Collective Modes in Nuclei

Hans Emling, ANUP, Goa, Nov. 2011

Collective motion – a universal phenomenon in nature

BI-SW: http://www.youtube.com/watch?v=V71hz9wNsgs

SHIBUYA:
http://www.youtube.com/watch?v=QXtOdSgf6Ic&feature=BFa&list=PL881859D3DB1AFA9F&lf=results_video

Ped: http://arxiv.org/abs/cond-mat/9805074

FI: http://www.youtube.com/watch?v=cIgHEhziUxU

Condensed Matter > Statistical Mechanics

Computer Simulations of Pedestrian Dynamics and Trail Formation

D. Helbing, P. Molnar, F. Schweitzer

(Submitted on 6 May 1998 (v1), last revised 7 May 1998 (this version, v2))

Abstract: A simulation model for the **dynamic behaviour of pedestrian crowds** is mathematically formulated in terms of a **social force model**, that means, pedestrians behave in a way as if they would be subject to an acceleration force and **to repulsive forces** describing the reaction to borders and other pedestrians. The computational simulations presented yield many realistic results that can be compared with video films of pedestrian crowds. Especially, they show the self-organization of **collective behavioural patterns**. By assuming that pedestrians tend to choose routes that are frequently taken the above model can be extended to an active walker model of trail formation. The topological structure of the evolving trail network will depend on the disadvantage of building new trails and the durability of existing trails. Computer simulations of trail formation indicate to be a valuable tool for designing systems of ways which satisfy the needs of pedestrians best. An example is given for a non-directed trail network.

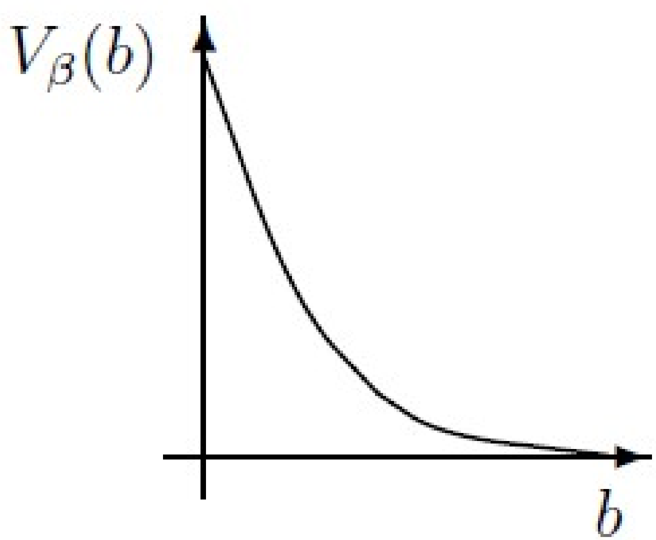
For related work see this http URL Statistical Mechanics (cond-mat.stat-mech); Pattern Formation and Solitons (nlin.PS) Pages 229-234 in: Evolution of Natural Structures (Sonderforschungsbereich Journal reference: 230, Stuttgart, 1994)
Cite as:arXiv:cond-mat/9805074v2 [cond-mat.stat-mech]

'SOCIAL' repulsive force:

$$\vec{f}_{\alpha\beta}(\vec{r}_\alpha - \vec{r}_\beta) = -\nabla_{\vec{r}_\alpha} V_\beta[b(\vec{r}_\alpha - \vec{r}_\beta)] \, . \tag{5}$$

The sum over the repulsive potentials V_β defines the *interaction potential* which influences the behaviour of each pedestrian:

$$V_{\text{int}}(\vec{r}, t) := \sum_\beta V_\beta\{b[\vec{r} - \vec{r}_\beta(t)]\} \, . \tag{6}$$



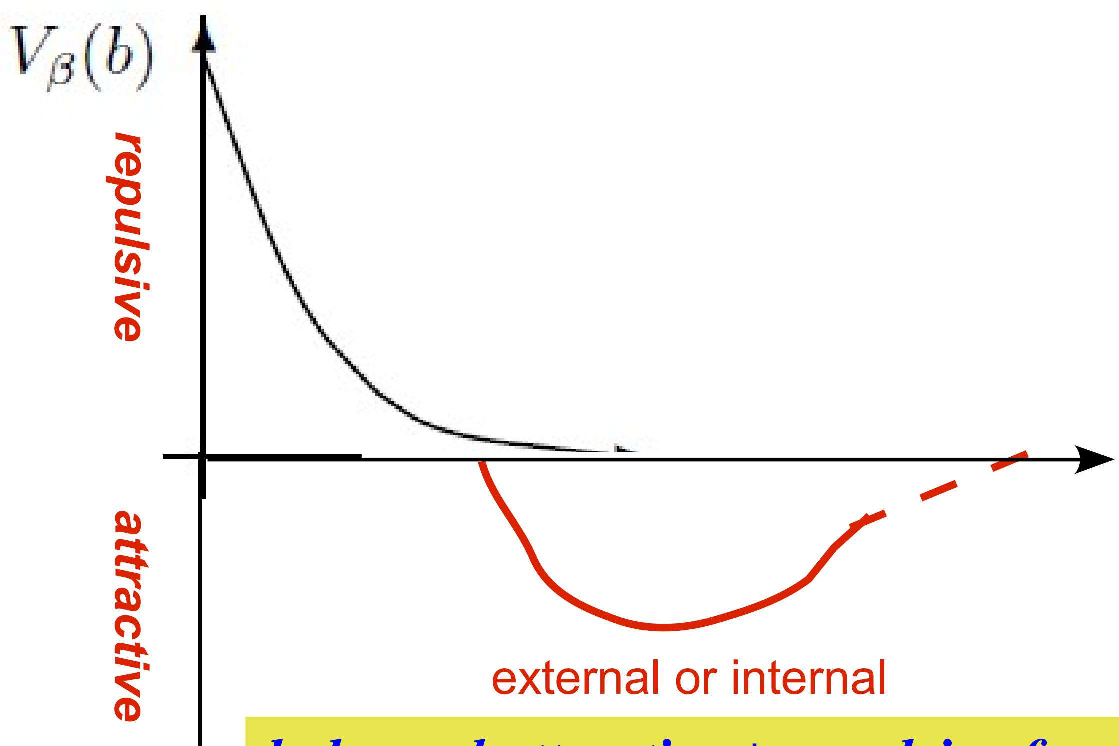
b = distance to neighbor

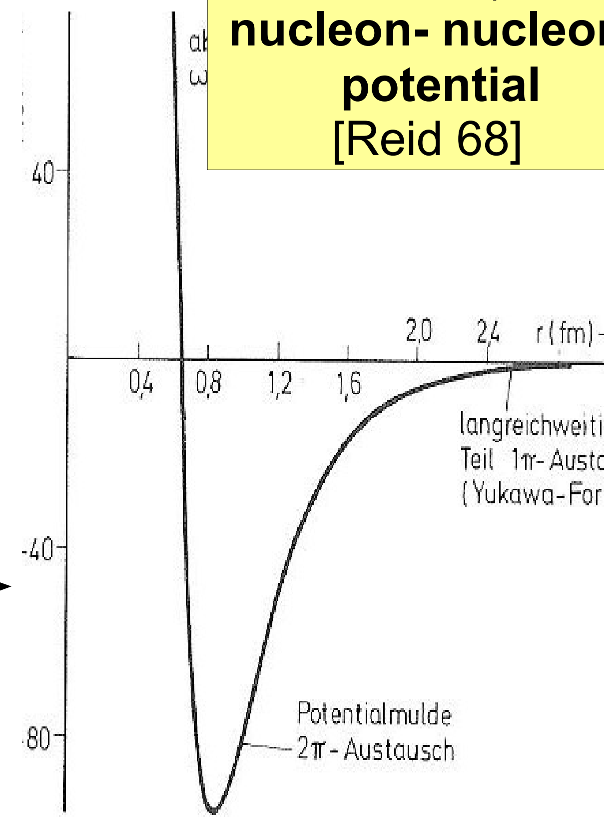
Repulsive 'social' force:

$$\vec{f}_{\alpha\beta}(\vec{r}_\alpha - \vec{r}_\beta) = -\nabla_{\vec{r}_\alpha} V_\beta[b(\vec{r}_\alpha - \vec{r}_\beta)] \,. \tag{5}$$

The sum over the repulsive potentials V_β defines the *interaction potential* which influences the behaviour of each pedestrian:

$$V_{\text{int}}(\vec{r},t) := \sum_\beta V_\beta\{b[\vec{r} - \vec{r}_\beta(t)]\} \,. \tag{6}$$





' hard core ' (Pauli !)
nucleon- nucleon potential
[Reid 68]

balanced attractive + repulsive forces ==> collective motion

How do we recognize COLLECTIVE MODES in Nuclei ??

*(Here: Nuclear Eigenstates,
not, e.g., collective flow in collisions)*

Recipe: Quantization of a classical collective system and search for the respective characteristic patterns in the nuclear spectral response

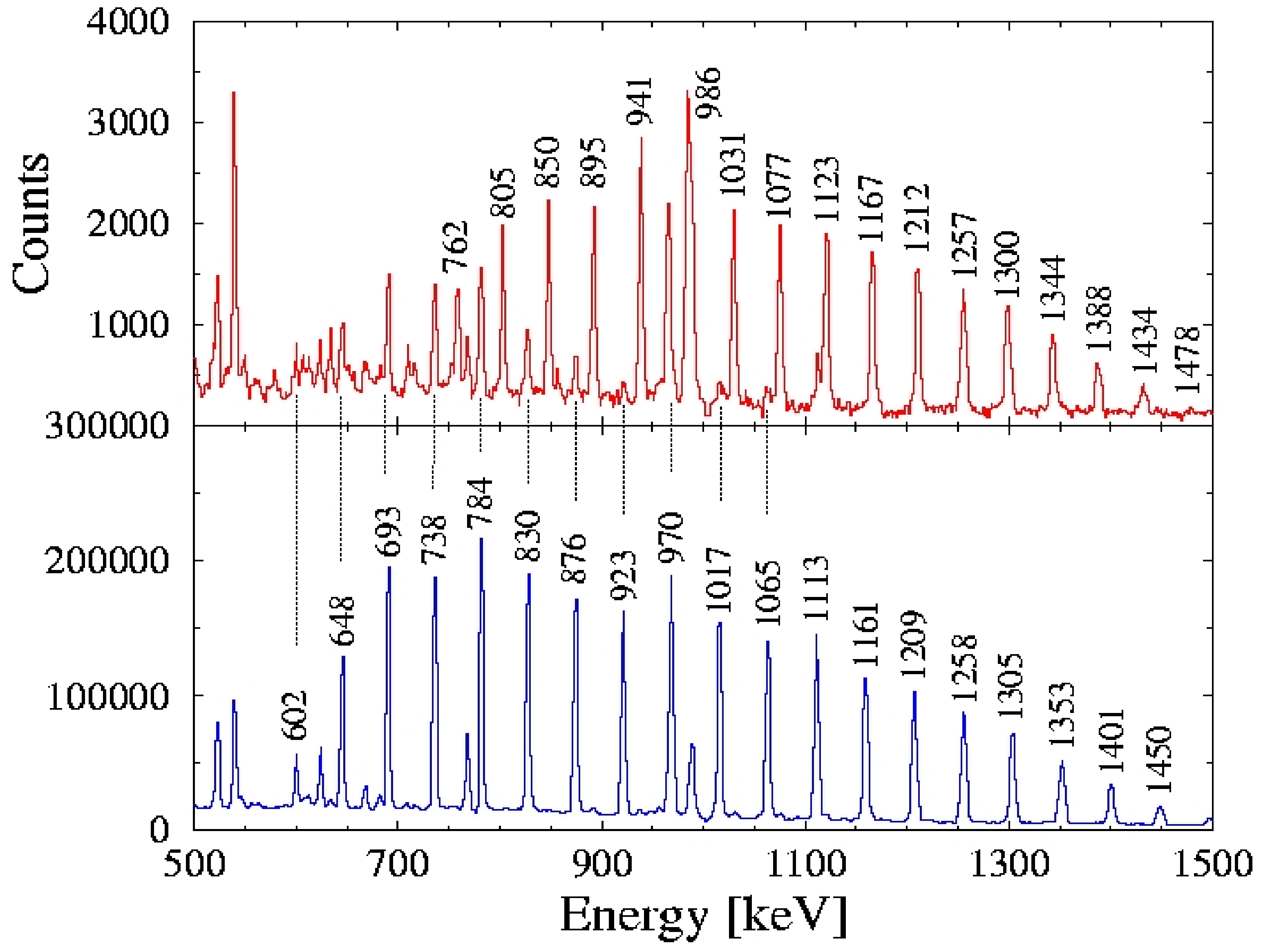
for example: rotational spectra

Classical rigid rotation: $E_L = L^2 / 2\Theta$ (continuous)

Quantized system: $E_I = \hbar^2 I(I+1) / 2\Theta$ (discrete eigenstates)

↓

E2-γ-transitions: $E_\gamma = \hbar^2 \, 2(I-1) / \Theta$ or $\Delta E_\gamma = \text{const.}$



- T. Lauritsen *et al.*, Phys. Rev. Lett. **88**, (2002). 042501
- T. Lauritsen *et al.*, Phys. Rev. Lett. **89** (2002) 282501

However:

Not much exp. information on two- (higher-) phonon states available

Vibrational nuclear states:

- Surface (β -, γ- , octupole) vibrations
- Density oscillations (' giant resonances ')

Quantized harmonic oscillator: $E_n = n\ E_o$

or $\Delta E = E_o$ ('phonon' !)

