Outline

Lecture I: Giant Resonances (GR) – Introduction

Phenomenology, properties, main facts
Classification schemes
Theoretical description – concepts
What we (might) learn form GR's
History – milestones
Tools (reactions) for GR excitation

Lecture II-IV: Giant Resonances – selected topics

Spin-flip resonances : Gamow-Teller puzzle
Isoscalar GMR and GDR : nuclear matter (in)compressibility

Multi-phonon Giant Resonances

Multipole Strength in (neutron-rich) 'exotic' nuclei
- Pygmy resonances, soft modes
- Symmetry energy
- Neutronstar – neutronskin and pygmy

Outlook

Outline

I. exp. tools/reactions for GR studies

not discussed: experimental techniques

II. selected topics / results *(1990 -- 2000 -- 2010)*

Today:

- puzzle of missing Gamow-Teller strength

- Isoscalar Giant Monopole Resonance &
isoscalar Giant Dipole Resonance
and the nuclear (in)compressibility

I. tools/reactions for GR studies

remember :
We'd like to have probes being selective
with regard to
multipolarity, spin- , and isospin-transfer
($\Delta L, \Delta S, \Delta T$)

notice: strength distributions of various modes
overlap in excitation energy to large extent,
Only selective probes allow to disentangle !

Microscopic classification of giant resonances

	$\Delta S = 0$ $\Delta T = 0$	$\Delta S = 0$ $\Delta T = 1$	$\Delta S = 1$ $\Delta T = 0$	$\Delta S = 1$ $\Delta T = 1$
$L = 0$		$\sum \tau_i$ IAS		$\sum \vec{\sigma}_i \tau_i$ GTR
Second order	$\sum r_i^2$ ISGMR	$\sum r_i^2 \tau_i$ IVGMR	$\sum r_i^2 \vec{\sigma}_i$ ISSMR	$\sum r_i^2 \vec{\sigma}_i \tau_i$ IVSMR
$L = 1$		$\sum r_i Y_m^1 \tau_i$ IVGDR	$\sum r_i Y_m^1 \vec{\sigma}_i$ ISSDR	$\sum r_i Y_m^1 \vec{\sigma}_i \tau_i$ IVSDR
Second order	$\sum r_i^3 Y_m^1$ ISGDR			
$L = 2$	$\sum r_i^2 Y_m^2$ ISGQR	$\sum r_i^2 Y_m^2 \tau_i$ IVGQR	$\sum r_i^2 Y_m^2 \vec{\sigma}_i$ ISSQR	$\sum r_i^2 Y_m^2 \vec{\sigma}_i \tau_i$ IVSQR
$L = 3$	$\sum r_i^3 Y_m^3$ ISGOR	$\sum r_i^3 Y_m^3 \tau_i$ IVGOR	$\sum r_i^3 Y_m^3 \vec{\sigma}_i$ ISSOR	$\sum r_i^3 Y_m^3 \vec{\sigma}_i \tau_i$ IVSOR

Selective Probes : Photoabsorption

i.e., standard tool for ivGDR

Consider a 10 MeV gamma-ray

- as a wave: wavelenght ≈ 100 fm
  compare to nucl. radius ~ 10 fm
  ==> nucleus essentially feels a dipole field

- as a photon: orbital angular momentum ≤ 0.25 ħ
  but photon spin = 1ħ ==> dipole exc.
  and ΔT = (0), 1

==> ideal, i.e., very selective probe for ivGDR excitation
and, moreover, since photon is a pure electromagnetic probe,
the transition operator is well understood

other electromagnetic probes: VIRTUAL Photons

Low-energy (< $E_{c.b.}$) HI-Coul. Exc. → rotational states, surface vibrations

see P. Reiter

Relativistic Heavy-Ion Coulomb Excitation ==> (multiple) GDR

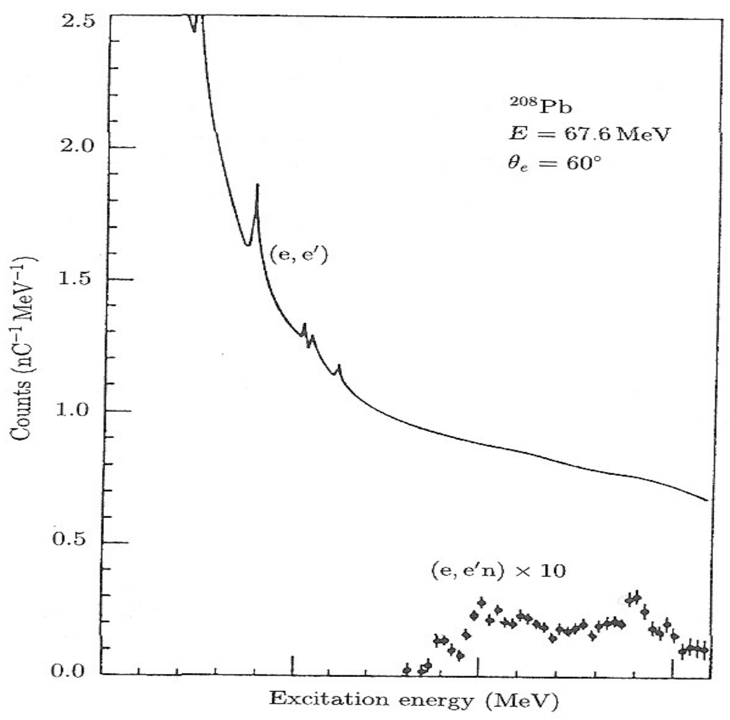
(see T. Aumann and below)

Inelastic Electron Scattering

- well-known electromagnetic interaction
- multi-step excitations negligible
- form factor $F_L(q)$ depends strongly on L *(q = momentum transfer)*

Disadvantages:

- *bremsstrahlung radiation 'tail'* → *requires coincidence measuremen*
- *not selective*



inelastic electron scattering

PWBA:

$$d\sigma / d\Omega = \sigma^{Mott} / \eta \cdot [\,|F^C(q)|^2 + (\tfrac{1}{2} + \tan(\vartheta/2)) \cdot (|F^E(q)|^2 + |F^M(q)|^2)]$$

Charge — *longitudinal*

Electric — *Magnetic* — *transversal*

longitudinal form factor $F^C(q)$

interaction of virtual photons longitudinally polarized with respect to momentum transfer ***q***

transverse form factors $F^E(q)$, $F^M(q)$

interaction of virtual photons polarized perpendicular to ***q***

Rosenbluth separation method

Measurements at various angles and electron energies (keeping q constant)

Spin-flip transitions at backward scattering angles

(~ relativistic electron => spin ‖ momentum => helicity conservation)

Selective probes: isoscalar non-spin-flip

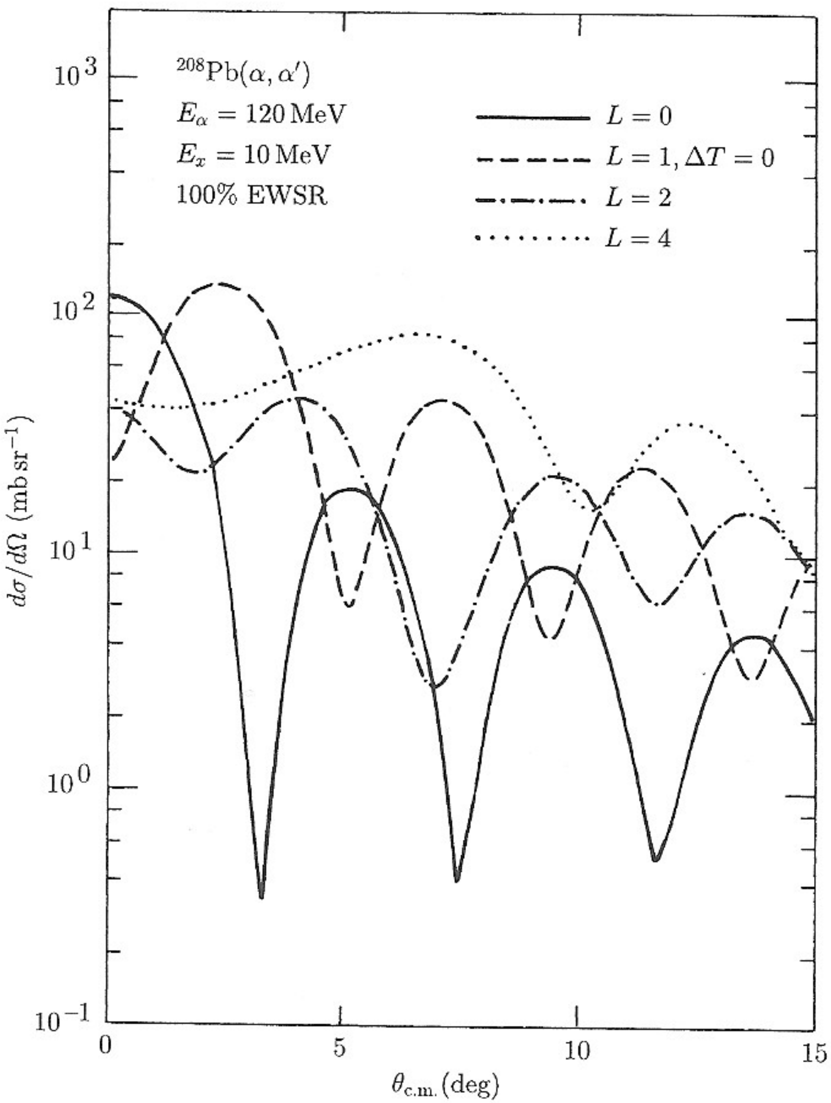
<u>Inelastic α scattering</u>

T = 0 => isoscalar excitations
(except Coulomb exc.)

