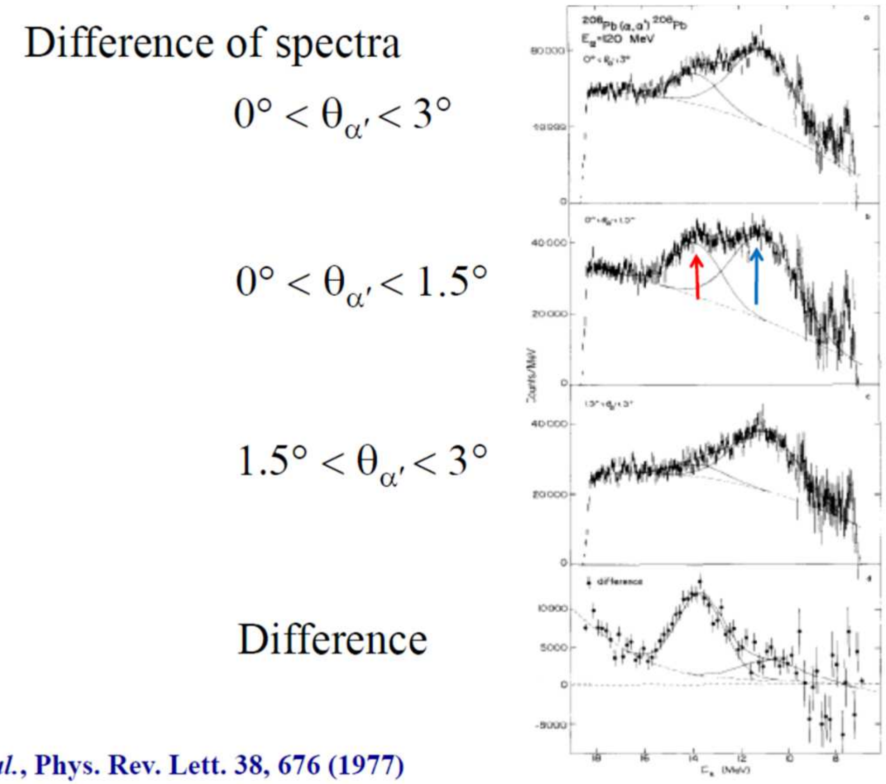


FIG. 3.6. Layout of the magnetic spectrograph system as used at the [illegible]I for 0° measurements. The full line indicates the trajectory of beam particles, and the dashed lines the trajectories of extreme rays reaching the focal-plane detection system. From (BRA87a).

Experimental results

- Discovered in the mid-seventies
- First observation claimed at IPN Orsay synchrocyclotron but never published except in annual report
- (α,α’) scattering at KVI Groningen (Harakeh, Van der Woude)
- ^{3}He scattering at ISN Grenoble (Buenerd)
- (α,α’) scattering at Texas A&M (Youngblood)

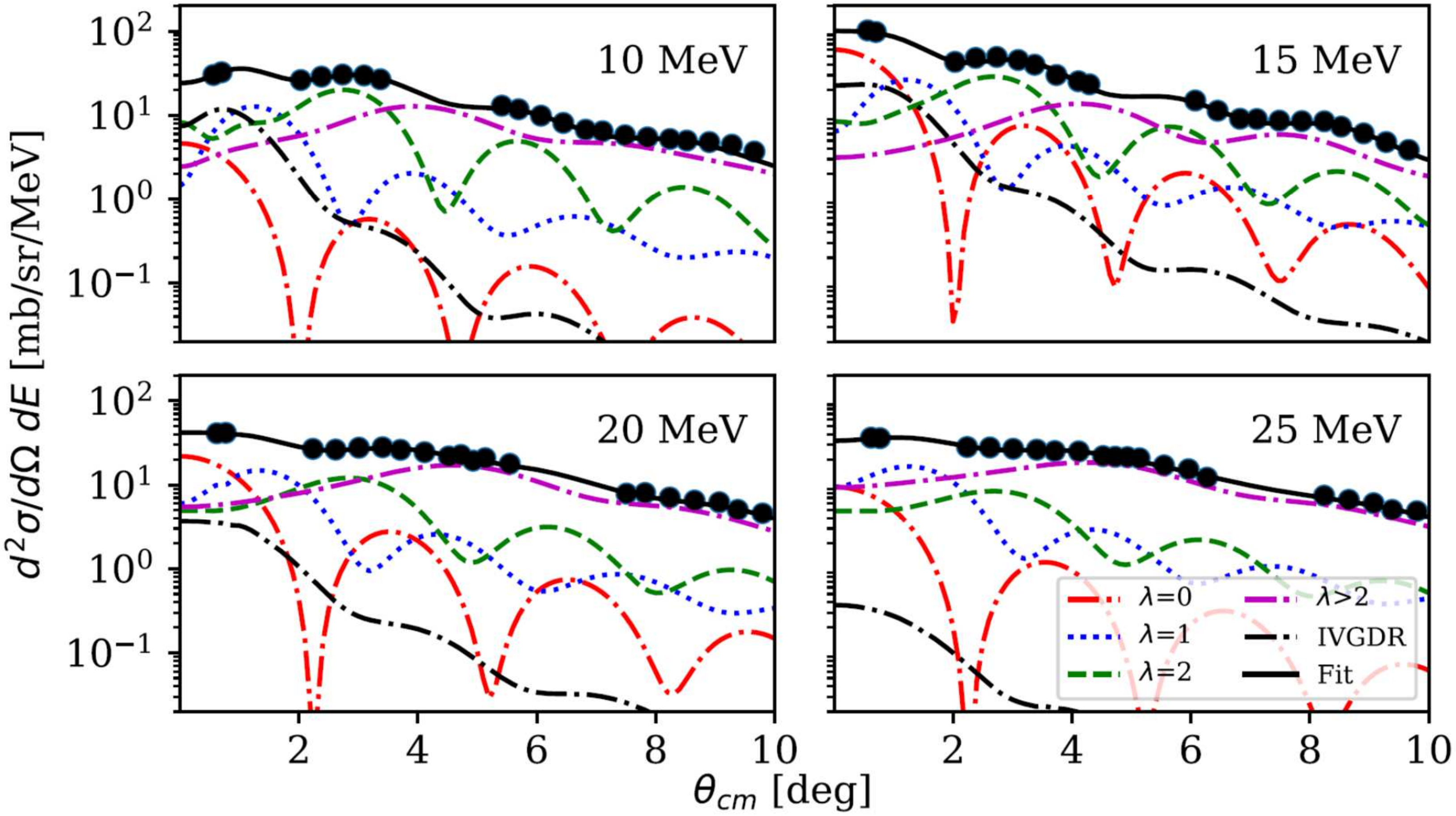




M. N. Harakeh *et al.*, Phys. Rev. Lett. 38, 676 (1977)

Multipole Decomposition Method

$$\frac{d\sigma^{\rm exp}}{d\Omega}(\theta_{\rm cm}, E_x) = \sum_{L=0}^{7} \alpha_L(E_x) \frac{d\sigma_L^{\rm cal}}{d\Omega}(\theta_{\rm cm}, E_x),$$