Rotatinal nuclear spectra and surface vibrations discussed already, see M. Carpenter, P. Regan, P. Reiter …

this lecture restricted to (specific aspects of) **giant resonances** !

Outline

Lecture I: Giant Resonances (GR) – Introduction, Basics

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

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

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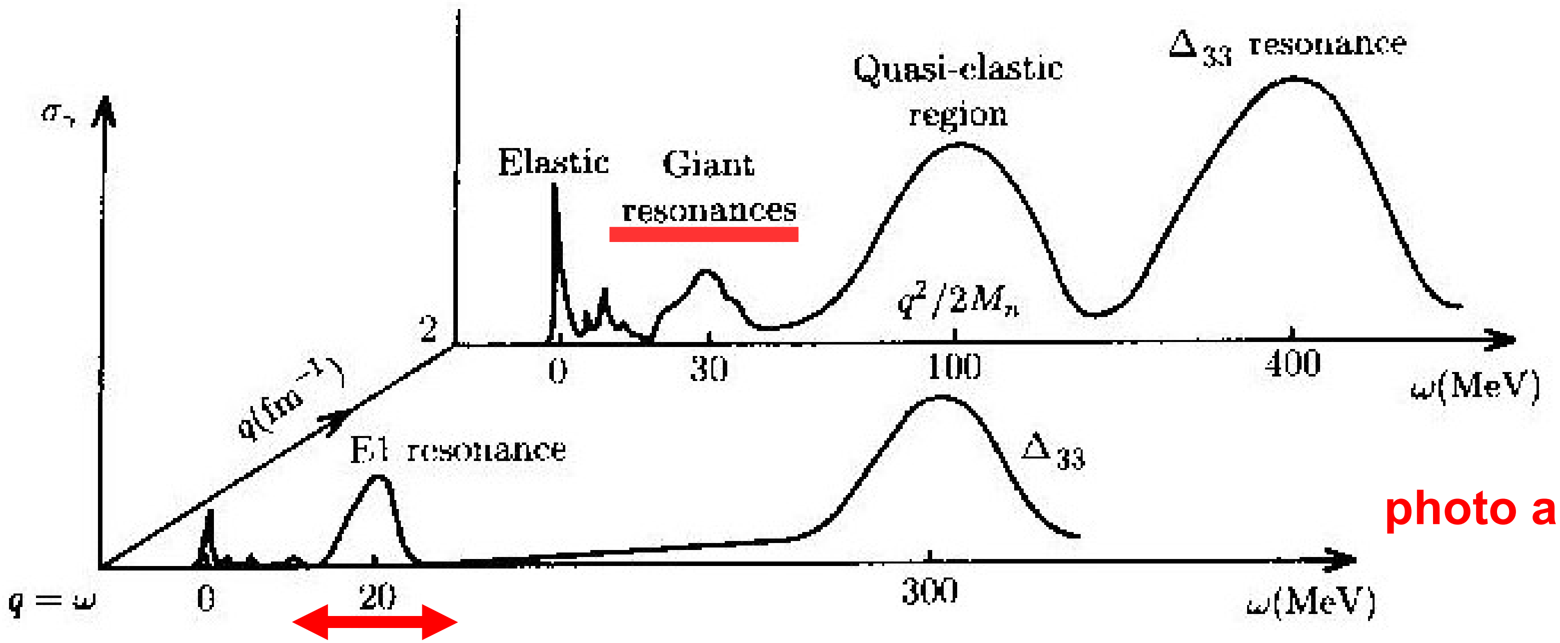
Giant Resonances

Fundamental High-Frequency Modes of Nuclear Excitation

M. N. HARAKEH
and
A. van der WOUDE

OXFORD SCIENCE PUBLICATIONS

Nuclear response to external field , at moderate energy (ω) and momentum (q) transfer

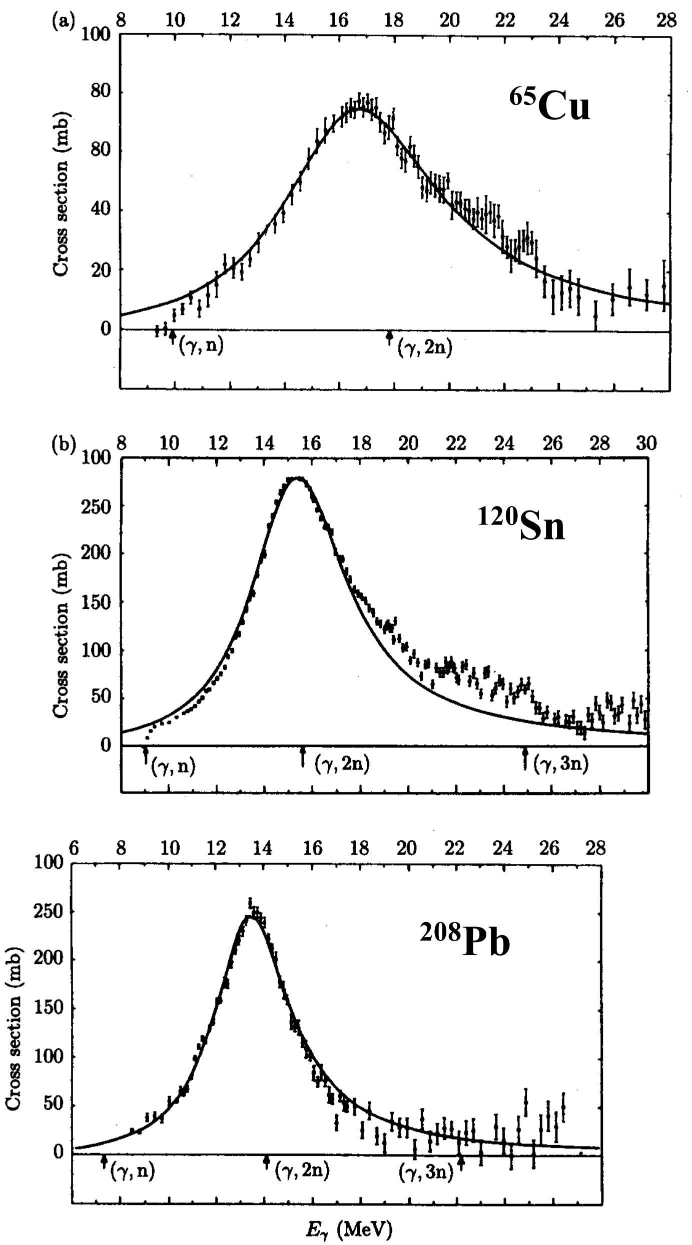


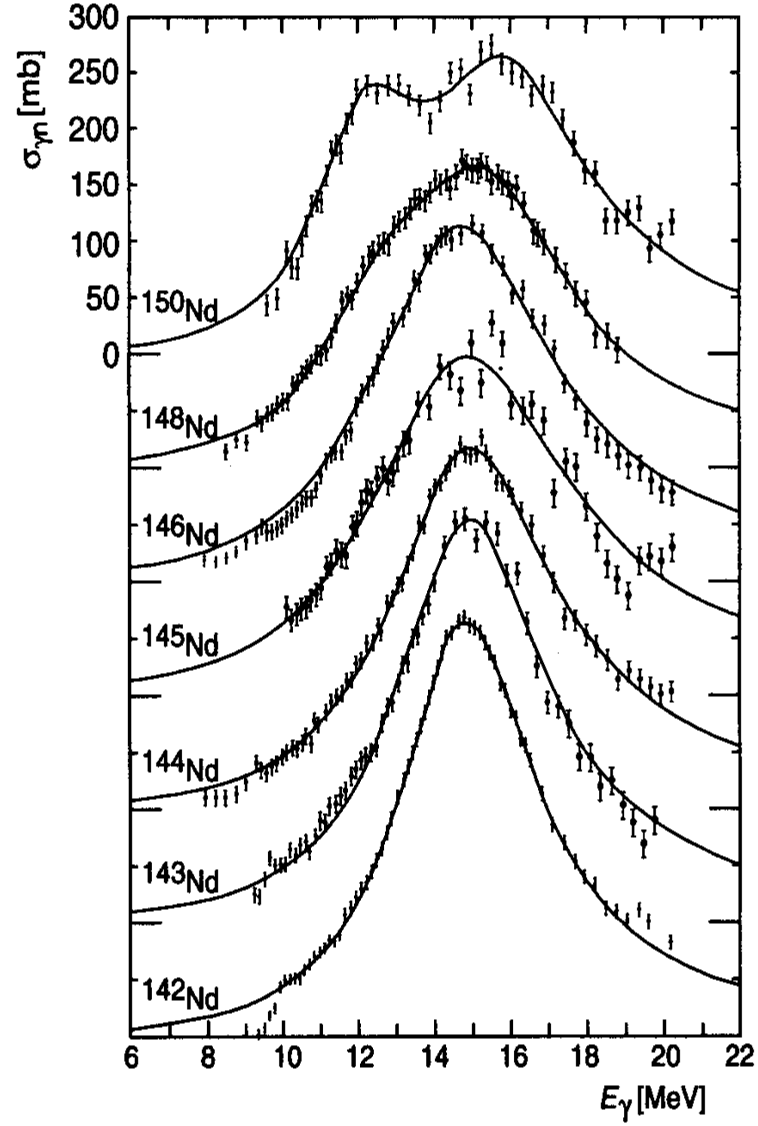
nucleon scattering

photo absorption (q = ω)

Photoabsorption (GDR)

Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47





Inelastic α scattering (GMR + GQR)