S = 0 => non-spin-flip

i.e., for a $J^\pi = 0^+$ g.s. nucleus :

J^π_{final} = ΔL *with* **$\pi = (-1)^{\Delta L}$**



. 3.1. DWBA predictions for the differential cross sections corresponding to various multipolarities exhausting 100% of the EWSR for ^{208}Pb for inelastic α scattering at 120 MeV

Note the strong Δ L = 0 excitation at 0°
=> isoscalar monopole resonance isGMR

strongly interacting probes

Inelastic proton scattering

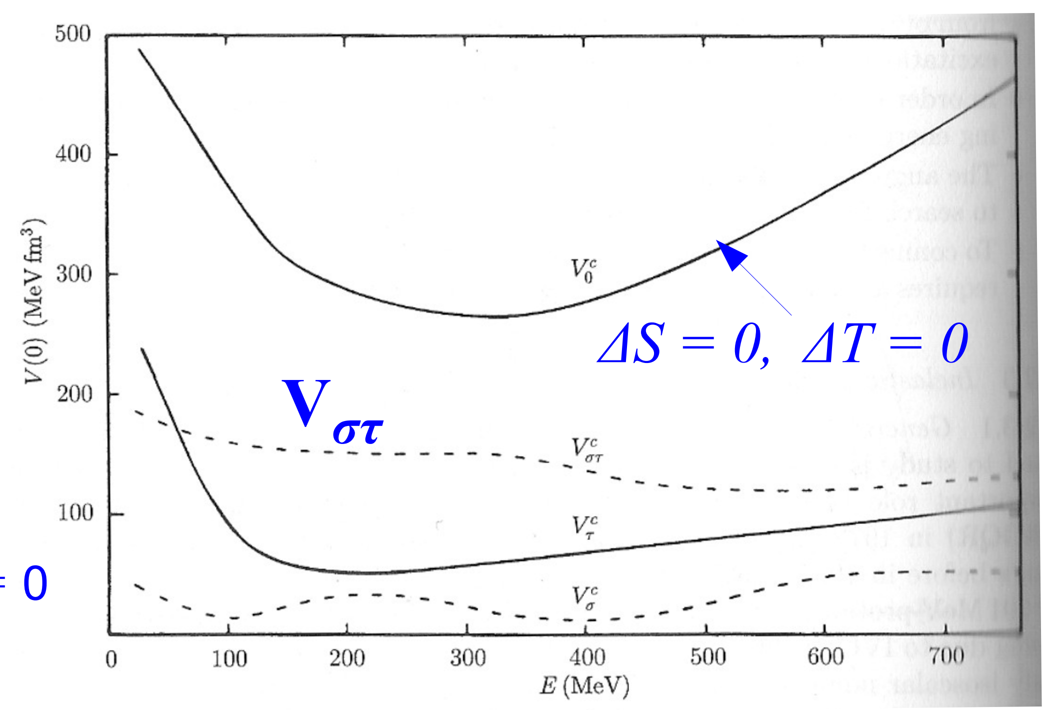
(discovery of isoscalar GQR)

S = ½ , T = ½ => ΔS = 0,1 and ΔT = 0,1

but ΔS = 0, ΔT = 0 predominant at low q

Inelastic heavy ion scattering

(similar properties,
but strong absorption)

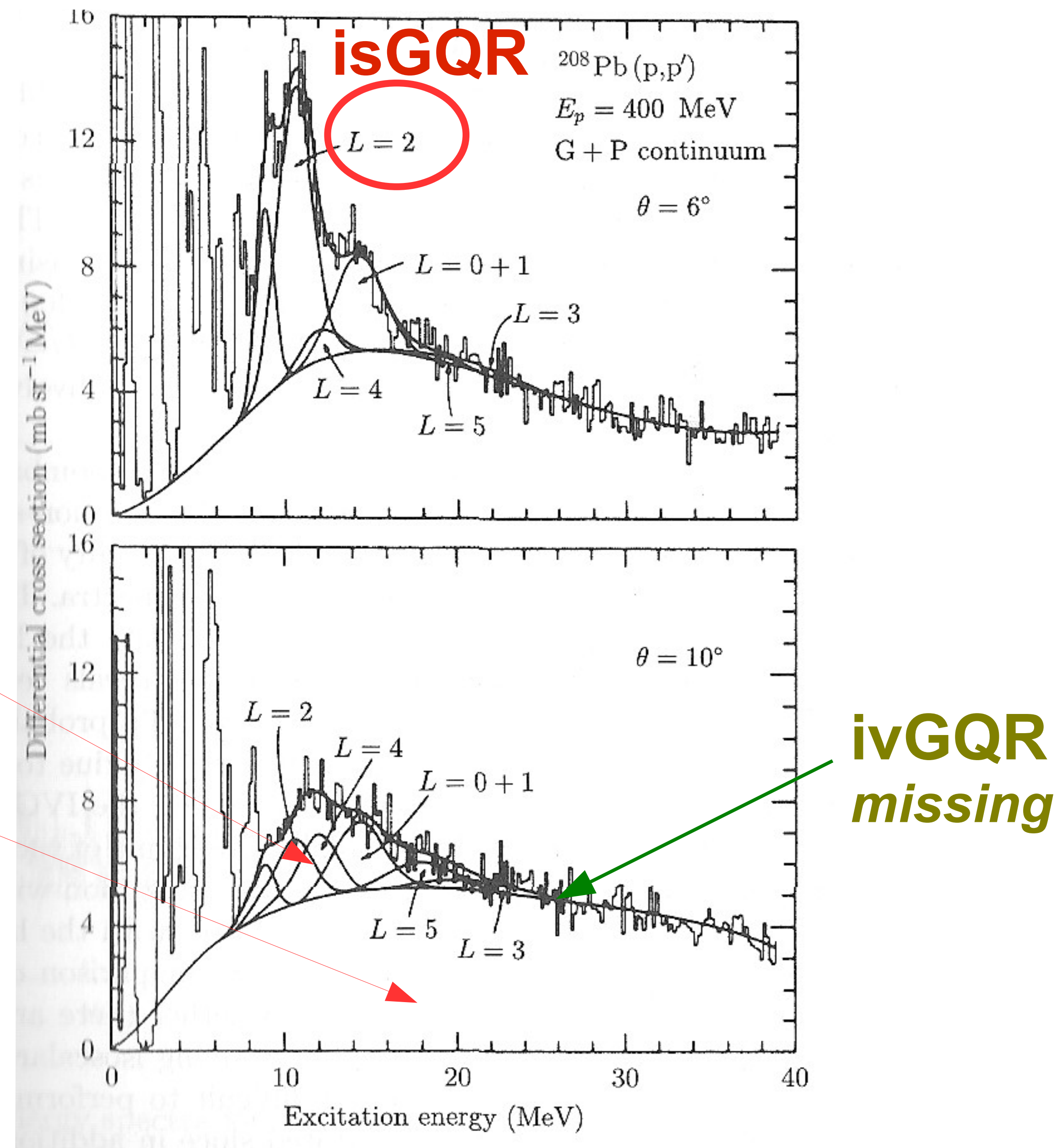


central parts of eff. T-matrix, q = 0

^{208}Pb (p,p')

E_p = 400 MeV

multipole decomposition
+
continuum 'background'



probes - **isovector** non-spin-flip

$\Delta S = 0$, $\Delta T = 1$ studied by electromagnetic probes (see above)

charge-exchange reactions (p,n), (^{3}He,t) ...

$\Delta S = 0$ *and* $\Delta S = 1$

PION charge-exchange reactions (π^+,π^o) , (π^-,π^o)

pion: $S = 0$ *and* $T = 1$

\+ *spin-orbit interaction small at forward sc. angle*

==> *$\Delta S = 0$, $\Delta T = 1$ preferentially*

Problems: secondary beam and π^o detection

(LAMPF , Los Alamos)

