Some introduction to giant resonances and related physics
Experiment and Theory

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Lectures at 4th international conference on "Collective Motion in Nuclei under Extreme Conditions" (COMEX4)
22-26 October 2012

Lecture 1: Compression Modes

- **Introduction**
  Giant resonances: Fundamental modes of nuclear excitation
- **Importance of studying compression modes in nuclei**
  ISGMR and ISGDR excitation
- **Experimental studies**
  Incompressibility of nuclear matter
  Asymmetry term
- **Conclusions and outlook**

In the following:

IS = Iso-Scalar

IV = Iso-Vector

S = Spin

G = Giant

M = Monopole

D = Dipole

Q = Quadrupole

O = Octupole

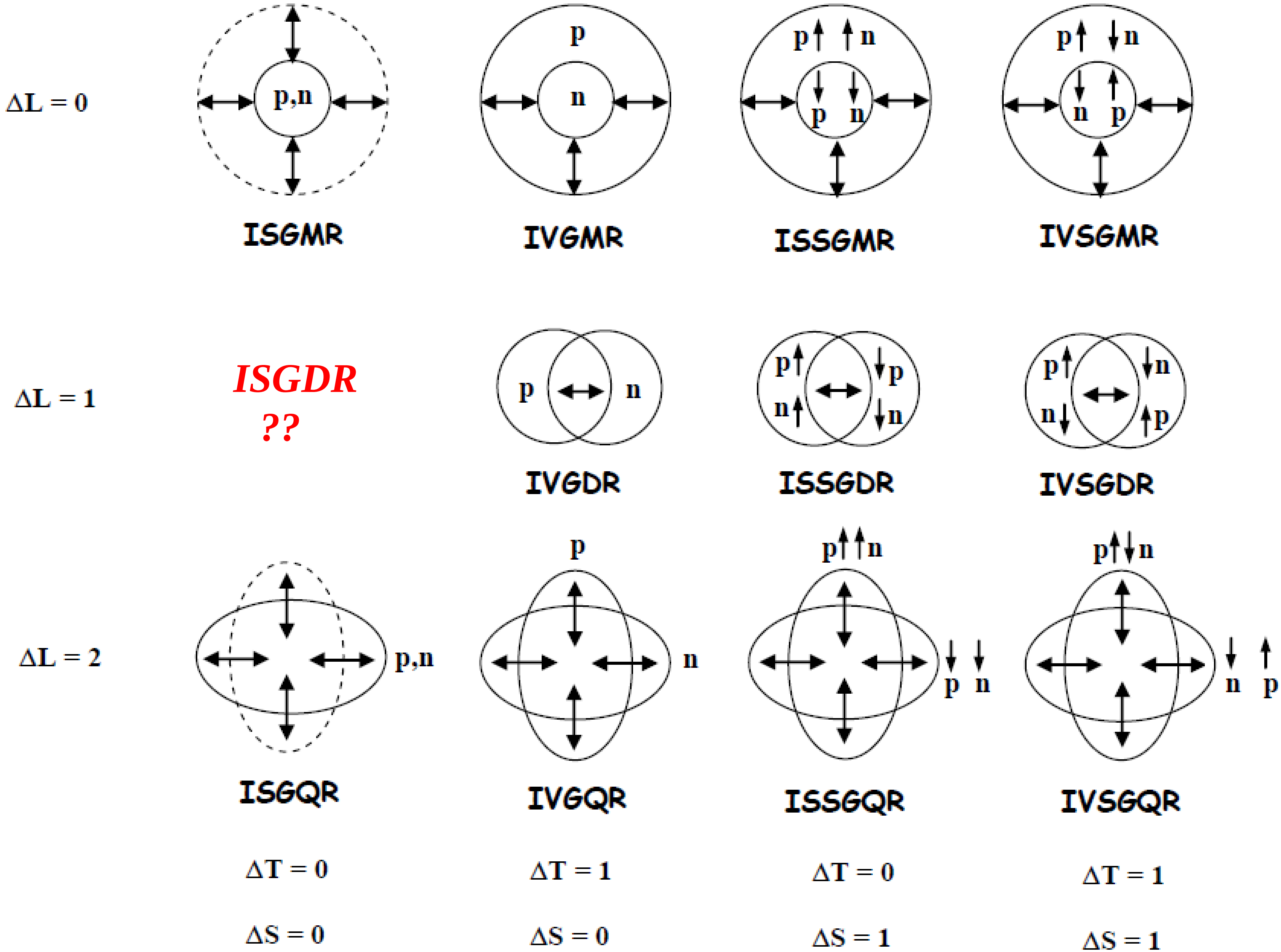
E.g. ISGMR = Isoscalar giant monopole resonance

ISGDR = Isoscalar giant dipole resonance

IVGDR = Isovector giant dipole resonance

IVSGMR= Isovector spin giant monopole resonance

IVSGDR = Isovector spin giant dipole resonance


ΔL = 0
p,n
ISGMR
p
n
IVGMR
p n
p n
ISSGMR
p n
n p
IVSGMR
ΔL = 1
ISGDR
??
p
n
IVGDR
p
p
n
n
ISSGDR
p
n
n
p
IVSGDR
ΔL = 2
p,n
ISGQR
p
n
IVGQR
p n
p n
ISSGQR
p n
n p
IVSGQR
ΔT = 0
ΔS = 0
ΔT = 1
ΔS = 0
ΔT = 0
ΔS = 1
ΔT = 1
ΔS = 1

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.**

Microscopic structure of ISGMR & ISGDR

Transition operators:

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

Constant — Overtone

2ħω excitation

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

Spurious c.o.m. motion — Overtone

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

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

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

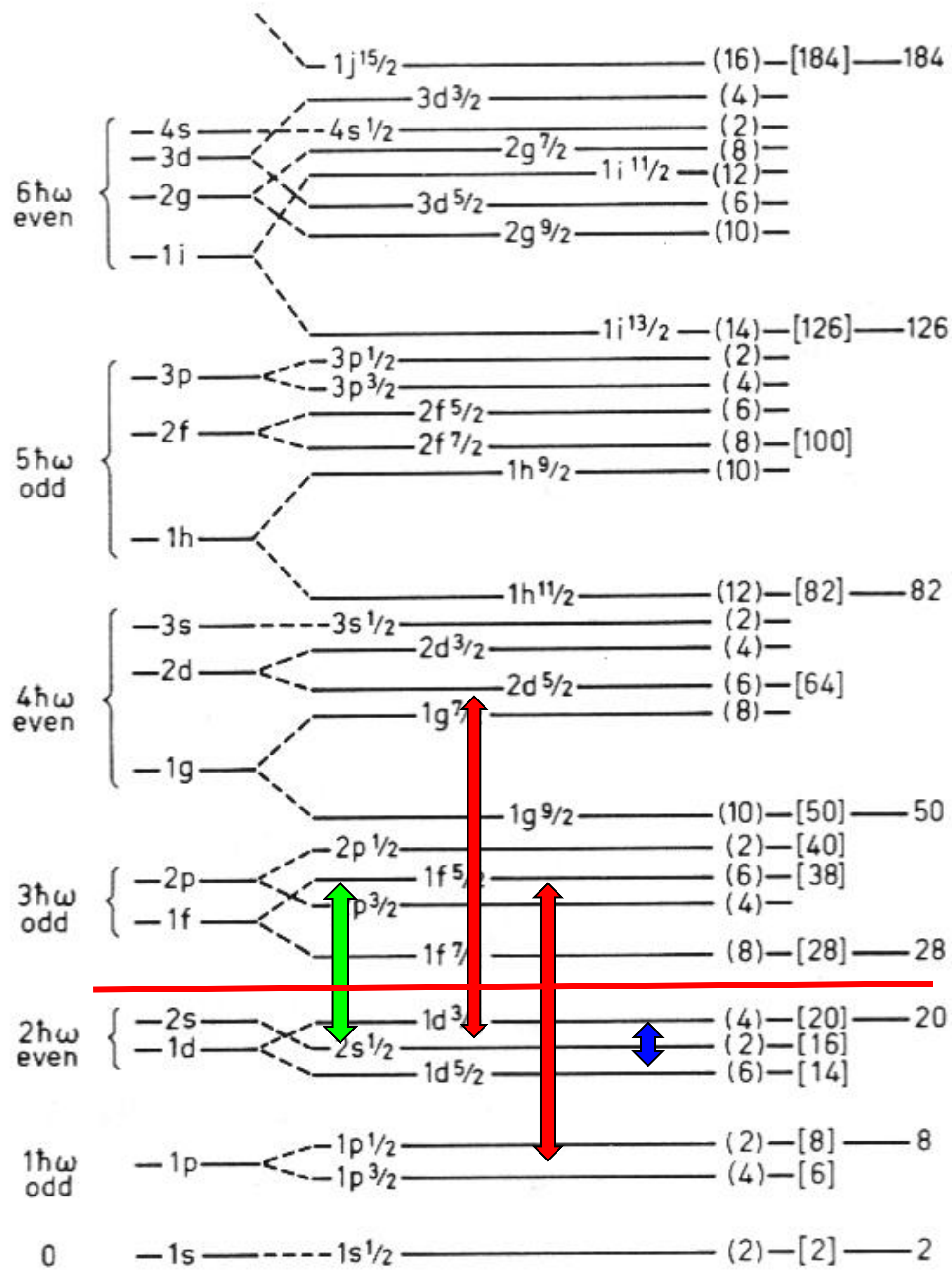
	ΔS=0, ΔT=0	ΔS=0, ΔT=1	ΔS=0, ΔT=1	ΔS=1, ΔT=1	ΔS=1, ΔT=1
L=0: Monopole	**ISGMR** r^2Y_0	**IAS** τY_0	**IVGMR** τr^2Y_0	**GTR** $\tau\sigma Y_0$	**IVSGMR** $\tau\sigma r^2Y_0$
L=1: Dipole	**ISGDR** r^3Y_1		**IVGDR** τrY_1		**IVSGDR** $\tau\sigma rY_1$
L=2: Quadrupole	**ISGQR** r^2Y_2		**IVGQR** τr^2Y_2		**IVSGQR** $\tau\sigma r^2Y_2$
L=3: Octupole	**LEOR, HEOR** r^3Y_3				

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

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

&

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



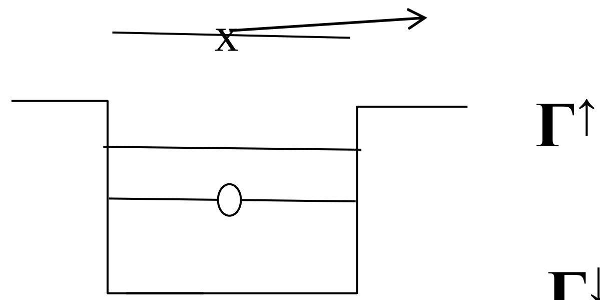
Decay of giant resonances

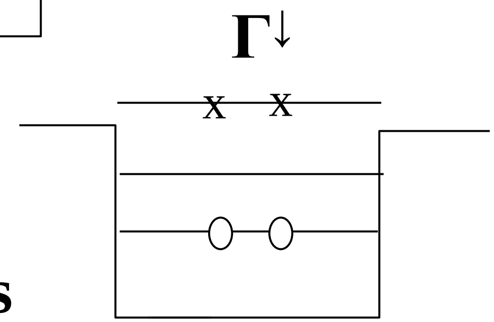
- **Width of resonance**

  $\Gamma, \Gamma^{\uparrow}, \ \Gamma^{\downarrow} \ (\Gamma^{\downarrow\uparrow}, \Gamma^{\downarrow\downarrow})$

  - **$\Gamma^{\uparrow}$: direct or escape width**
  - **$\Gamma^{\downarrow}$: spreading width**

  $\Gamma^{\downarrow\uparrow}$: pre-equilibrium, $\Gamma^{\downarrow\downarrow}$: compound

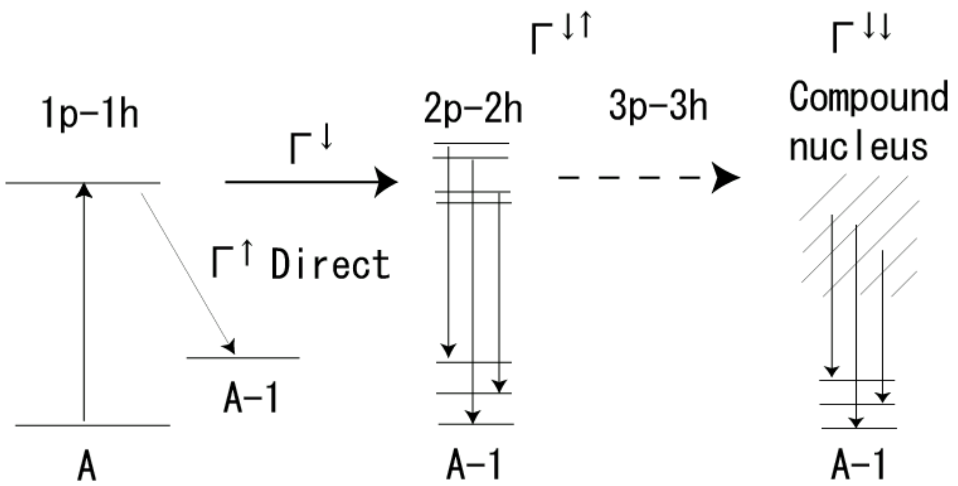




- **Decay measurements**

  ⇒ Direct reflection of damping processes

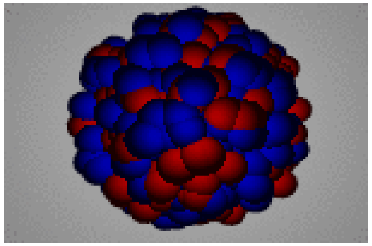
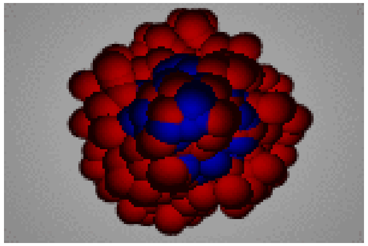
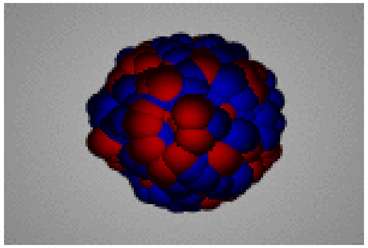
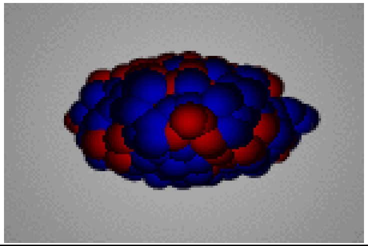
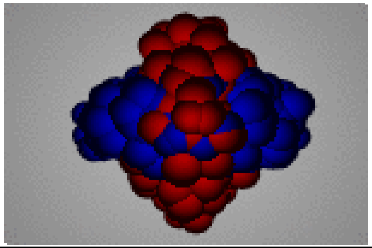
  Allows detailed comparison with theoretical calculations



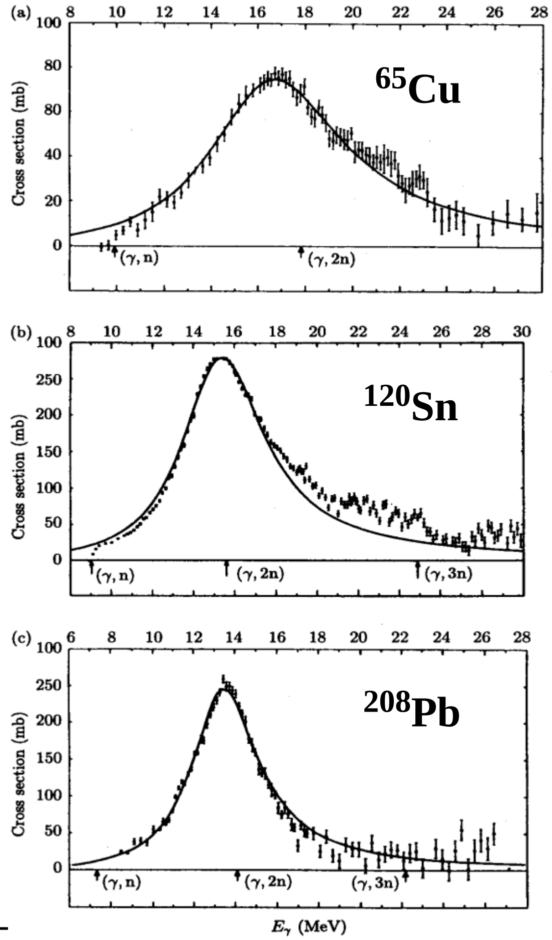
The collective response of the nucleus
Giant Resonances

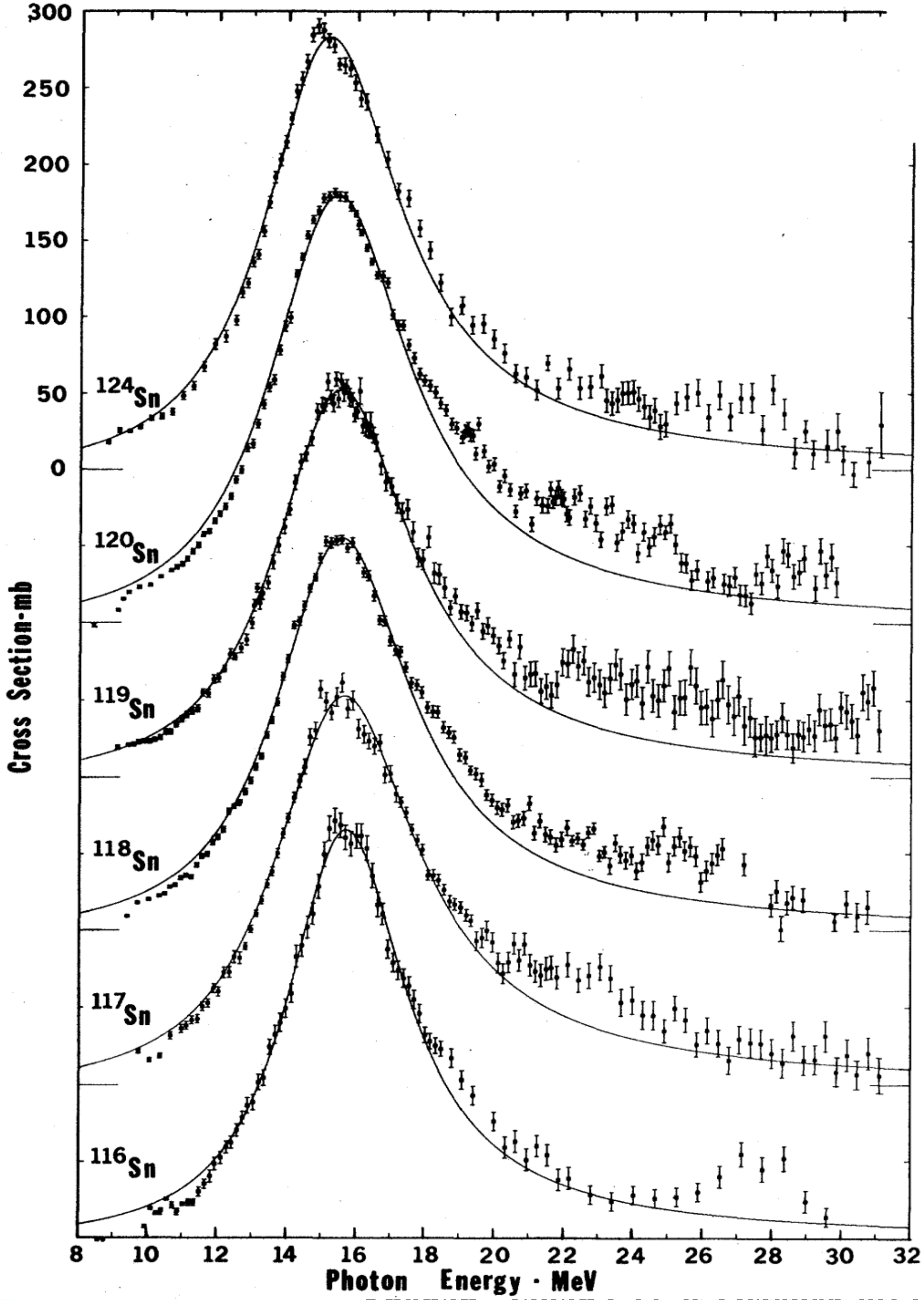
Electric giant resonances

Photo-neutron cross sections

	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

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

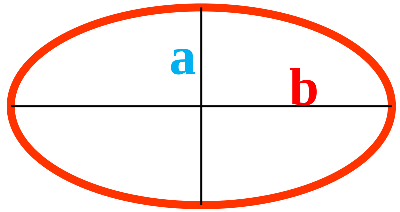




Measurement of the giant dipole resonance with mono-energetic photons

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

Nucleus	Centroid (MeV)	Width (MeV)
^{116}Sn	15.68	4.19
^{117}Sn	15.66	5.02
^{118}Sn	15.59	4.77
^{119}Sn	15.53	4.81
^{120}Sn	15.40	4.89
^{124}Sn	15.19	4.81

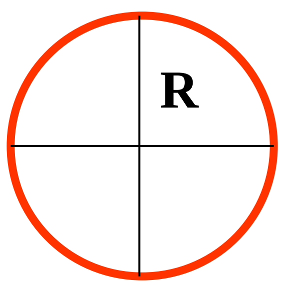


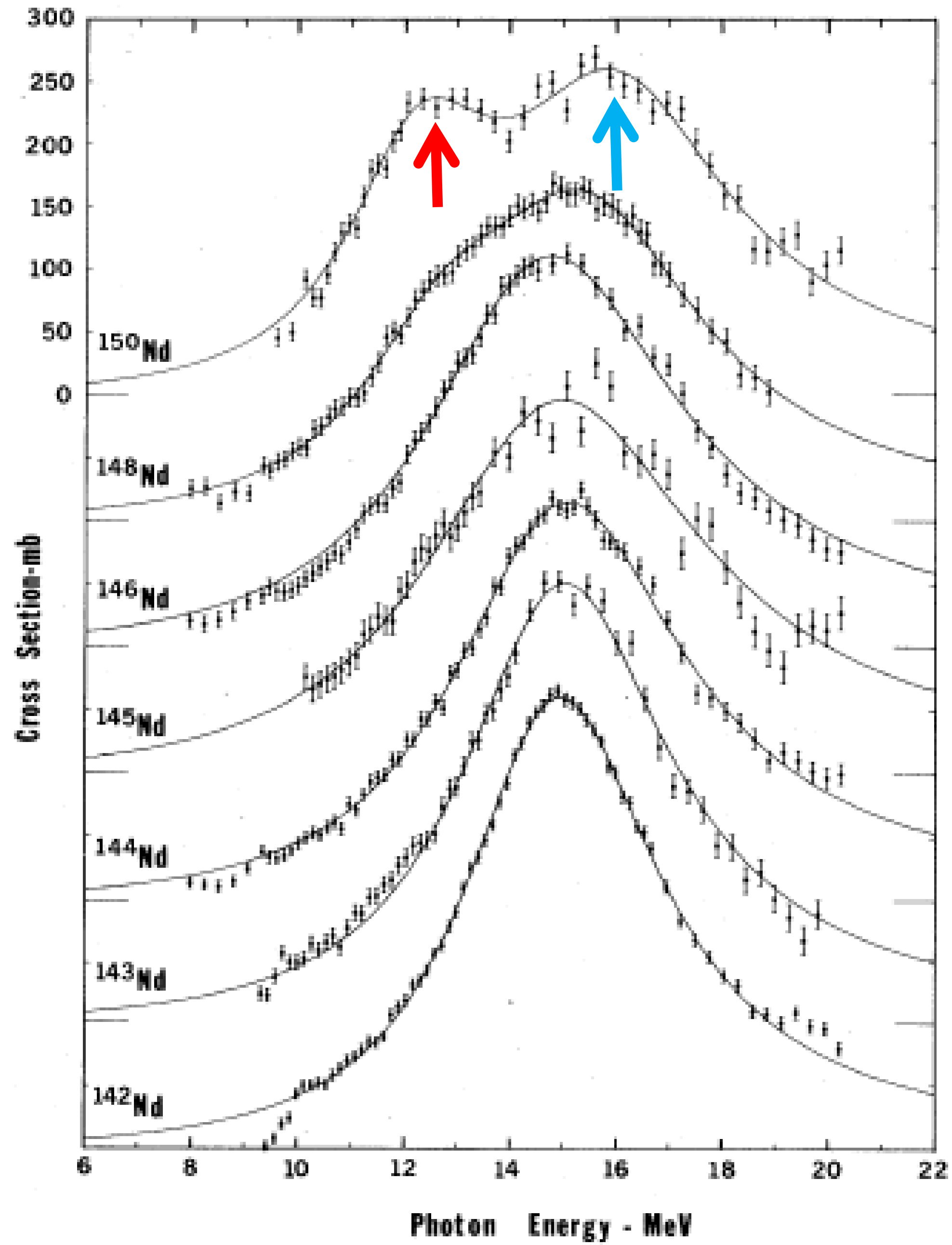
Quadrupole deformation:
$\beta_2 = 0.275$

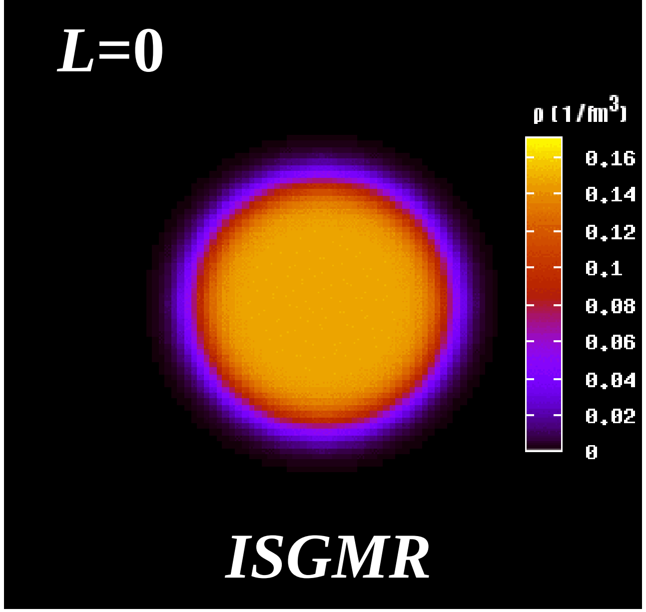
Excitation energies:
$E_2/E_1 = 0.911\eta + 0.089$