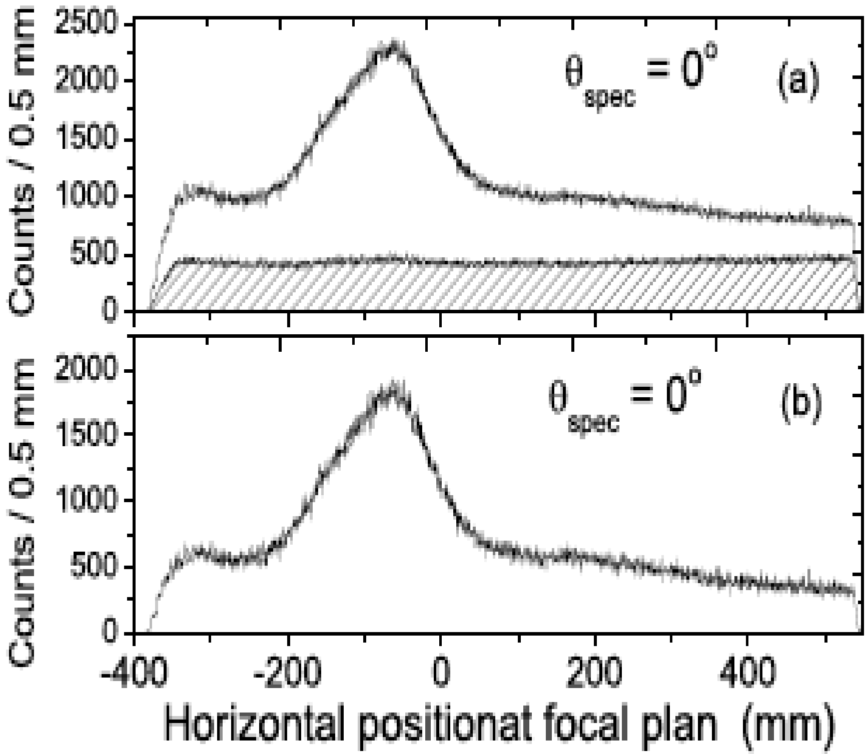
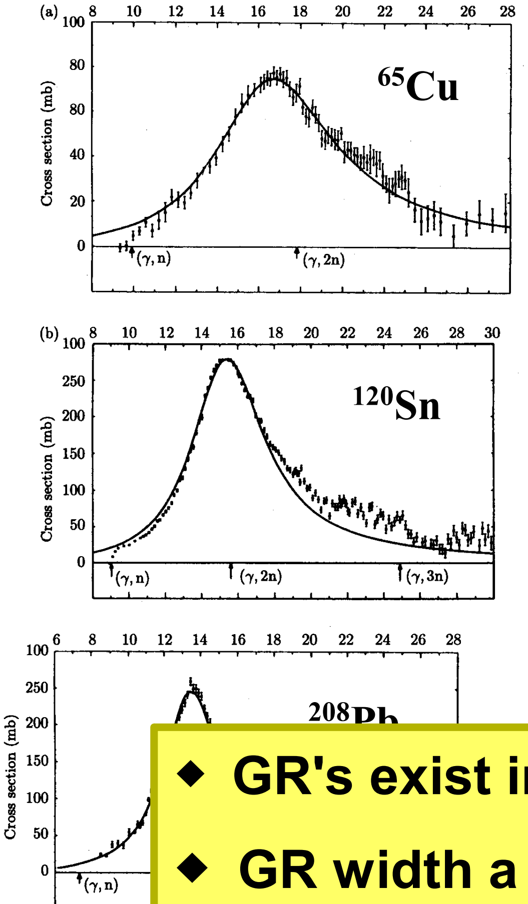
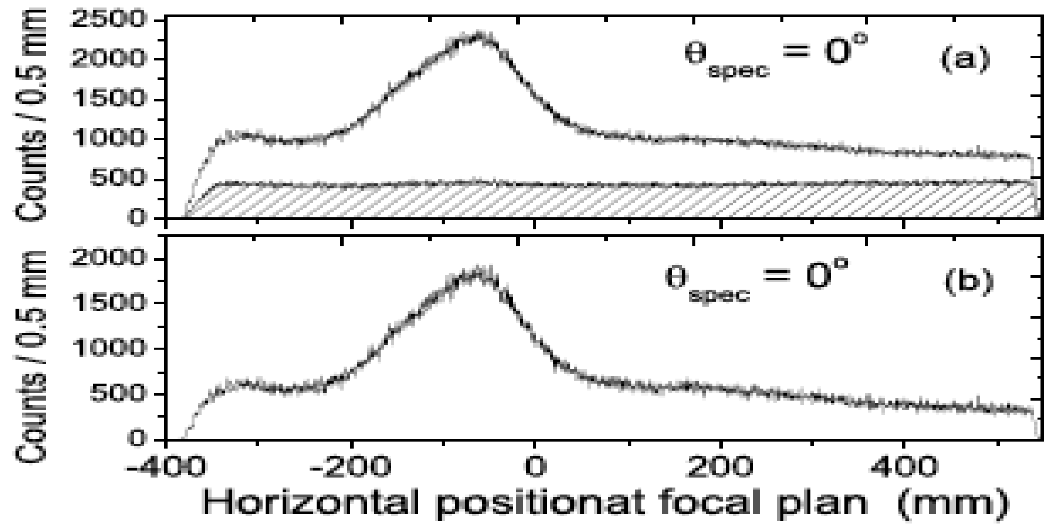


FIG. 2: (a) Horizontal-position spectrum of the ^{112}Sn(α,α') reaction at 0°. The hatched region is background events. (b) Background-free spectrum

Courtesy of U. Garg

Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47





- GR's exist in all nuclei – typically around E* ≈ 10 ...30 MeV
- GR width a few MeV
- GR shape of Lorentzian type (e.g., GDR); frequently fragmented
- GR parameter vary smoothly with Z,N,A
- GR strength exhausts large fraction of sum rules
- appear as prominent structures in the spectra obtained from <u>various</u> scattering experiments

==> reflecting bulk properties of nucl. matter

Classification of giant resonances (macroscopic view)

Four fluids in the nucleus, characterized by spin and isospin

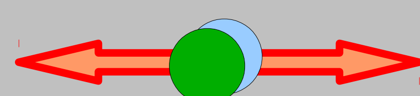
neutron ***($T_z = 1/2$)***

proton ***($T_z = -1/2$)***

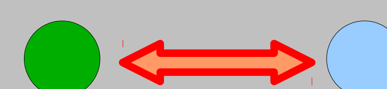
Spin up ($\sigma_z = ½$) – down ($\sigma_z = - ½$)

Accordingly, 4 basic modes :

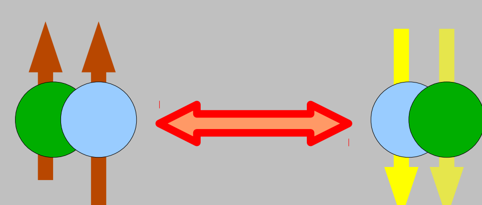
Electric isoscalar



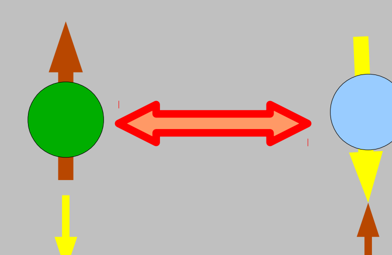
Electric isovector



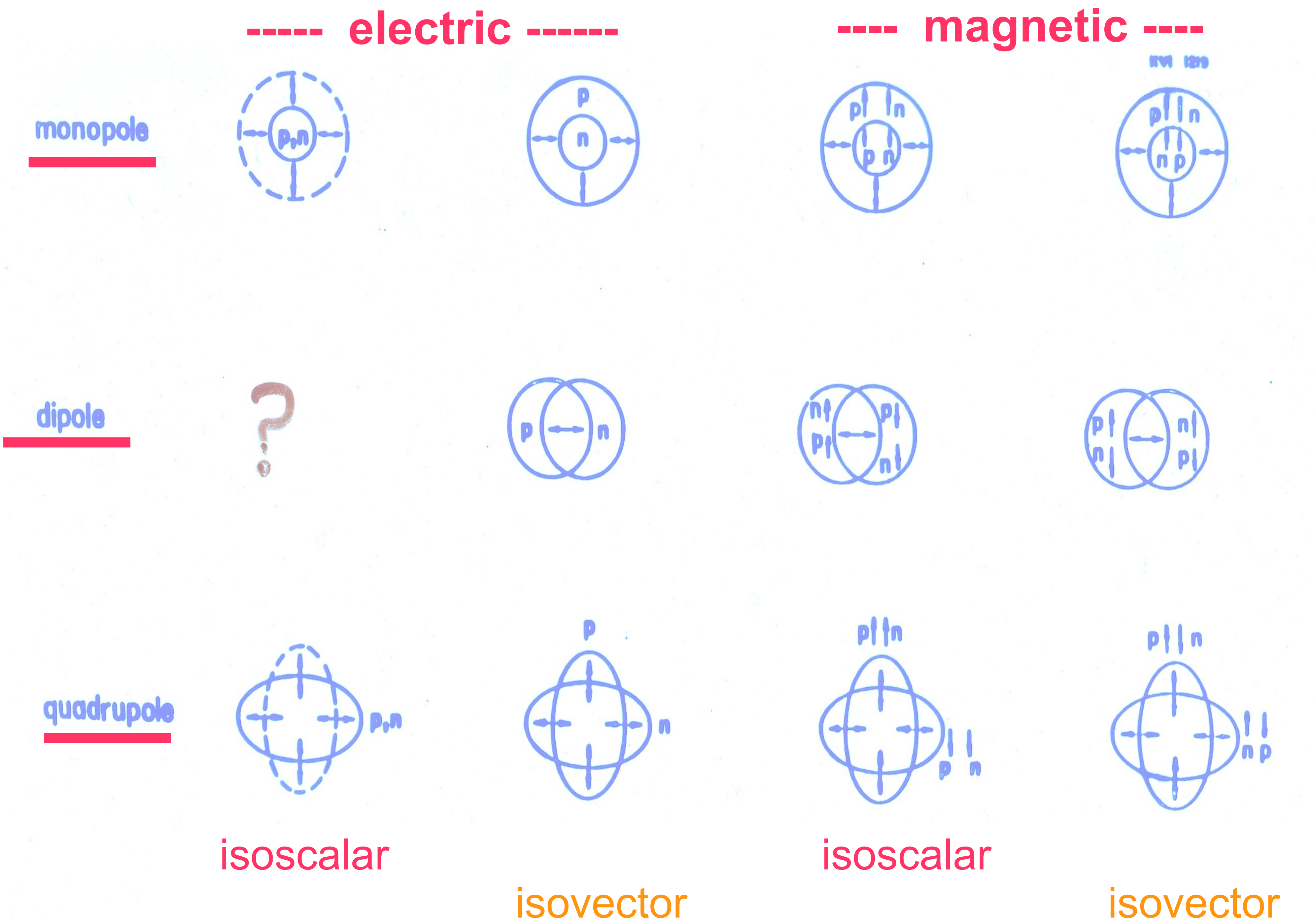
Magnetic isoscalar



Magnetic isovector



rich pattern of GR's :



Nomenclature:

L (λ) – multipolarity
S (σ) – spin
T (τ) – isospin
ΔS, ΔT – spin-, isospin transfer

Eλ – electric transition
Mλ – magnetic transition

IS (is) – isoscalar ***(p – n in phase)***
IV (iv) – isovector ***(p – n out of phase)***

GMR,GDR,GQR...
– giant monopole resonance ....

e.g. ivSGDR = isovector spinflip giant dipole resonance

Microscopic understanding of the GR

GR created by the action of a
one-body transition operator
onto the ground state of a nucleus:

$$| \Psi_{GR}^{\lambda,\sigma,\tau} > \; = \; O^{\lambda,\sigma,\tau} \, | \Psi_{g.s.} >$$

The transition operator contains
a multipole-type operator
(e.g. $\Sigma_i \, r_i^{\lambda} \, Y_m^{\lambda}$)
and/or may involve appropriate
spin and/or isospin operator