isovector $\Delta T = 1$

in product nucleus

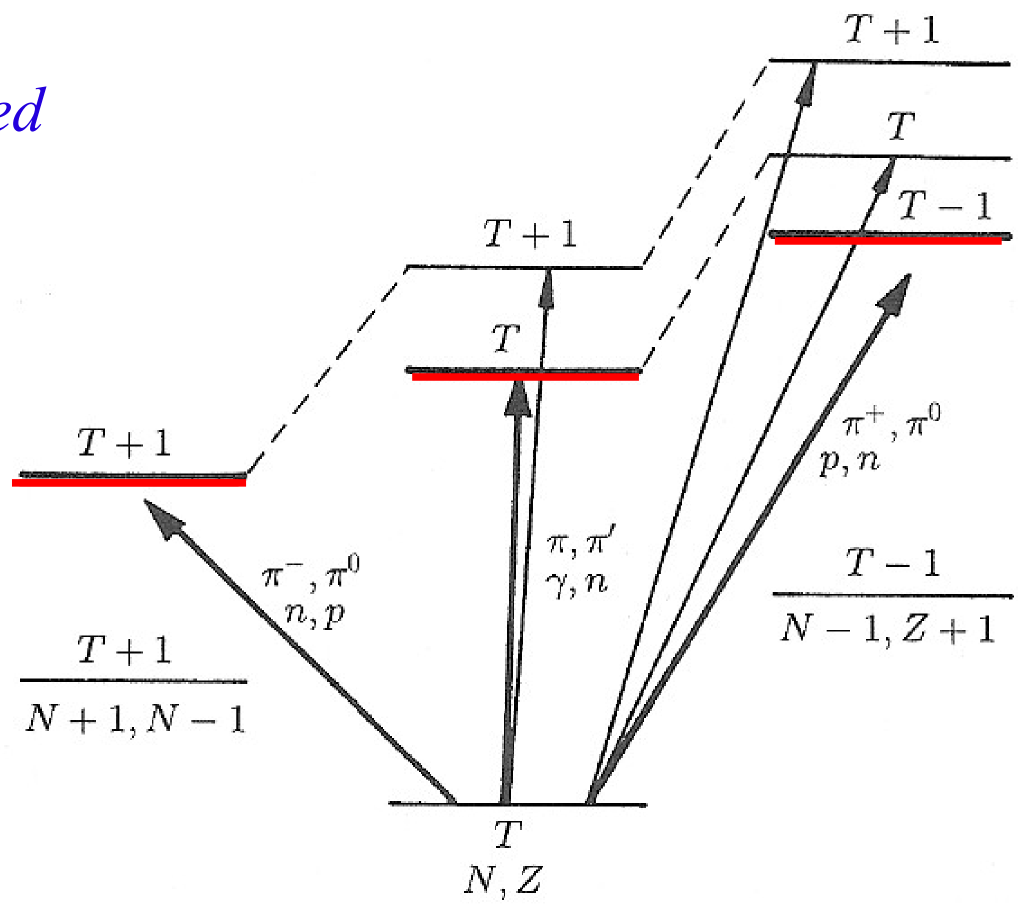
***Isospin Triplett** excited*

(but $T \geq T_z$)

due to Clebsch-Gordan coeff.,

lowest T component (strongly) favored

(heavy nuclei)



spin-flip transitions *(only marginally discussed here)*

Electron scattering (see above)

Inelastic scattering (polarized proton beams)

<u>*Tool for $\Delta T = 1$, $\Delta S = 1$ transitions:*</u>

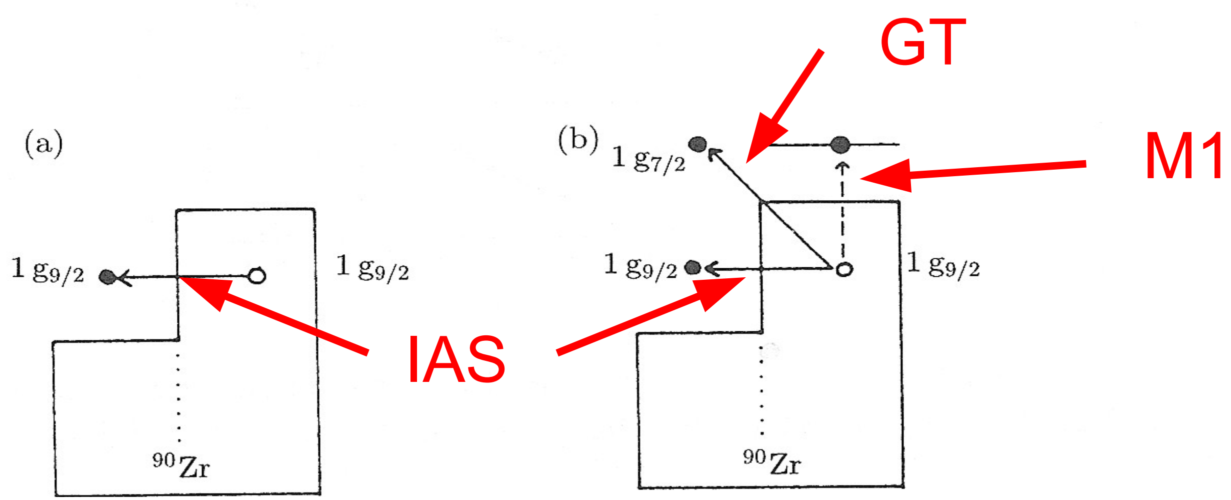
charge-exchange reactions (p,n), (n,p), (^{3}He,t) ...

SPIN-FLIP OR MAGNETIC RESONANCES

Possible low-multipolarity isovector spin-flip transitions.

$\hbar\omega$	ΔL	ΔJ^π	T_z	Name	Status
0	0	1^+	T_0	M1	***
0	0	1^+	$T_0 \pm 1$	Gamow–Teller (GT)	***
1	1	$0^-, 1^-, 2^-$	T_0	M0, E1, M2	*
1	1	$0^-, 1^-, 2^-$	$T_0 \pm 1$	spin-flip dipole	**
2	0	1^+	T_0	M1	?
2	0	1^+	$T_0 \pm 1$	spin-flip monopole	*
2	2	$1^+, 2^+, 3^+$	T_0	M1, E2, M3	?
2	2	$1^+, 2^+, 3^+$	$T_0 \pm 1$	spin-flip quadrupole	*
≥ 3					?

from [HAR01]



II. Giant Resonances – Results

the puzzle of missing Gamow-Teller strenght

Gamow-Teller (GT) resonance – $\Delta L=0$, $\Delta S=1$, $\Delta T=1$

$\rightarrow J_f^{\pi} = 1^+$ (for 0^+ g.s.)

One-body operator: $O^{+-} = \Sigma_i \, \sigma_i \, \tau_i^{+-}$

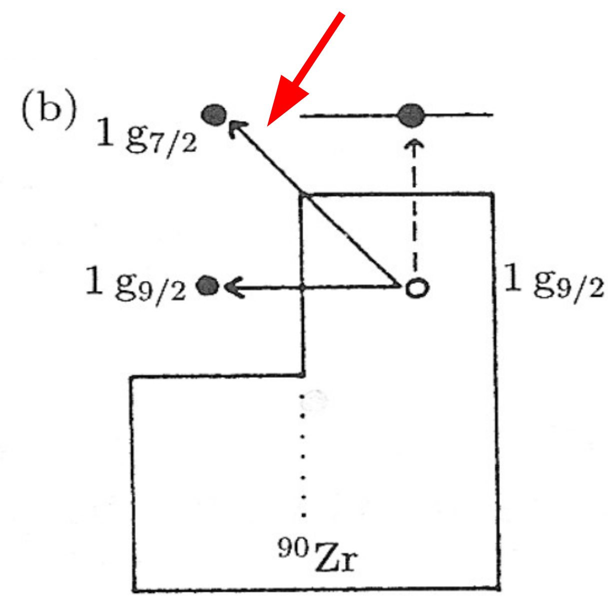
$$\sigma^+ \, | p > \; = \; | n >$$

$$\sigma^- \, | n > \; = \; | p >$$

proton ←→ neutron

equivalent to allowed GT transitions in β-decay, but not restricted in excitation energy

GT



missing GT strength

Gamow-Teller (Ikeda) sum rule: $S_{-}(GT) - S_{+}(GT) = 3(N-Z)$

$S \equiv \Sigma_f < f \mid O^{GT} \mid i >$

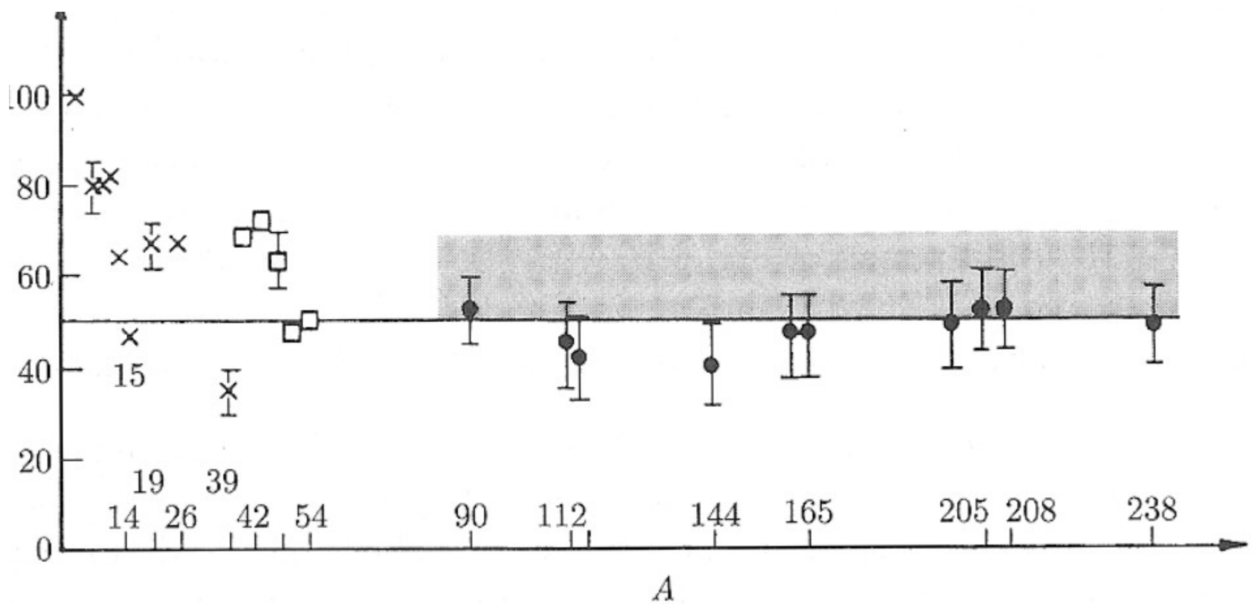
$S_+ : p \rightarrow n$
$S_- : n \rightarrow p$