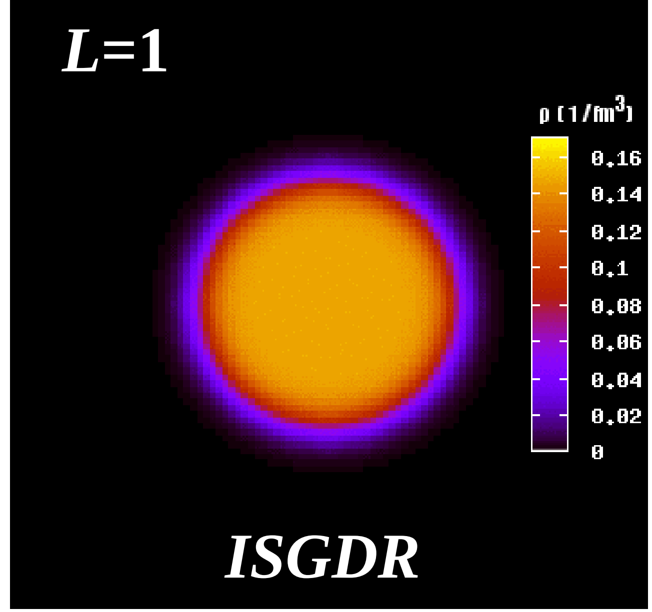
Where $\eta = b/a$

$s_1/s_2 = 1/2$

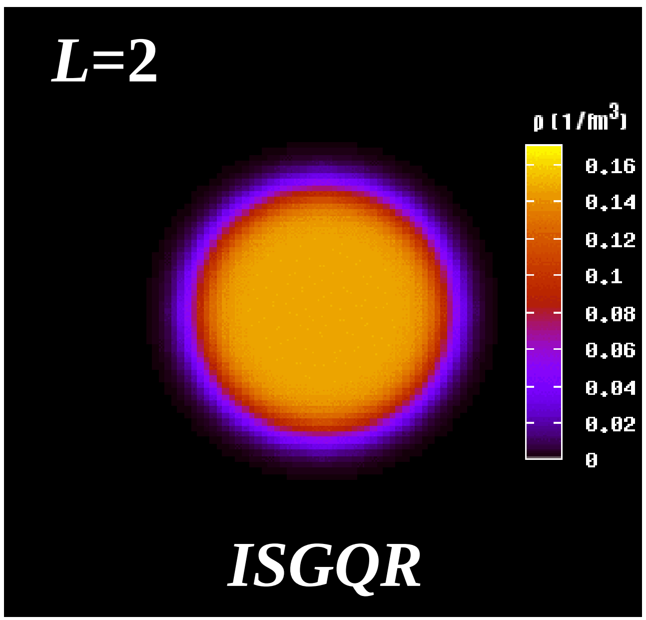


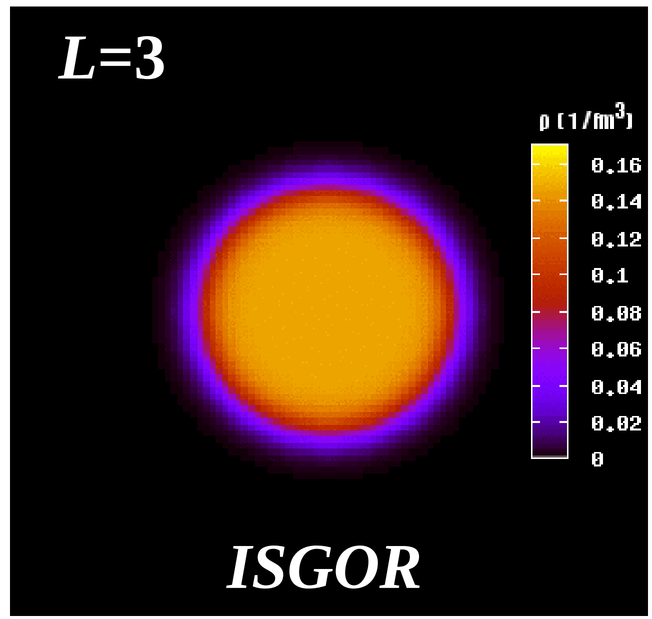



L=0
ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ISGMR


L=1
ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ISGDR

M. Itoh


L=2
ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ISGQR


L=3
ρ (1/fm³)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
ISGOR

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:

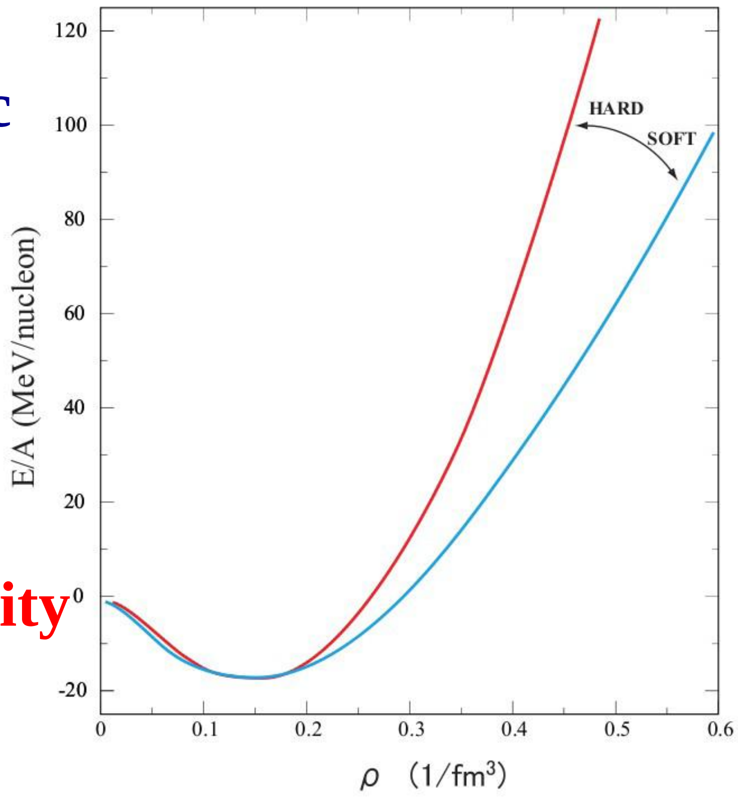
$$K = -V\frac{\partial P}{\partial V}$$

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

Equation of state (EOS) of nuclear matter:

More complex than for infinite neutral liquids:
Neutrons and protons with different interactions
Coulomb interaction of protons

1. **Governs the collapse and explosion of giant stars (supernovae)**

2. **Governs formation of neutron stars (mass, radius, crust)**

3. **Governs collisions of heavy ions.**

4. **Important ingredient in the study of nuclear properties.**

Isoscalar Excitation Modes of Nuclei

Hydrodynamic models/Giant Resonances

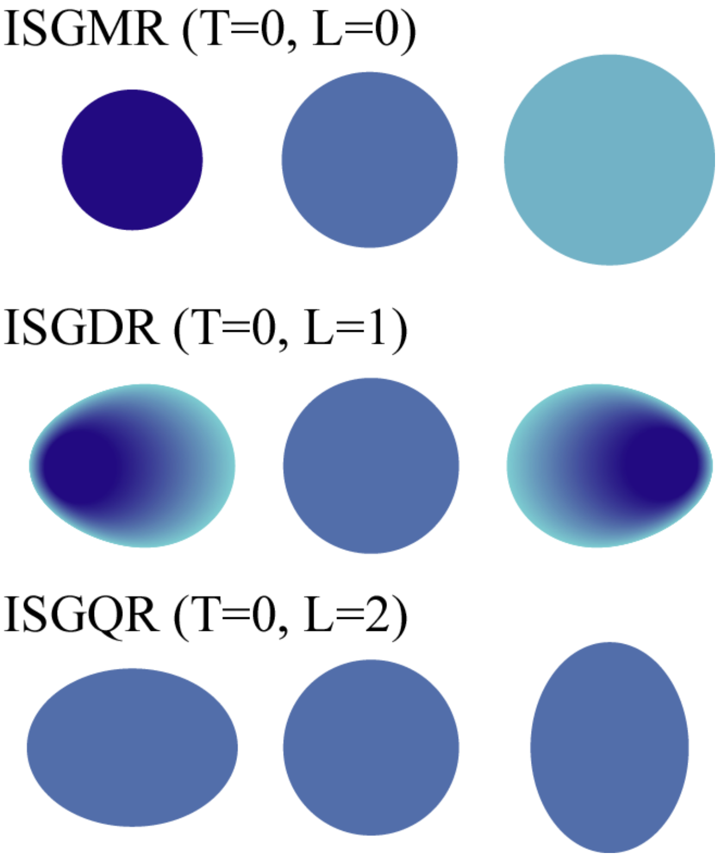
Coherent vibrations of nucleonic fluids in a nucleus.

Compression modes : ISGMR, ISGDR

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:

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

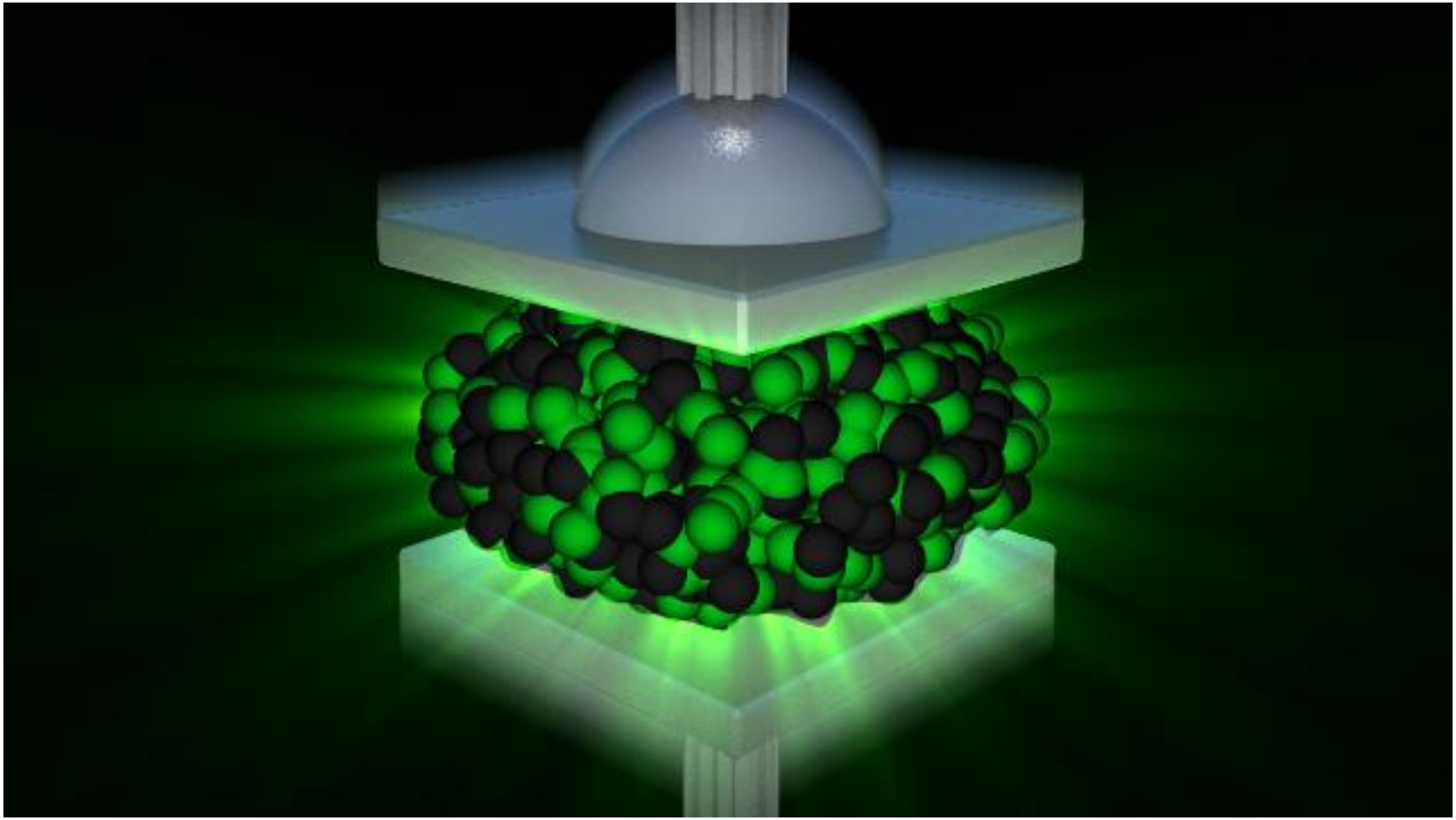
J.P. Blaizot, Phys. Rep. 64 (1980) 171

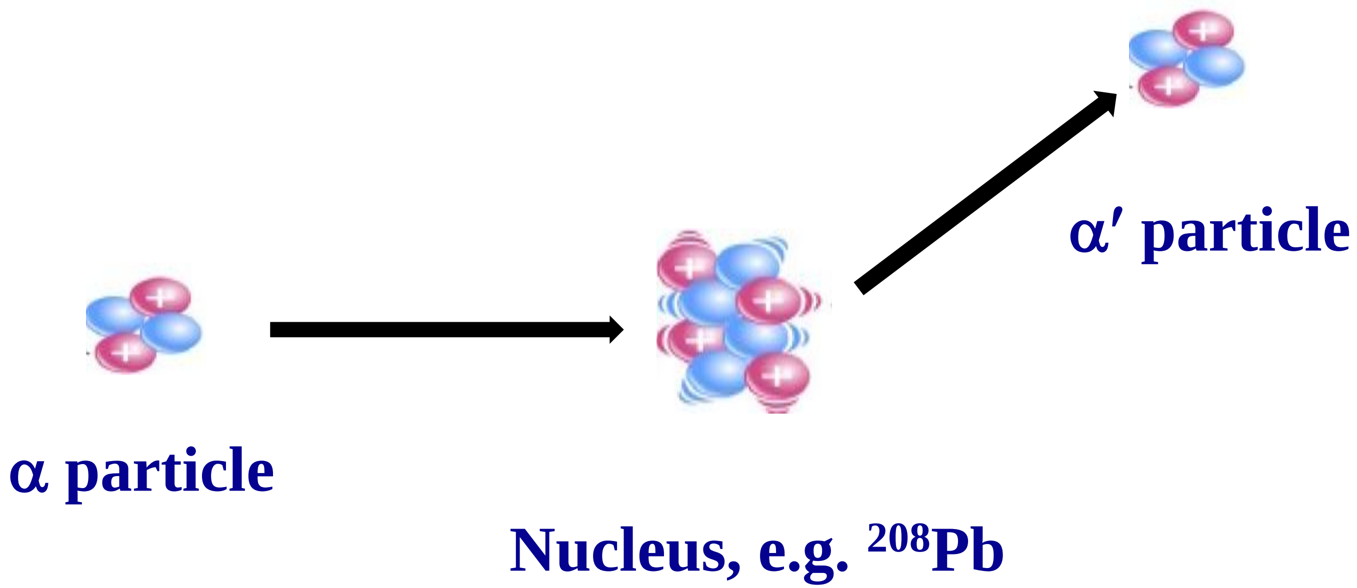
Giant resonances

- **Macroscopic properties: E_x, Γ, %EWSR**
- **Isoscalar giant resonances; compression modes**

  ISGMR, ISGDR ⇒ Incompressibility, symmetry energy

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

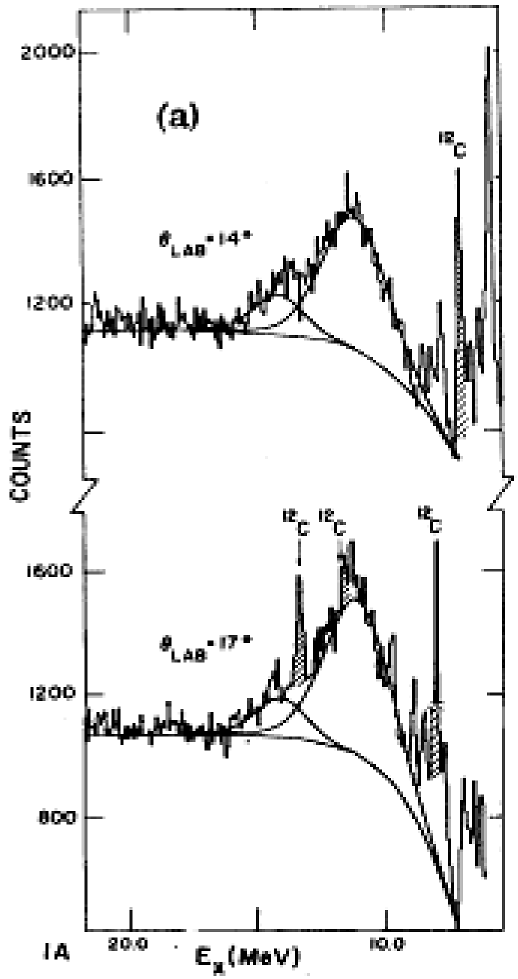




Inelastic α scattering

ISGQR, ISGMR

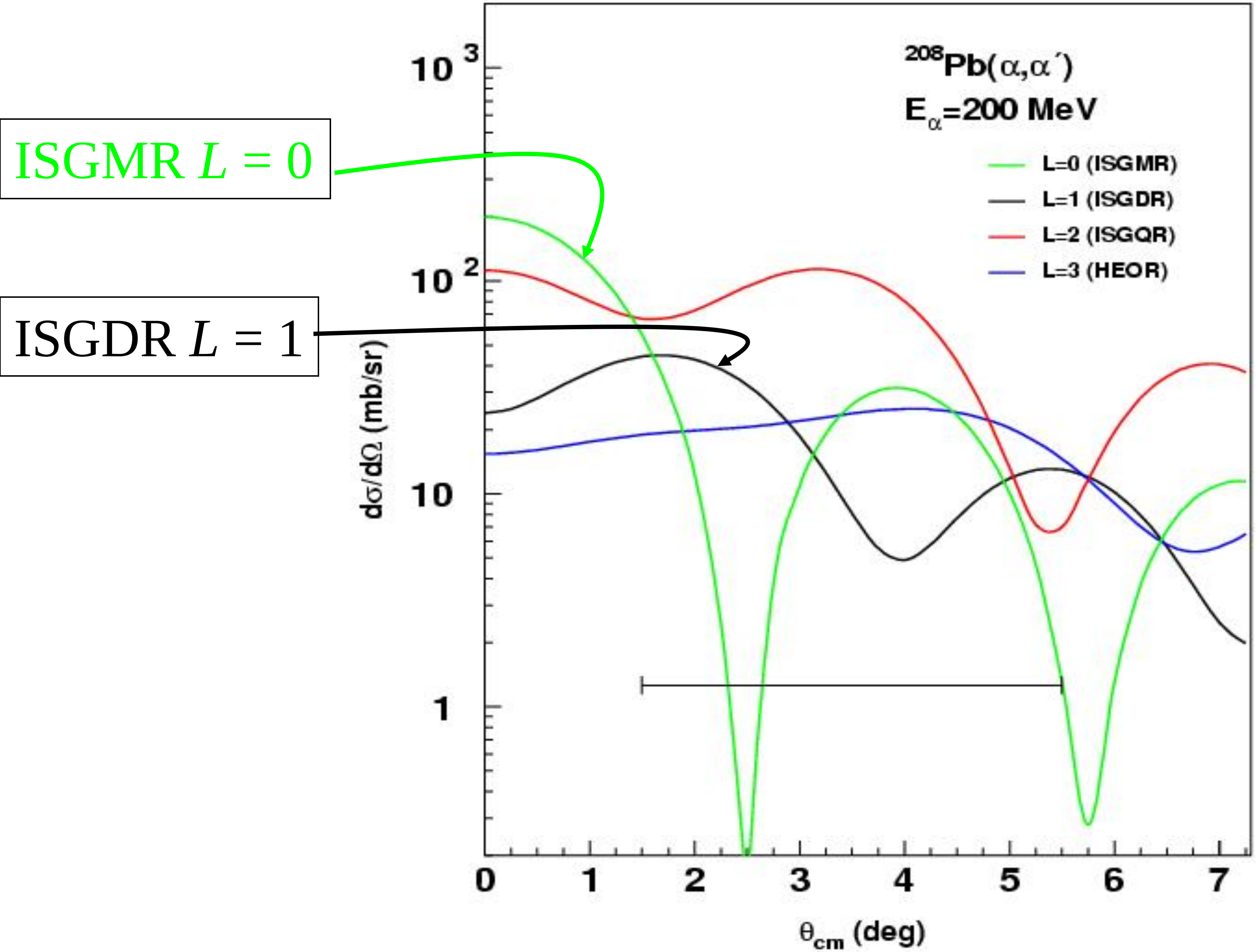
KVI (1977)



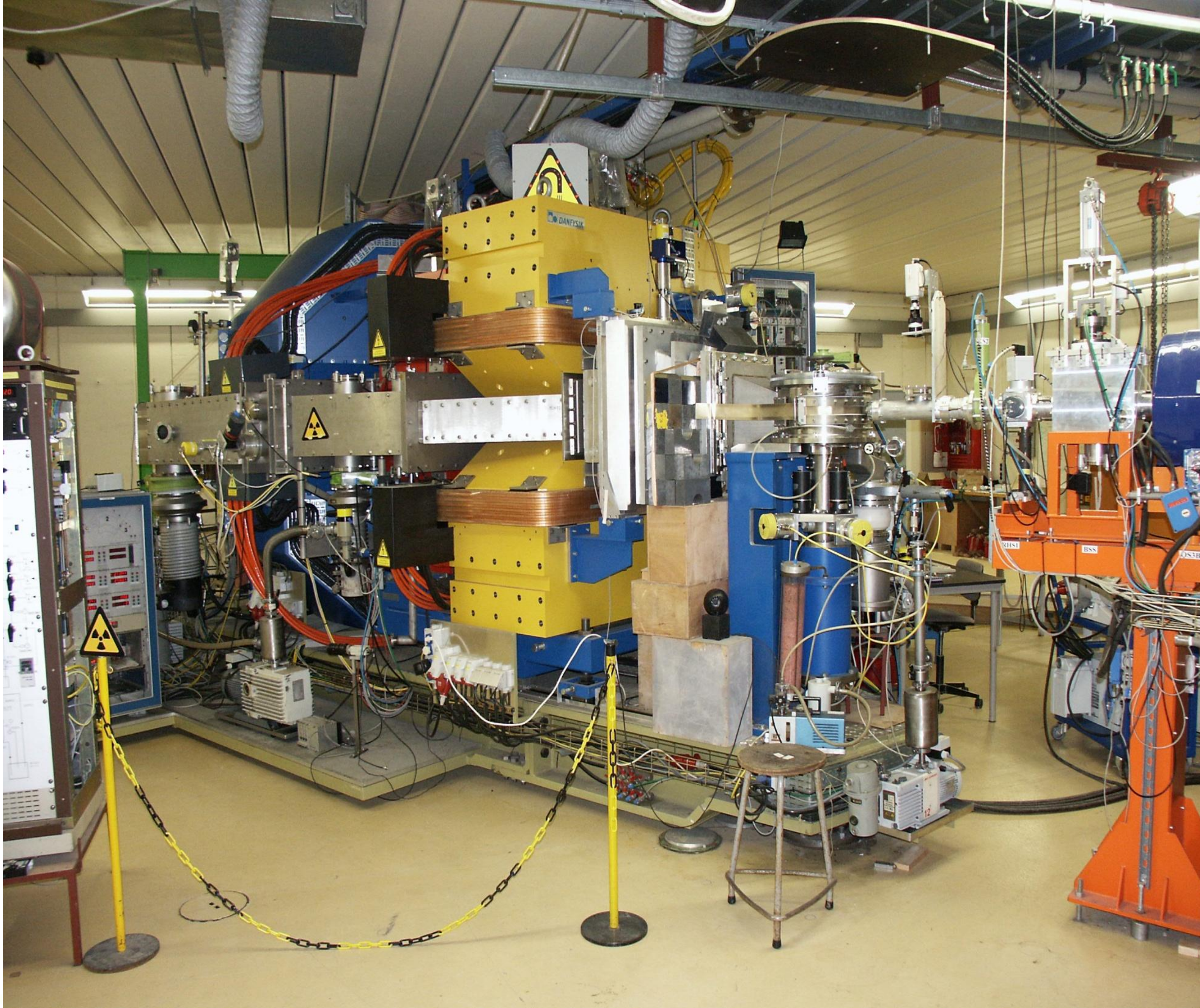
Large instrumental background!