Microscopic classification of giant resonances

-- electric ($\Delta S = 0$) ---- -- magnetic ($\Delta S = 1$) --

isoscalar ($\Delta T = 0$) isovector

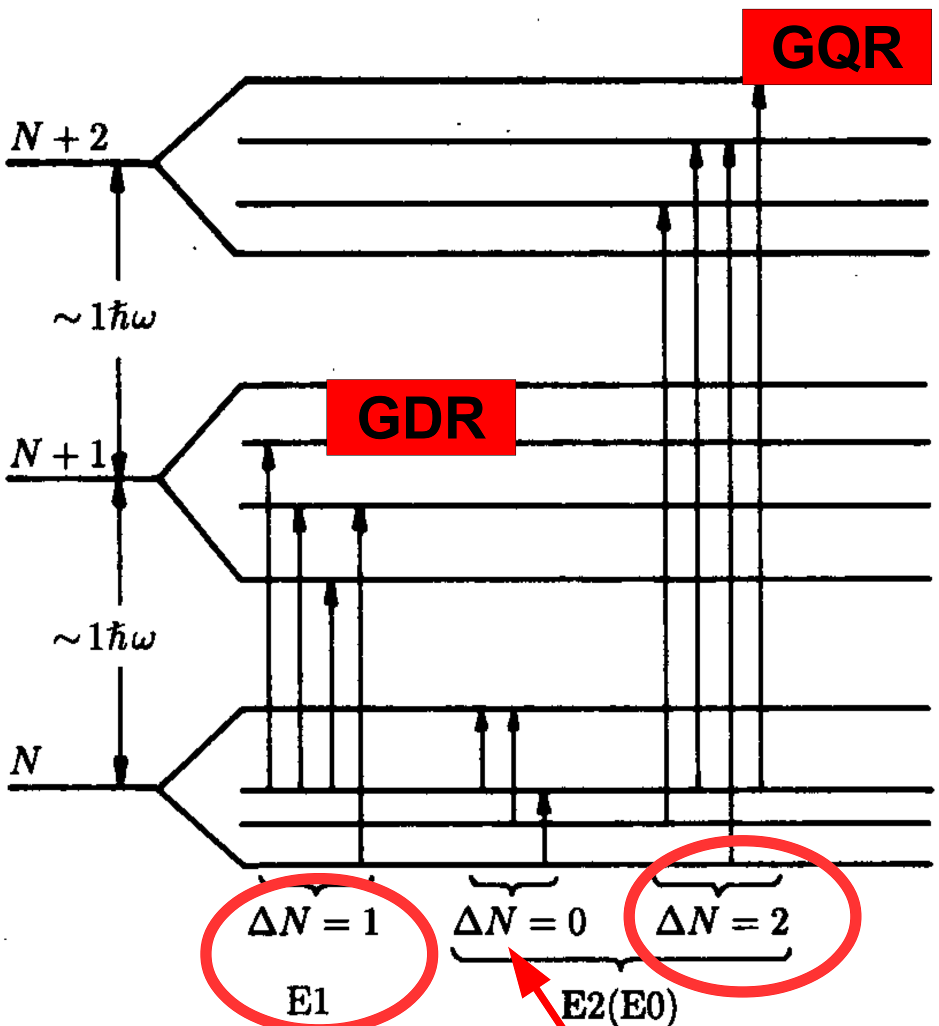
	$\Delta S = 0$, $\Delta T = 0$	$\Delta S = 0$, $\Delta T = 1$	$\Delta S = 1$, $\Delta T = 0$	$\Delta S = 1$, $\Delta T = 1$
$L = 0$	X	$\sum \tau_i$ IAS	X	$\sum \vec{\sigma}_i \tau_i$ GTR
Second order	$\sum r_i^2$ ISGMR	$\sum r_i^2 \tau_i$ IVGMR	$\sum r_i^2 \vec{\sigma}_i$ ISSMR	$\sum r_i^2 \vec{\sigma}_i \tau_i$ IVSMR
$L = 1$	X	$\sum r_i Y^1_m \tau_i$ IVGDR	$\sum r_i Y^1_m \vec{\sigma}_i$ ISSDR	$\sum r_i Y^1_m \vec{\sigma}_i \tau_i$ IVSDR
Second order	$\sum r_i^3 Y^1_m$ ISGDR			

not allowed: center of gravity to be conserved

How are such operators realized in nuclear reaction experiments ?

i.e., how do we relate
nuclear reaction cross section ↔ strength distribution ??

consider a (naive) shell model (harmonic osc.):



Excited states from p-h excitations within / across major shells N

remember:
Parity alternates with N,
thus, for multipolarity, e.g.,
$\Delta L = 1 \implies \Delta N = 1$
$\Delta L = 2 \implies \Delta N = 0$ or 2 etc...

however, exp. value: 13 MeV !!

GR's are understood as a

<u>Coherent</u> <u>superposition</u> of **<u>many</u>** 1p-1h excitations across major shells.
<u>Strongly shifted</u> in energy by **<u>residual</u>** <u>interactions.</u>

Low-lying E2: rotation, surface vibration

Theoretical description of giant resonances – microscopic approach

Keywords:

Level of sophistication

mean field

(relativistic and non-relativistic approaches)

> average one-body potential
> obtained empirically (e.g. Woods-Saxon)
> or from effective nn interactions
> via self-consistent Hartree-Fock method
>
> ↓
>
> Excitations: 1p-1h ...... np-nh,
> no two-body interactions
> => no coherent excitations !

TDA Tamm-Da

RPA random-ph

QRPA quasi-particle RPA

S-,E-,C-RPA

second-, extended, continuum RPA

Theoretical description of giant resonances – microscopic approach

Keywords:

Level of sophistication

mean field

TDA   Tamm-Dancoff approximation

switch on residual interaction
=> mixing of 1p-1h states

may cause strong energy shifts
and collective excitations !

RPA   random-

QRPA   quasi-pa

S-,E-,C-RPA
second-, extended, continuum RPA

Eigenstates of single-particle Hamiltonian ($\mathbf{H = \Sigma_i h_i}$) with energy : $\boldsymbol{\varepsilon_i}$

thus, the 1p-1h states | $\mathbf{ni}^{-1}$ > with excitation energies : $\boldsymbol{\varepsilon_n - \varepsilon_i}$

The 1p-1h states | $\mathbf{ni}^{-1}$ > form a complete orthonormal set, thus

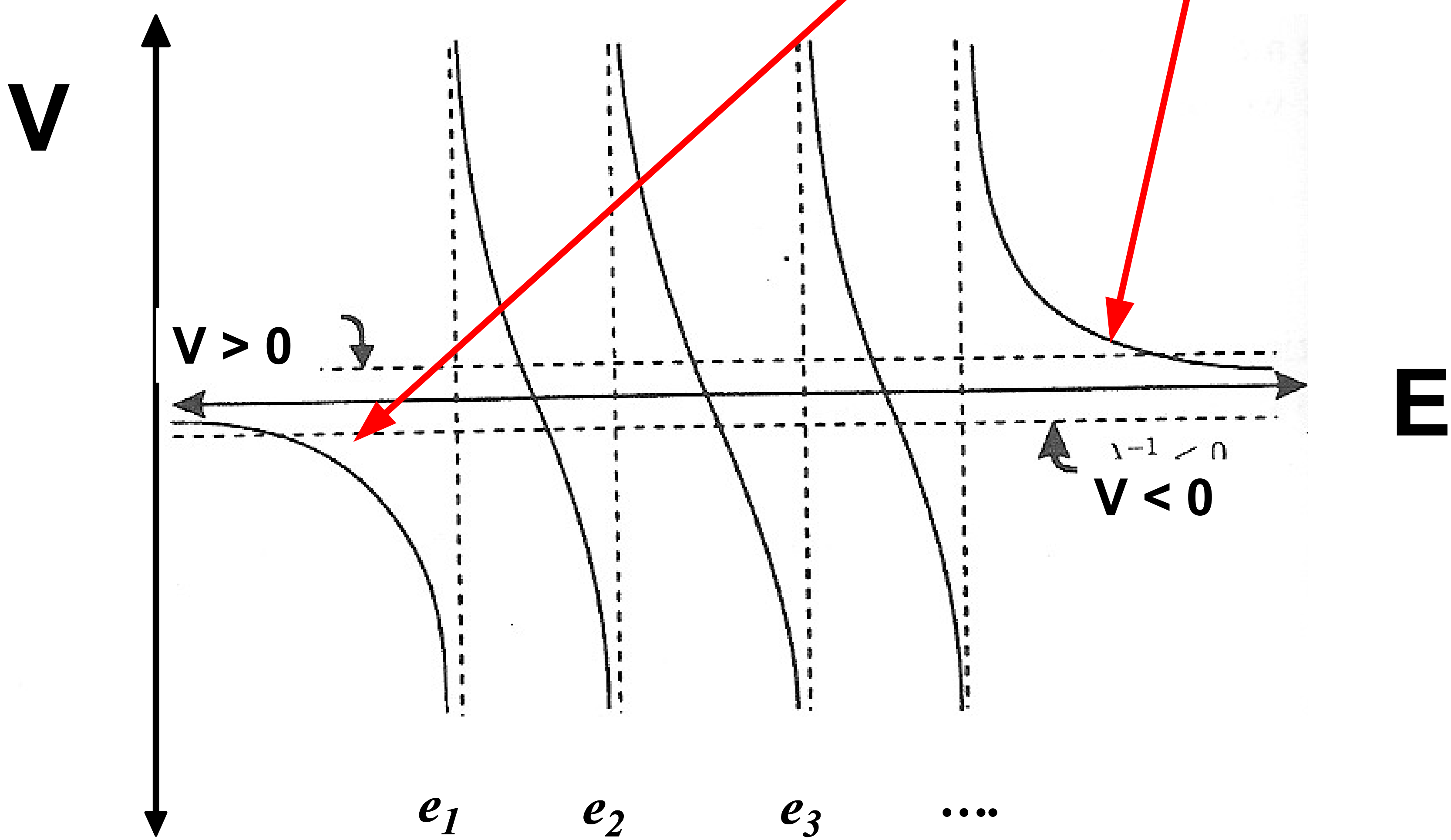
with a (simplified) residual interaction **V** ($\mathbf{H = \Sigma_i h_i + V}$), obtain the 'perturbed' particle-hole energies:

$$\mathbf{E} = \boldsymbol{\varepsilon_n} - \boldsymbol{\varepsilon_i} + \Sigma_{mj} < \mathbf{ni}^{-1} \,|\, \mathbf{V} \,|\, \mathbf{mj}^{-1} > c_{mj}/c_{ni}$$

(notice: ground state remains untouched)