Model-independent if nucleons are <u>structure less</u>

in heavy nuclei $S_+ = 0$ *because of Pauli blocking !*

missing GT strength

fraction of GT sum rule observed in (p,n) reactions, $E_x \leq 20$ MeV



~ 60 %

[GAA85]

missing GT strength

Explanation - scheme A :

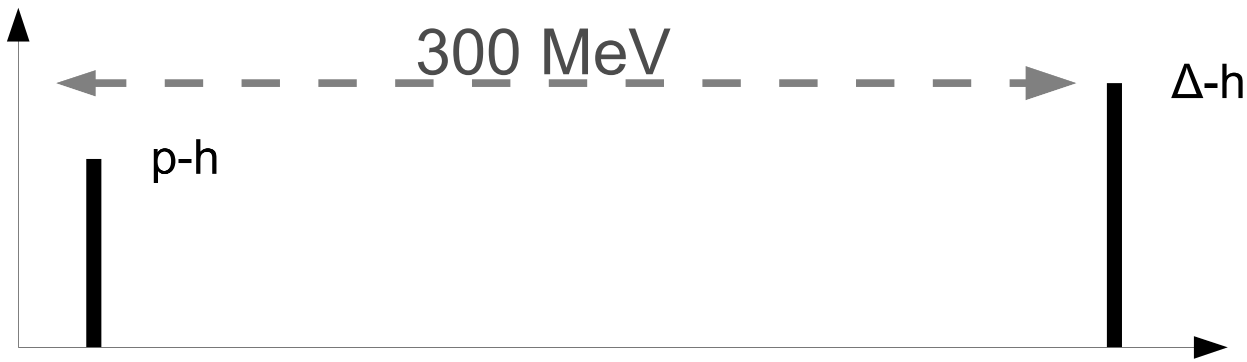
nucleons are not structure less

→ GT strength moved into Δ-Isobar region

n*ucleon N → Δ(1232)* *(quark spin flip)*

i.e. 'ordinary' p-h excitations mixed with Δ-h excitations

~ 300 MeV shift

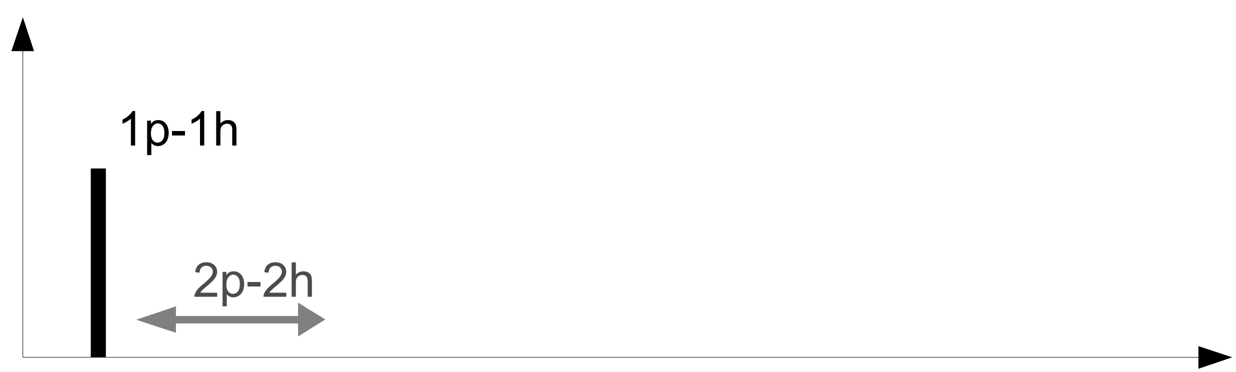


missing GT strength

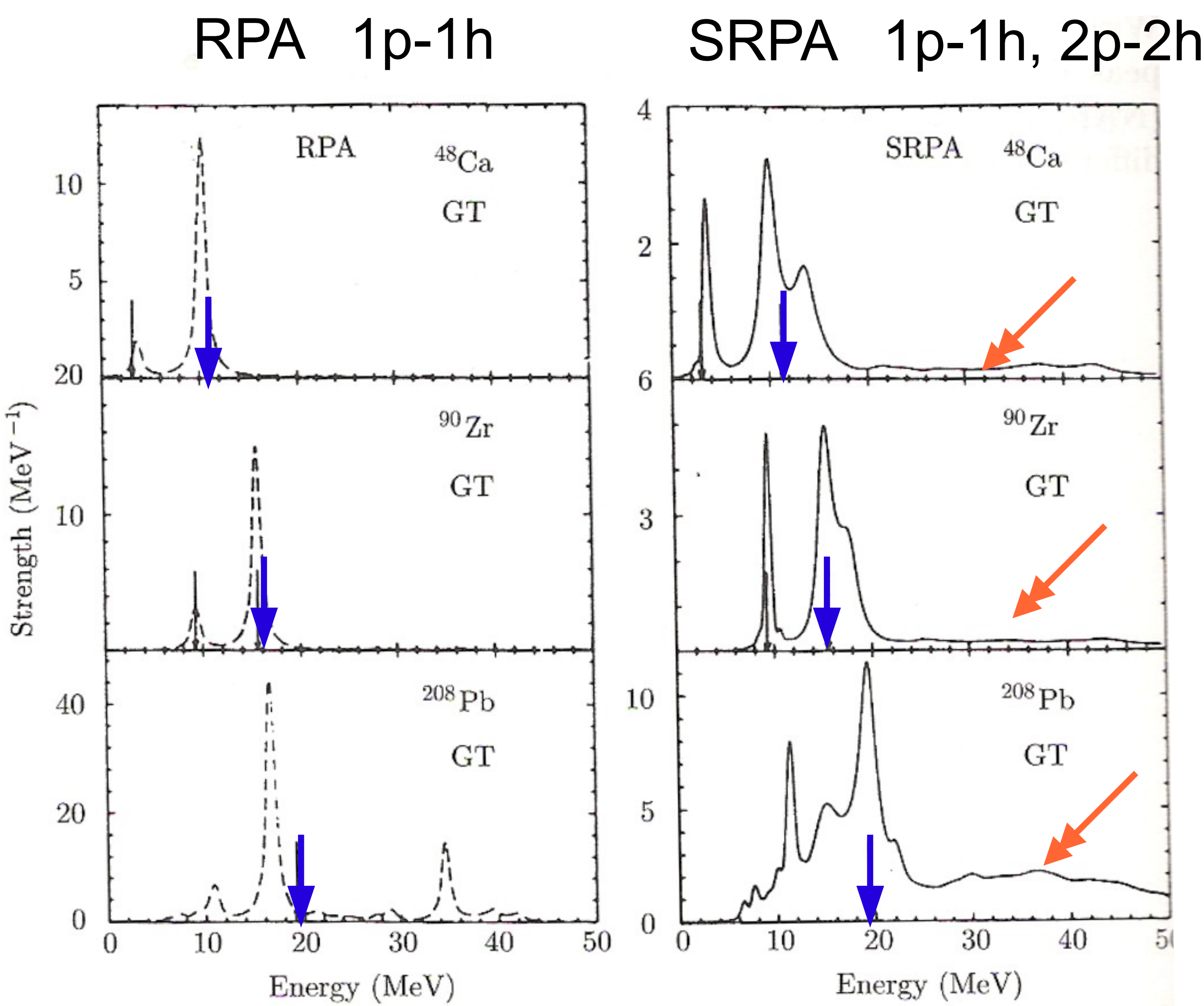
Explanation - scheme B :

1p-1h excitations mixed with 2p-2h

i.e. GT strength partly moved into continuum above GT peak



missing GT strength



[Drozdz et al., PL B189, 27]