⇐ ^{208}Pb(α,α′) at E_{α}=120 MeV

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



ISGMR L = 0
ISGDR L = 1
208Pb(α,α´)
Eα=200 MeV
L=0 (ISGMR)
L=1 (ISGDR)
L=2 (ISGQR)
L=3 (HEOR)
dσ/dΩ (mb/sr)
θcm (deg)



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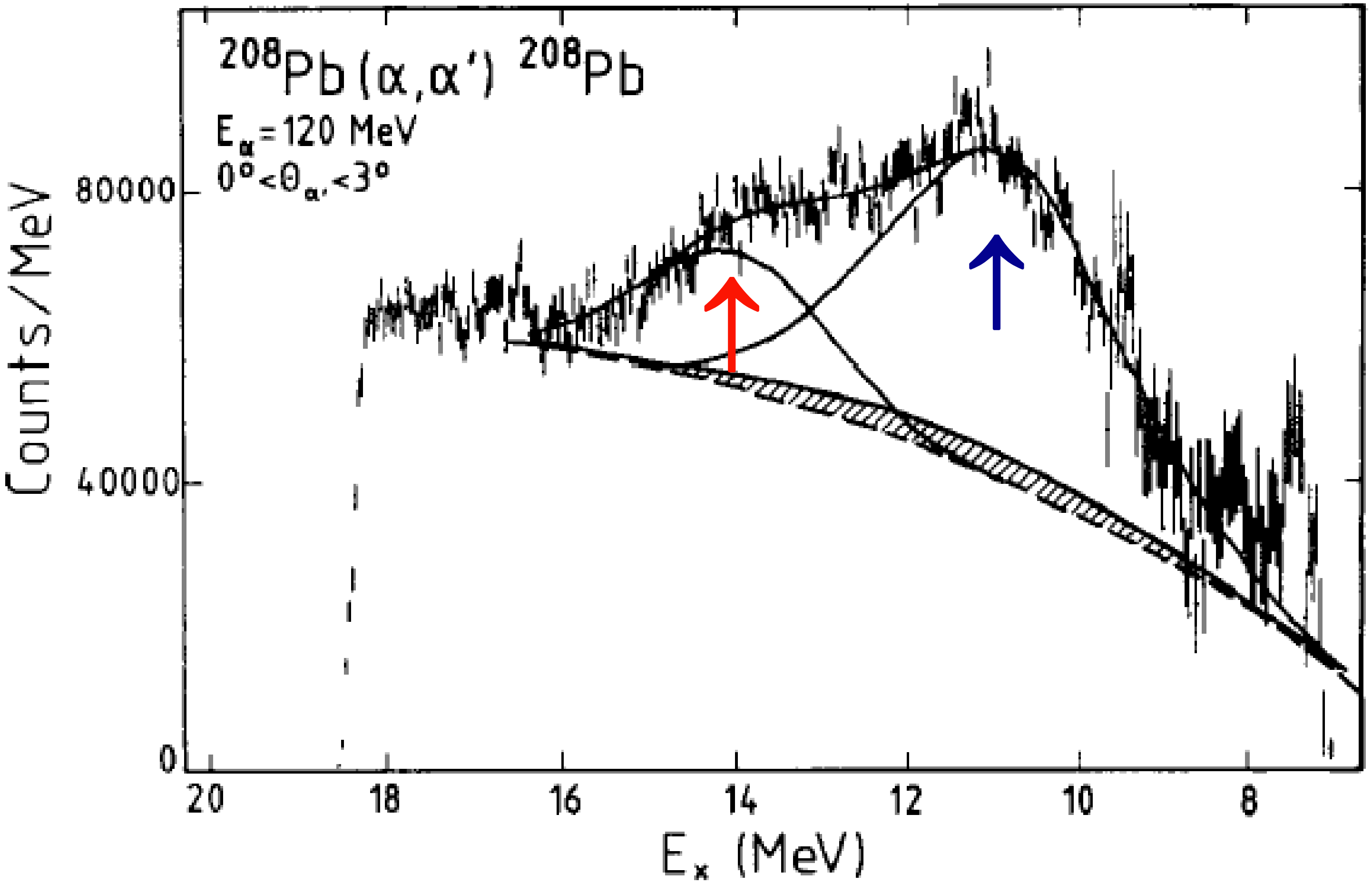
ISGQR at 10.9 MeV

ISGMR at 13.9 MeV



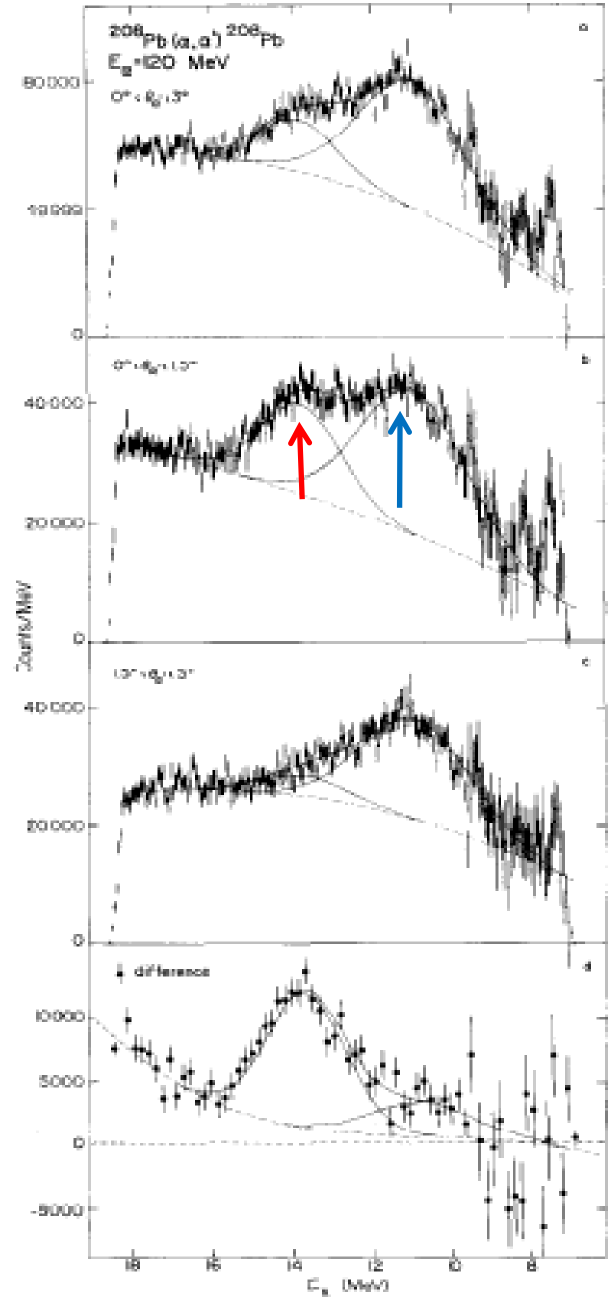
Difference of spectra

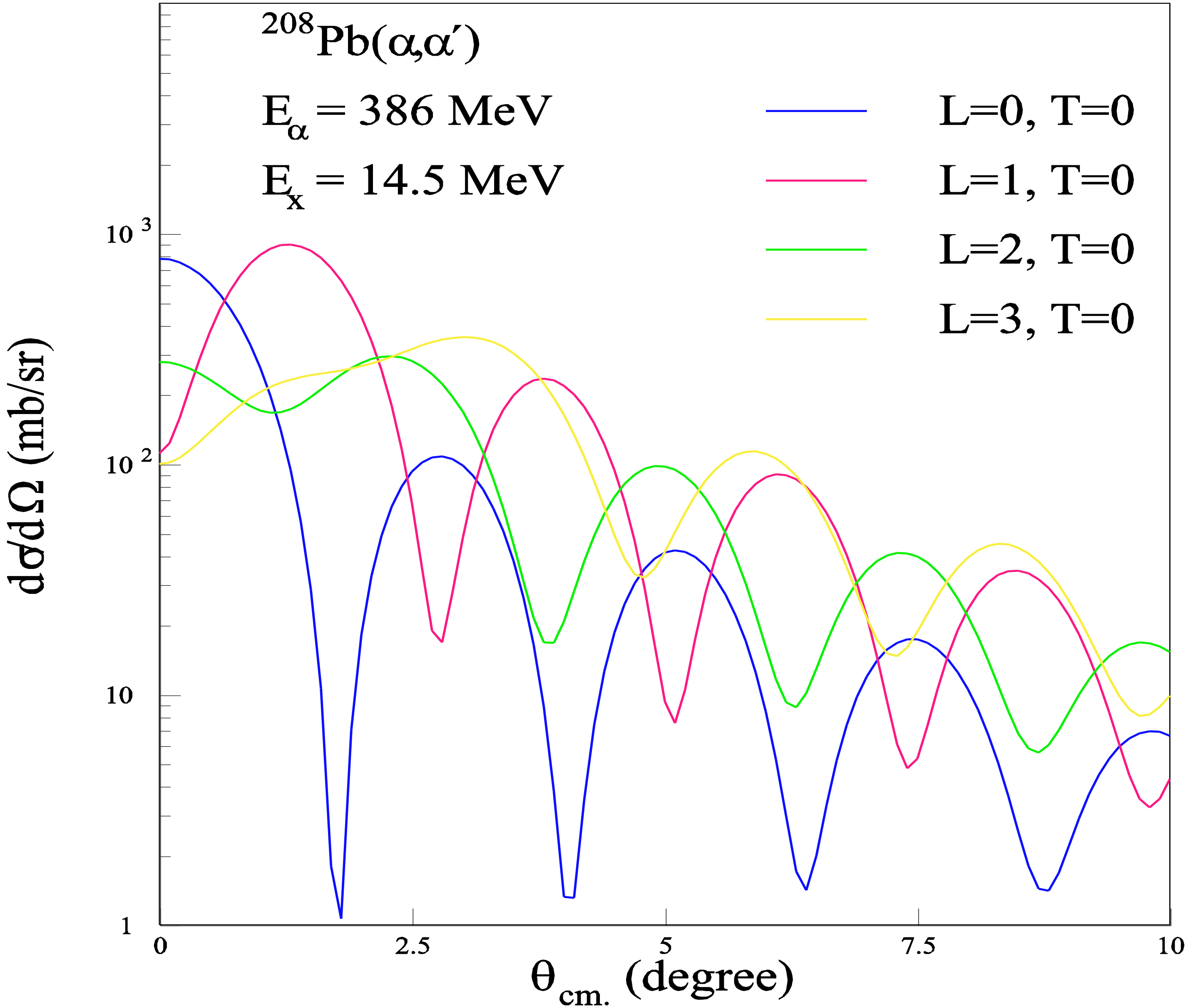
$0° < \theta_{\alpha'} < 3°$

$0° < \theta_{\alpha'} < 1.5°$

$1.5° < \theta_{\alpha'} < 3°$

Difference



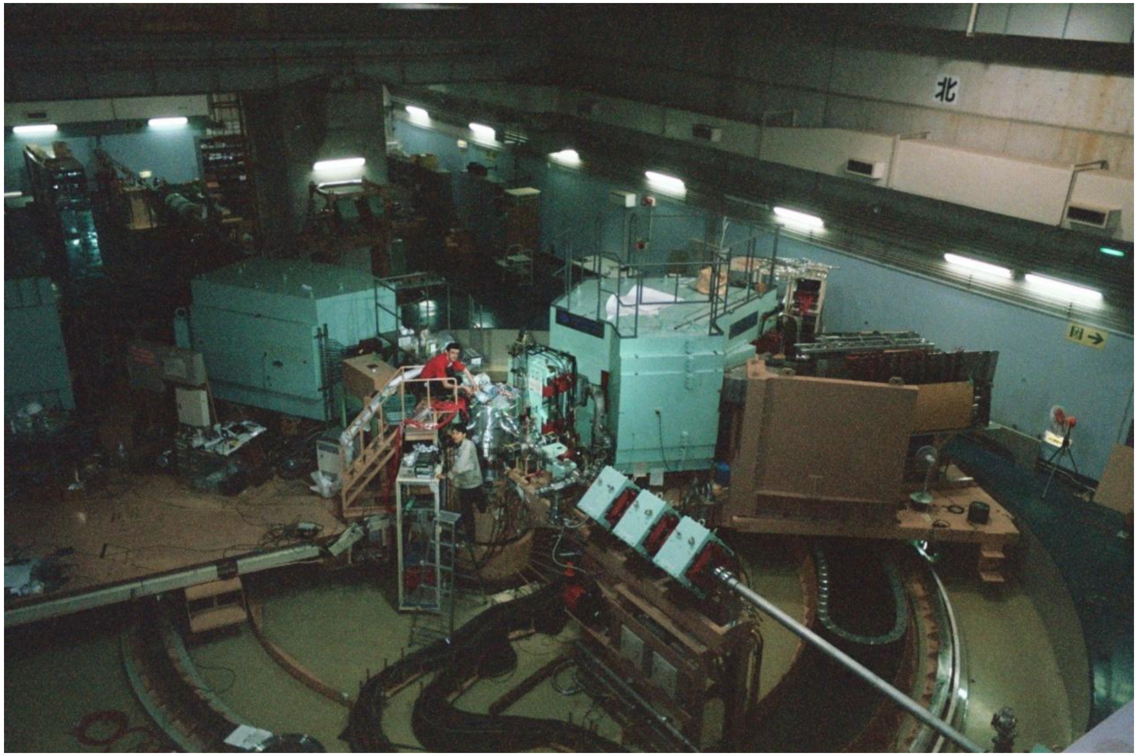


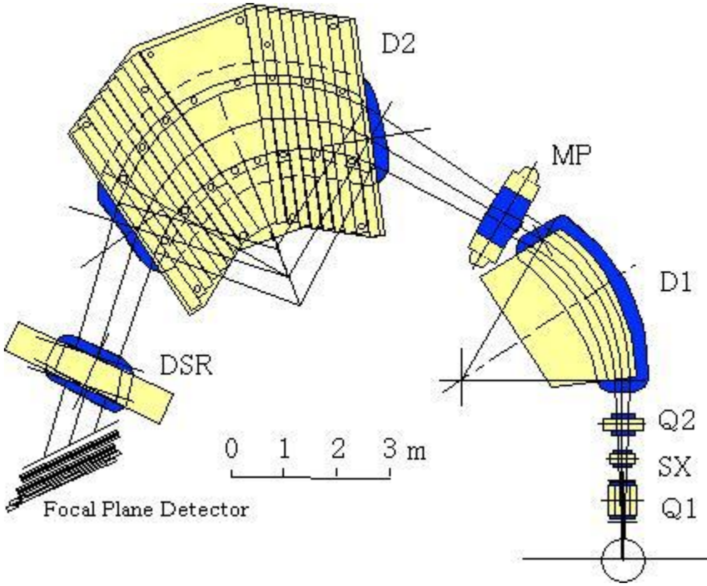
ISGMR, ISGDR

ISGQR, HEOR

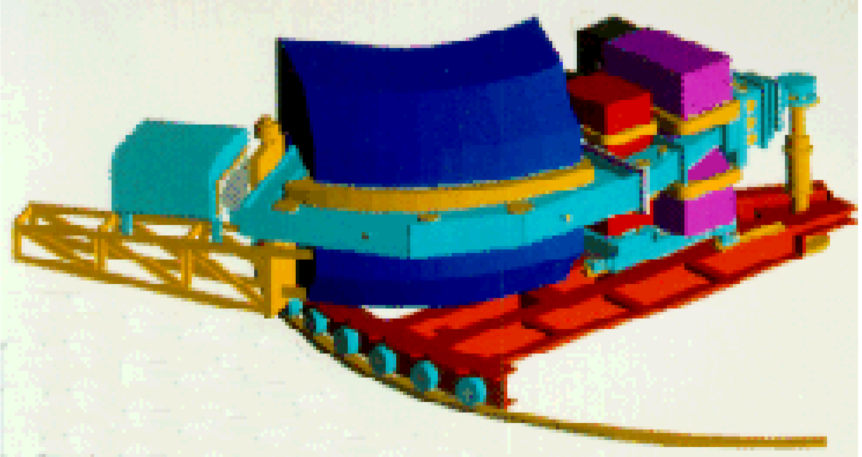
100 % EWSR

At E_x= 14.5 MeV



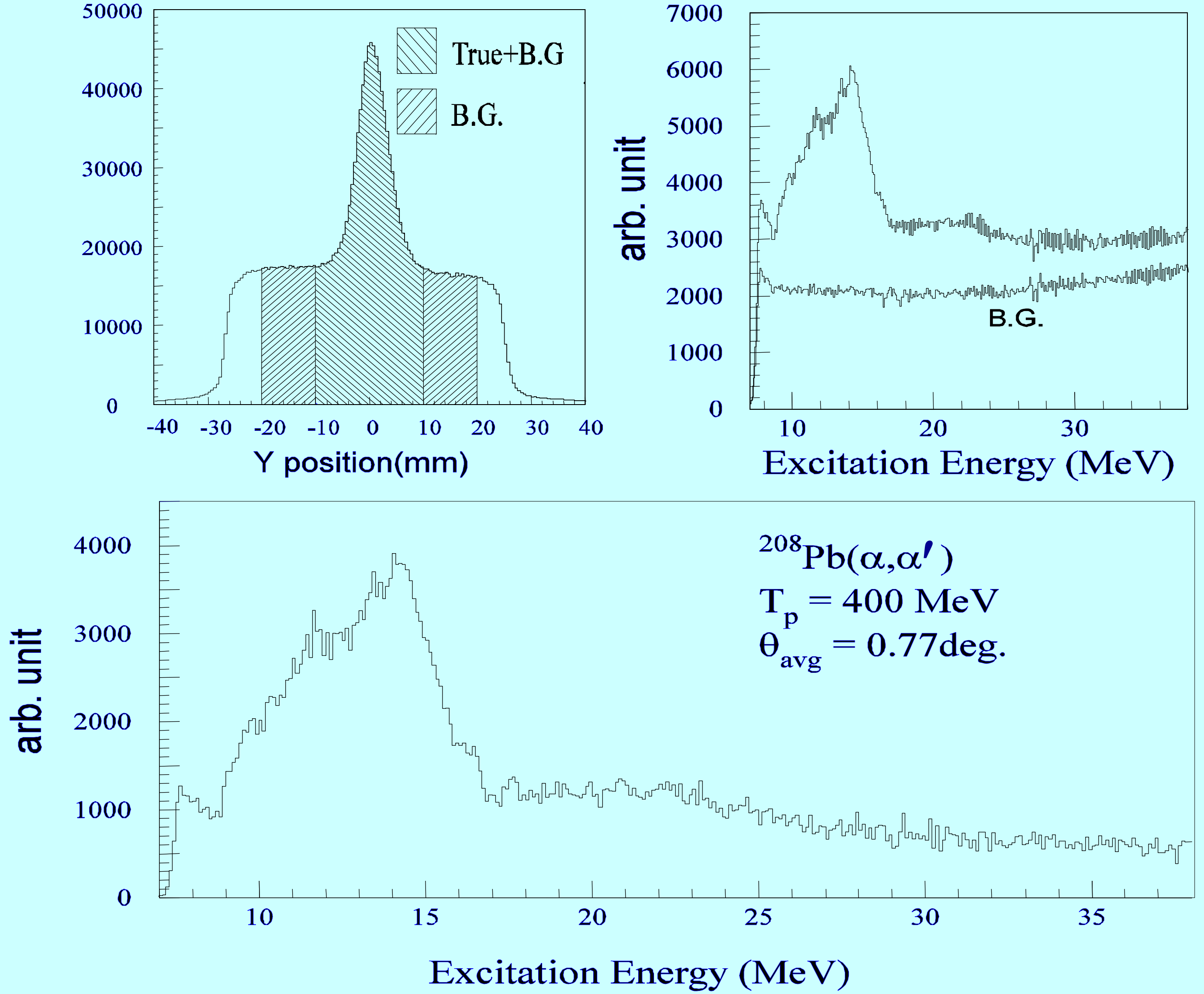


Grand Raiden@ RCNP



(α,α') at E_α~ 400 & 200 MeV at RCNP & KVI, respectively

BBS@KVI


True+B.G
B.G.
Y position(mm)
arb. unit
B.G.
Excitation Energy (MeV)
arb. unit
^{208}Pb(α,α′)
T_p = 400 MeV
θ_{avg} = 0.77deg.
Excitation Energy (MeV)

Multipole decomposition analysis (MDA)

$$\left(\frac{d^2\sigma}{d\Omega dE}(\vartheta_{c.m.},E)\right)^{\exp.} = \sum_L a_L(E)\left(\frac{d^2\sigma}{d\Omega dE}(\vartheta_{c.m.},E)\right)_L^{calc.}$$

$$\left(\frac{d^2\sigma}{d\Omega dE}(\vartheta_{c.m.},E)\right)^{\exp.} : \text{Experimental cross section}$$

$$\left(\frac{d^2\sigma}{d\Omega dE}(\vartheta_{c.m.},E)\right)_L^{calc.} : \text{DWBA cross section (unit cross section)}$$

$a_L(E)$: EWSR fraction

a. **ISGR (L<15)+ IVGDR (through Coulomb excitation)**
b. **DWBA formalism; single folding ⇒ transition potential**

$$\delta U(r,E) = \int d\vec{r}'\,\delta\rho_L(\vec{r}',E)[V(|\vec{r}-\vec{r}'|,\rho_0(r')) + \rho_0(r')\frac{\partial V(|\vec{r}-\vec{r}'|,\rho(r'))}{\partial\rho_0(r')}]$$

$$U(r) = \int d\vec{r}'\,V(|\vec{r}-\vec{r}'|,\rho_0(r'))\rho_0(r')$$

$$P^{(\lambda)} = \frac{1}{2}\sum_i r_i^{\lambda+2} Y_\lambda^0(\hat{r}_i)$$

$$\sum_n (E_n - E_0)\,\tilde{P}_{0n}^{(1)} = -\frac{\hbar^2 A}{32 m\pi}[11 < \mathrm{r}^4 > -\frac{25}{3} < \mathrm{r}^2 >^2 - 10\varepsilon < \mathrm{r}^2 >]$$

$$\varepsilon = (\frac{4}{E_2} + \frac{5}{E_0})\frac{\hbar^2}{3mA}$$

$$Q^{(\lambda)} = \sum_i r_i^\lambda Y_\lambda^0(\hat{r}_i)$$

$$S_\lambda = \lambda(2\lambda+1)\frac{\hbar^2 A}{8m\pi} < \mathrm{r}^{2\lambda-2} >$$

Transition density

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

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

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

- **ISGDR Harakeh & Dieperink, Phys. Rev. C23 (1981) 2329**

$$\delta\rho_1(r,E) = -\frac{\beta_1}{R\sqrt{3}}[3r^2\frac{d}{dr} + 10r - \frac{5}{3} < r^2 > \frac{d}{dr} + \varepsilon(r\frac{d^2}{dr^2} + 4\frac{d}{dr})]\rho_0(r)$$

$$\beta_1^2 = \frac{6\pi\hbar^2}{mAE}\frac{R^2}{(11 < r^4 > -(25/3) < r^2 >^2 - 10\varepsilon < r^2 >)}$$

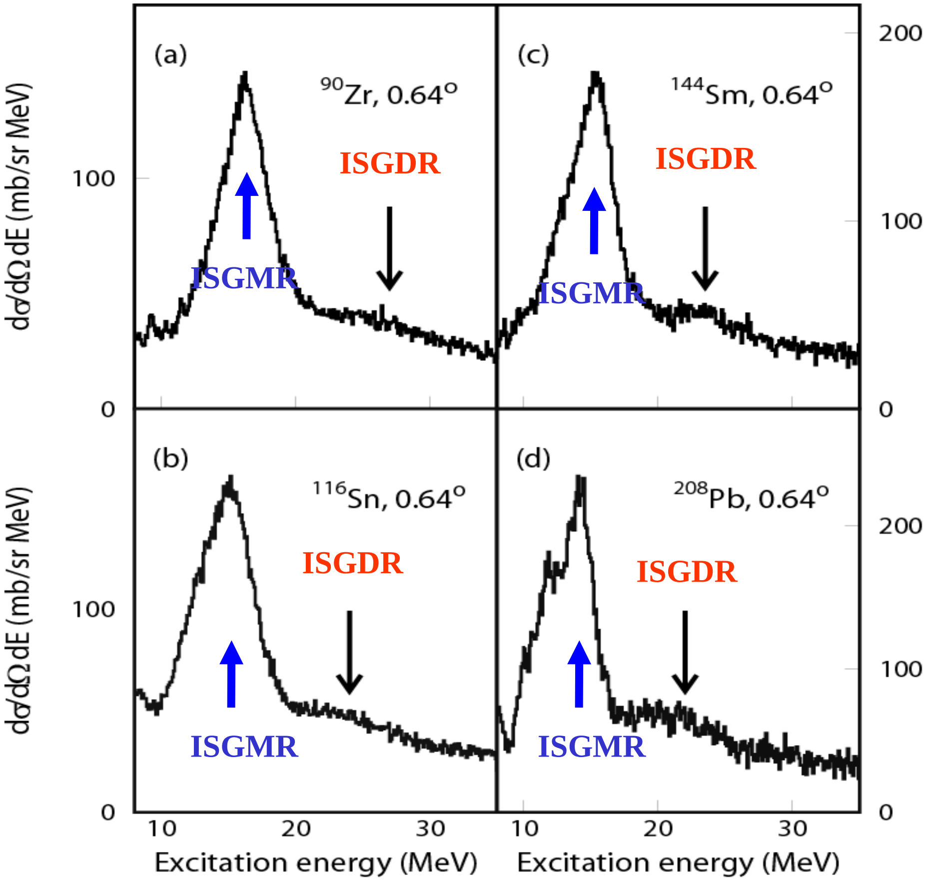
- **Other modes Bohr-Mottelson (BM) model**

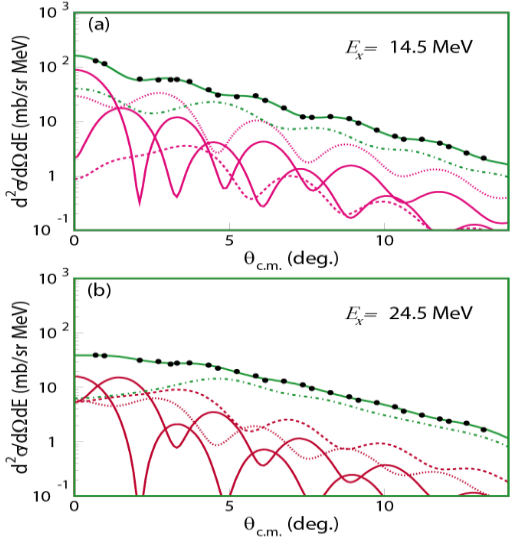
$$\delta\rho_L(r,E) = -\delta_L\frac{d}{dr}\rho_0(r)$$

$$\delta_L^2 = (\beta_L c)^2 = \frac{L(2L+1)^2}{(L+2)^2}\frac{2\pi\hbar^2}{mAE}\frac{< r^{2L-2} >}{< r^{L-1} >^2}$$