Residual interaction is positive for isovector transitions => upshift

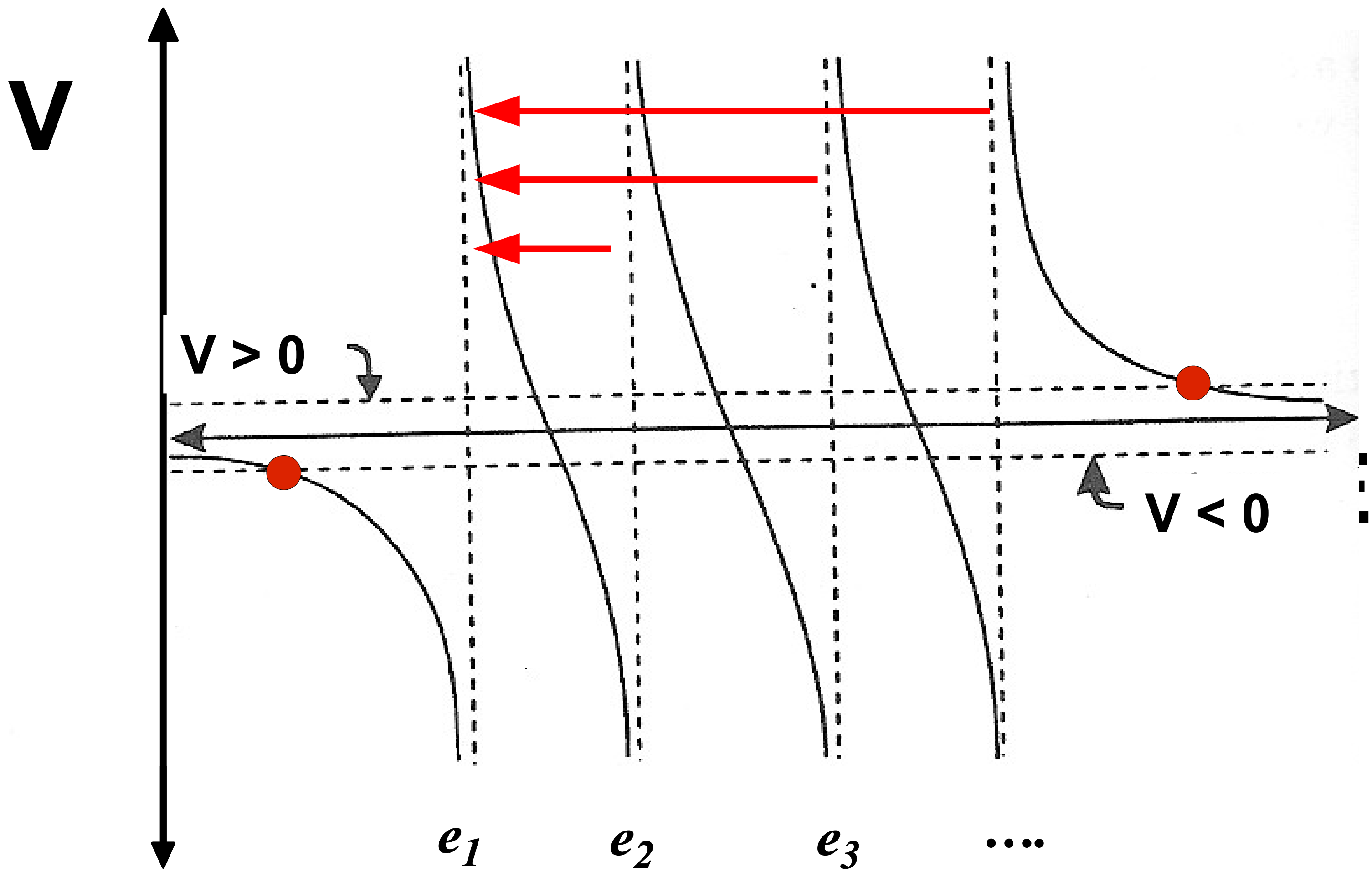
negative for isoscalar transitions => downshift



Further (over-) simplifying by adopting all e_k to be equal, apparently
only one state is shifted up (down) *maximally and*

most importantly:
it receives 100% of the transition probability *('the winner takes it all' -ABBA)*
(i.e. the sum of the transition probability between the unperturbed states)

==> *the collective state !*



Theoretical description of giant resonances – microscopic approach

Keywords:

Level of sophistication

mean field

TDA Tamm-Dancoff approximation

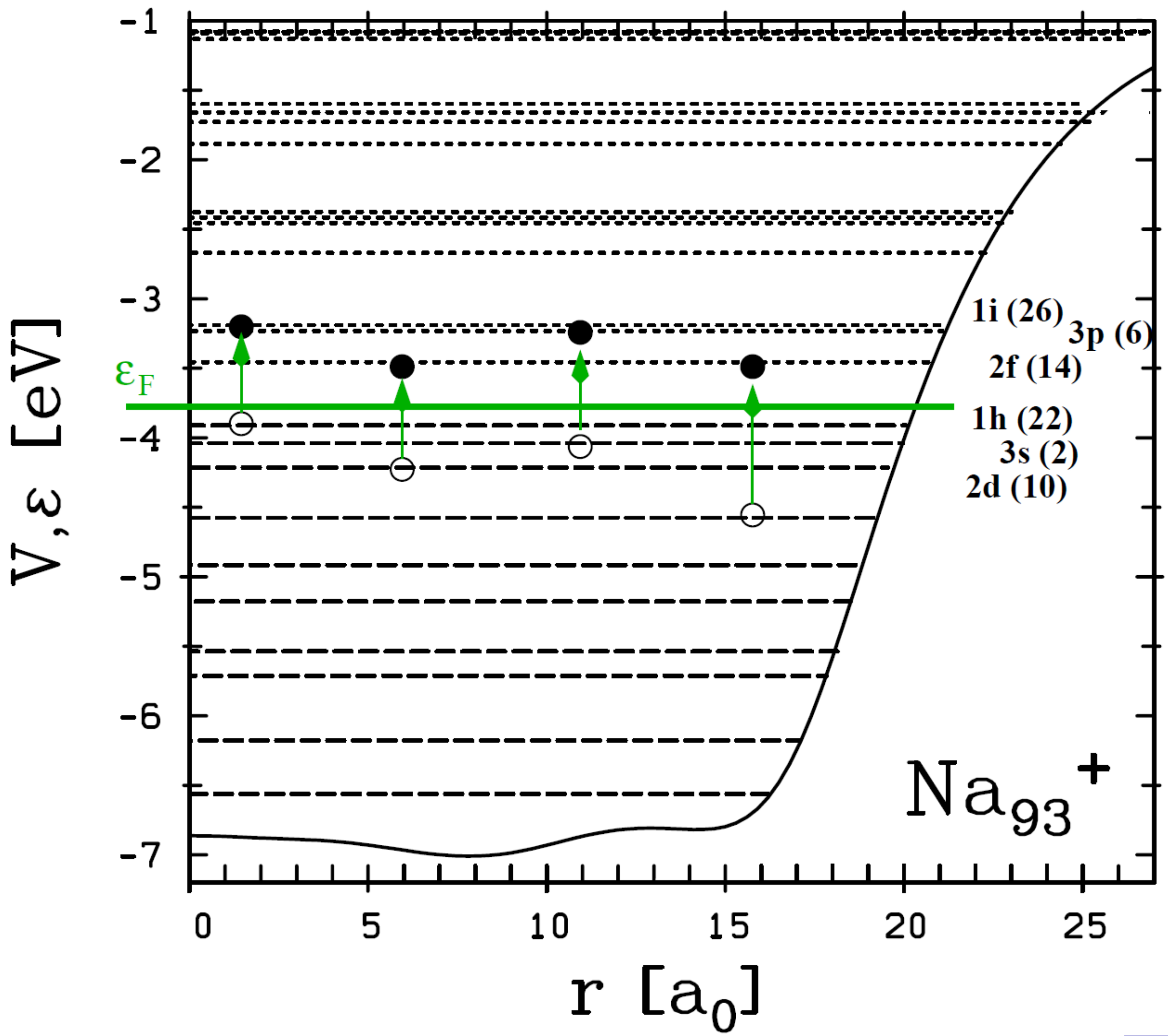
STANDARD method:
allow for correlated ground state

RPA random-phase approximation

QRPA quasi-particle RPA

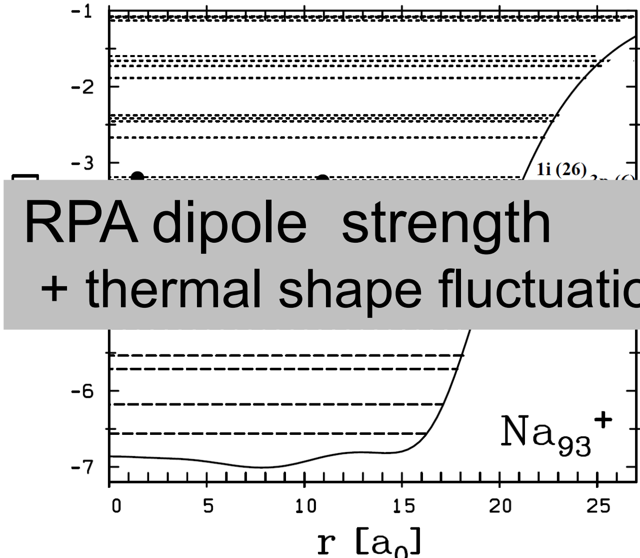
S-,E-,C-RPA
second-, extended, continuum RPA

atomic Na_{93}^+ Cluster



single-electron levels
and
some ph - excitations

P.–G. Reinhard (Inst.Theor.Physik, Erlangen)