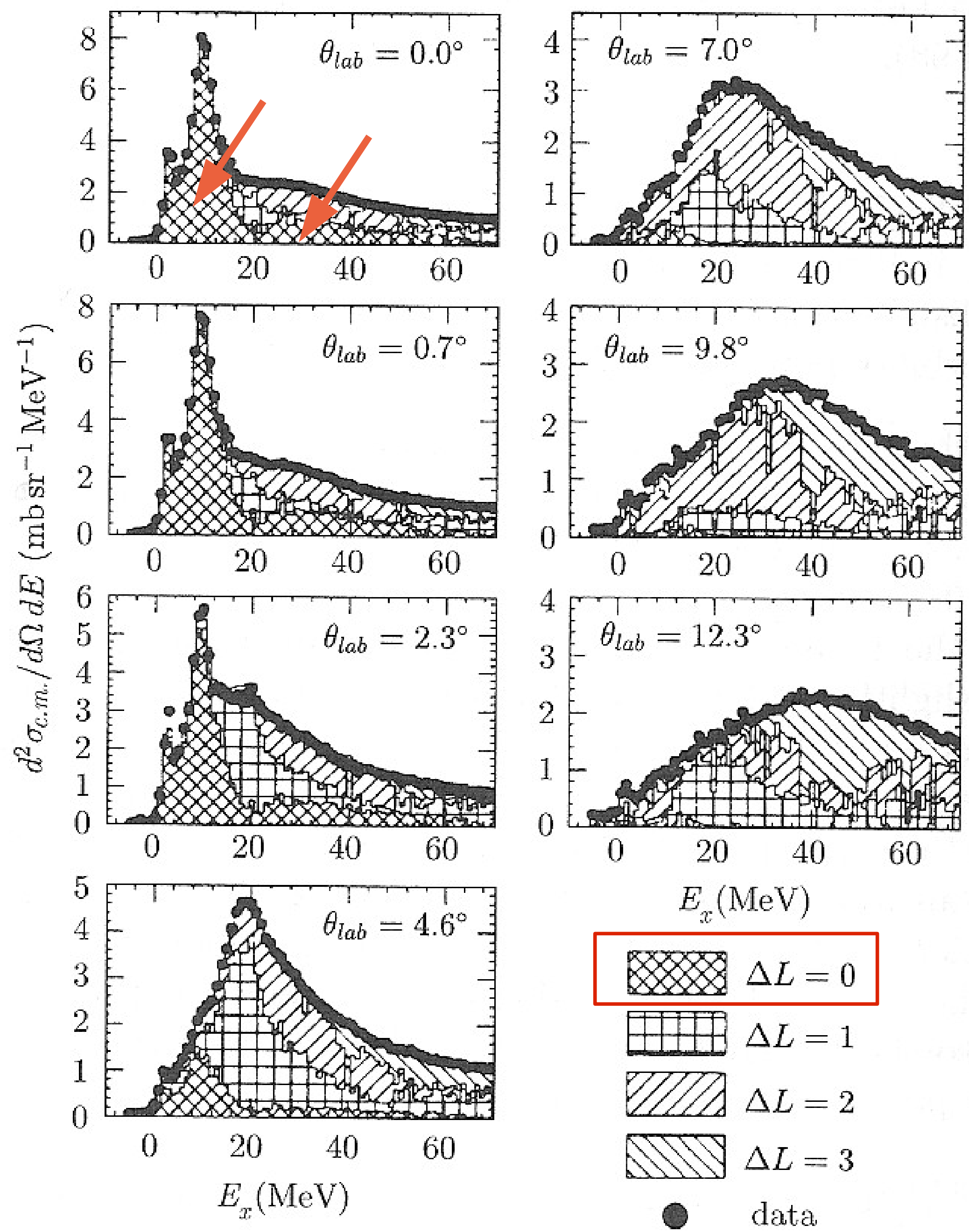
exp. centroid energy

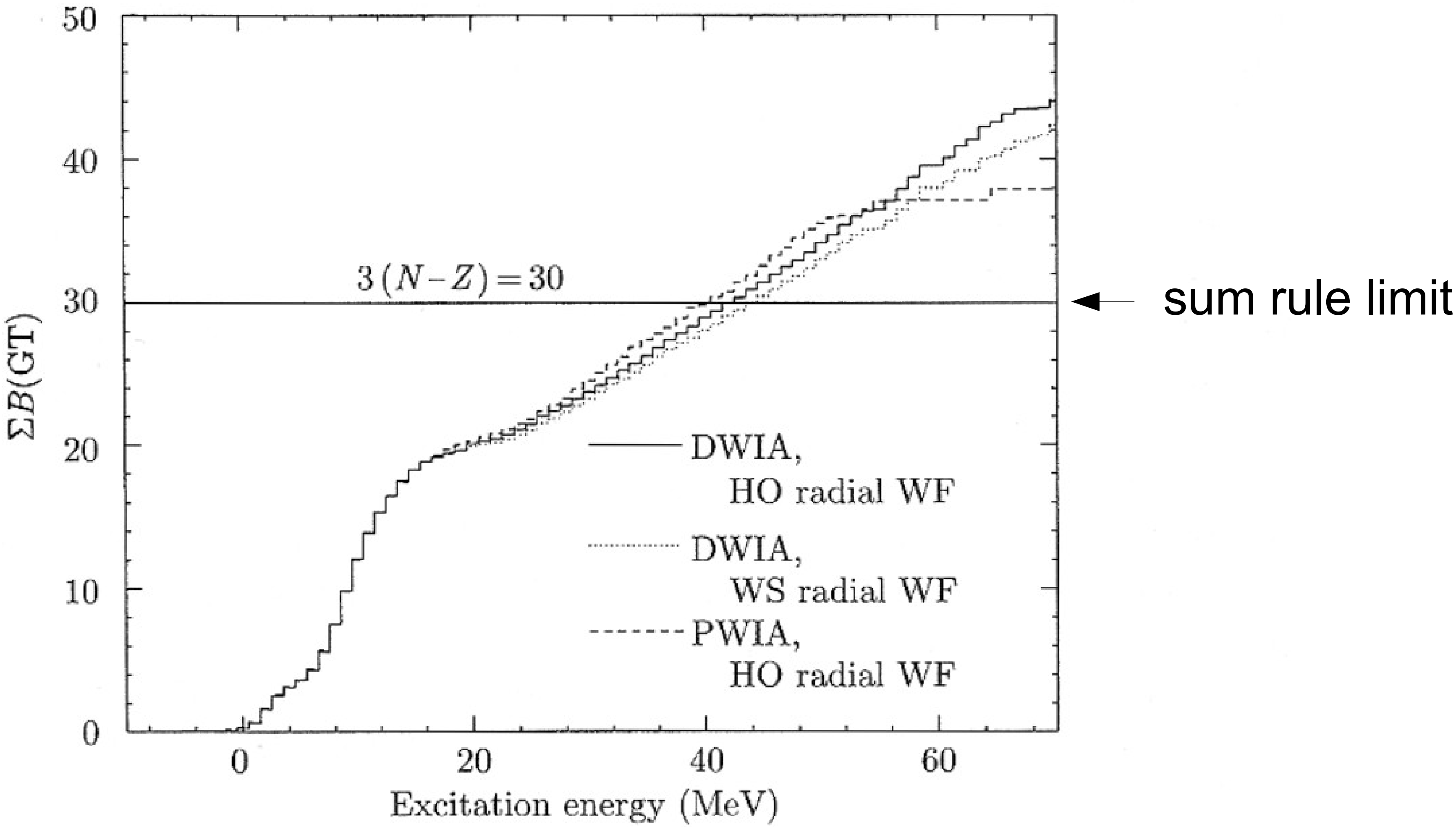
missing GT strength: experimental solution

Multipole Decomposition Analysis (MDA)

Requires high-quality data,

here, $^{90}Zr(p,n)$, E_p *= 200 MeV from [Wakasa et al. , PRC 55, 2909], Osaka*

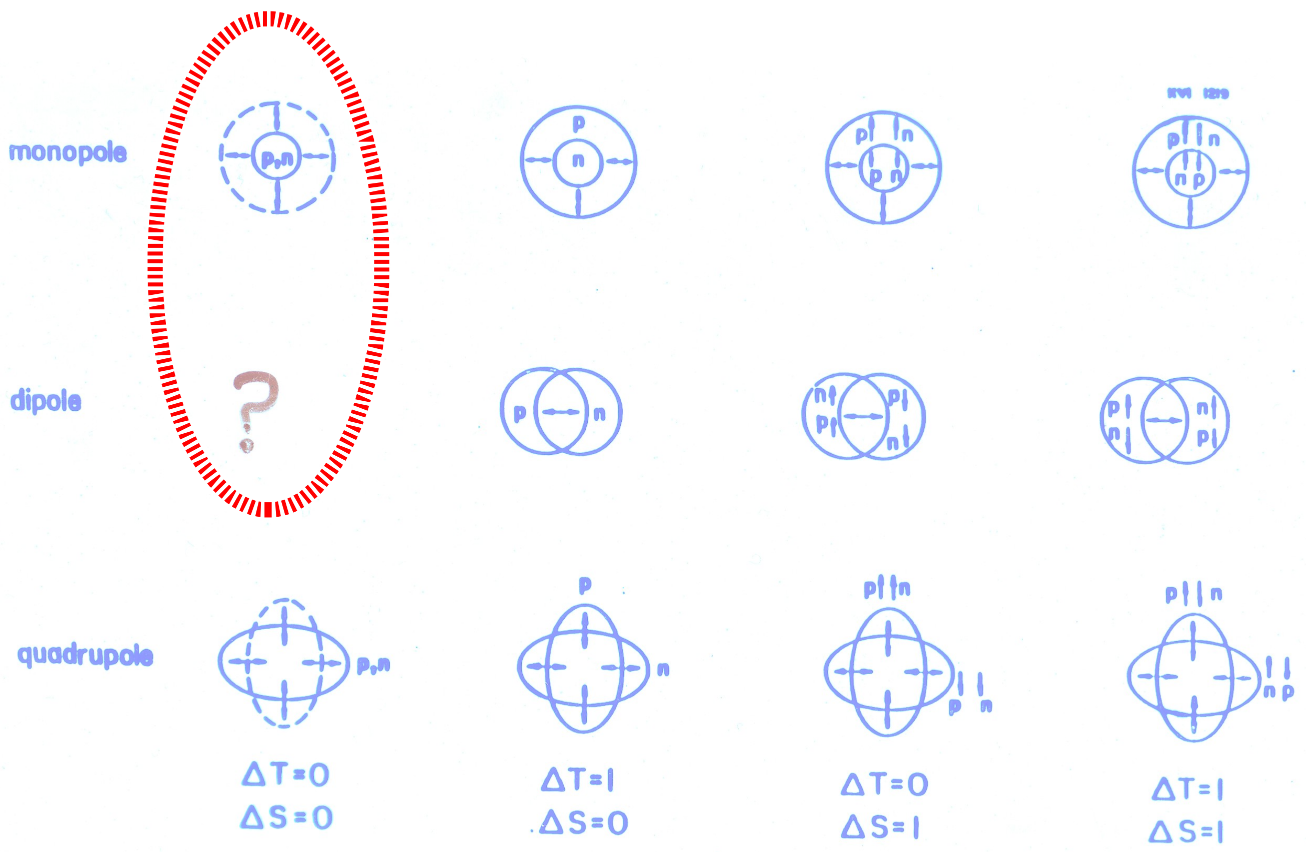




accumulated B(GT) from MDA of $^{90}Zr(p,n)$

Isoscalar Giant Monopole and Isoscalar Giant Dipole Resonance

and the **(in)compressibility of nuclear matter** *electric*



isoscalar

compression modulus *K*
(' scaling ' model)