Uchida *et al.*,
Phys. Lett. B557 (2003) 12
Phys. Rev. C69 (2004) 051301

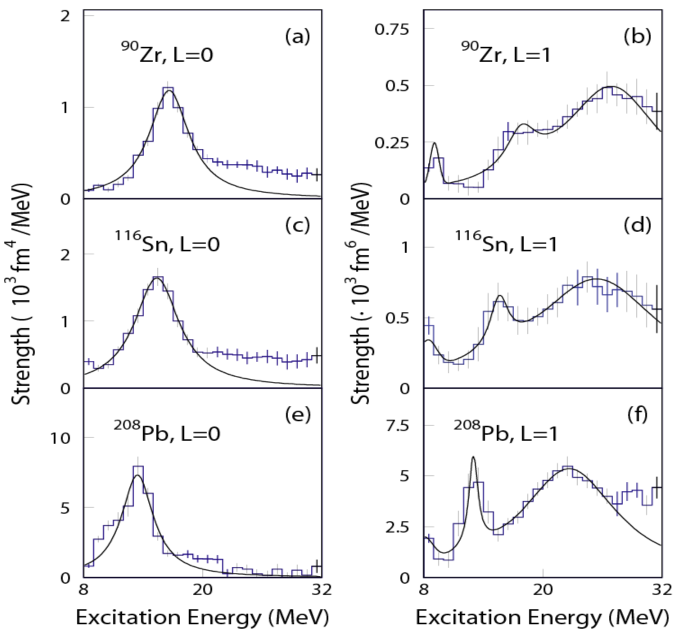
(α,α′) spectra at 386 MeV

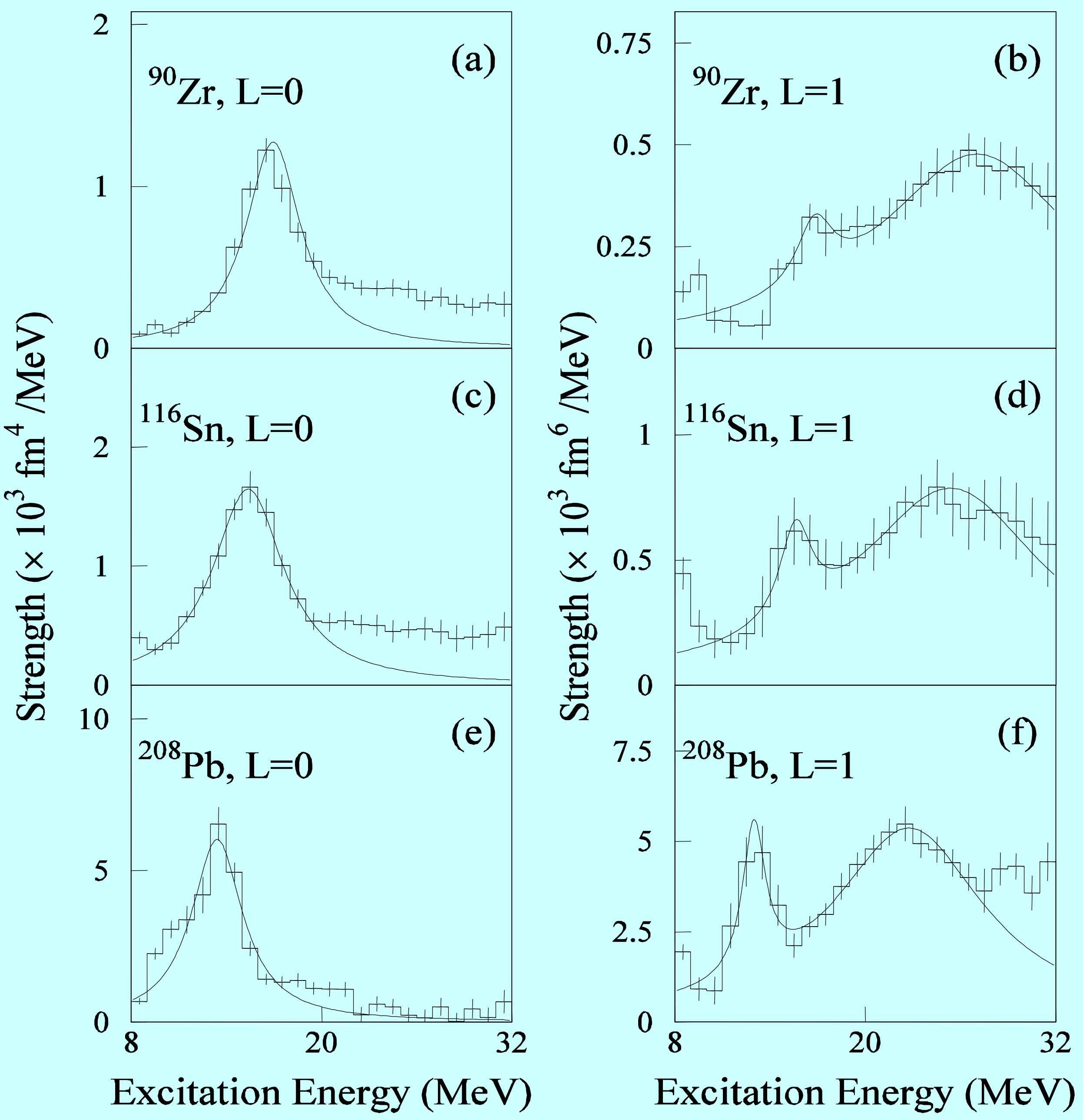




^{116}Sn

MDA results for L=0 and L=1




(a)
90Zr, L=0
(b)
90Zr, L=1
(c)
116Sn, L=0
(d)
116Sn, L=1
(e)
208Pb, L=0
(f)
208Pb, L=1
Strength (× 10³ fm⁴ /MeV)
Strength (× 10³ fm⁶ /MeV)
Excitation Energy (MeV)
Excitation Energy (MeV)
8
20
32
0
0.25
0.5
0.75
1
2
5
10
2.5
7.5

In HF+RPA calculations,

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

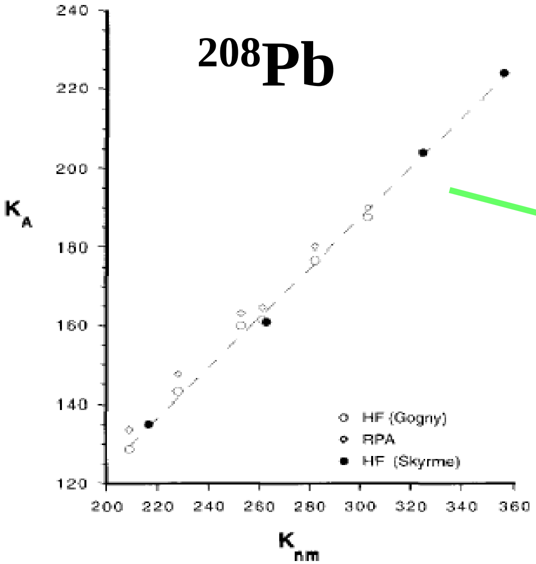
Nuclear matter

***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

$K_A = 0.64 K_{nm} - 3.5$

J.P. Blaizot, NPA591 (1995) 435

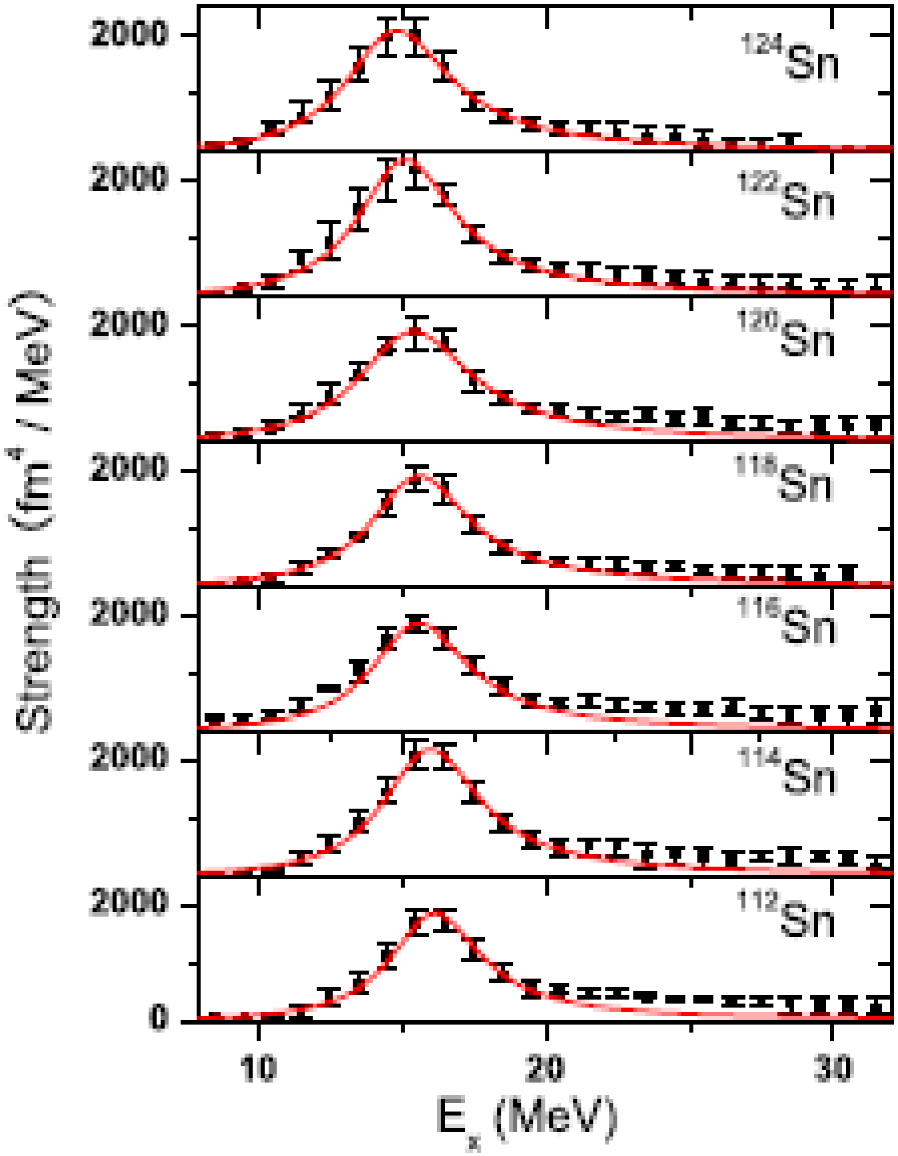
From GMR data on ^{208}Pb and ^{90}Zr,

K_∞ = 240 ± 10 MeV

[See, *e.g*., G. Colò *et al*., Phys. Rev. C 70 (2004) 024307]

This number is consistent
with both ISGMR and ISGDR Data
and
with non-relativistic and relativistic calculations

Isoscalar GMR strength distribution in Sn-isotopes obtained by Multipole Decomposition Analysis of singles spectra obtained in ^{A}Sn(α,α′) measurements at incident energy 400 MeV and angles from 0º to 9º



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

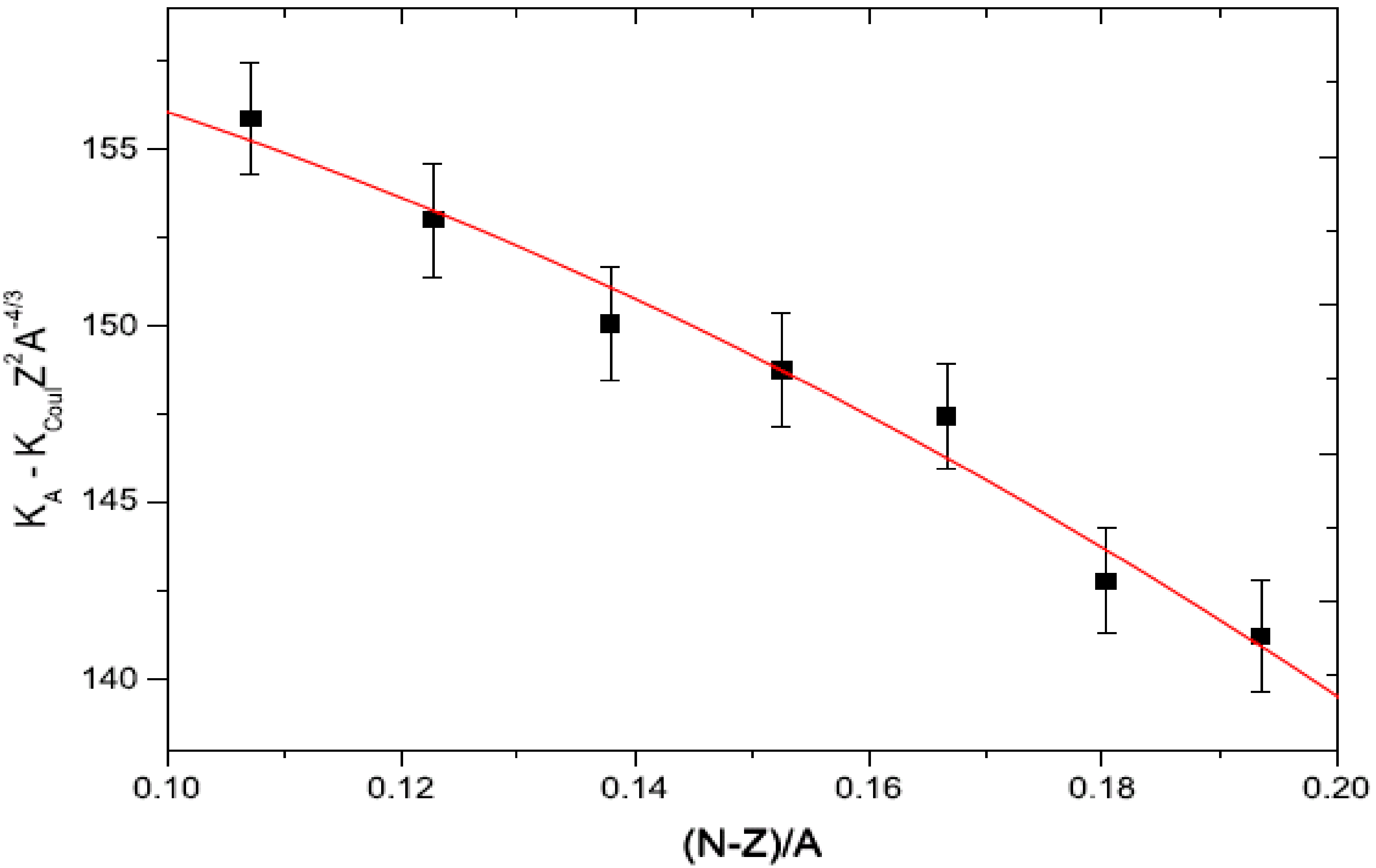
$$K_A - K_{Coul} Z^2 A^{-4/3} \sim K_{vol}(1 + cA^{-1/3}) + K_\tau((N - Z)/A)^2$$

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

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

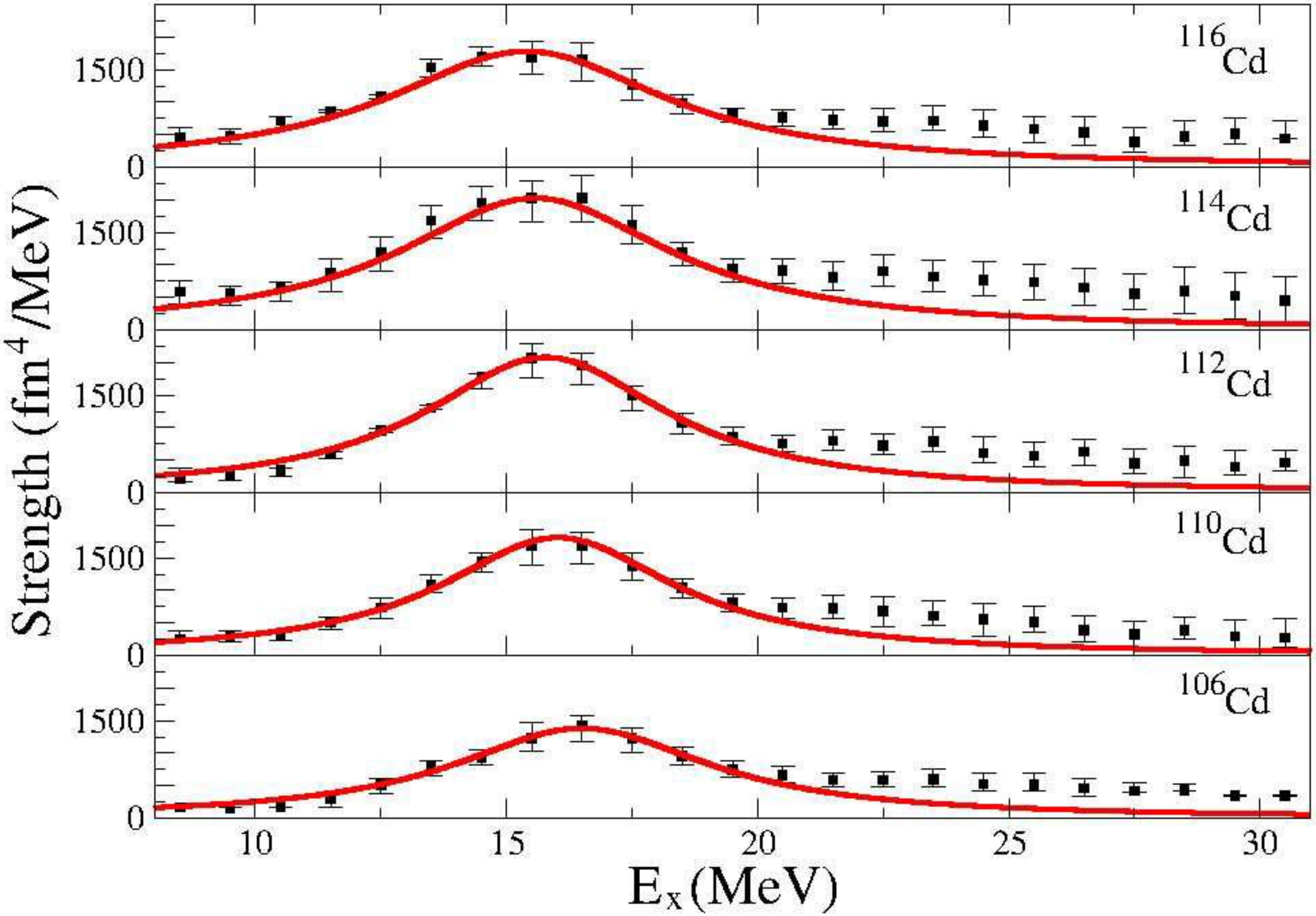
$(N - Z)/A$

^{112}Sn – ^{124}Sn: 0.107 – 0.194

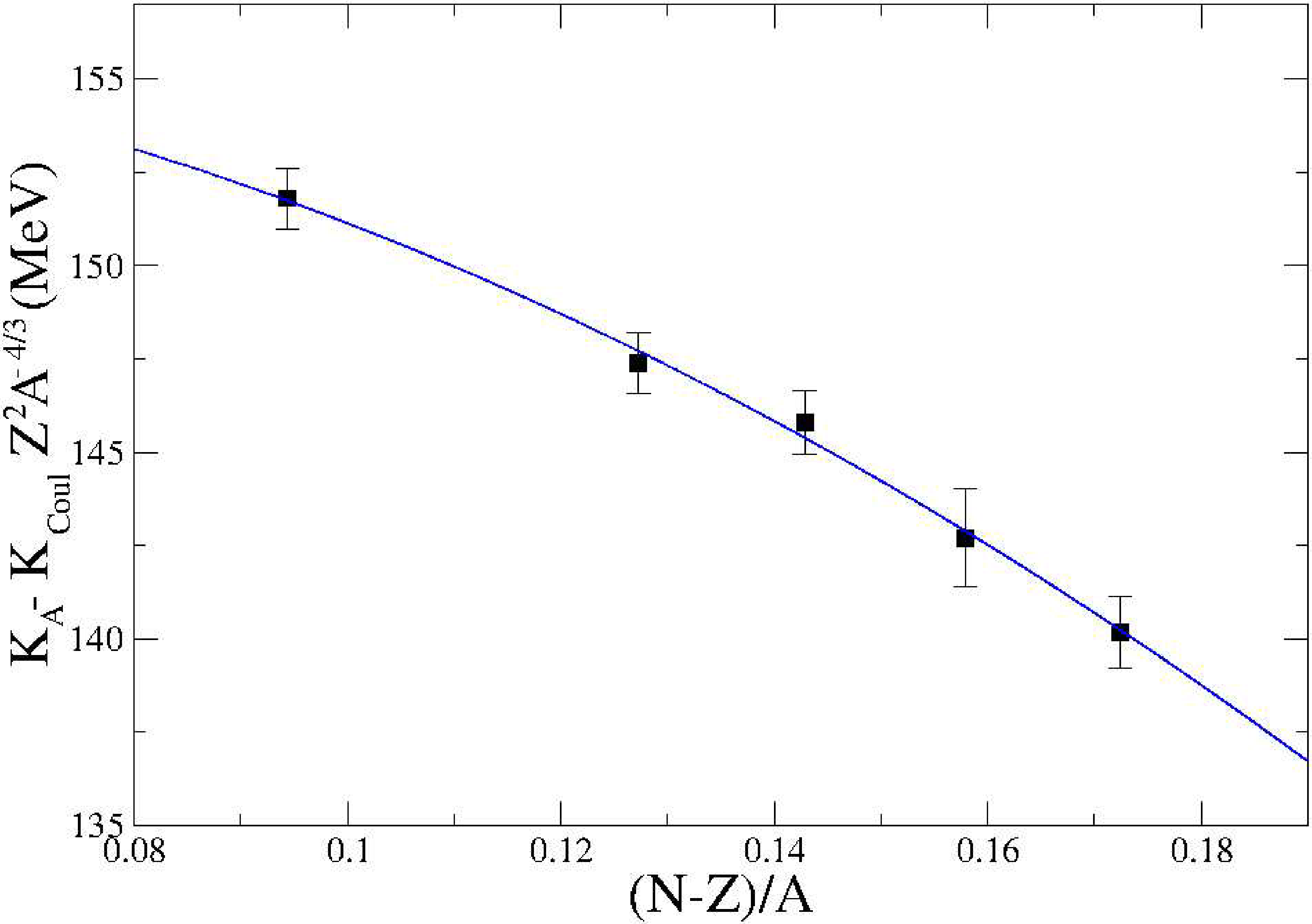


$$K_\tau = -550 \pm 100 \text{ MeV}$$

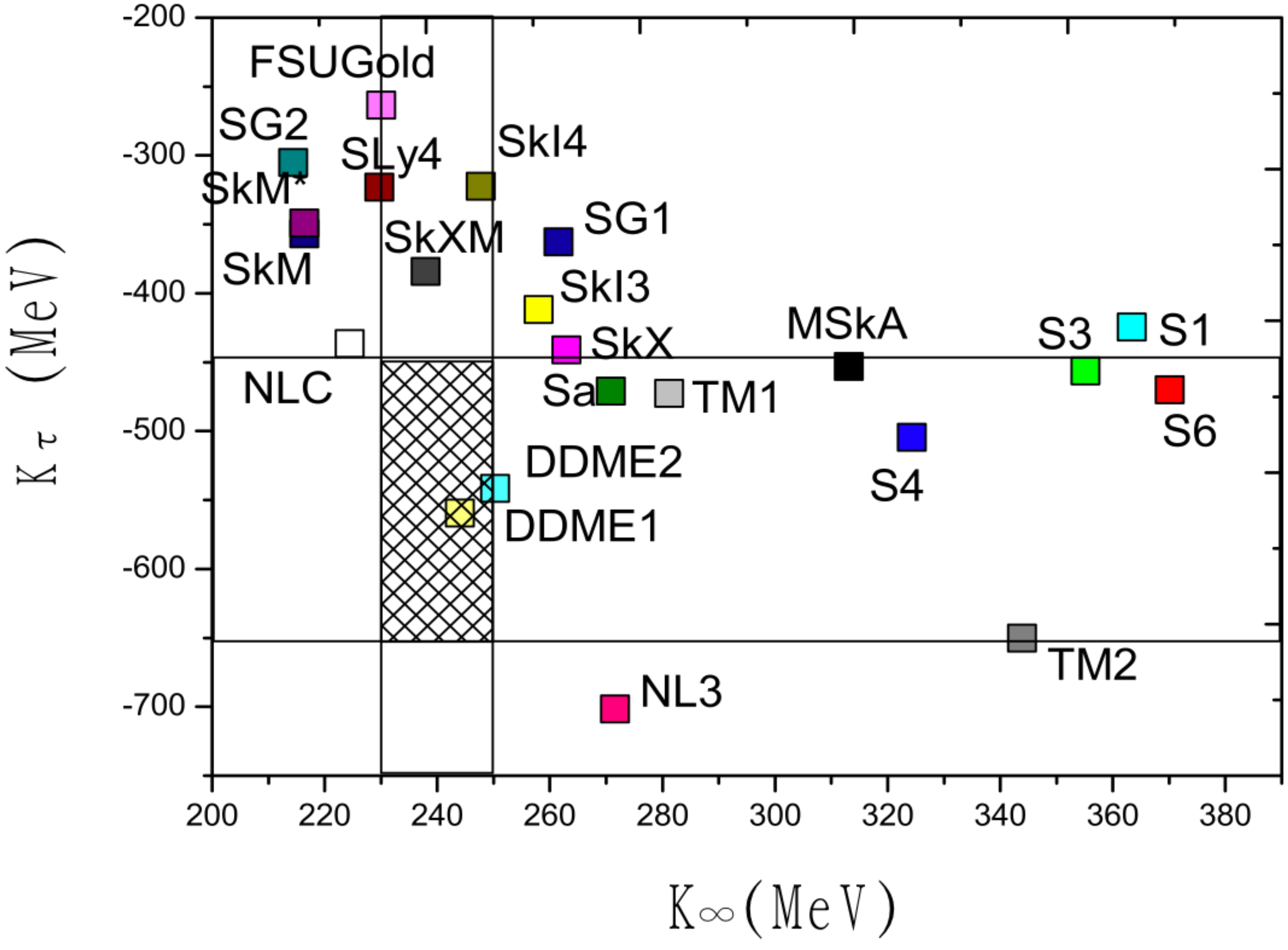
Monopole strength Distribution



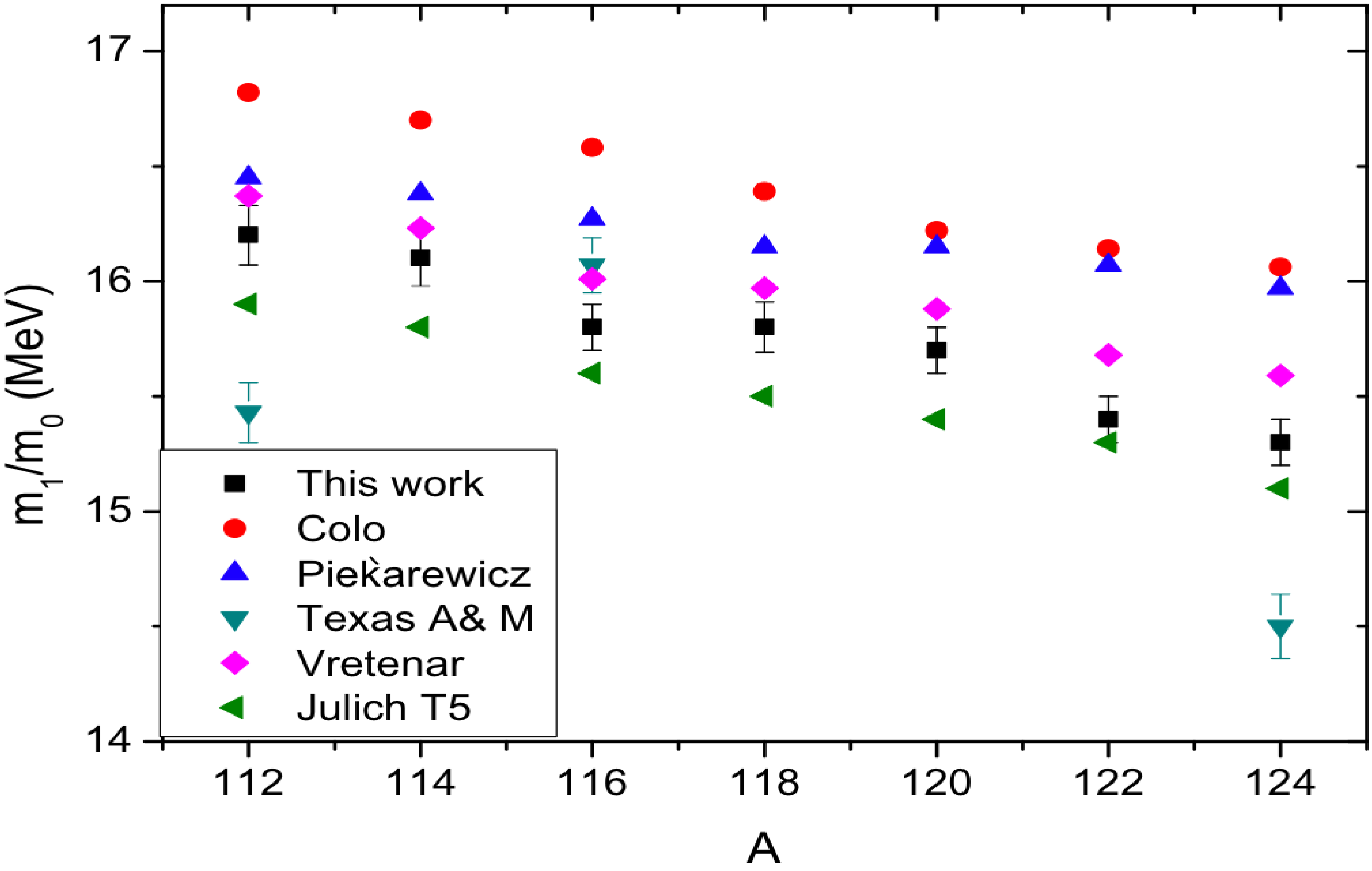
KVI
university of groningen



$$K_\tau = -555 \pm 75\,\mathrm{MeV}$$



Data from H. Sagawa *et al*., Phys. Rev. C **76**, 034327 (2007)


17
16
15
14
m_1/m_0 (MeV)
112
114
116
118
120
122
124
A
This work
Colo
Piekarewicz
Texas A& M
Vretenar
Julich T5

Colò *et al*.: Non-relativistic RPA (without pairing) reproduces ISGMR in ^{208}Pb and ^{90}Zr.