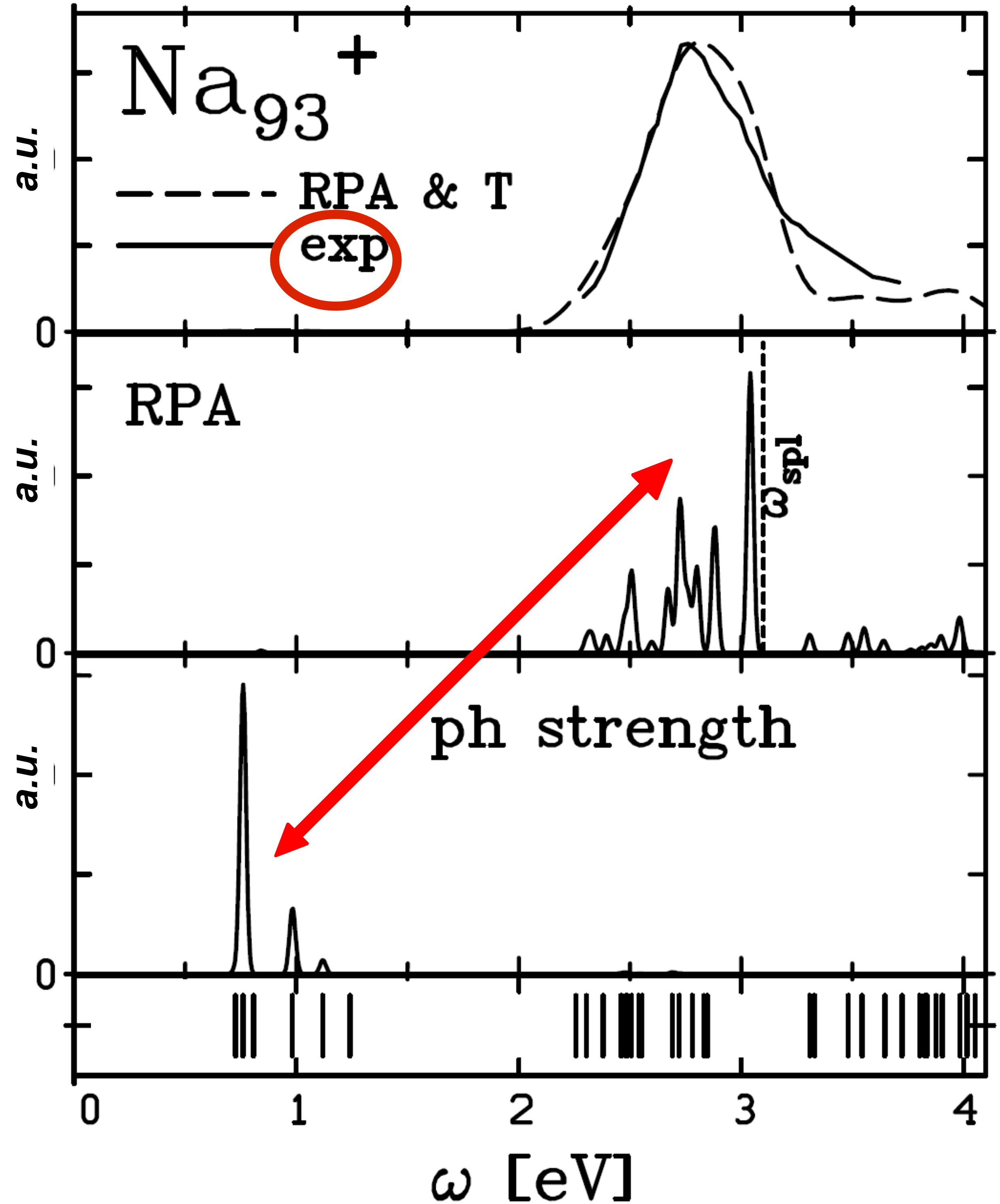


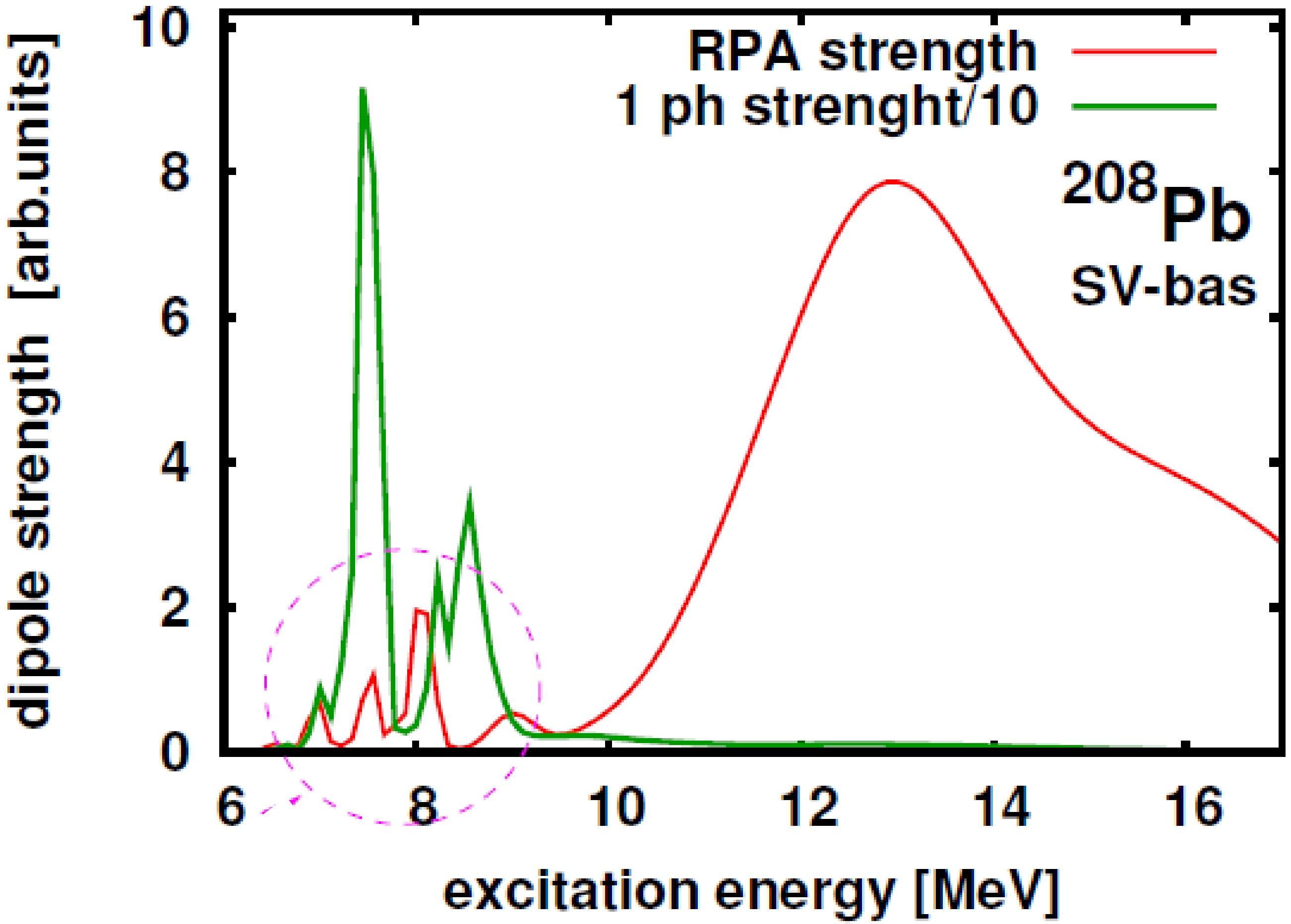
RPA dipole strength
+ thermal shape fluctuations

RPA dipole strength
(notice up-shift !)

Dipole strength
pure 1p-1h transitions

Dipole (L = 1)
pure 1p-1h transitions





1ph dipole strength gathers in narrow energy band

looks "resonance like" but is composed of several different 1ph states

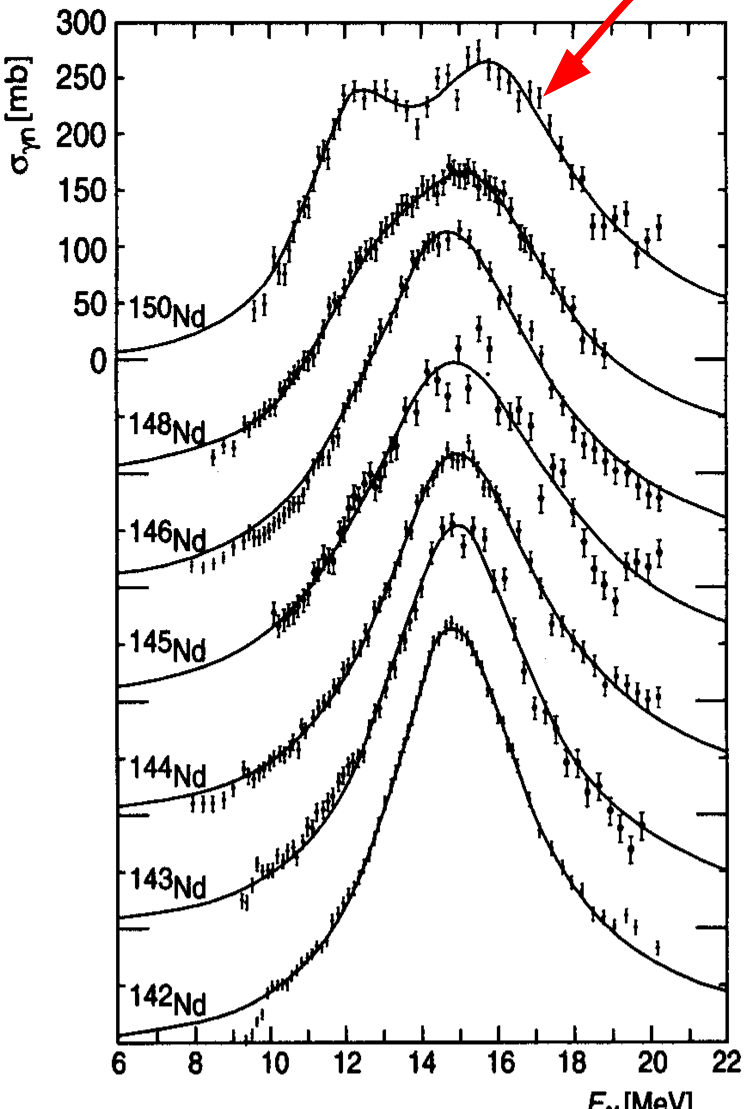
RPA dipole strength collected in resonance peak (and somewhat fragmented to 1ph ...)

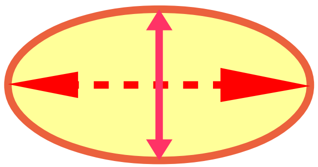
Watch green curve only !

Theoretical description of giant resonances – microscopic approach

Keywords:

mean field





deformation splitting

ancoff approximation

-phase approximation

Include pairing:
Open-shell nuclei, deformation

article RPA

ended, continuum RPA

Theoretical description of giant resonances – microscopic approach

Keywords:

Level of sophistication

mean field

TDA Tamm-Dancoff approximation

RPA random-phase ap

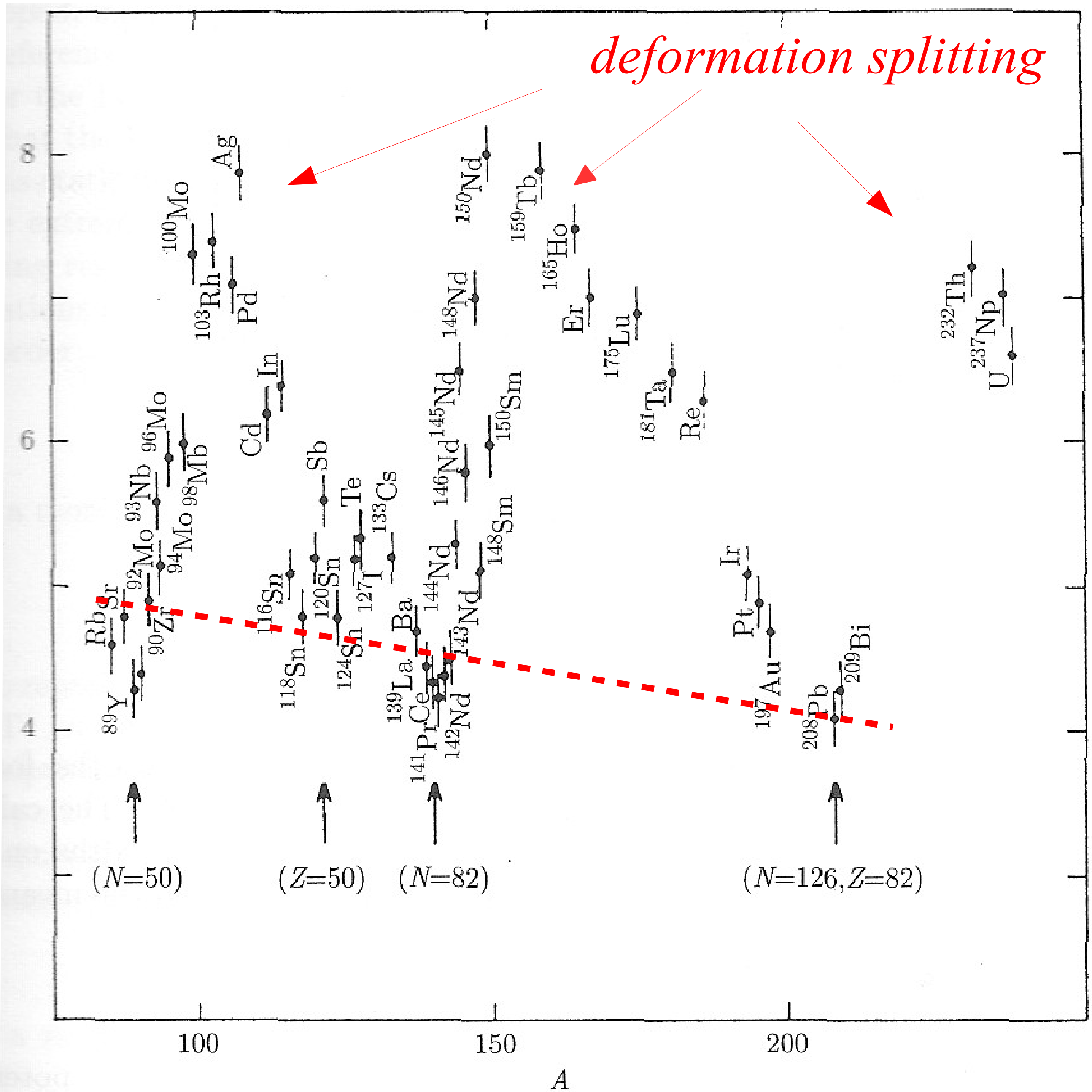
QRPA quasi-particle

S-,E-,C-RPA
second-, extended, continuum RPA

WIDTH

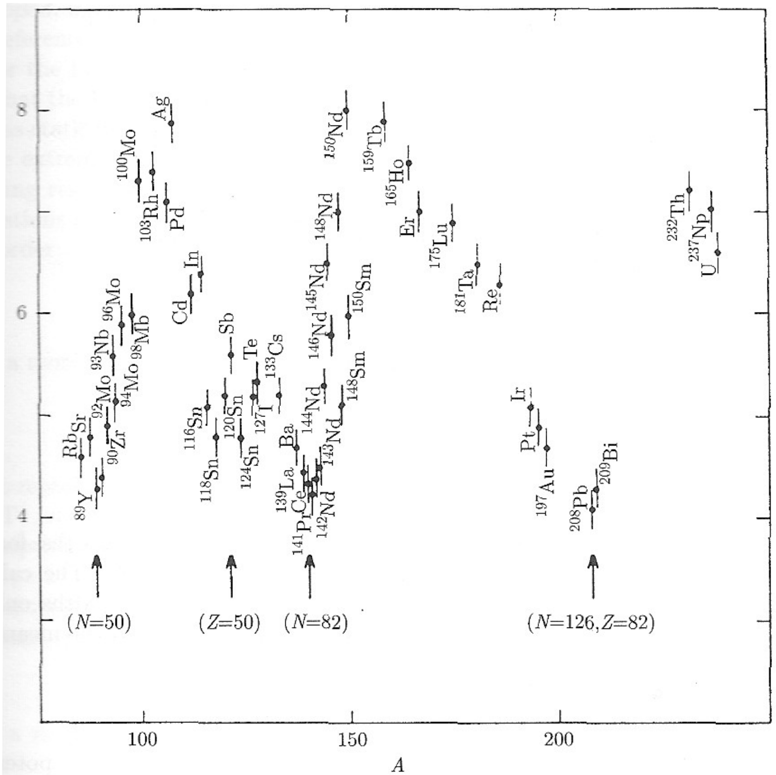
of giant resonances

WIDTH of GDR in heavy nuclei



closed shell nuclei:
Γ ~ 4 – 5 MeV

giant resonances – WIDTH and Damping



^{208}Pb:

E_{GDR} = 13 MeV

Γ_{GDR} = 4 MeV

GDR vibration period T_s : $\mathbf{E_{GDR}} = h\nu = h / \mathbf{T_s}$

Heisenberg - lifetime τ : $\mathbf{\Gamma_{GDR}} = h / 2\pi \boldsymbol{\tau}$

^{208}Pb ==> $\boldsymbol{\tau = 0.5\ T_s}$

strongly damped motion !

giant resonances – WIDTH - damping

Apparent GR width due to -

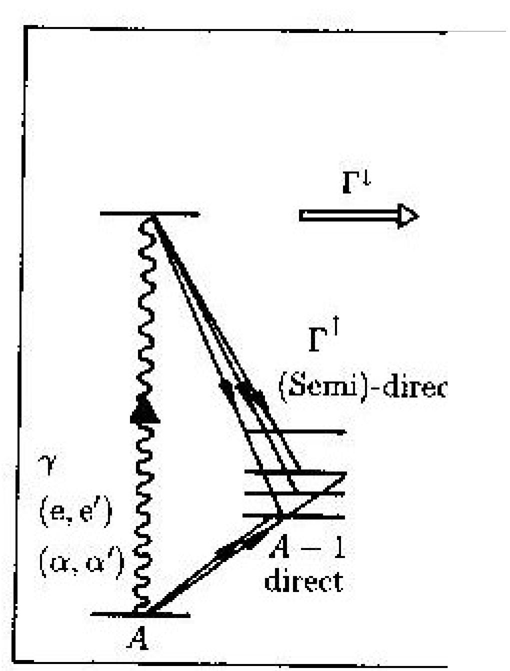
- fragmention of strength
  ('Landau damping')

- particle decay

GR as a 1p-1h state should decay predominantly into particular hole states in the (A-1) nucleus

However:
in heavier nuclei mainly statistical decay observed !

==> coupling to
2p-2h.....



' spreading width '

Damping / Width of giant resonances :

Strength fragmentation (Landau damping)

Deformation splitting (open-shell nuclei)

Direct particle decay (lighter nuclei): $\Gamma^{\uparrow}$ *escape width*

Statistical (compound nucleus) decay: $\Gamma^{\downarrow}$ *spreading width*

What do we (hope to) learn from GR's ?

unperturbed particle-hole states ↔ mean field

collective state ↔ interaction between ph states

➔ learn about <u>effective in-medium interactions</u>

(can be differentiated .. ΔL, ΔT, ΔS)

GR's are density vibrations → <u>learn about nuclear *bulk* properties :</u>

Finite matter (i.e. nuclei): radii, deformations, skins, clusters ...(GEOMETRY)

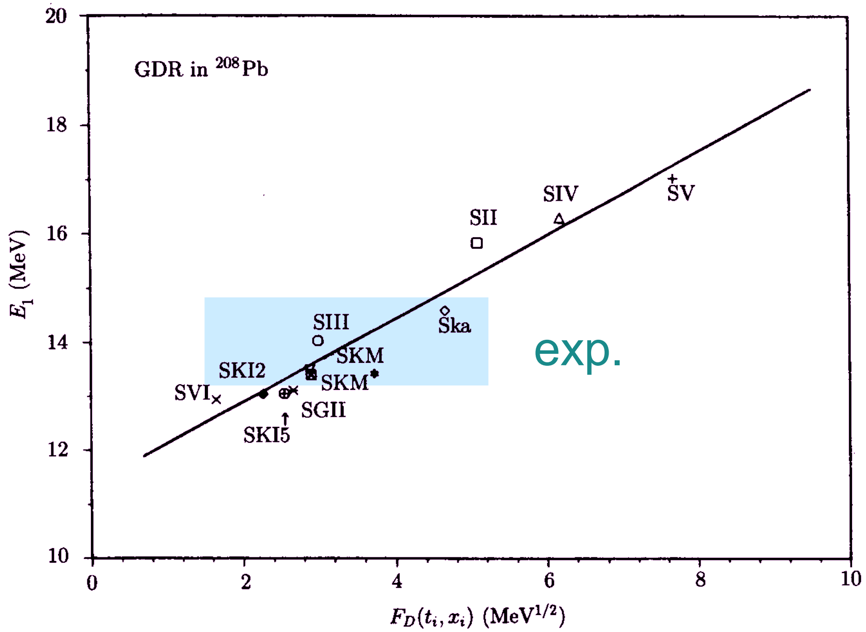
Infinite matter: symmetry energy, compressibility etc.

restricted, however, to around saturation density and (near) zero temperature

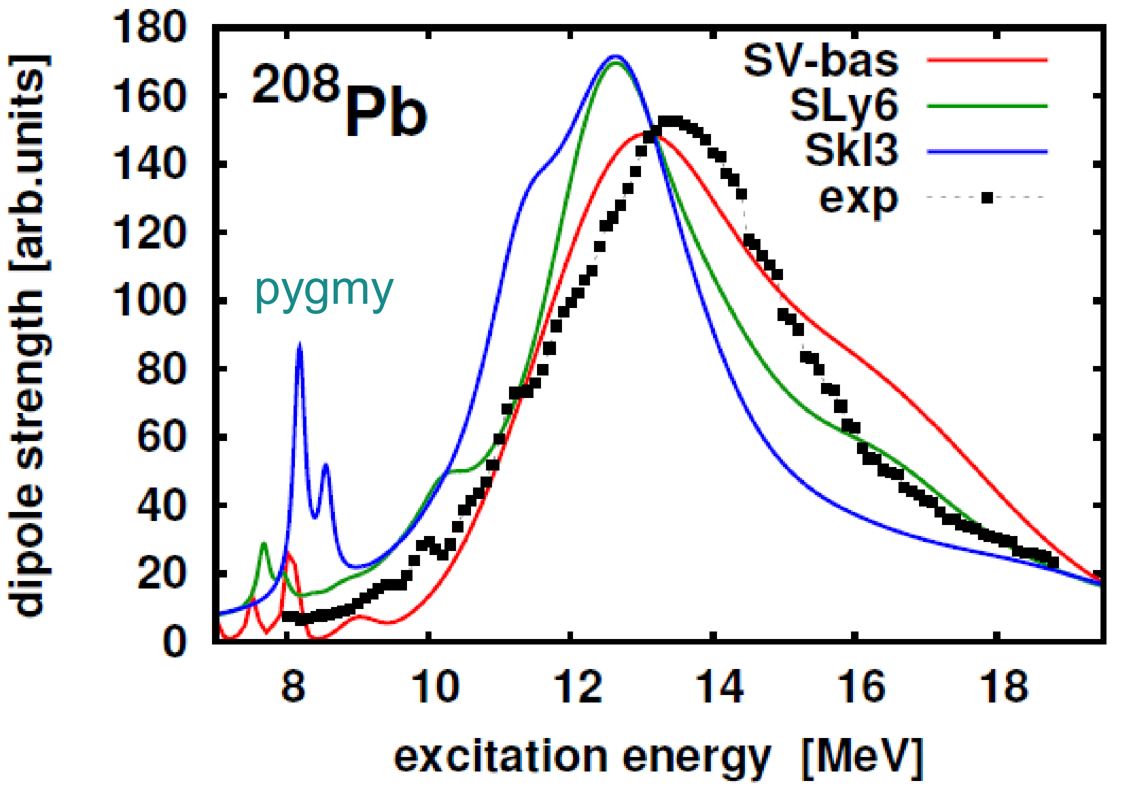
<u>reaction and decay rates</u> (astrophysical interests)