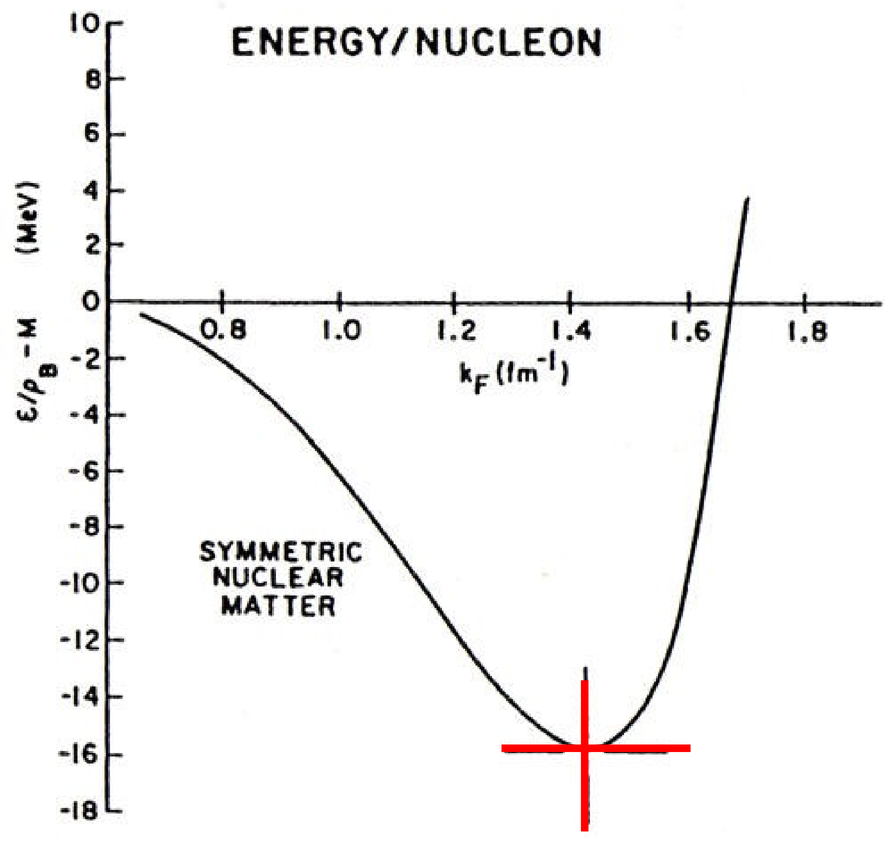
GMR
'breathing' mode

$$E_{GMR} = \hbar \sqrt{\frac{K_A}{m < r^2 >}}$$

isGDR
'squeezing' mode

$$E^S = \sqrt{\frac{7}{3}\hbar^2 \frac{K_A + (27/25)\epsilon_F}{m\langle r^2 \rangle}}$$

infinite symmetric (N=Z) nuclear matter – compression modulus $\boldsymbol{K_\infty}$



$\rho_0 \equiv$ *nucleon density*

$K_F \equiv$ *Fermi momentum*

$$K_\infty = K_F^2 \frac{\partial^2}{\partial K^2}\left(E_B / A \right)_{K = K_F}$$

$$K_F = \left(\frac{3\pi^2}{2} \rho_0 \right)^{1/3}$$

The excitation energy of the GMR is expressed in the scaling model as:

$K_A \equiv$ nucleus (mass A)

$K_\infty \equiv$ nuclear matter

$$E_{GMR} = \hbar\sqrt{\frac{K_A}{m < r^2 >}} \quad (1)$$

where K_A can be expressed as:

corrections for
- surface effects
- N-Z asymmetry
- Coulomb effects

$$K_A \approx K_\infty(1 + cA^{-1/3}) + K_\tau((N-Z)/A)^2 + K_{Coul}Z^2A^{-4/3}. \quad (2)$$

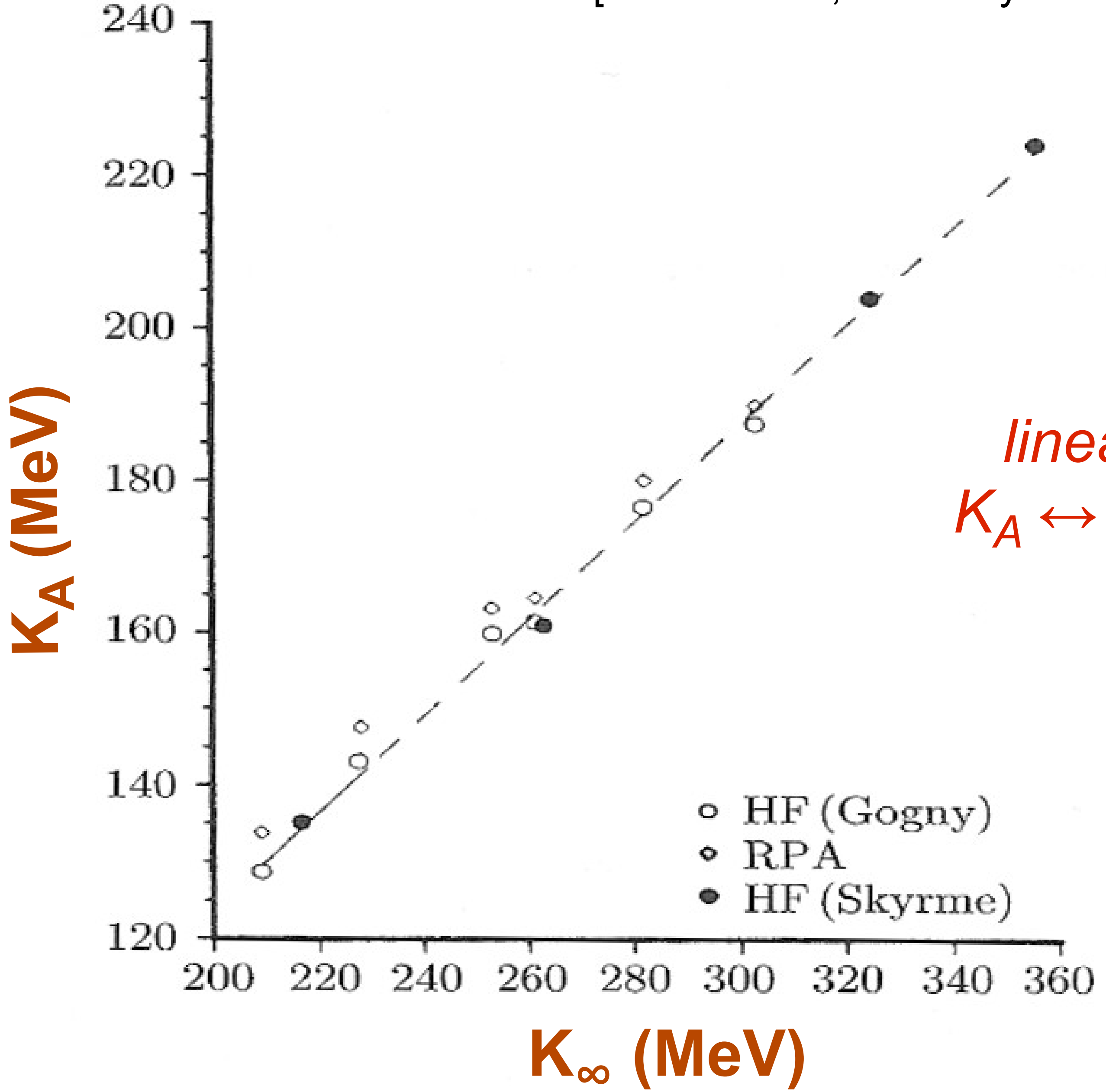
c $\sim$ -1.

K_{Coul} is, basically, model-independent

K_τ ?? see below

It is estimated that the difference in K_τ would be observable in the differences in E_{GMR} of ^{112}Sn and ^{124}Sn.