Systematics

$$E_x \approx (78 \pm 4) A^{-1/3}\ \mathrm{MeV}$$

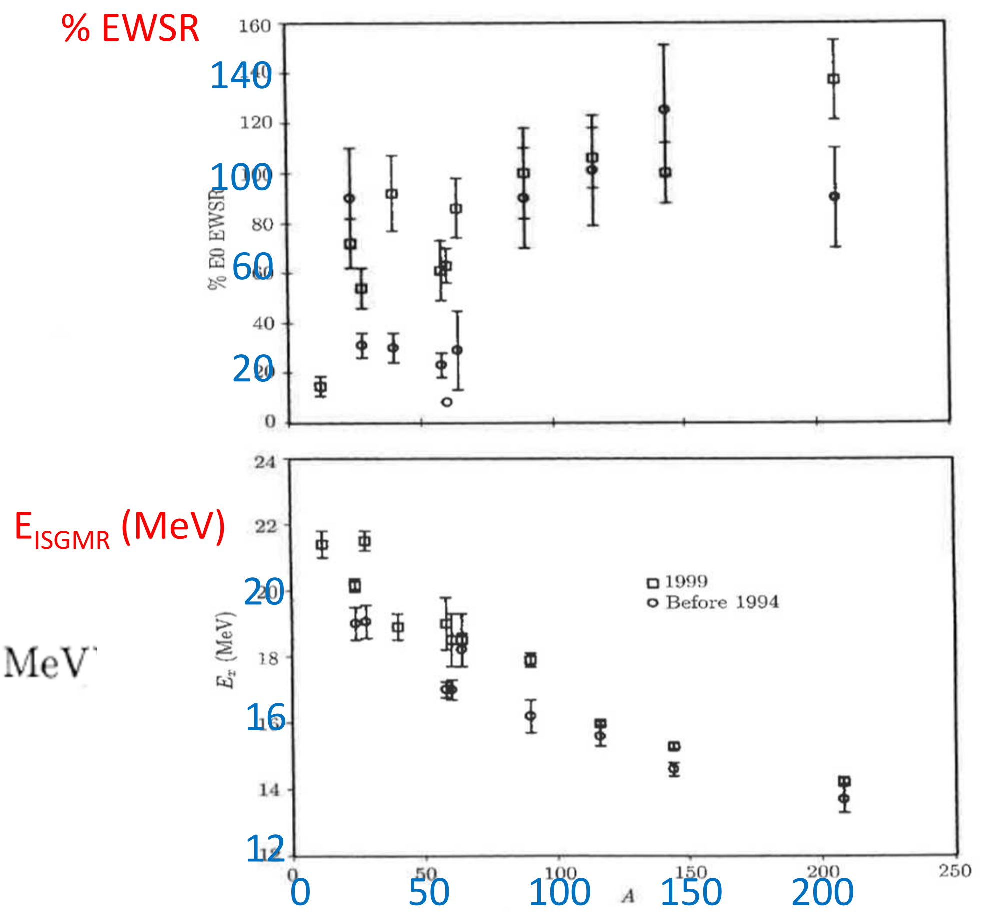


FIG. 4.1. Overview of ISGMR data on GMR centroid energies and fractions of EWSR versus A. Data indicated by open squares are from the summary in (YOU99c) and the open circles from (SHL93). Adapted from (YOU99c).

How do we get K_∞?

$$K_A = K_\infty + K_{surf}A^{-1/3} + K_{sym}((N-Z)/A)^2 + K_{Coul}Z^2A^{-4/3}$$

Fit the K parameters on experimental data: Very Imprecise

Base on RPA calculations and compare with experiment

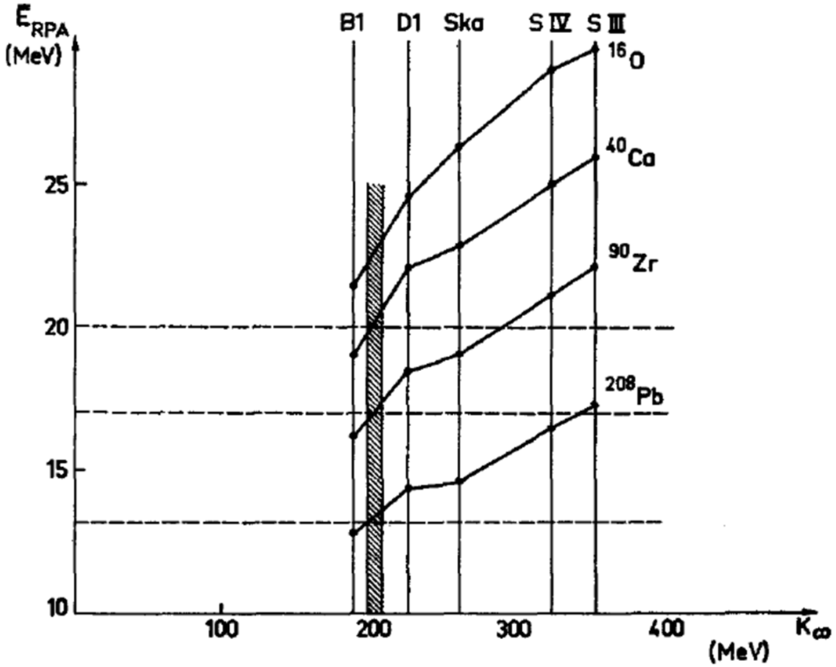
J.P. Blaizot, D. Gogny and B. Grammaticos NPA265 (1976) 315
J.P Blaizot Phys. Rep. 64 (1980) 171

K_∞= 210 ± 30 MeV

Already in 1976

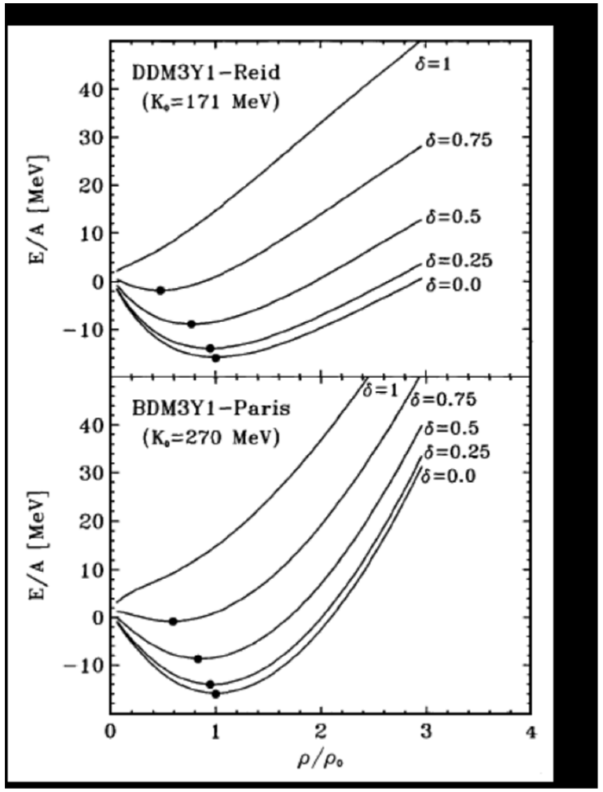
We have not done much better since with some scatter depending on the type of theory (non-relativistic or relativistic)

Colo et al (2004) give K_∞= 240 ± 20 MeV



Dependence on N-Z : K_τ

K_∞ is for symmetric nuclear matter. This is not the case for a neutron star for example. So one wants to measure the dependence on N-Z.