test of effective forces

GDR centroid energy



GDR strength distribution for several Skyrme forces



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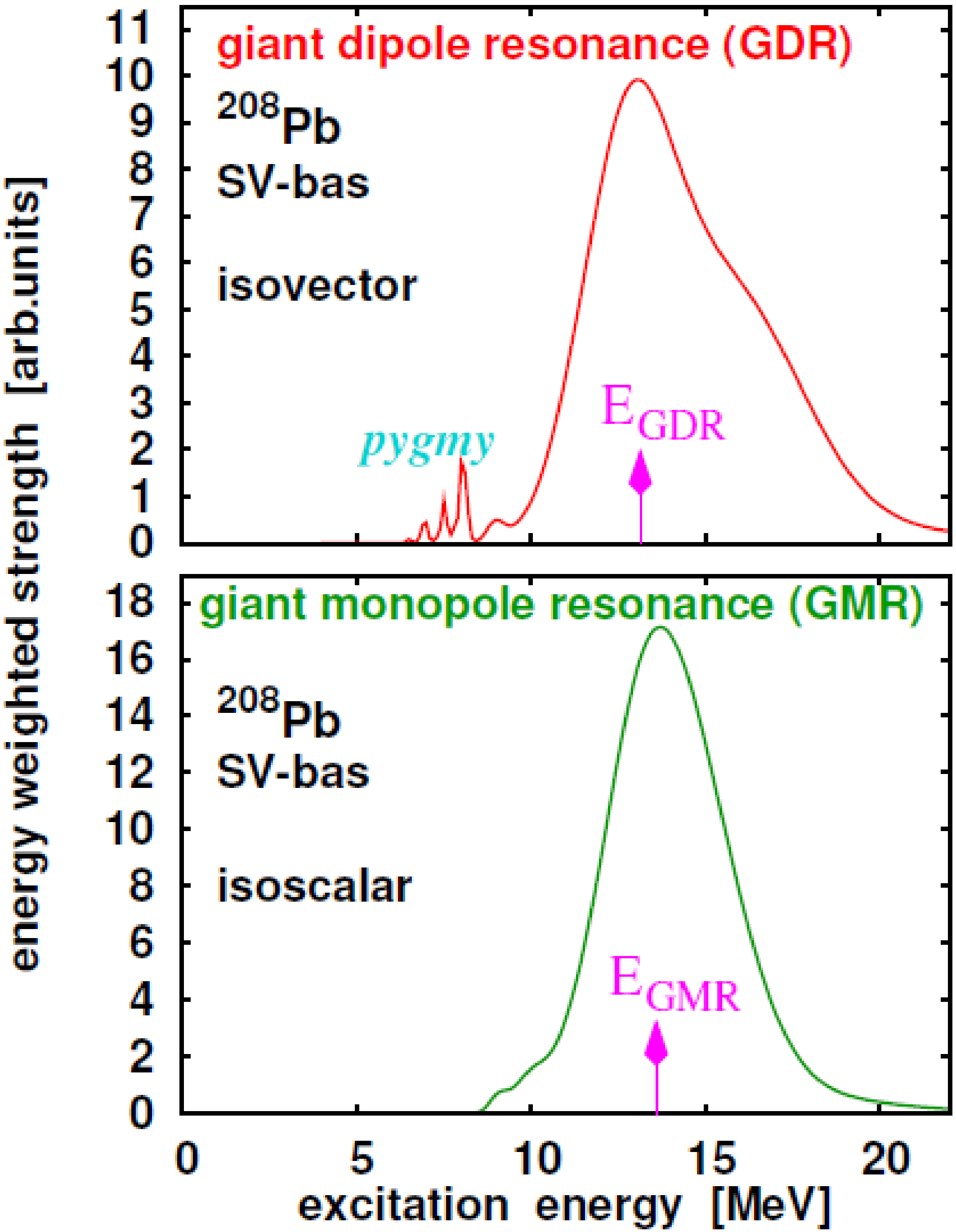
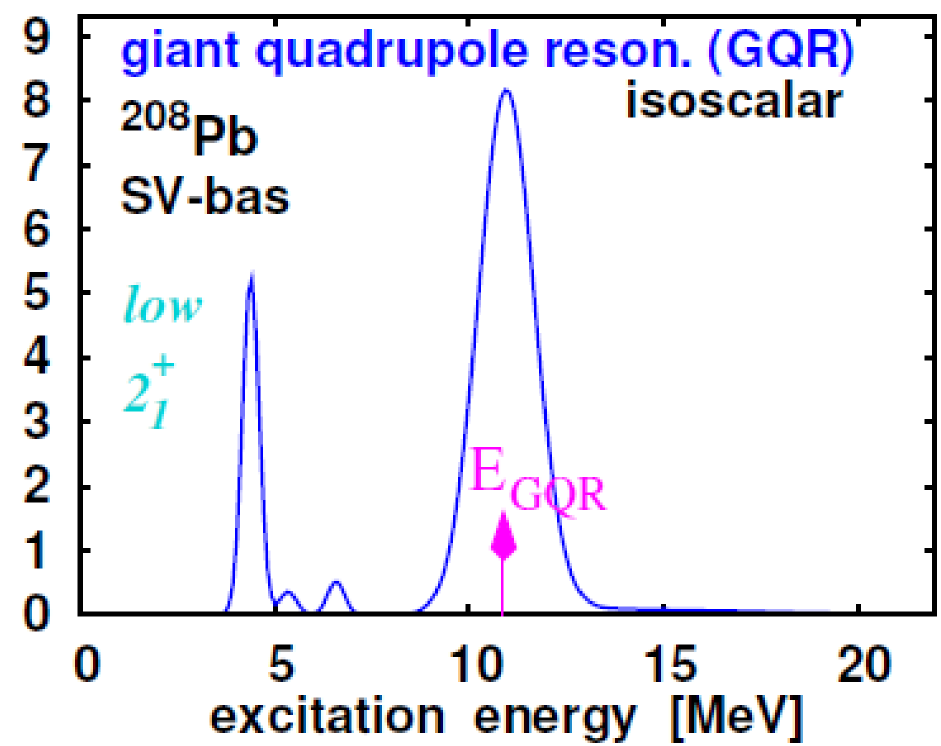
Collective resonance excitations (example ^{208}Pb)

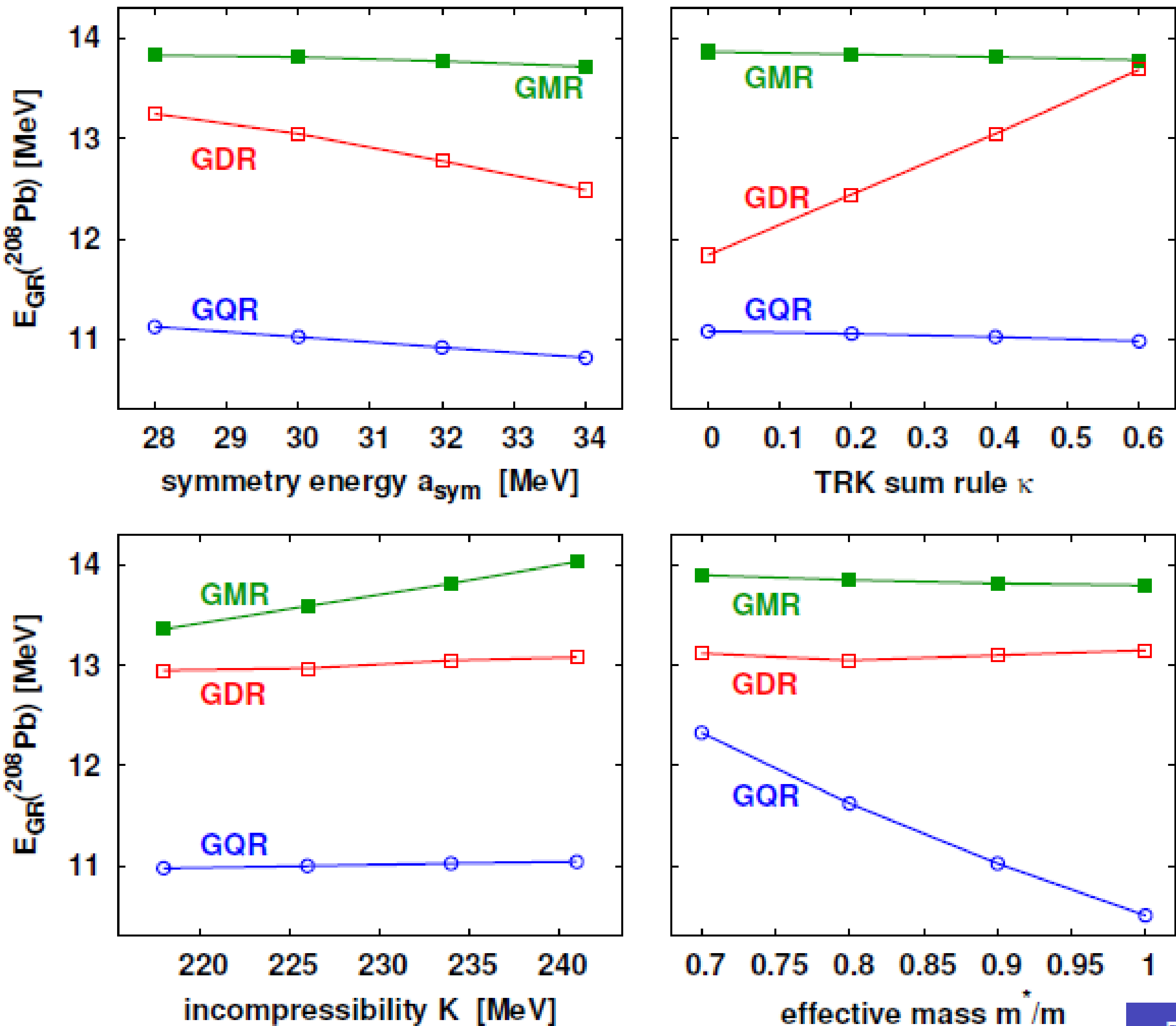


marked resonance peaks
in the region E ~ 12 MeV
well characterizeable by
one resonance energy

width: Landau fragmentation
escape, 2ph collisions



Systematic variation of Skyrme forces



each bulk property is sensitive preferably to one of the 3 modes:

K	$\leftrightarrow$	*GMR*
m^*/m	$\leftrightarrow$	*GQR*
a_{sym}, κ	$\leftrightarrow$	*GDR*

Sum Rules

Sum rules may be derived from algebraic relations between transition operators and (powers of) the Hamiltonian

Energy-weigthed sum rules are model independent to the extent that

– nn interactions do not depend on the particle momenta (electric isoscalar transitions)

– and charge-exchange components are absent (electric isovector transitions)

some Sum rules

GDR:

TRK : $\int \sigma(E)\, dE \sim N Z / A$

$\int \sigma(E)/E\, dE \sim N Z / A < r^2 >_p$

Migdal: $\int \sigma(E)/E^2\, dE \sim R^2 A / E_{sym}$

$\sigma(E) \sim E \cdot dB(E1, 0 \rightarrow E)/dE$

Cluster: $TRK = TRK_1 + TRK_2 + TRK_{12}$

other sum rules:

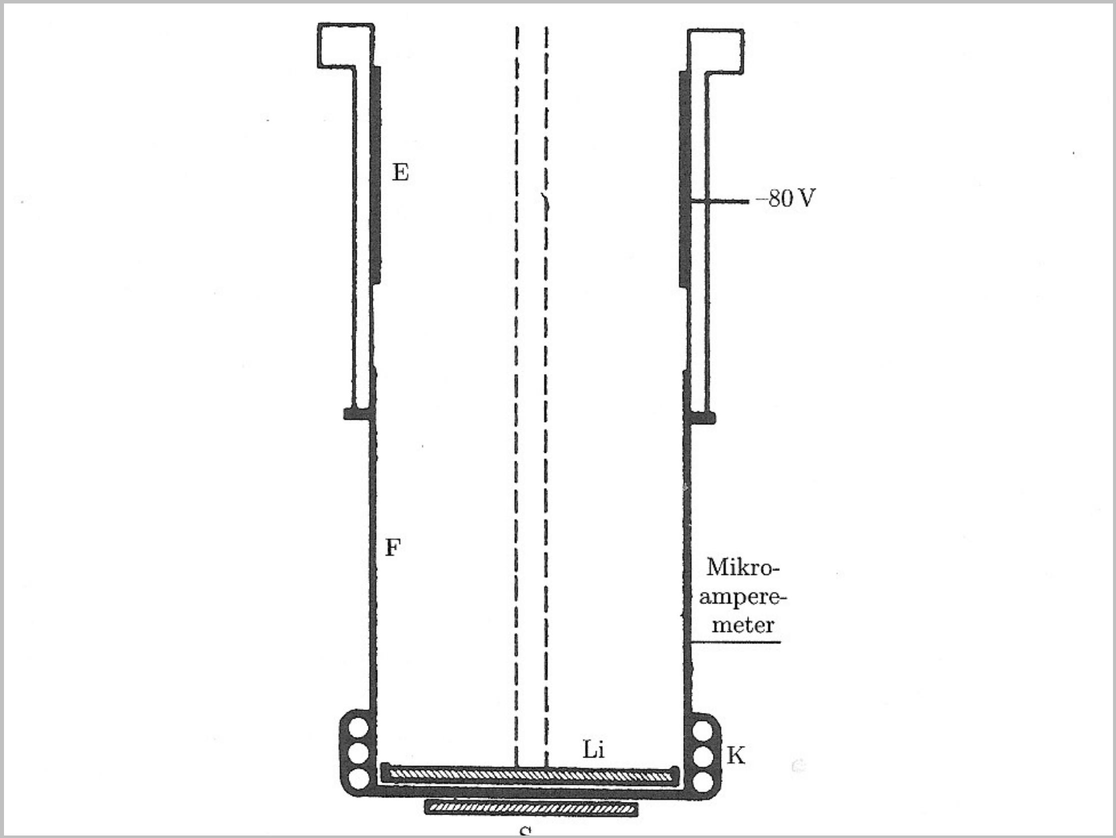
Ikeda: $S_-(GT) - S_+(GT) = 3(N\text{-}Z)$

$S_-(IVSDR) - S_+(IVSDR) \sim N <r^2>_n - Z <r^2>_p$

etc..

History
- Milestones

1937 - Bothe and Gentner



300 keV proton 'beam'

→ Li(p, γ)

→ γ-radiation onto sample S, e.g. ^{63}Cu

→ radioactivity from (γ,n) measured

„ vielleicht spielen hier Resonanz - verhältnisse eine entschiedene Rolle „

History
- Milestones

1937 - Bothe and Gentner

1947 – Balwin and Klaiber
GDR in γ-absorption spectra

19717“ – isGQR Pitthan and Walcher

1977 – isoscalar monopole

:

:

1980... GR in hot nuclei

1985... M1 scissor mode

1985... multiphonon GDR,GQR

~ 2000 …. dipole strength in unstable nuclei