Piekarewicz: Relativistic RPA (FSUGold model) reproduces g.s. observables and ISGMR in ^{208}Pb, ^{144}Sm and ^{90}Zr [K_∞ = 230 MeV]

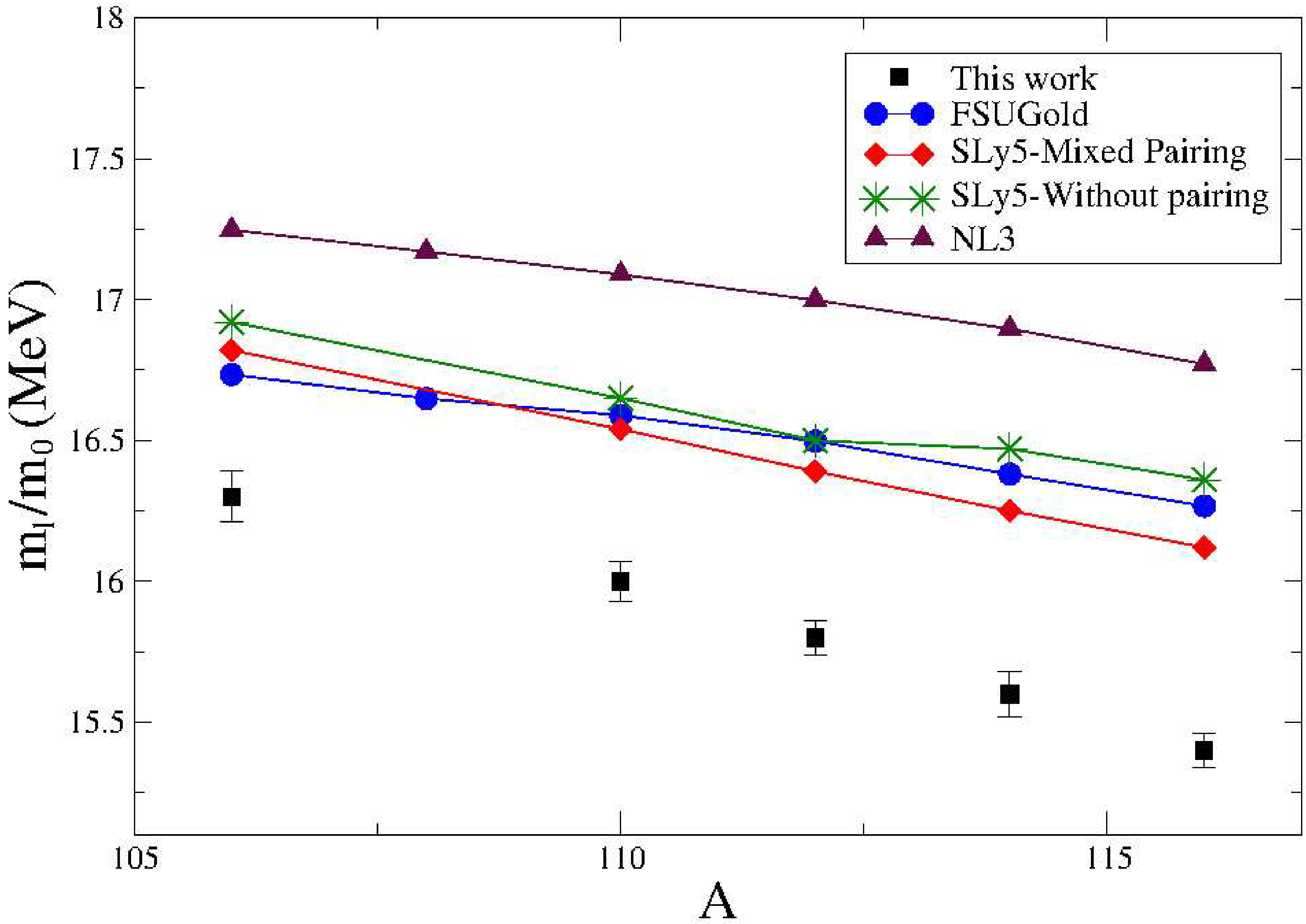
Vretenar: Relativistic mean field (DD-ME2: density-dependent mean-field effective interaction).

[K_∞ = 240 MeV]. Possibly agreement is fortuitous since strength distributions are not much different from those by Colò *et al*. and Piekarewicz.

Tselyaev *et al*.: Quasi-particle time-blocking approximation (QTBA) (T5 Skyrme interaction)

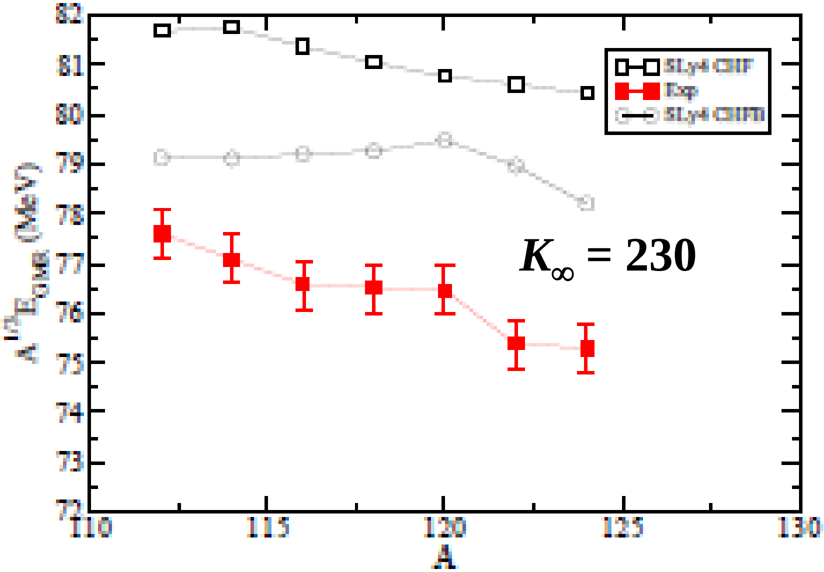
[K_∞ = 202 MeV?!]

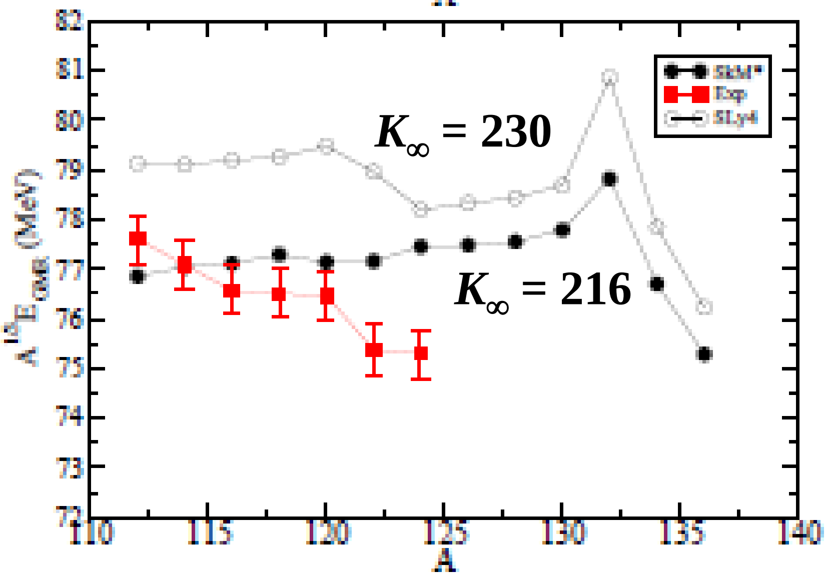
Softness of Sn-nuclei is still unresolved



RRPA:FSUGold [K_∞ = 230 MeV]; SLy5 [K_∞ = 230 MeV]; NL3 [K_∞ = 271 MeV]

E. Khan, PRC 80, 011307(R) (2009)





The Giant Monopole Resonances in Pb isotopes

E. Khan, Phys. Rev. C 80, 057302 (2009).

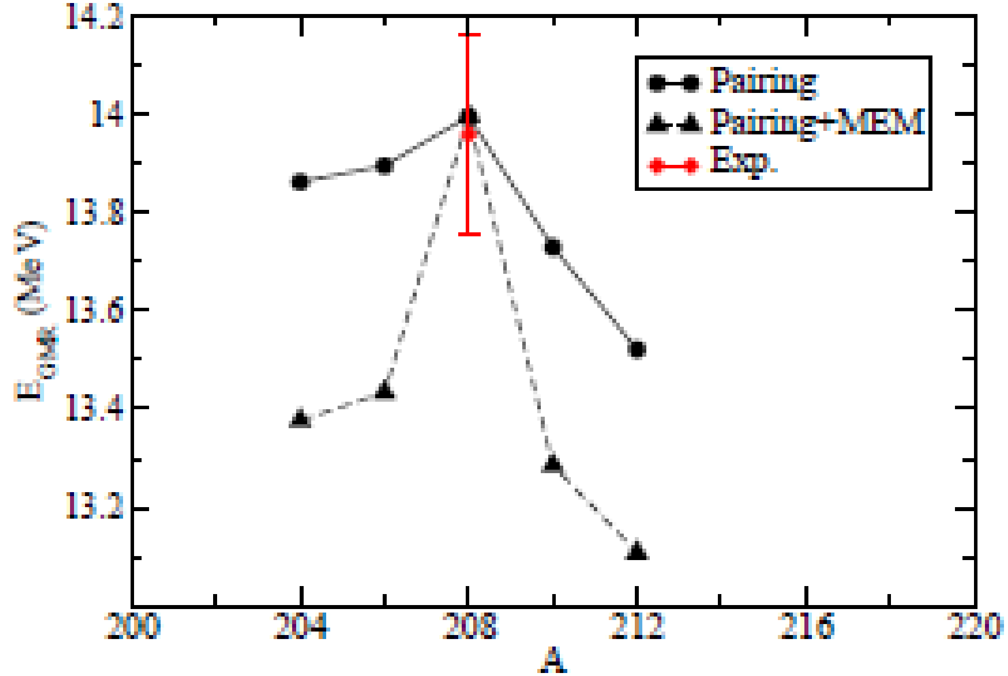
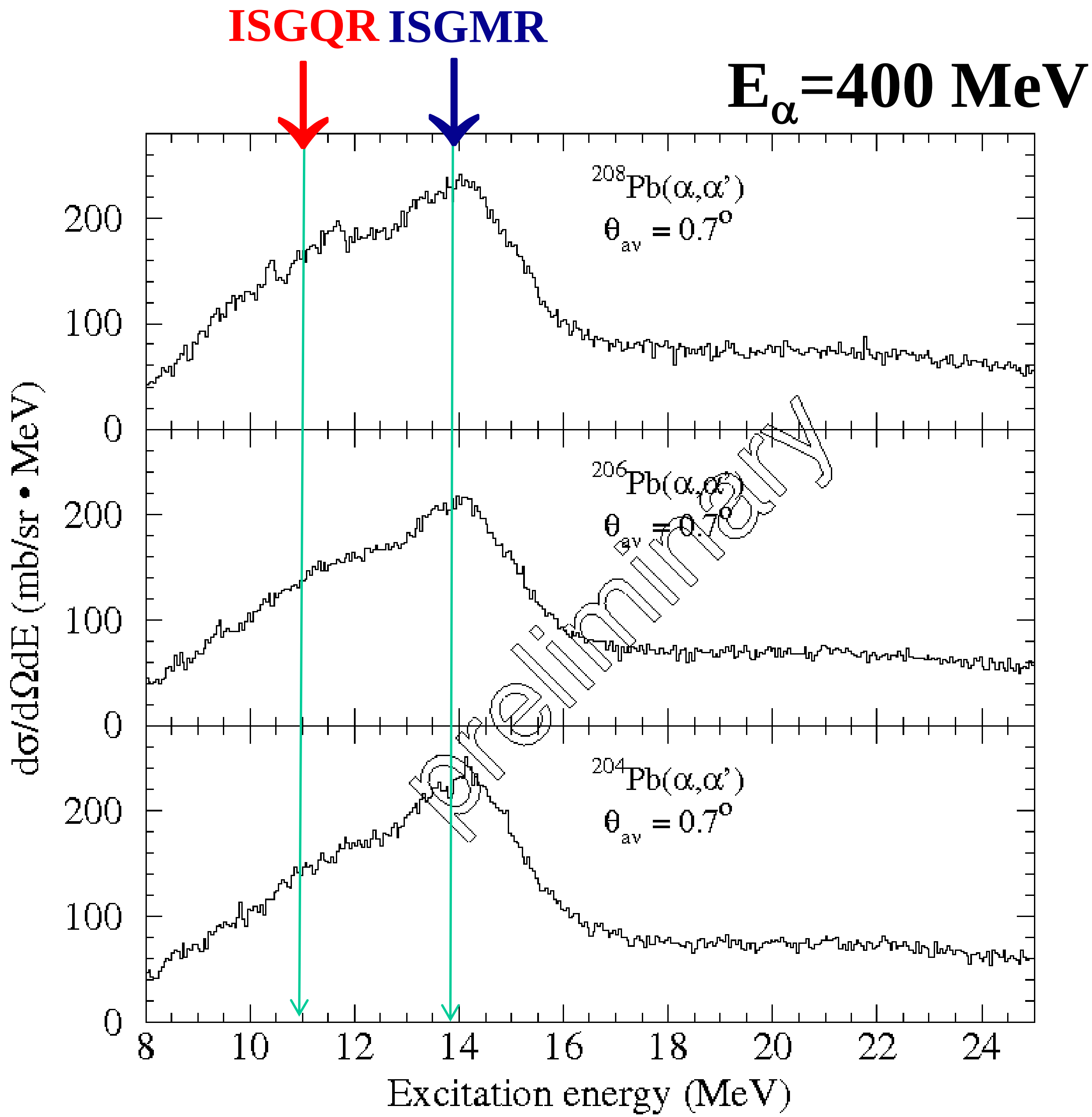


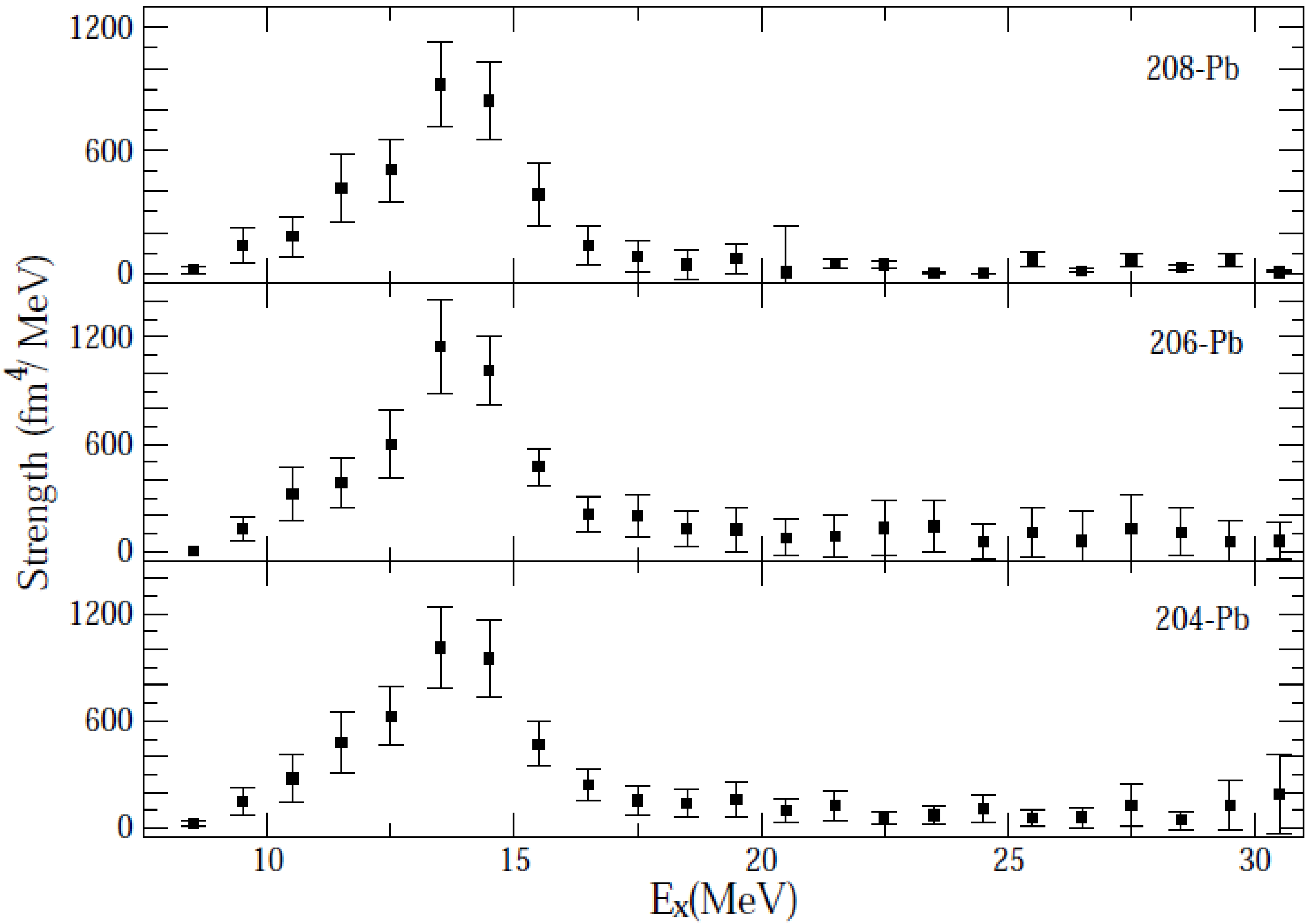
FIG. 2: Excitations energies of the GMR in $^{204-212}$Pb isotopes calculated with constrained HFB method, taking into account the MEM effect (see text). The experimental data is taken from Ref. [22]

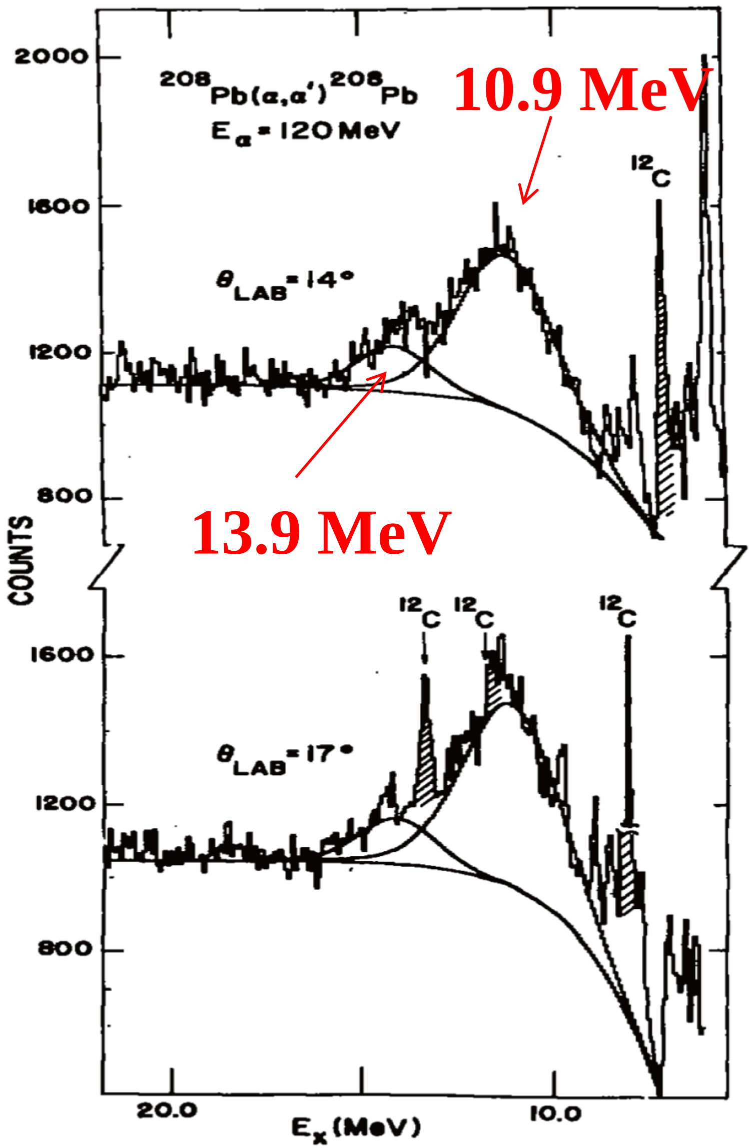
Mutually Enhanced Magicity (MEM)?