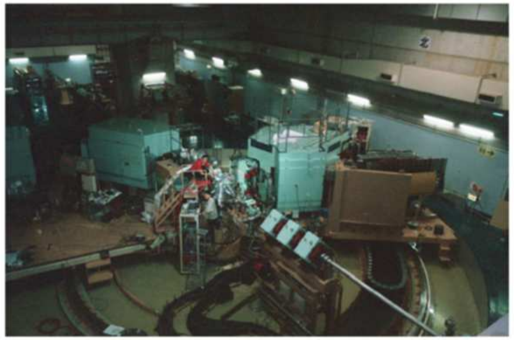


$$K_A - K_{Coul} Z^2 A^{-4/3} \sim K_{vol}(1 + cA^{-1/3}) + K_\tau((N - Z)/A)^2$$

$$\sim \text{Constant} + K_\tau((N - Z)/A)^2$$

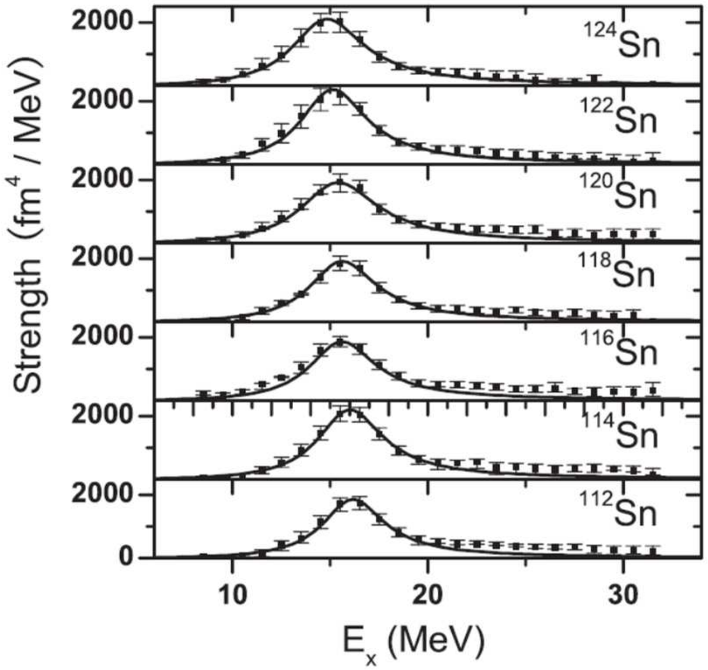
Measure along an isotopic chain

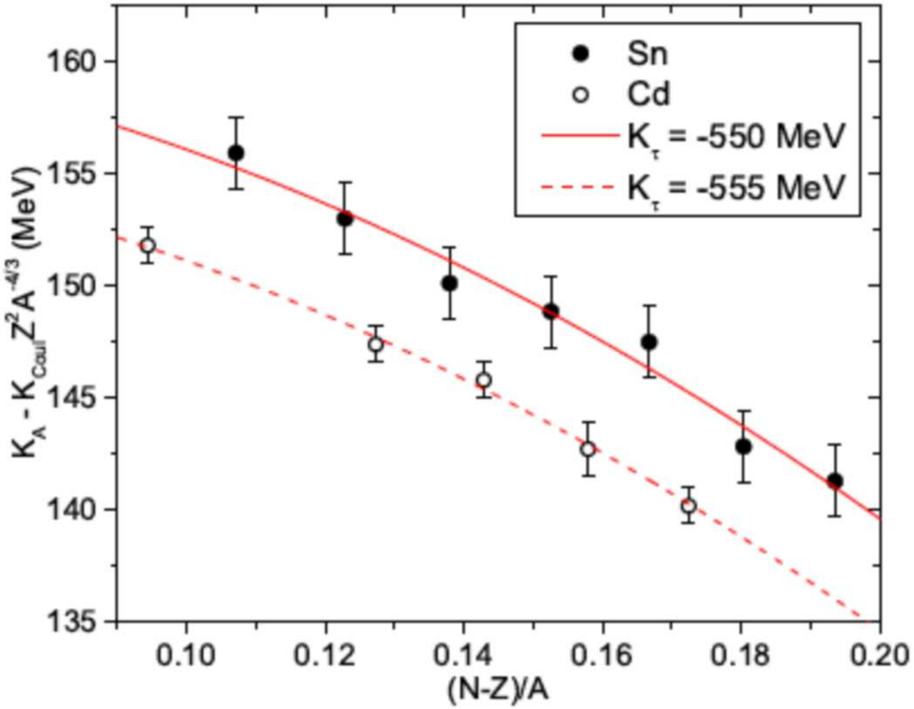
Grand Raiden Osaka



D.T. Khoa et al. NPA602 (1996) 98

Results for Kτ



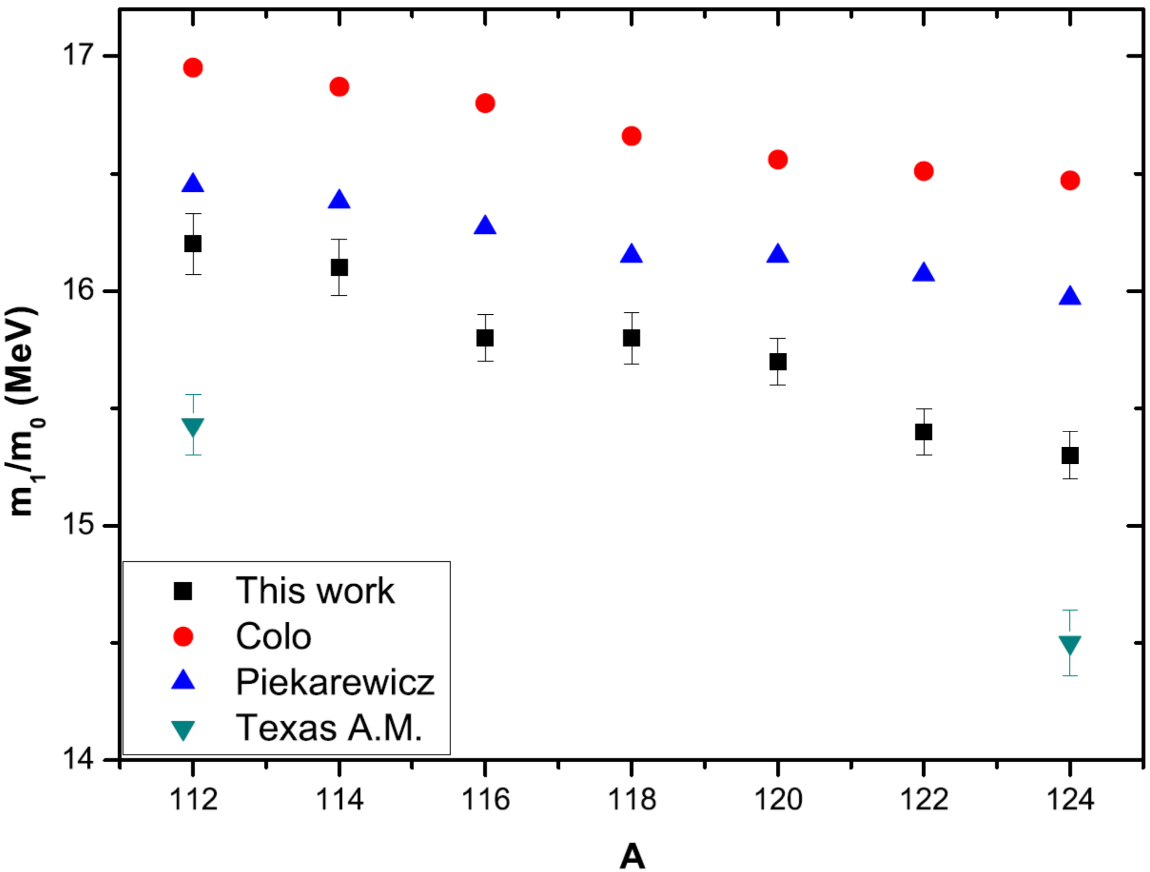


$$K_\tau = -550 \pm 100 \text{ MeV}$$

T. Li, U. Garg et al. PRL 99 (2007) 162503

Why is Sn Fluffy?

Sn Isotopes



U. Garg et al., Nucl. Phys. A788 (2007) 36c

Sn appears less rigid than Pb or Zr!
Gianluca has solved this mystery and
will reveal the solution tomorrow

ZZ.Li, Y.F.Yu and G. Colò, PRL131 082501 (2023)

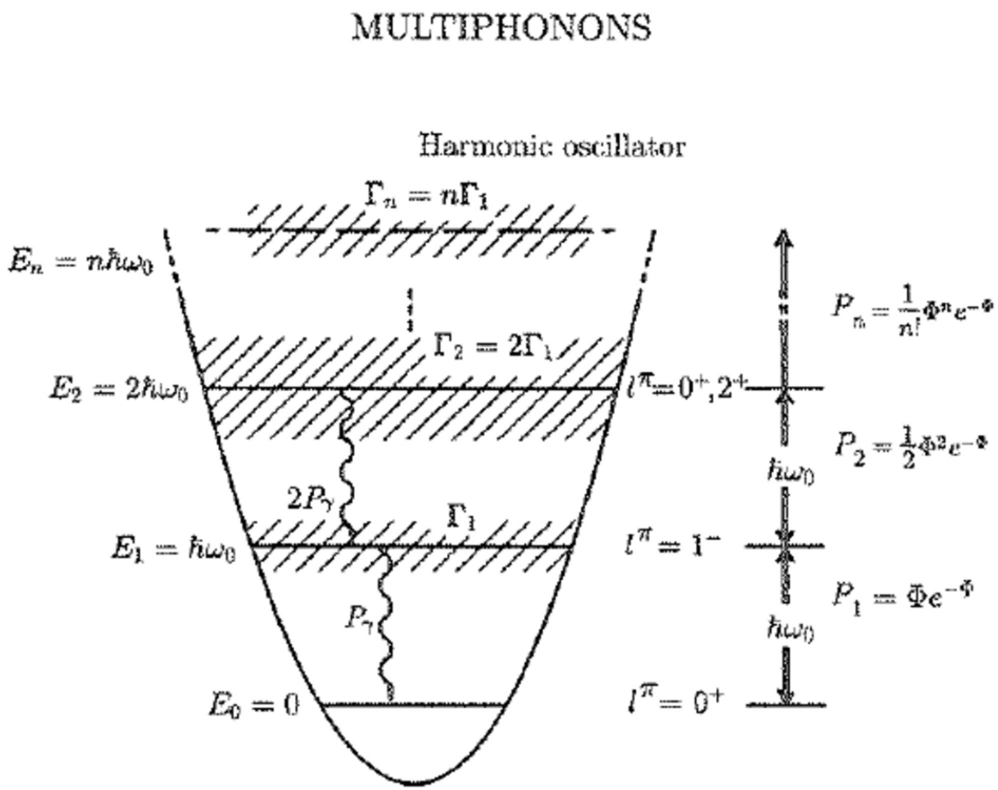
Brink-Axel Hypothesis