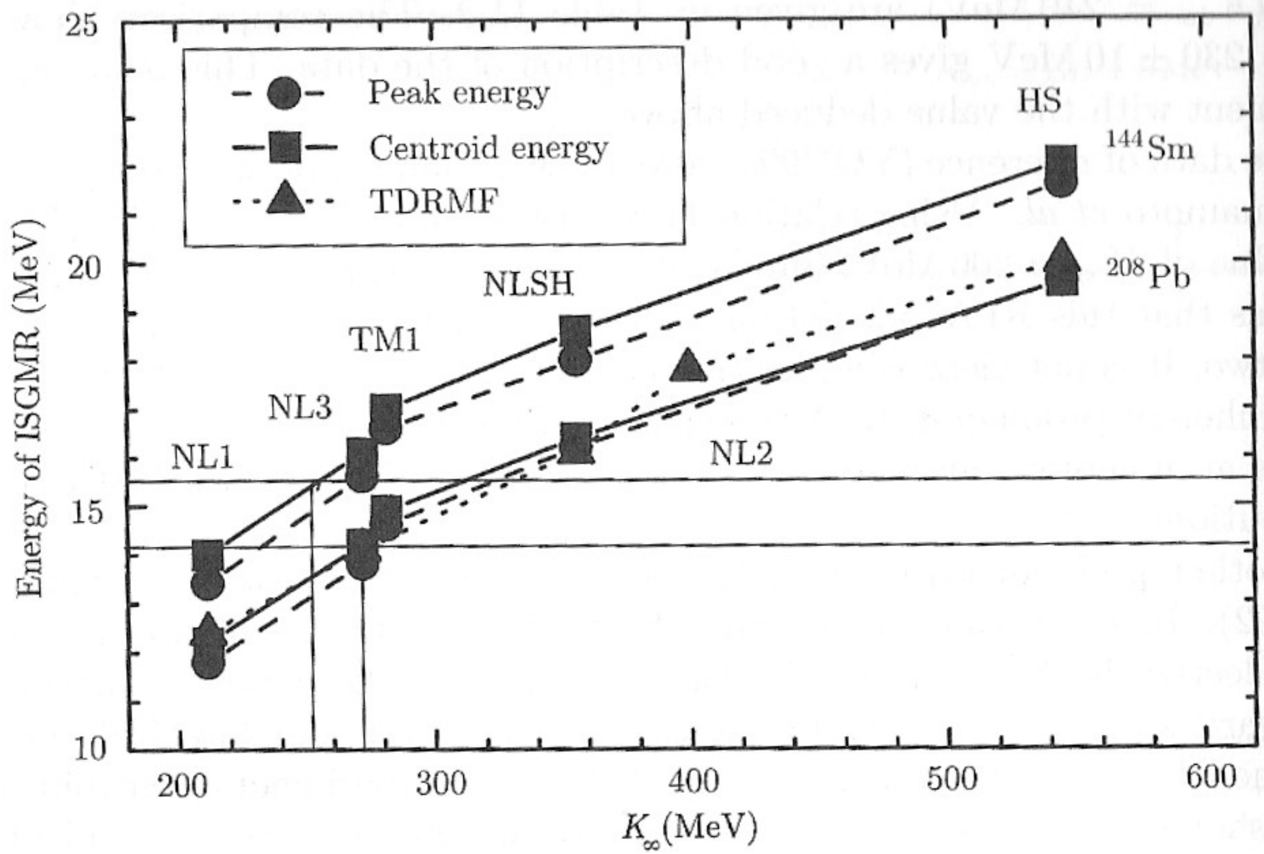
[Blaizot et al., Nucl.Phys A595, 435]



linear relation
$K_A \leftrightarrow K_\infty$ *inferred*

isGMR energy vs. K_∞

calculated with various relativistic RPA Lagragians [GIAI-99]



exp.

Experimental methods and results

exp. GMR slides below by courtesy of U. Garg, Notre Dame

U. Garg

Inelastic α scattering

T = 0 => isoscalar exc.

S = 0 => non-spin-flip

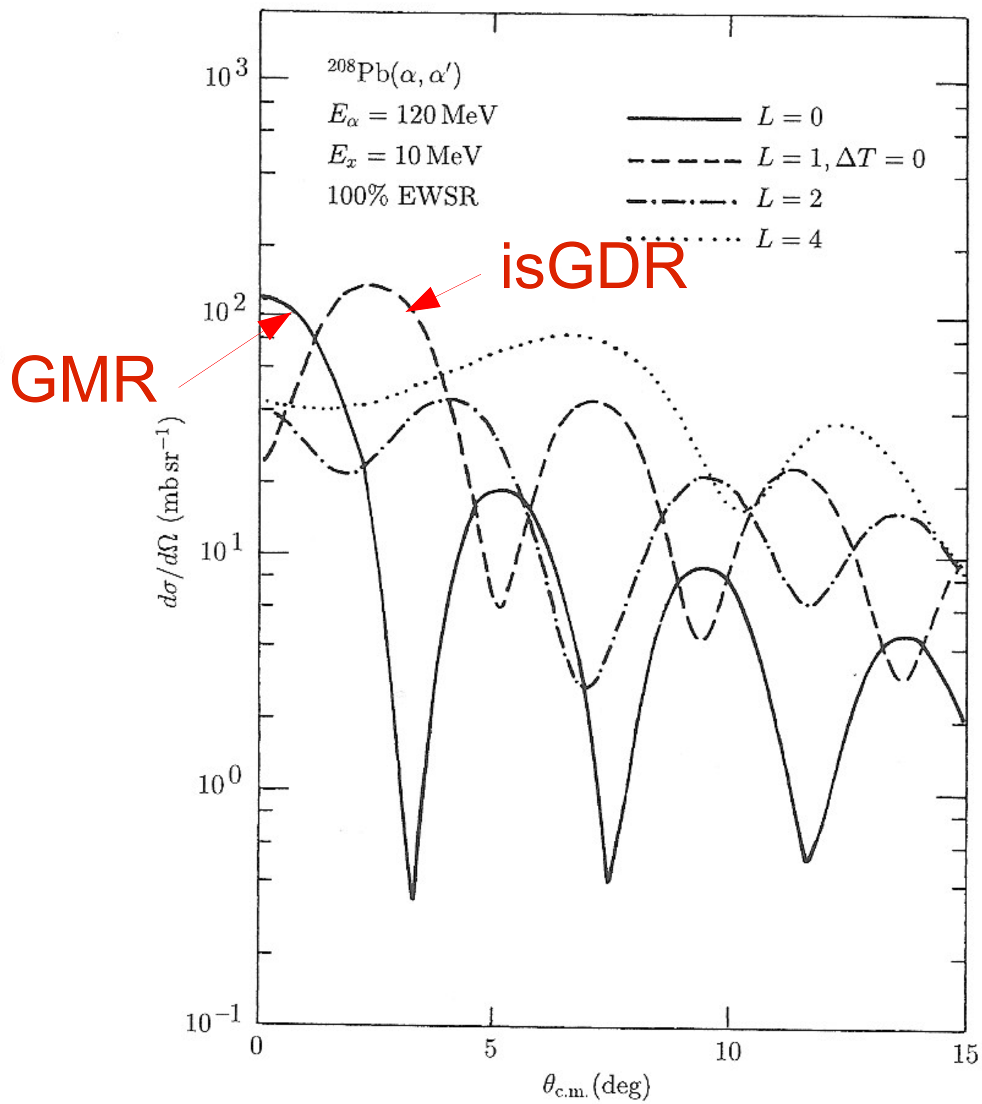
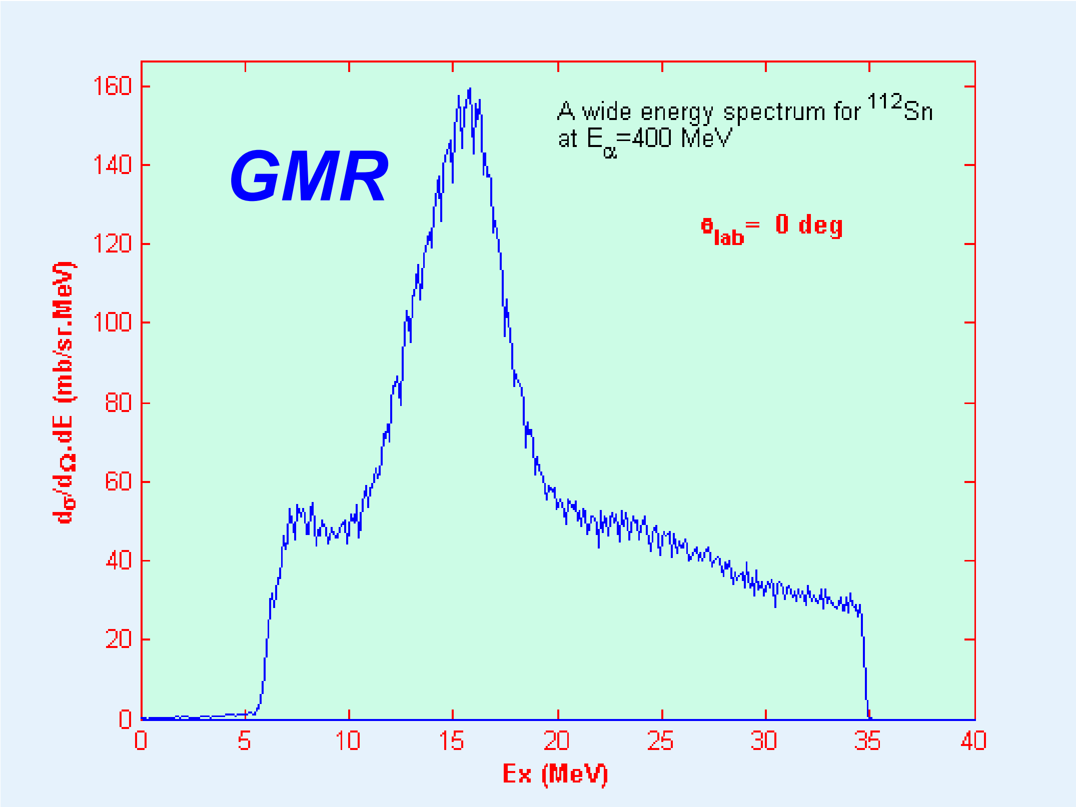


FIG. 3.1. DWBA predictions for the differential cross sections corresponding to various multipolarities exhausting 100% of the EWSR for ^{208}Pb for inelastic α scattering at 120 MeV and at 0°.