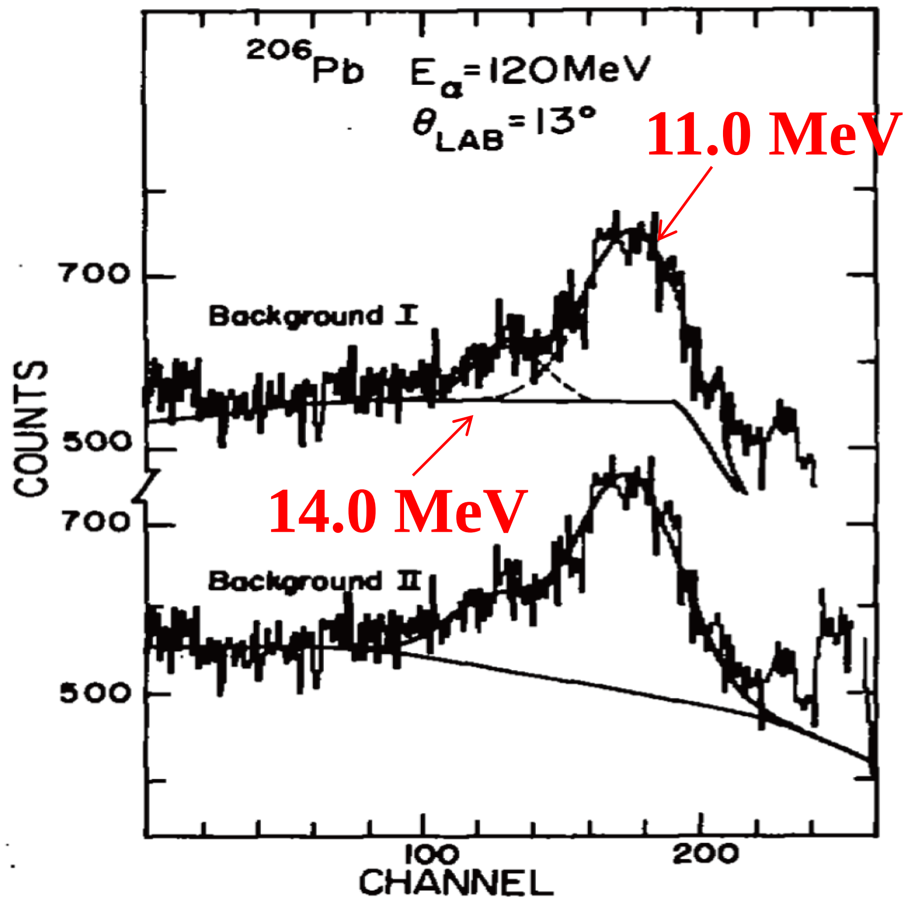


208	**13.9**	**MeV**
206	**13.94**	**MeV**
204	**13.98**	**MeV**

Monopole strength Distribution







M.N. Harakeh *et al*., Nucl. Phys. A327, 373 (1979)

Decay of giant resonances

- **Width of resonance**

  $\Gamma, \Gamma^{\uparrow}, \Gamma^{\downarrow} (\Gamma^{\downarrow\uparrow}, \Gamma^{\downarrow\downarrow})$

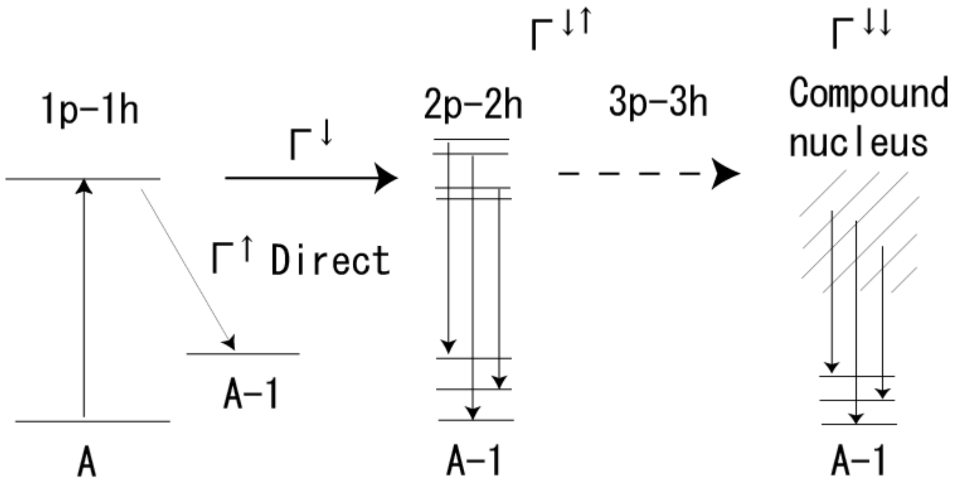
  - **$\Gamma^{\uparrow}$: direct or escape width**
  - **$\Gamma^{\downarrow}$: spreading width**

    $\Gamma^{\downarrow\uparrow}$: pre-equilibrium, $\Gamma^{\downarrow\downarrow}$: compound

- **Decay measurements**

  ⇒ Direct reflection of damping processes

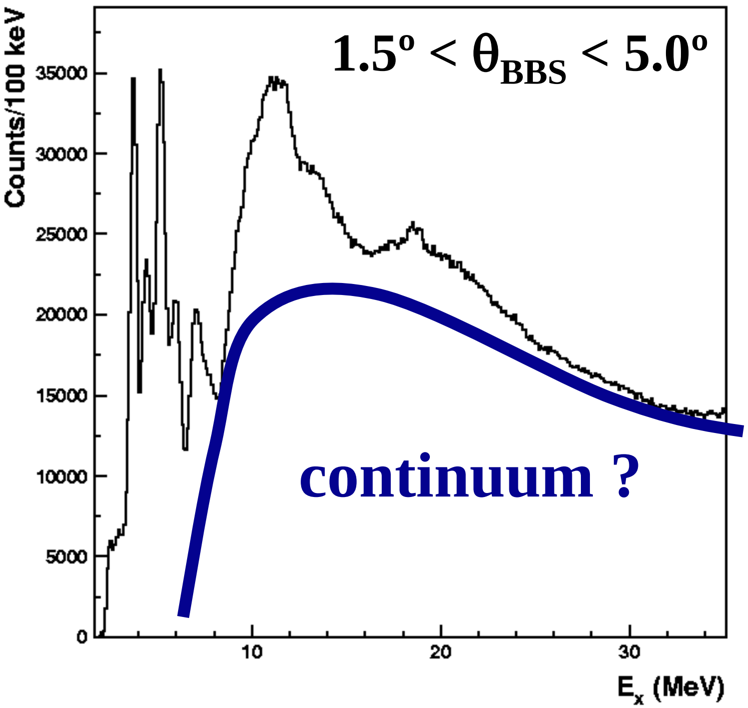
  Allows detailed comparison with theoretical calculations



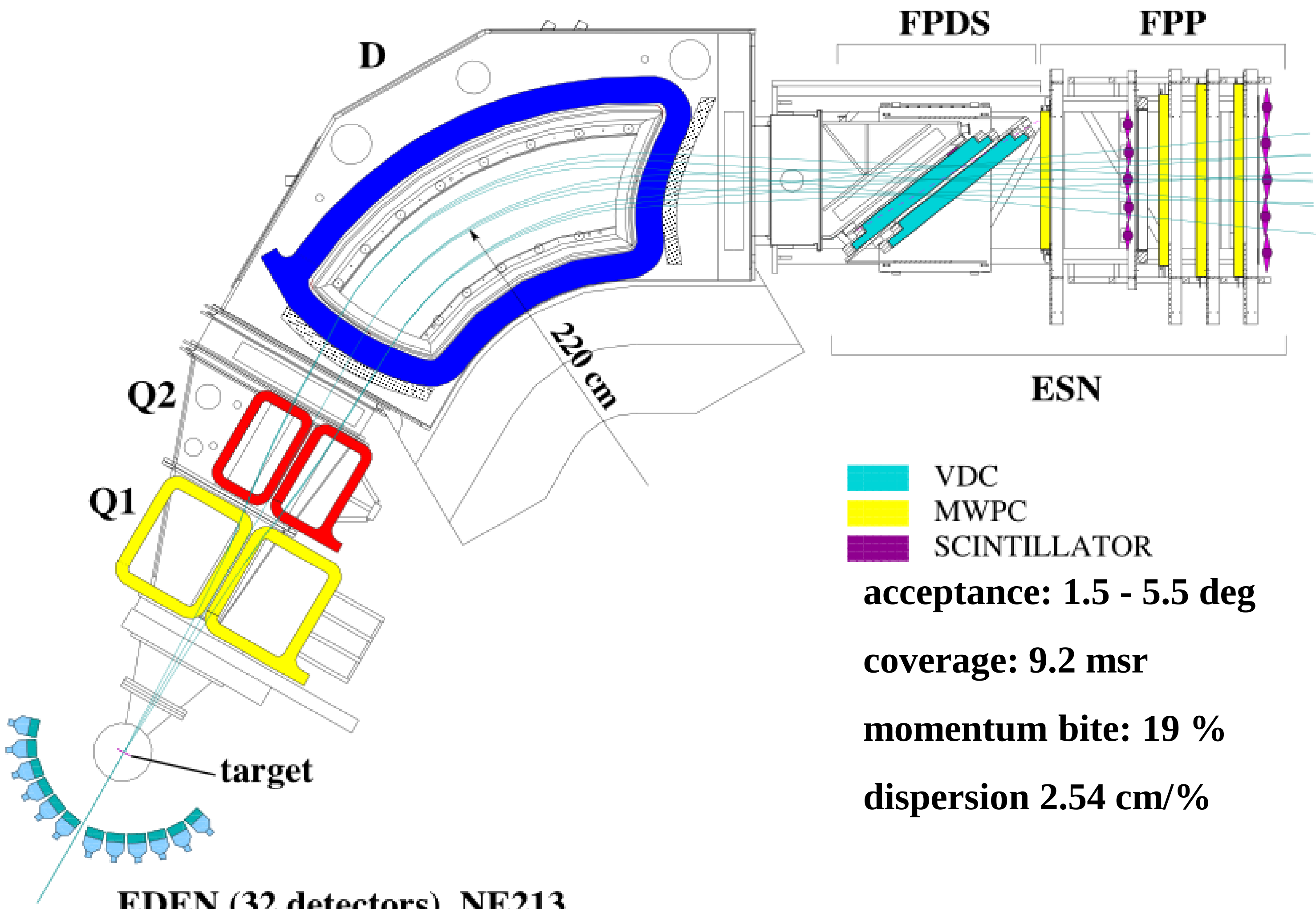
Excitation of ISGDR in ^{208}Pb

- In ^{208}Pb located around 22 MeV and width of 4 MeV
- *L=1* angular distribution peaks close to a scattering angle of 0^{o}
- Difficult to identify in nuclear continuum and rides on instrumental background

Singles ^{208}Pb(α,α') 200 MeV $\Rightarrow$



Si-ball
16 Si-detectors at
10 cm from the target
total solid angle: 1 sr



acceptance: 1.5 - 5.5 deg

coverage: 9.2 msr

momentum bite: 19 %

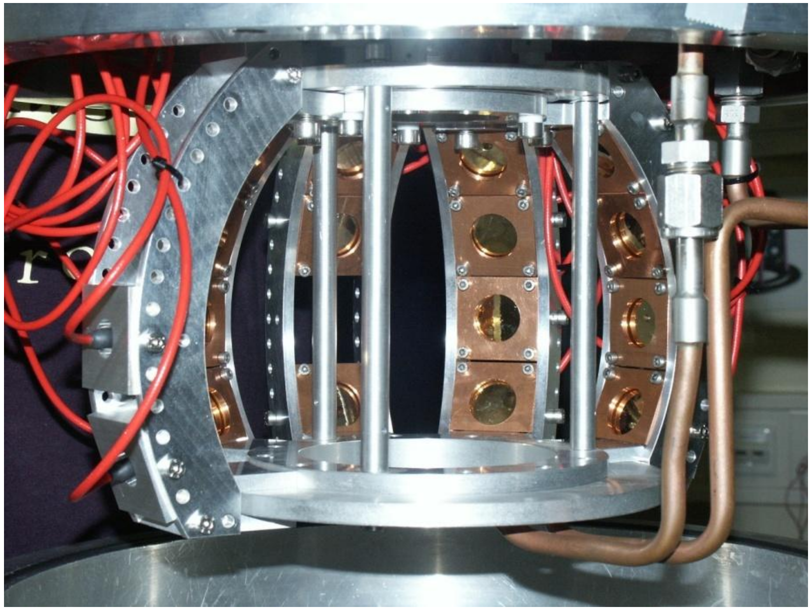
dispersion 2.54 cm/%

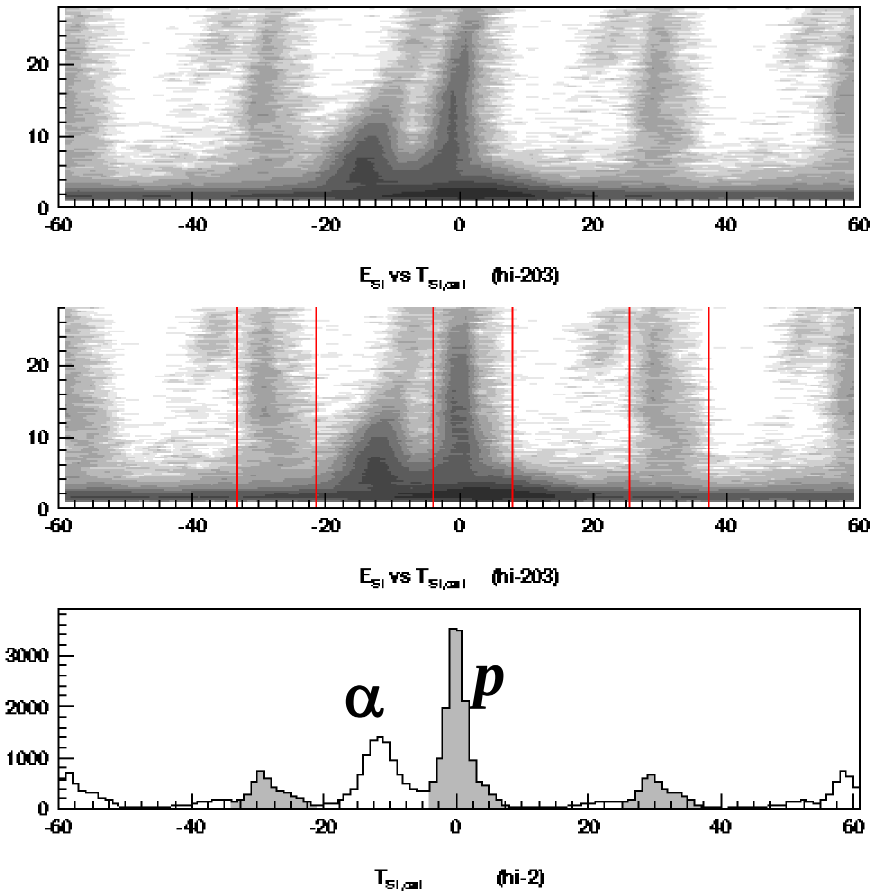
EDEN (32 detectors), NE213

total solid angle: 0.37 sr

KVI Big-Bite Spectrometer (BBS)

Proton-decay detection





α-*p* separation using rise time of signal SiLi

Microscopic structure of ISGDR

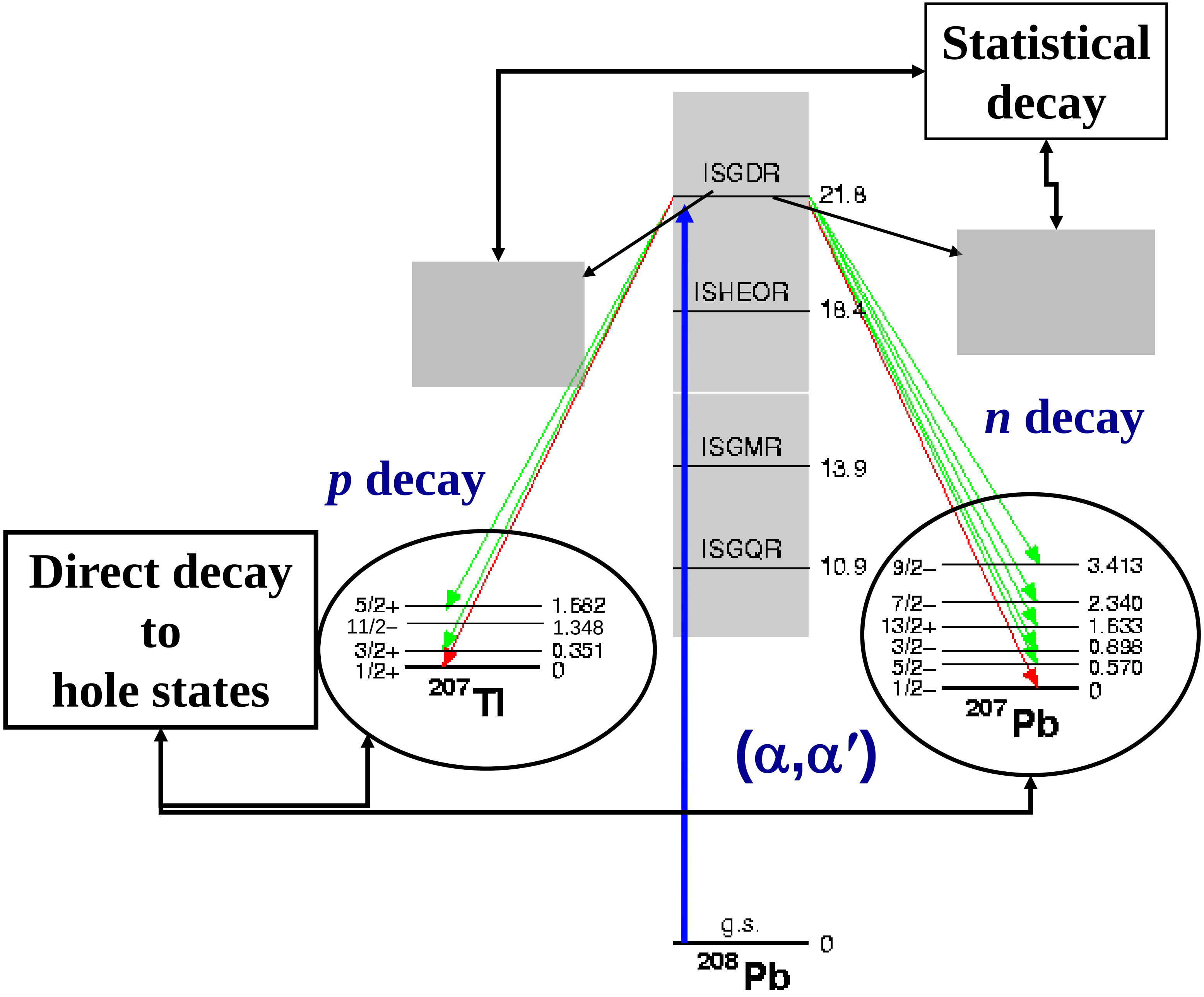
Transition operator

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

Spurious center of mass motion

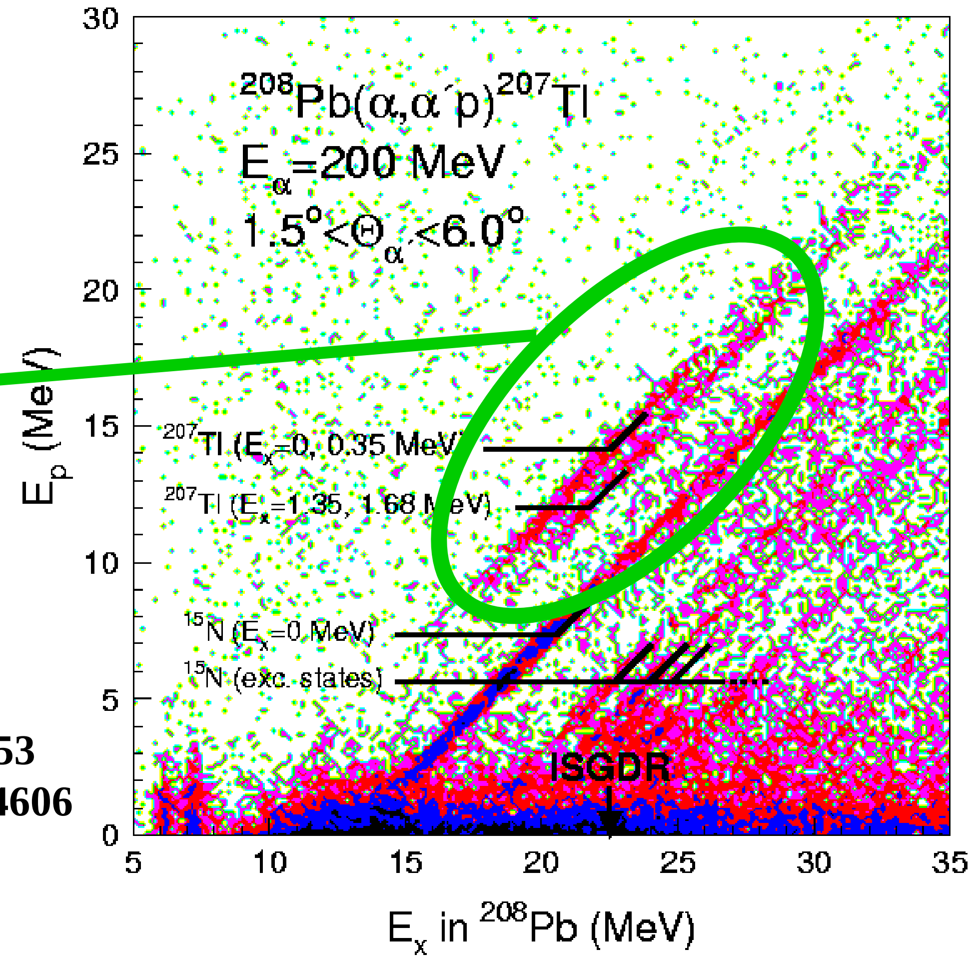
Overtone

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


Statistical decay
ISGDR
21.8
ISHEOR
18.4
ISGMR
13.9
ISGQR
10.9
n decay
p decay
Direct decay to hole states
5/2+ 1.682
11/2– 1.348
3/2+ 0.351
1/2+ 0
207Tl
9/2– 3.413
7/2– 2.340
13/2+ 1.633
3/2– 0.898
5/2– 0.570
1/2– 0
207Pb
(α,α′)
g.s. 0
208Pb