- A GR can be built on any excited state and its characteristics do not depend on the detailed microscopic structure of this state (D.M. Brink PhD thesis Oxford 1955; P. Axel Phys. Rev. 126 (1962) 671)
- In the following we will investigate
  - GRs built on another GR (multiphonon states)
  - GRs built on equilibrated compound nuclear states (GRs in hot nuclei)

Multiphonon Giant Resonances

- GRs are small amplitude vibrations so expected to be harmonic.
- In quantum mechanics they can be considered as phonons so multiphonon states are possible
- In the harmonic picture
  - $E_{2p} = 2\ E_{1p}$
  - $\sqrt{2}\ \Gamma_{1p} < \Gamma_{2p} < 2\ \Gamma_{1p}$
  - $Prob_{2p} = (Prob_{1p})^2/2$
- To observe the 2-phonon state a large cross section for the GR is necessary

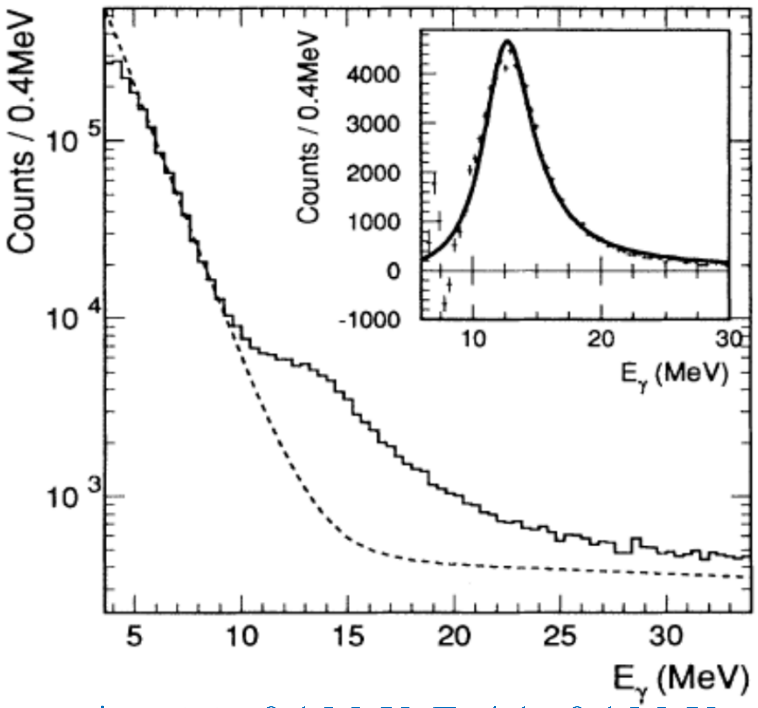
→ High Energy Heavy Ion collisions.