U. Garg



- General property of nuclei
- Excitation energy varies smoothly with mass

$$E_x \propto A^{-1/3}$$

- Exhausts a large fraction of *sum rule strength*

- Generally well localized in energy, $\Gamma \sim 2 - 3$ MeV

U. Garg

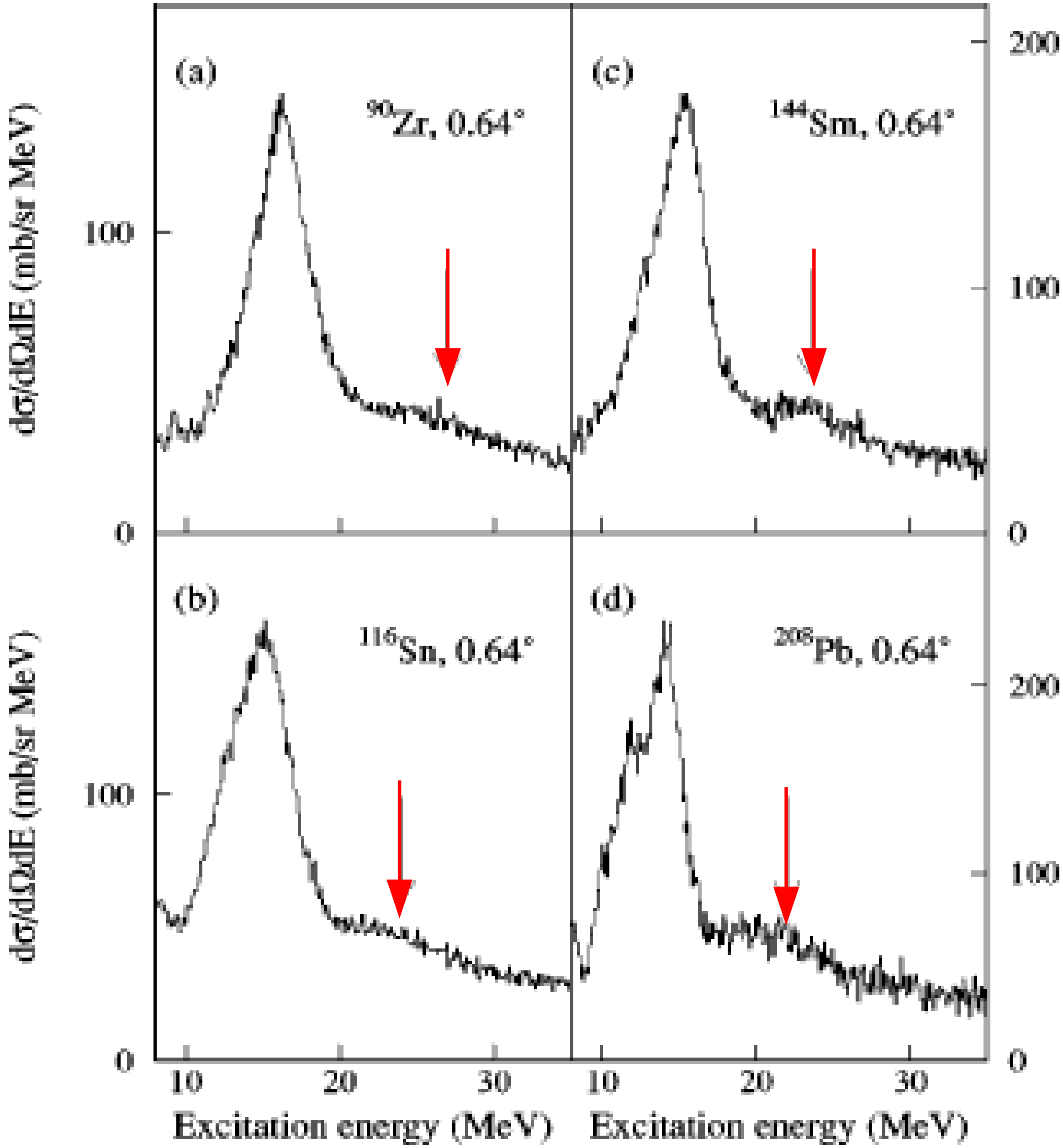


FIG. 1. Excitation energy spectra for ^{90}Zr, ^{116}Sn, ^{144}Sm, and ^{208}Pb at θ=0.64°. The arrows indicate the locations of the HE ISGDR. Note that the ^{144}Sm(α,α') spectrum from our previous work [21] is also included.

Isoscalar GDR

U. Garg

Conclusion

from GMR data on ^{208}Pb and ^{90}Zr

$K_{\infty} = 240 \pm 20$ MeV

This number is consistent with both GMR and ISGDR data and with non-relativistic and relativistic calculations

Isospin dependence – K_τ

$K_{vol} = K_\infty$

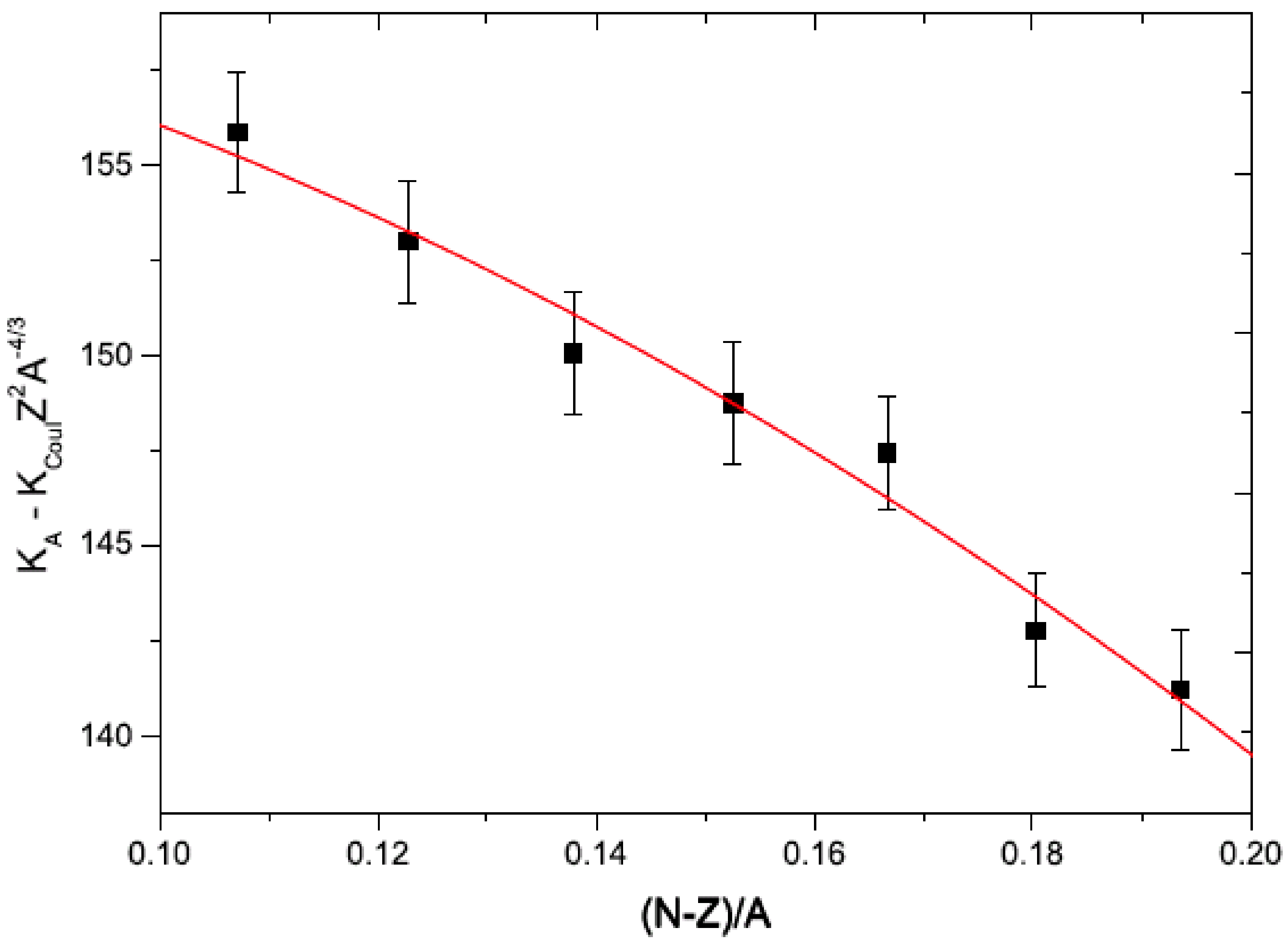
$$K_A \sim K_{vol}\,(1 + cA^{-1/3}) + K_\tau\,((N - Z)/A)^2 + K_{Coul}\,Z^2A^{-4/3}$$

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

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

use K_{Coul} = - 5.2 MeV (from Sagawa)

result for Sn isotopes (U.Garg)



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

U. Garg

Towards very neutron-rich nuclei

- K_τ
- K_{core} and K_{skin}

  "soft GMR" akin to pigmy GDR's.

- Need inverse reactions

  ^{2}H, ^{4}He, or ^{6}Li targets

  beams of 35-100 MeV/A

- First experiment performed at GANIL

  ^{56}Ni + ^{2}H, with active target MAYA

The End