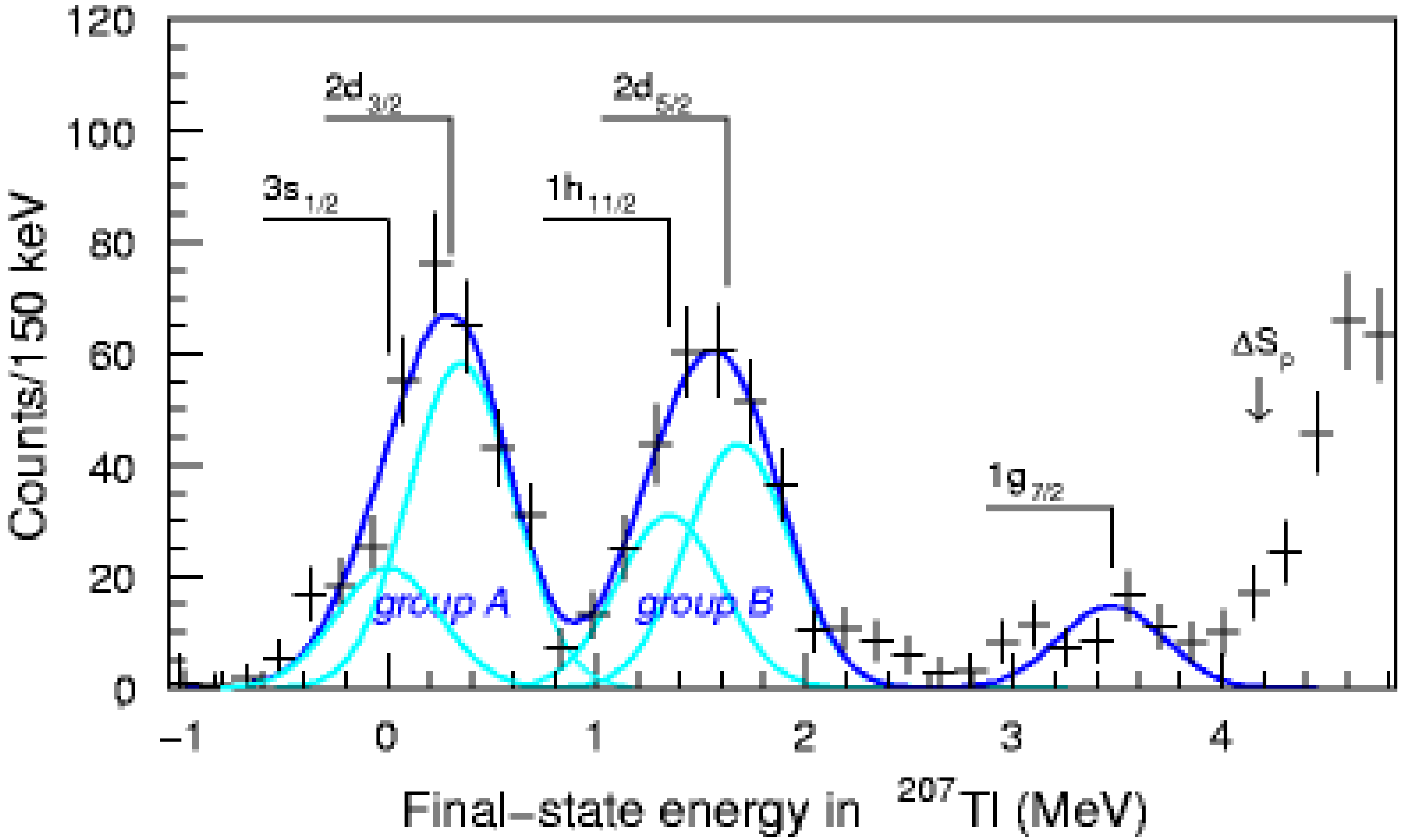
^{208}Pb(α,α′) followed by *p* decay

Decay to hole states in ^{207}Tl; branching ratios predicted by Gorelik *et al.*



M. Hunyadi *et al.*, Phys. Lett. B576 (2003) 253
M. Hunyadi *et al.*, Phys. Rev. C75 (2007) 014606

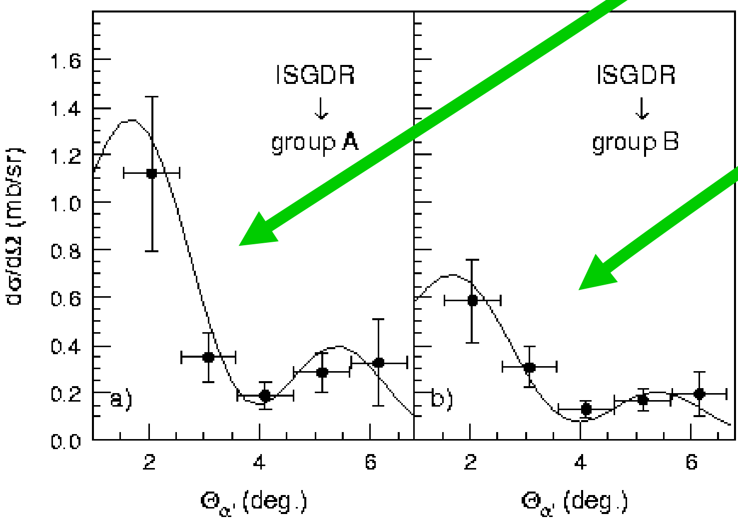
Branching ratios for decay

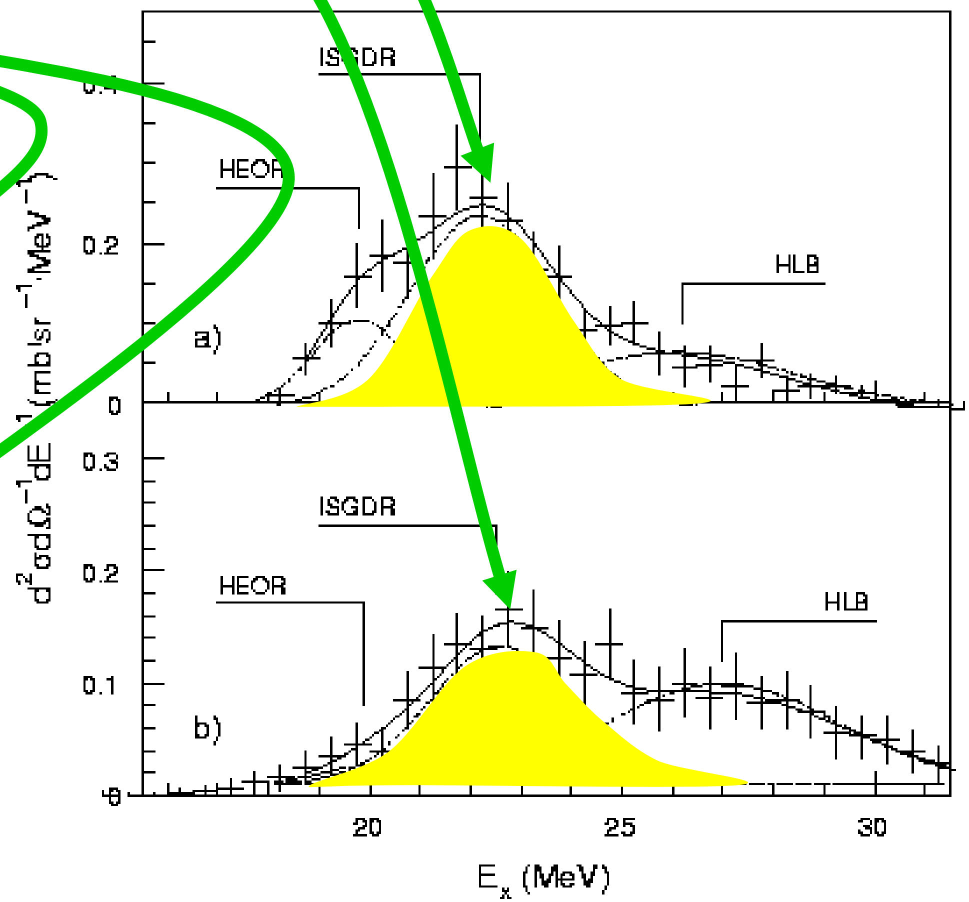


ISGDR in ^{208}Pb in p decay

E_x = 22.1 ± 0.3 MeV
L = *1* transition

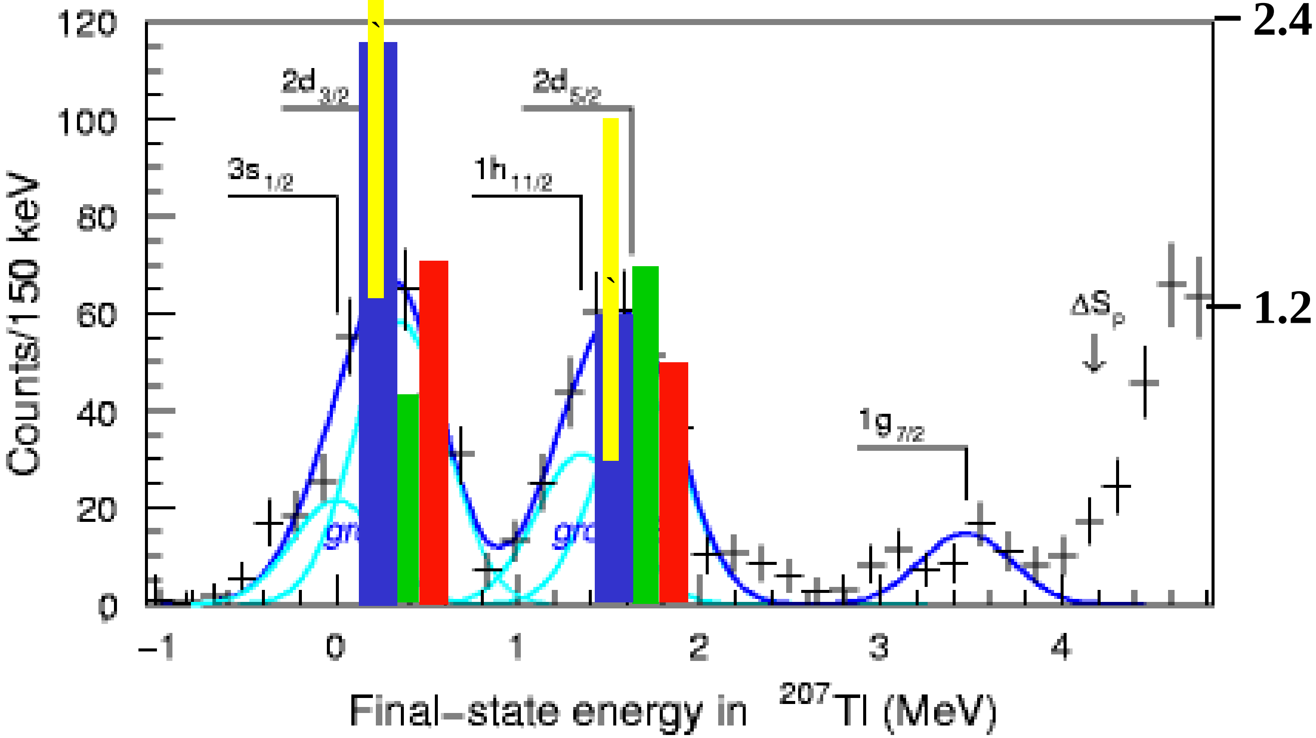
gated on hole states





KVI GSI university of groningen

Branching ratios for decay



This work

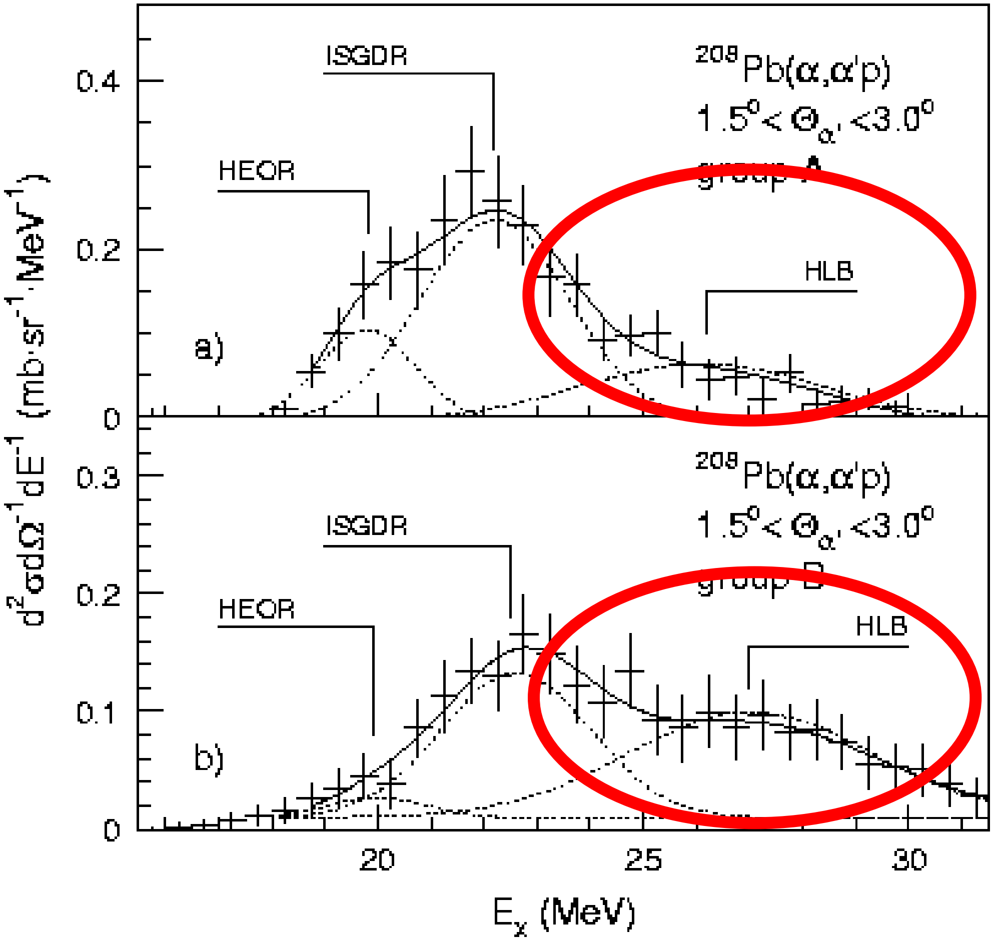
Gorelik *et al.*, PRC 62 (2000) 047301;

Continuum RPA;
Landau-Migdal
Parameters: f^{ex}, f';
Smearing parameter
Δ energy-dependent

Gorelik *et al.*, PRC 69 (2004) 054322

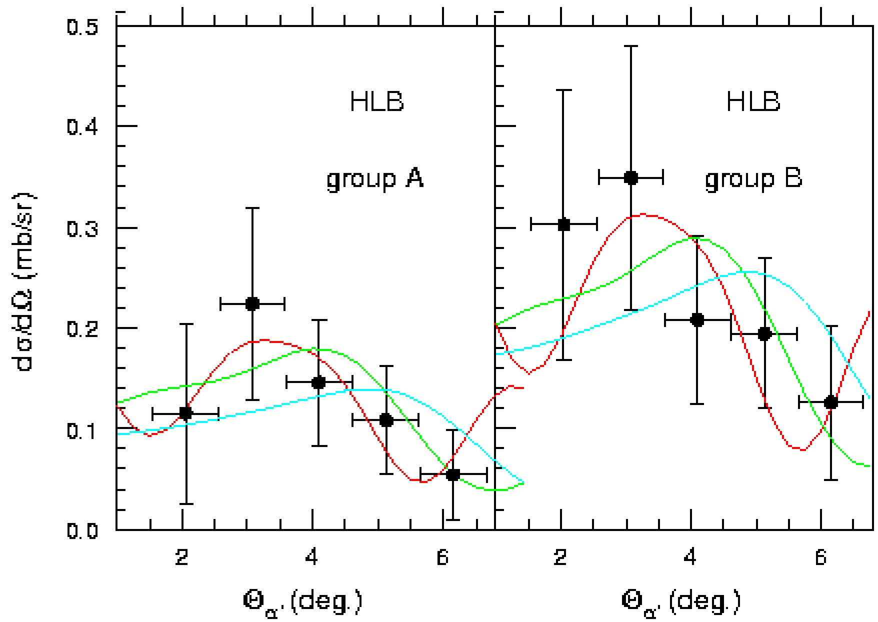
$1/2^+ + 3/2^+$	**2.6%**	**(S~0.56) 1.45%**	**2.3 ± 1.1**
$11/2^- + 5/2^+$	**1.9%**	**(S~0.56) 1.04%**	**1.2 ± 0.7**

Overtone of the ISGQR? [r^4Y_2]

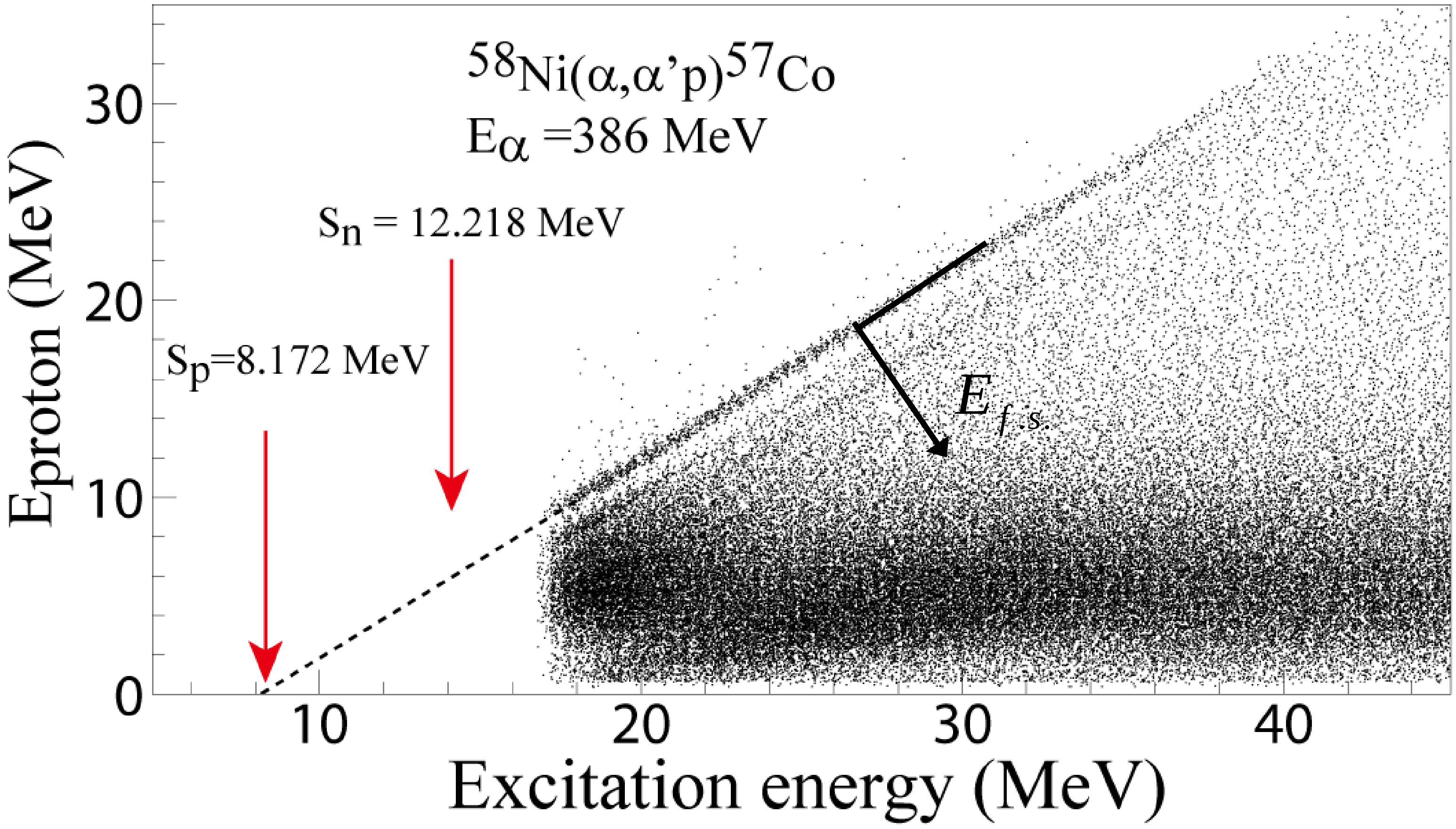


E_x = 26.9 ± 0.7 MeV

Muraviev and Urin
Bull. Acad. Sci. USSR
Phys. Ser. 52 (1988) 123
E_x = 28.3 MeV



Data analysis: Proton decay



Final-state energy

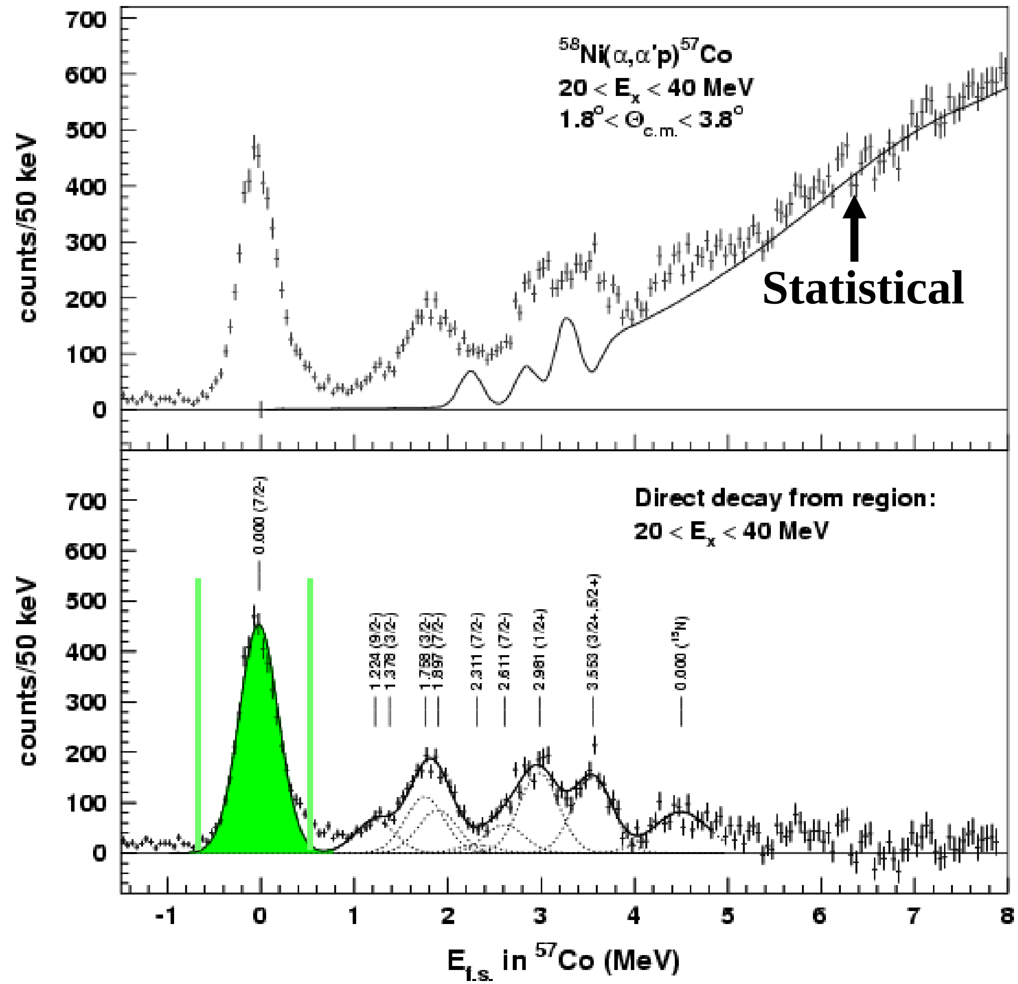
$$E_{f.s.} = E_X - E_p - S_p$$

Experimental results

M. Hunyadi *et al*., Phys. Rev. C80 (2009) 044317

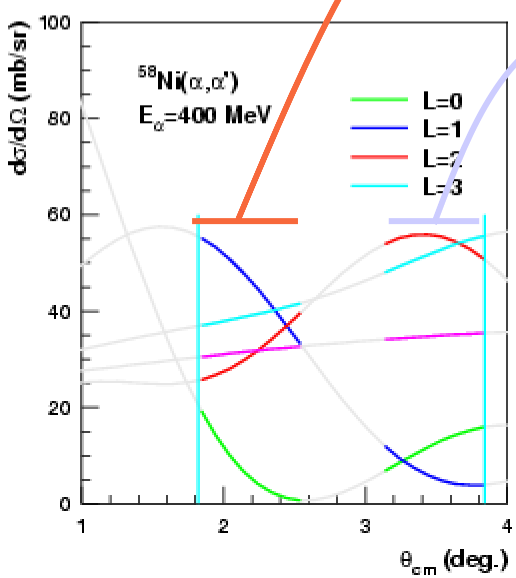
Final-state energy spectra

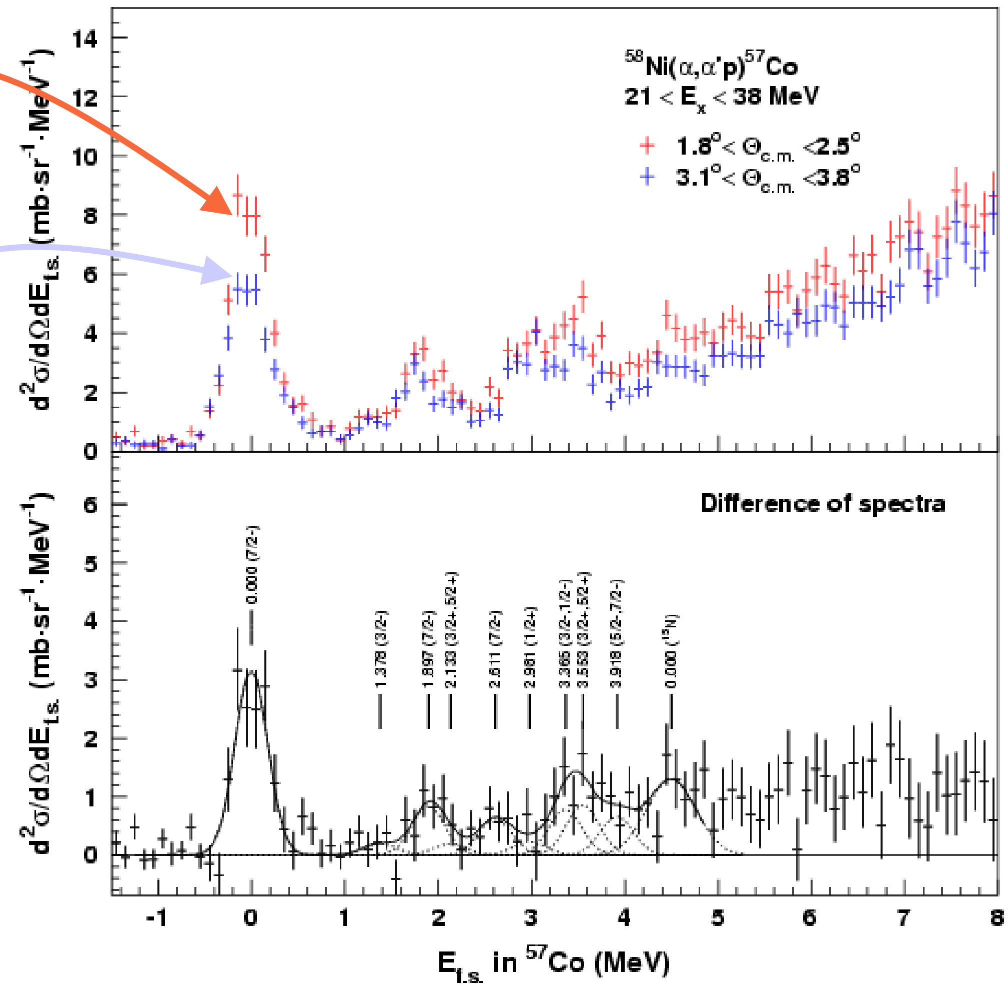
Final-state energy spectra after subtracting statistical contribution



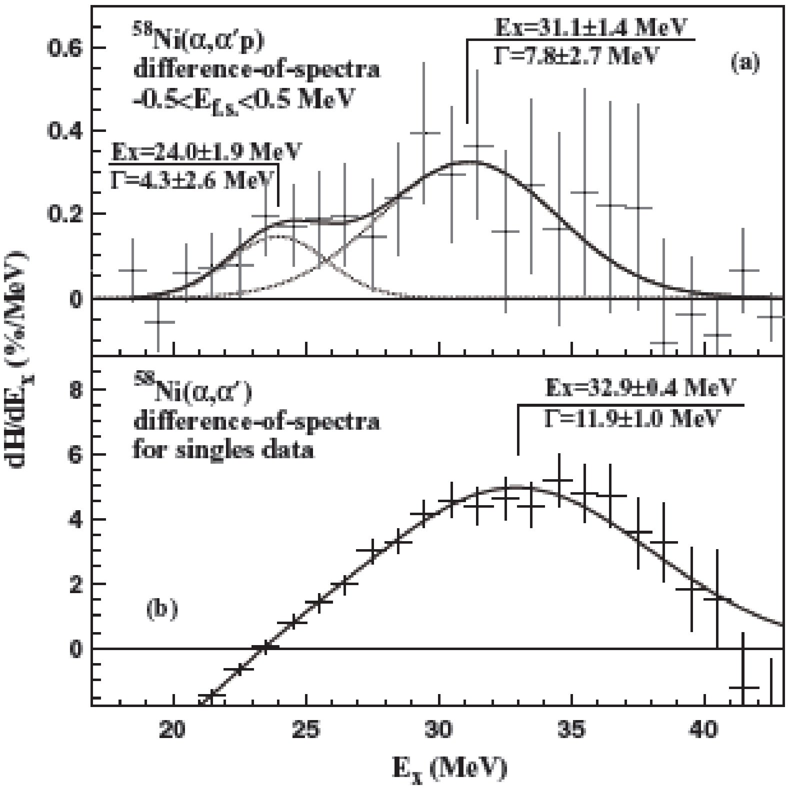
Experimental results

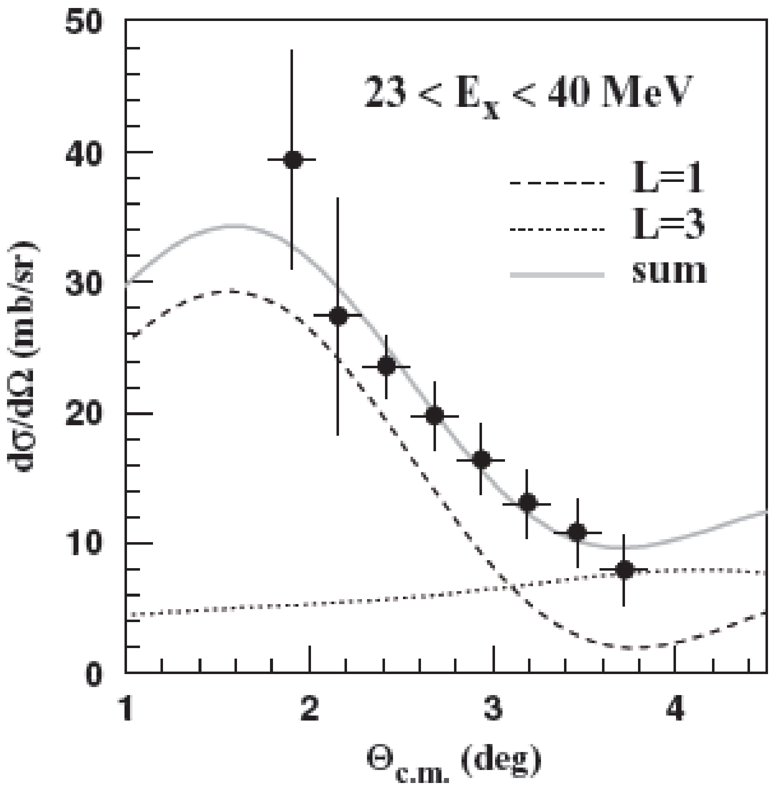
Difference of $E_{f.s.}$-spectra





Strength distribution of ISGDR in ^{58}Ni





Spectra of L = 1 strengths obtained with DOS method in percentage of isoscalar EWSR; a) coincidence data gated on g.s. decay and b) singles data.

Differential cross section of resonance structure fitted with *L* = 1 and *L* = 3 DWBA calculations.

Proton-decay branching ratios Normalized to 100%

	Exp. (%) (24-38 MeV)	Cal. (%) (15-40 MeV)
$7/2^-$	61.3 (with $5/2^-$)	47
$3/2^-$	7.9	3.1
$3/2^-$, $1/2^-$	9.9	2.2 (only for 1/2-)
$5/2^-$	3.2 ± 3.4	-
$1/2^+$	2.0 ± 4.2	13.4
$3/2^+$, $5/2^+$	15.9	34.3
Σ	100 %	100%

Calculations: M.L. Goerlik, I.V. Safonov, and M.H. Urin, Phys. Rev. C69 (2004) 054322

Conclusions!