Double GDR @GSI: Coulex

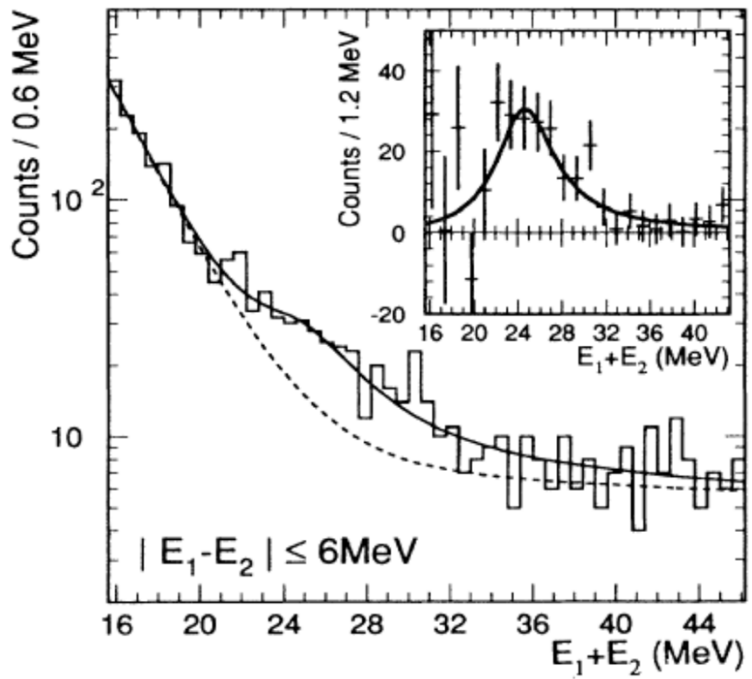
$^{209}Bi + ^{208}Pb$ @ 1 GeV/u

One photon – one phonon



E* = 13.3 ±0.1 MeV; Γ=4.1 ±0.1 MeV

Two photons – Two phonons



E* = 25.6 ±0.9 MeV; Γ=5.8 ±1.1 MeV

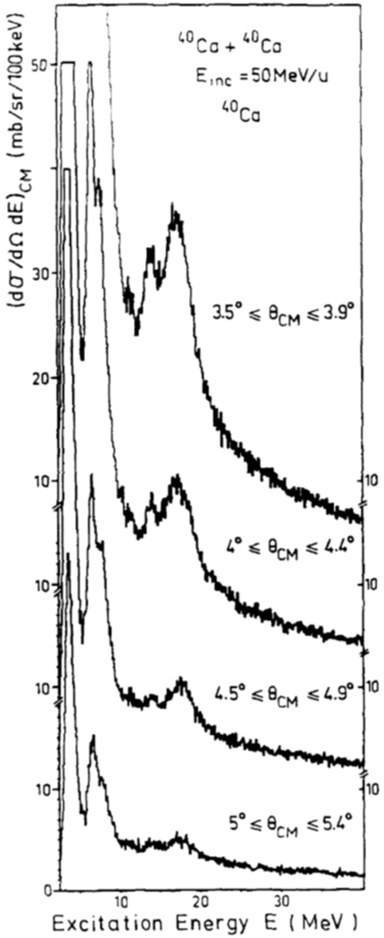
J. Ritman et al.,PRL 70 (1993) 533

Double GQR @GANIL: Nuclear Excitation

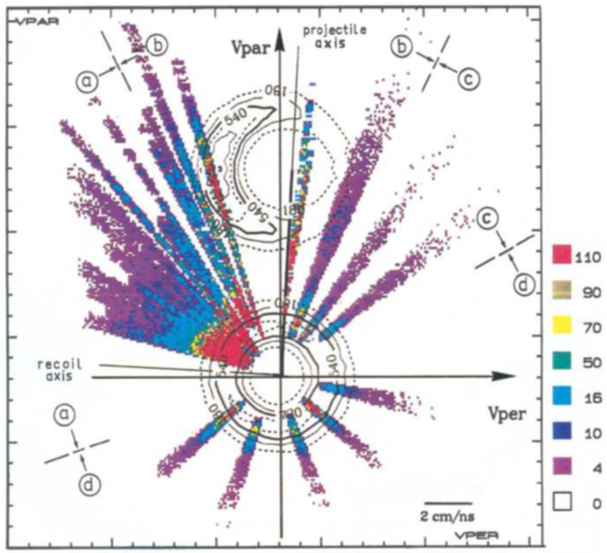
Singles

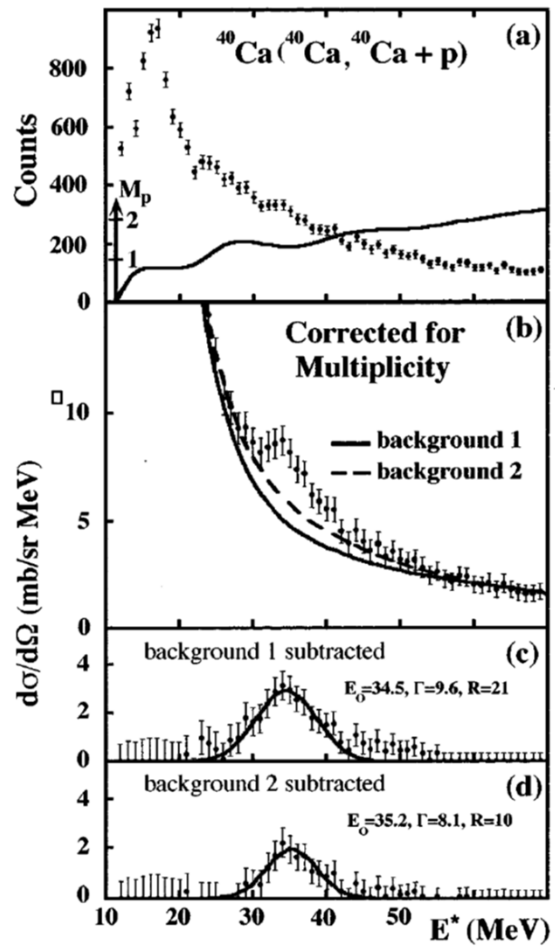
$^{40}Ca + ^{40}Ca$ @50 MeV/u

Coincidences with backward emitted protons



Proton Cross Section





J. A. Scarpaci et al. PLB 258 (1991) 279;
PRL 71 (1993) 3766

Multiphonons

- The characteristics of multi-phonon states show that GRs are remarkably harmonic
- The double GMR would be of great interest since it would have higher compression that the GMR, unfortunately it has never been observed.

Hot GRs

- GRs built on equilibrated compound nucleus states
- Excited in heavy ion fusion reactions
- Measured through their γ decay so restricted to the IVGDR
- Follow their characteristics as a function of excitation energy or temperature

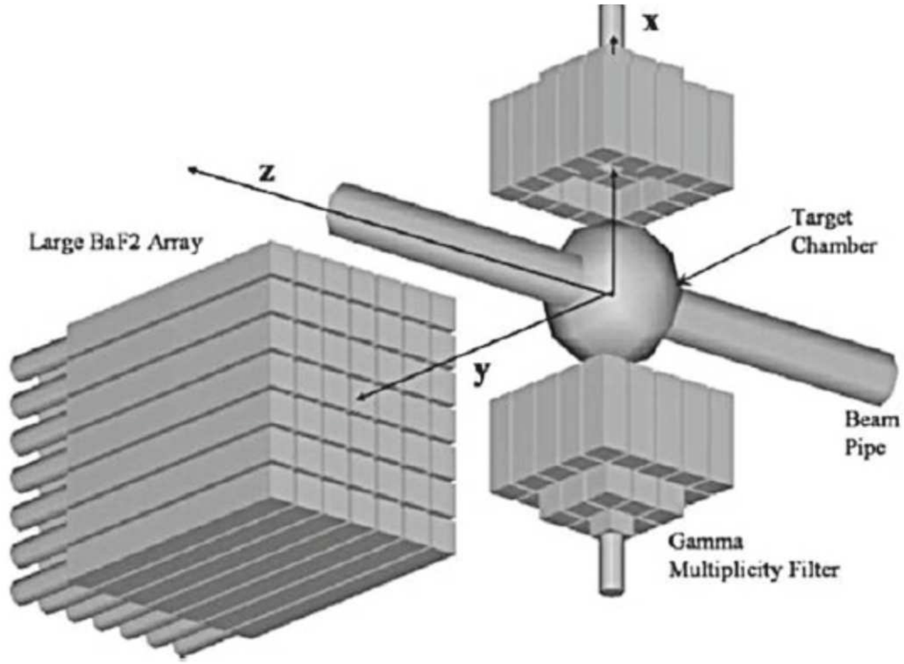
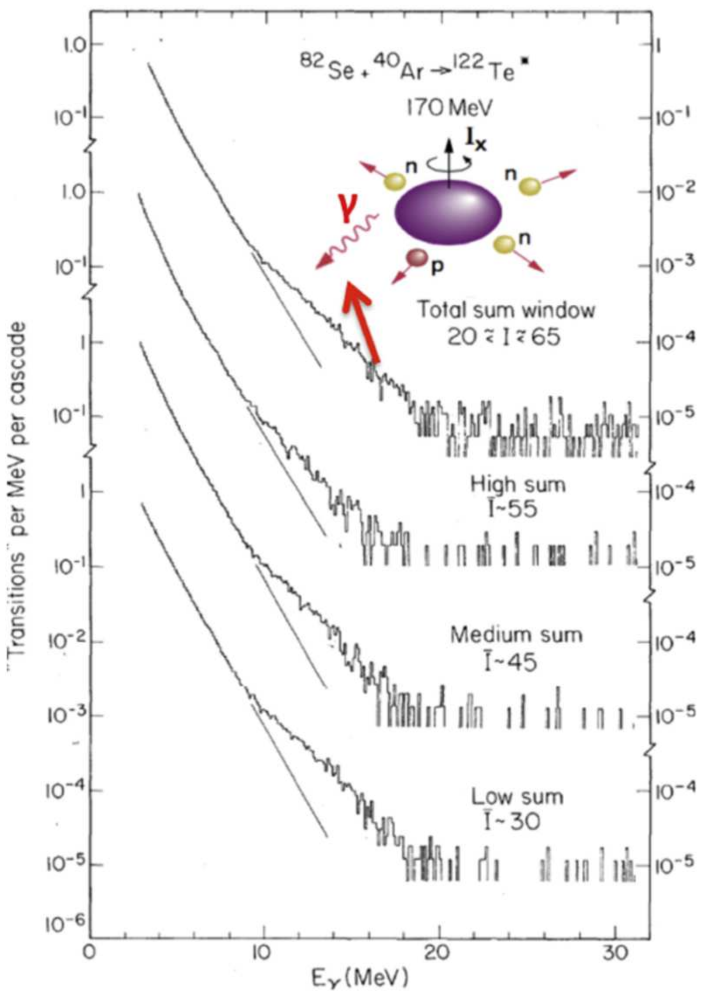


Fig. 1 Schematic view of the experimental setup for the LAMBDA spectrometer in a 7×7 matrix arrangment along with the low energy γ-ray multiplicity filter [21]

Recent Review: D. Santonocito and Y.B., Eur. Jour. Phys. A56 279 (2020)

Typical high energy γ spectra



J.O. Newton et al, PRL46 (1981) 1383

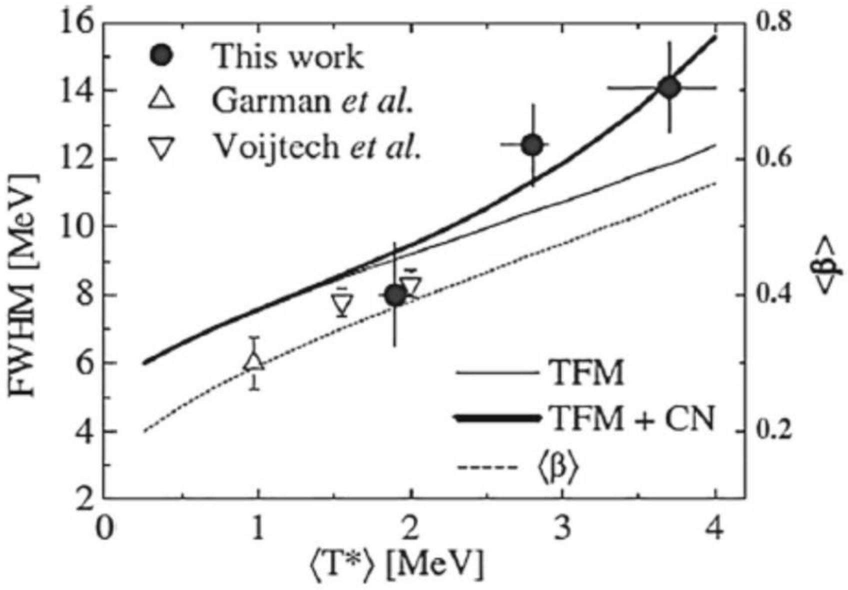
$$f_{\mathrm{GDR}}(E_\gamma) = \frac{4e^2}{3\pi\hbar mc^3}\frac{NZ}{A} \times \sum_{i=1}^{3} \frac{S_i \Gamma_i E_\gamma^4}{(E_\gamma^2 - E_i^2)^2 + E_\gamma^2 \Gamma_i^2}$$

$$T = \left[\frac{(E^* - E_{\mathrm{rot}} - E_{\mathrm{GDR}})}{a}\right]^{1/2}$$

GDR Characteristics as a Function of Temperature and Spin at Moderate Temperature

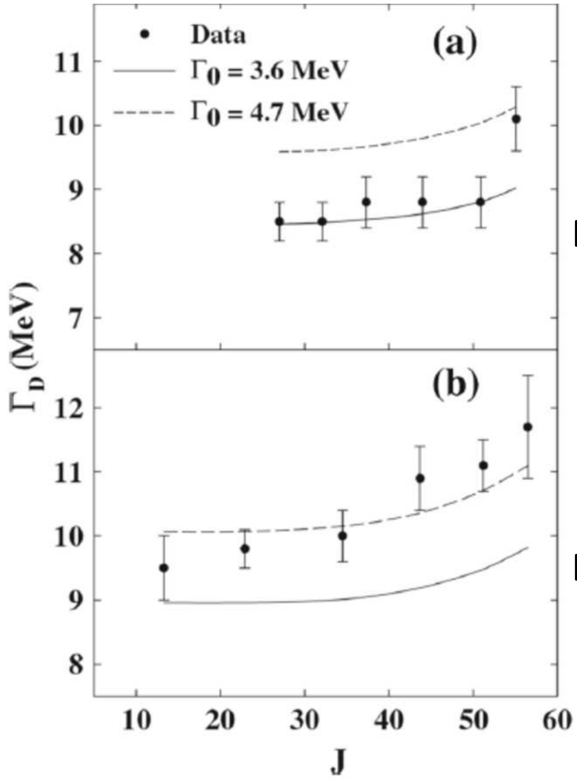
Thermal Fluctuation Model

$^{64}Ni + ^{68}Zn$



O. Wieland et al., PRL97 012501 (2006)

$^{28}Si + ^{124}Sn$



E_{beam} = 149 MeV

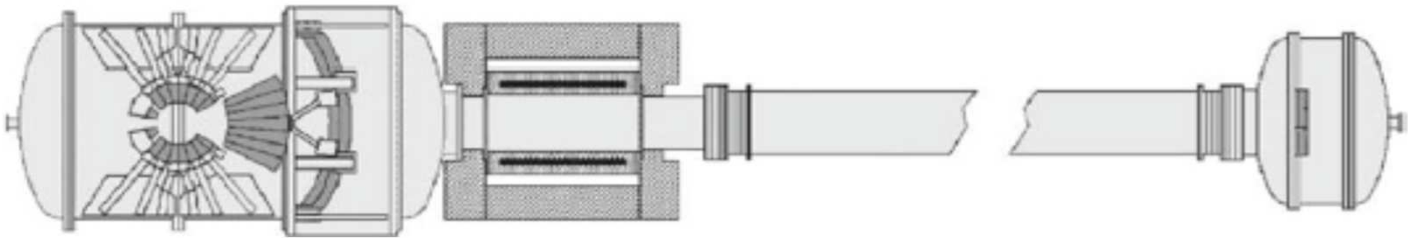
E_{beam} = 185 MeV

D.R.Chakrabarty et al. JPhysG 37 055105 (2010)

GDR Quenching at High Temperatures

- Higher beam energies > 15 MeV/u → Incomplete fusion
- Characterize the compound nucleus → Measure evaporation residues and light particles

MEDEA – SOLE setup @ LNS Catania, Sicily



Proton Spectra

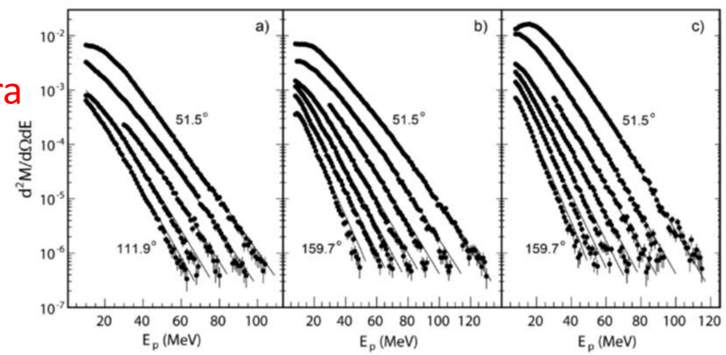


FIG. 4: Proton spectra detected with MEDEA in coincidence with evaporation residues in the reactions (a) ^{116}Sn+^{12}C at 17A MeV, (b) ^{116}Sn+^{12}C at 23A MeV, (c) ^{116}Sn+^{24}Mg at 17A MeV. The solid lines are the result of the moving source fit described in the text.

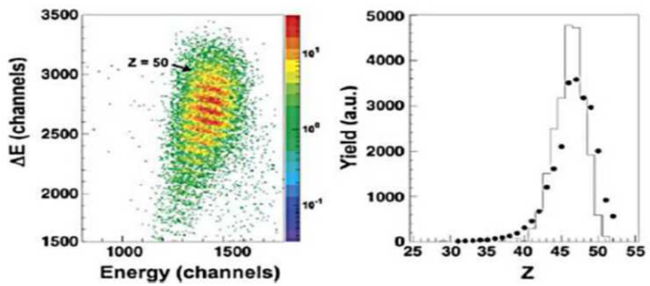


Fig. 6 Left: ΔE–E plot of evaporation residues from ^{116}Sn + ^{24}Mg at 23A MeV; right: Z distribution (points) compared to statistical GEMINI++ calculation using inputs determined as described in text (from Ref. [29])

Evaporation residues

GDR Quenching for A~130

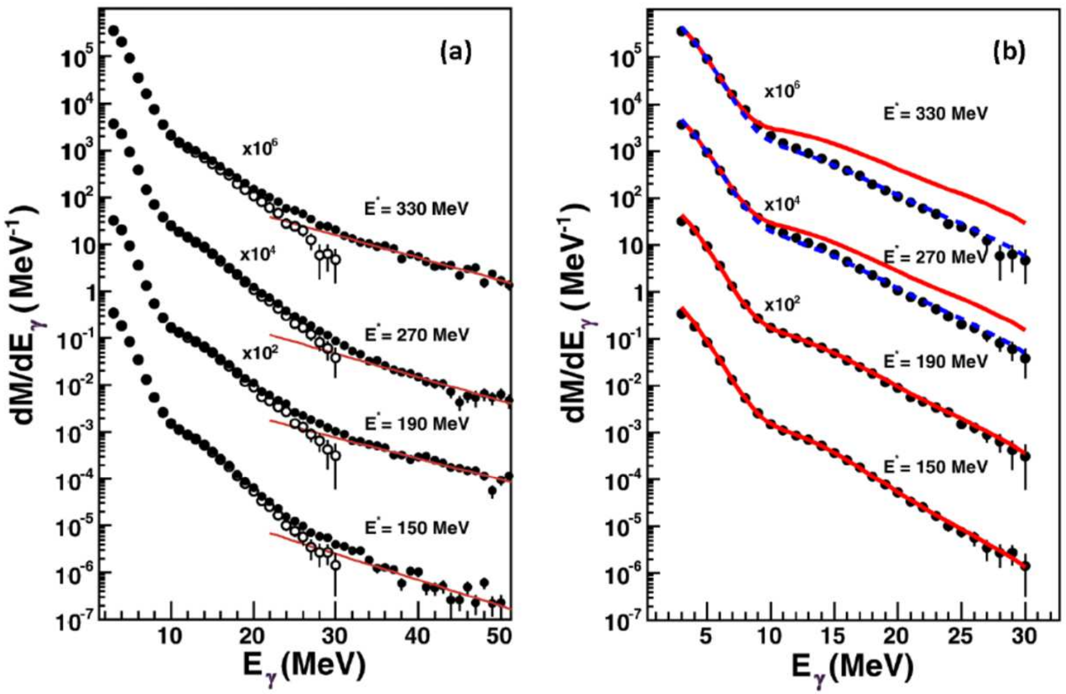
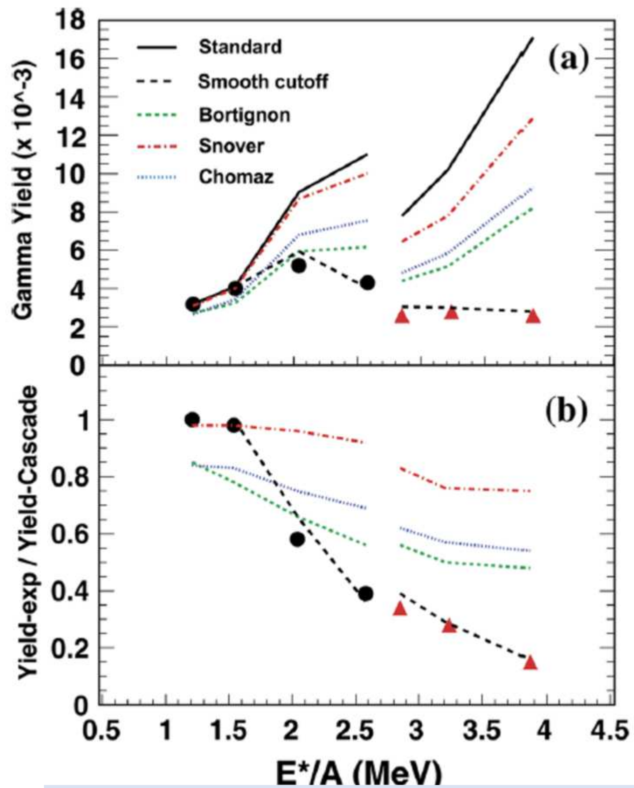
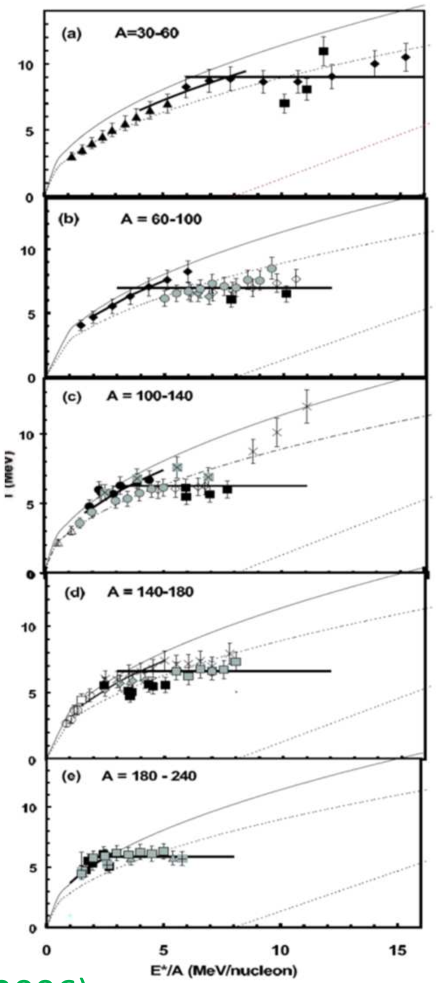


Fig. 1. a) Gamma-ray energy spectra measured at 83^o and 97^o for all the reactions investigated. Red full lines represent the fit of the bremsstrahlung component while open symbols show the gamma spectra after bremsstrahlung subtraction. b) Comparison of the statistical gamma spectra with DCASCADE calculations shown as red full lines. Sharp cut-off calculations, performed at $E^* = 270$ and $E^* = 330$ MeV are indicated as blue dashed lines [25].



GDR cutoff
E*~230 MeV; T~4 MeV

Is the GDR quenching linked to the Liquid-Gas phase transition?



curves for five selected regions of mass.
1].

A.Kelic et al.
EPJ A30 203 (2006)

Limiting Temperatures

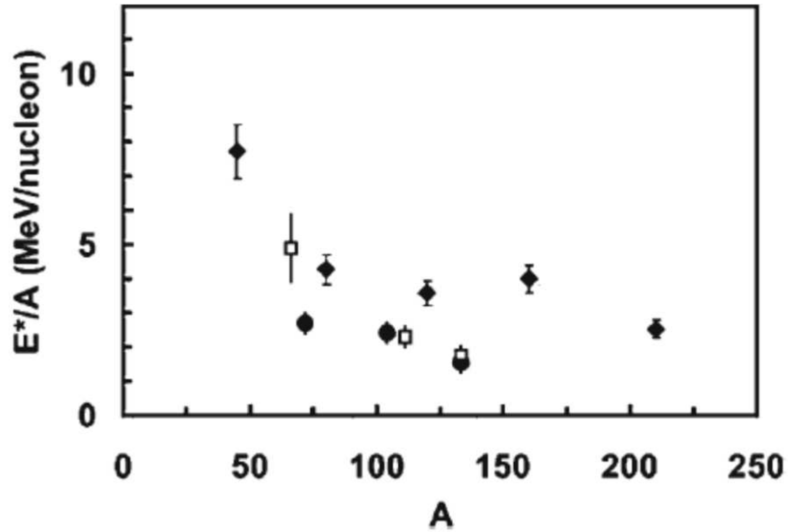


Fig. 25 Values of excitation energies per nucleon at which the plateau in the nuclear caloric curve sets in, shown as full diamonds, are compared to the limiting excitation energy for the collective motion as a function of the system mass. MEDEA and TRASMA data are shown as open squares while RIKEN data are shown as full circles

A Word of Conclusion

- GRs have been a central theme of Nuclear Physics since 75 years.
- Their understanding involves nuclear structure, nuclear dynamics, nuclear reactions and has prompted many instrumental developments
- They have fascinated experimentalists and theorists alike
- And the story is far from over as we will learn this week…

Thank you for your attention