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

  Systematics: E_x, Γ, %EWSR

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

  $\Rightarrow K_{\tau} \approx$ – 500 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**

Outlook

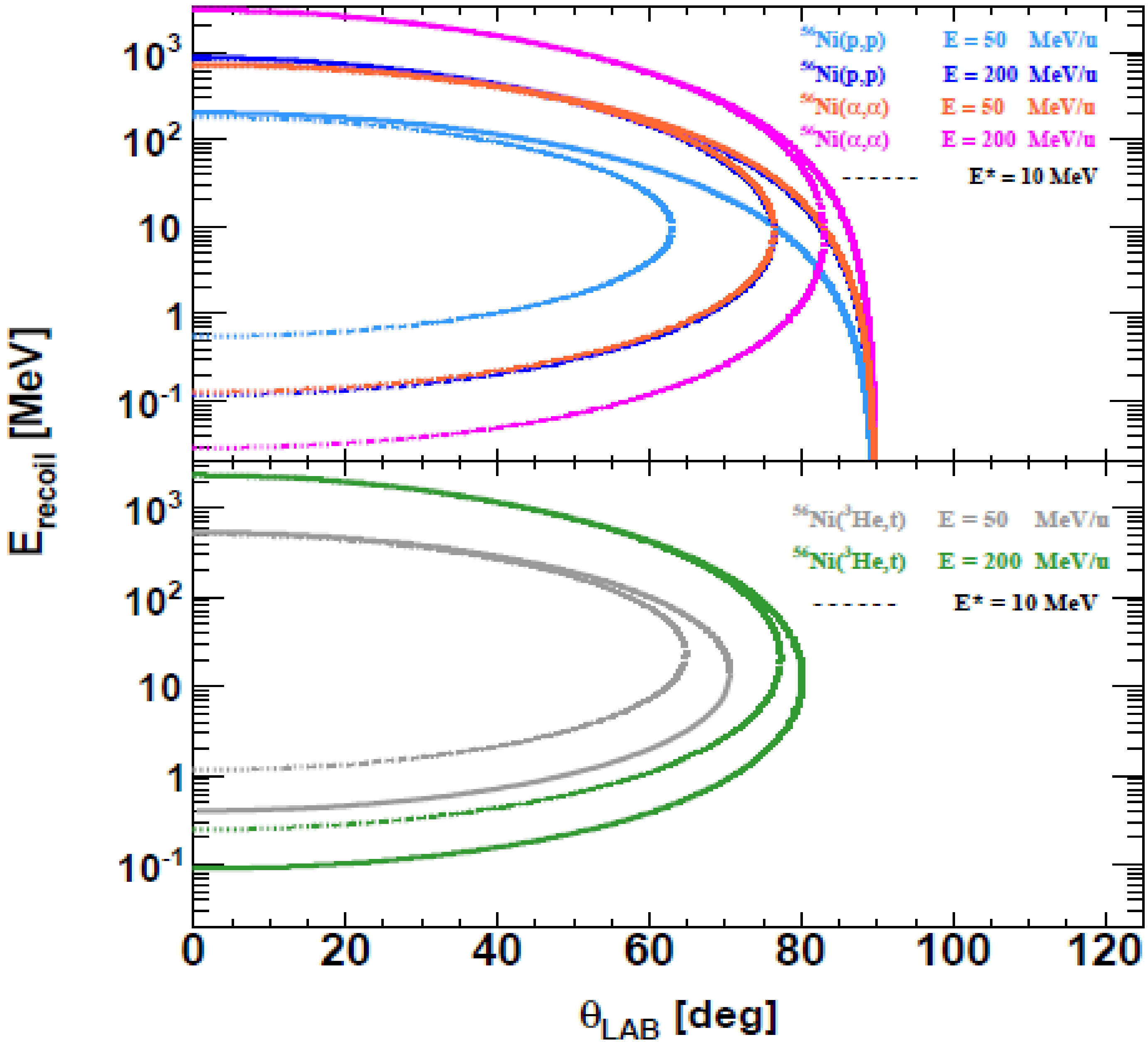
Radioactive ion beams will be available at energies where it will be possible to study excitation of ISGMR and ISGDR

RIKEN, FAIR, SPIRAL2, NSCL, EURISOL

Determine ISGMR and ISGDR in unstable Sn nuclei.

***A* = 106 to 134 possible**

⇒A more precise determination of K_τ


^{56}Ni(p,p) E = 50 MeV/u
^{56}Ni(p,p) E = 200 MeV/u
^{56}Ni(α,α) E = 50 MeV/u
^{56}Ni(α,α) E = 200 MeV/u
E* = 10 MeV
^{56}Ni(^{3}He,t) E = 50 MeV/u
^{56}Ni(^{3}He,t) E = 200 MeV/u
E* = 10 MeV
E_{recoil} [MeV]
θ_{LAB} [deg]
10^3
10^2
10
1
10^{-1}
0
20
40
60
80
100
120

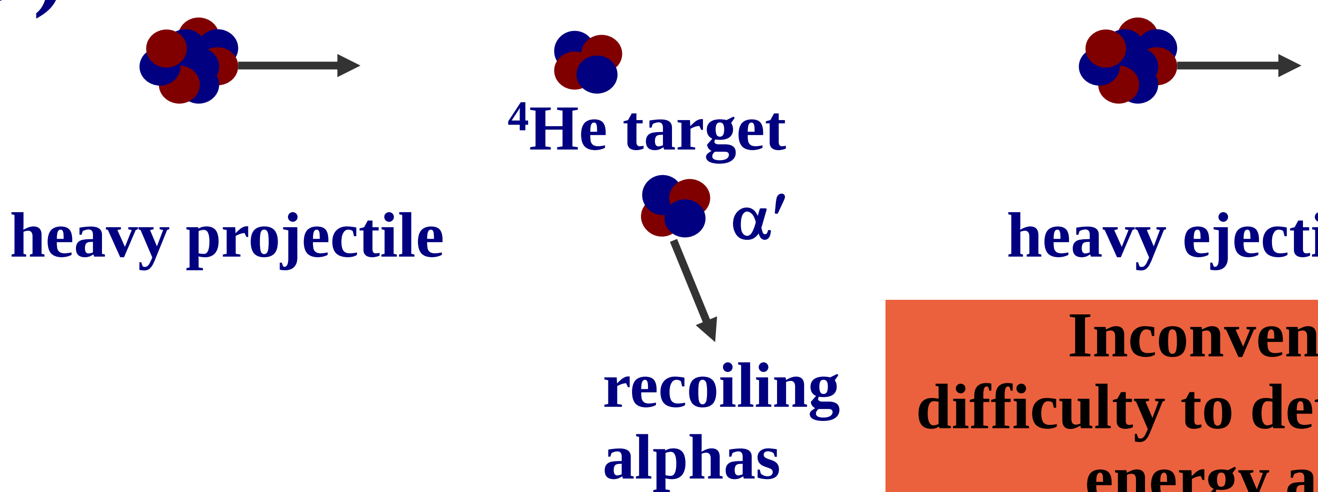
Nuclear structure studies with reactions in inverse kinematics

- Possible at FAIR and RIKEN

(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

Detection system @ FAIR

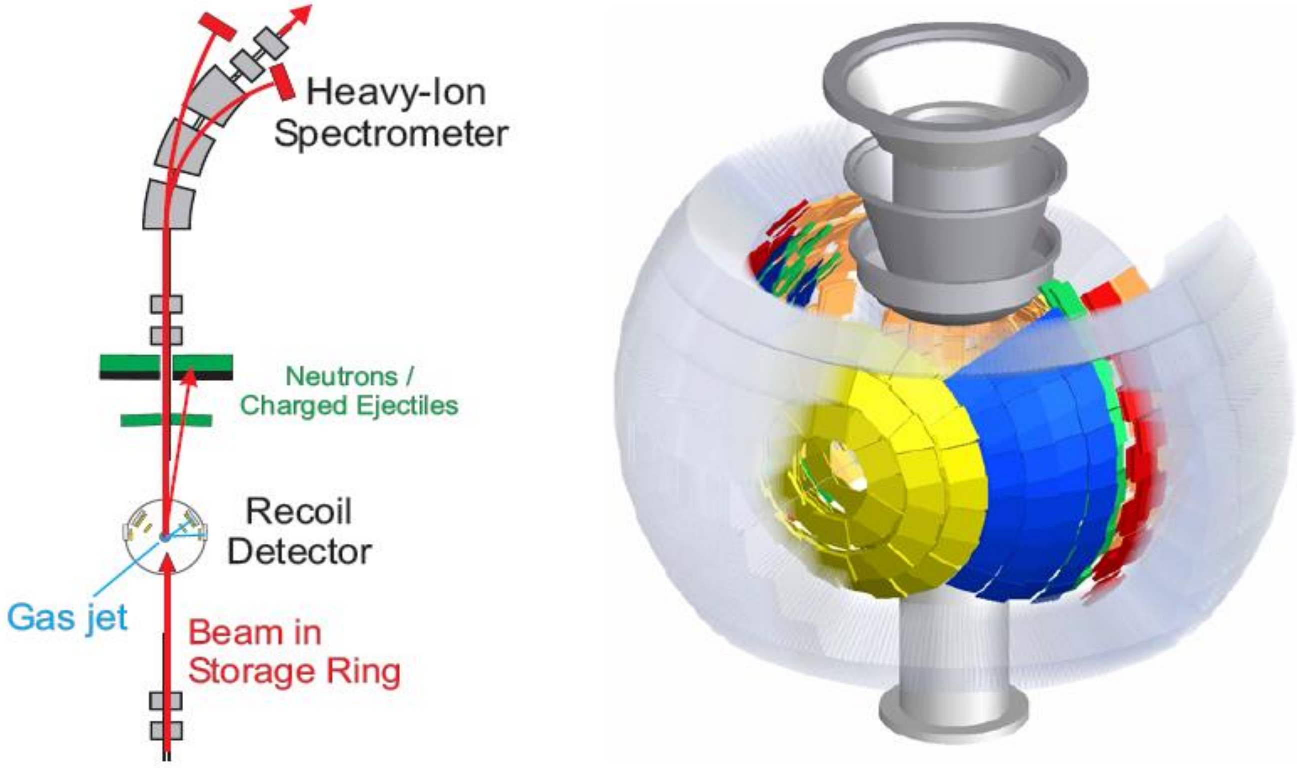


Figure 1: *Schematic view of the EXL detection systems. Left: Set-up built into the NESR storage ring. Right: Target-recoil detector surrounding the gas-jet target.*

Use of EXL recoil detector is under evaluation

ISGDR in ^{56}Ni: 2nd ISGDR in Ni after ^{58}Ni

Conditions

- ^{56}Ni(α,α') and ^{56}Ni(α,α'p)
- LISE beam at the highest energy possible ($\geq 50A$ MeV)

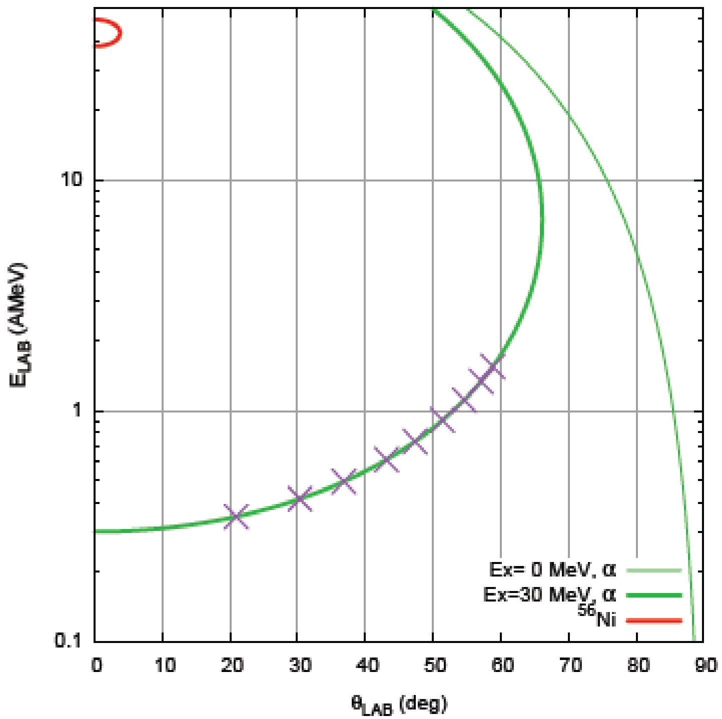
Setup

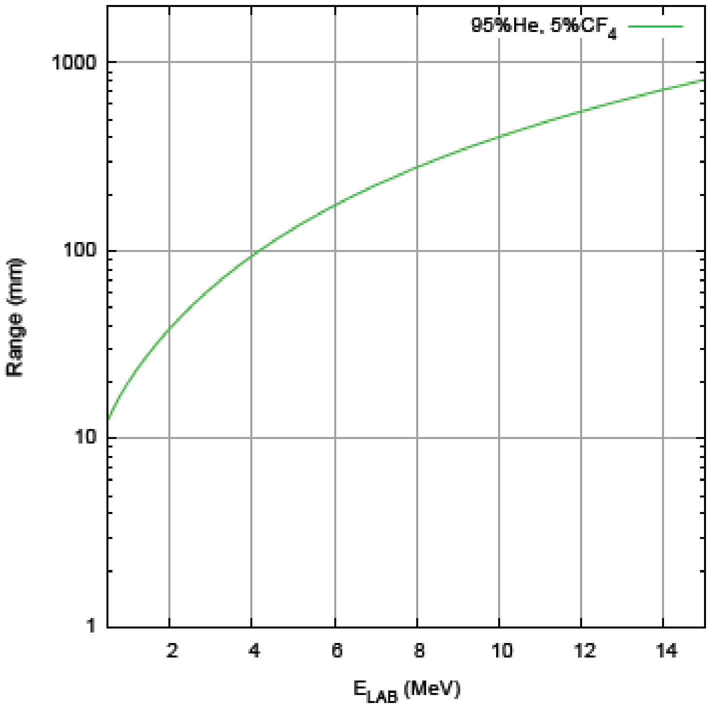
- MAYA in D6, filled w/ He (>95%), CF_4 mixture.
- All ancillary detectors (Si & CsI + S1)
- "Active" masking of the beam

Predictions

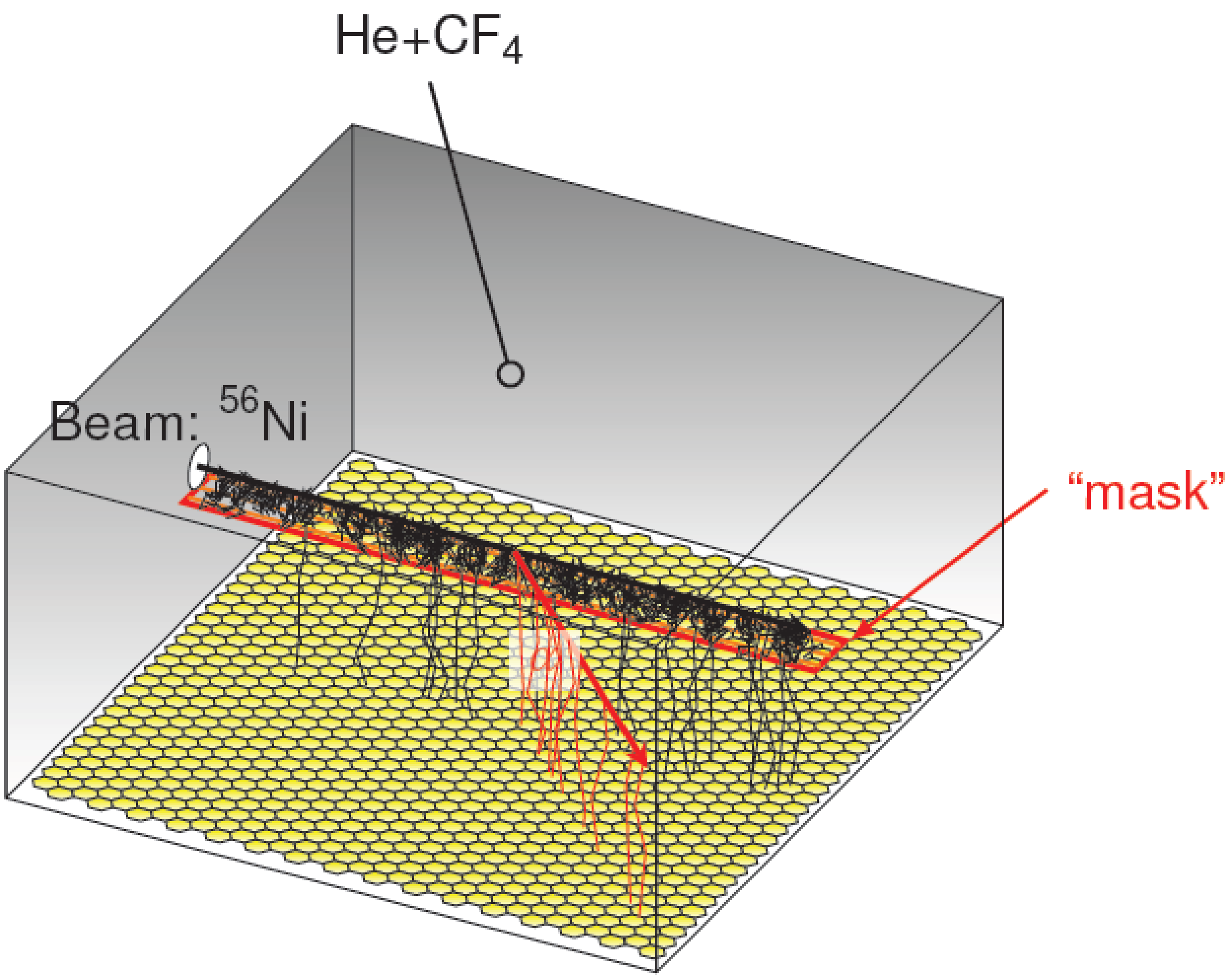
- Detect alpha down to ≈ 1 MeV, between [2°,10°] in C.M.
- Remeasure ISGMR in ^{56}Ni
- Detect protons coming from ISGDR decay

Kinematics: energies

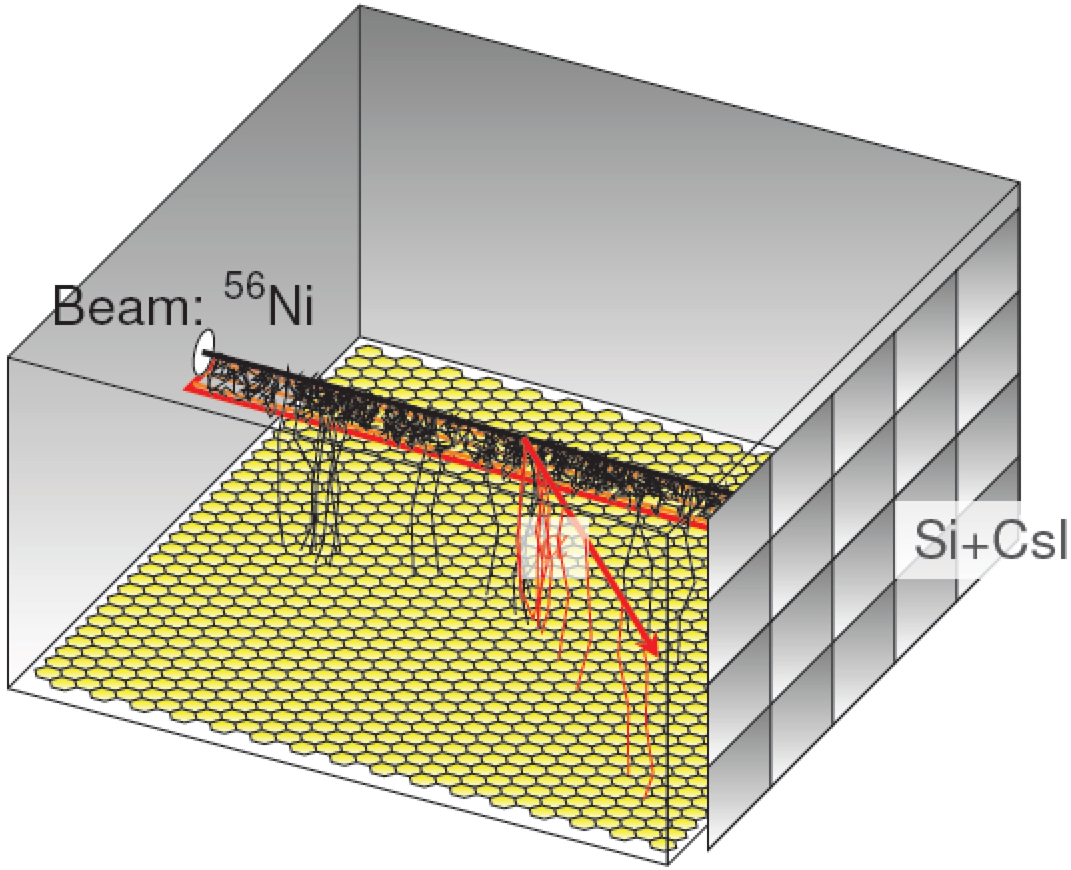




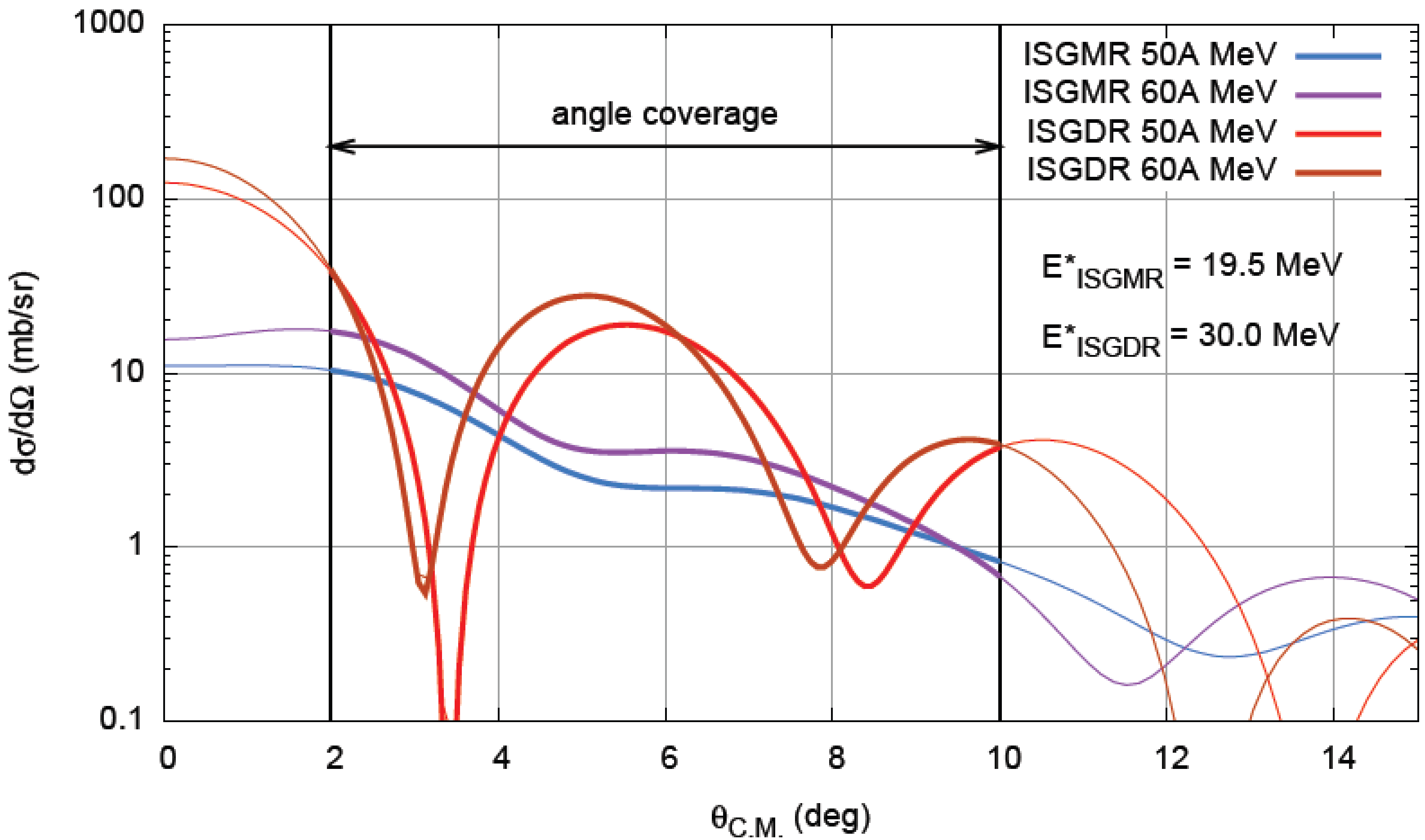
Setup: MAYA (Active target)



Setup: MAYA (Active target)



Predicted angular distribution

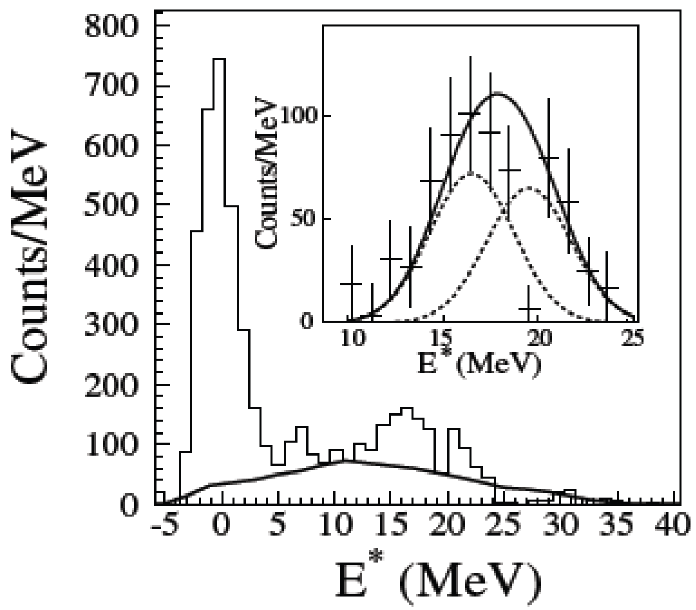


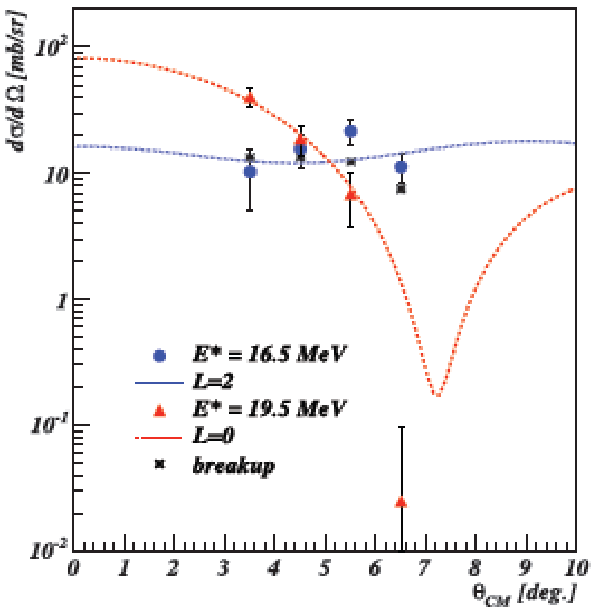
Recent works: ISGMR

ISGMR in unstable nuclei

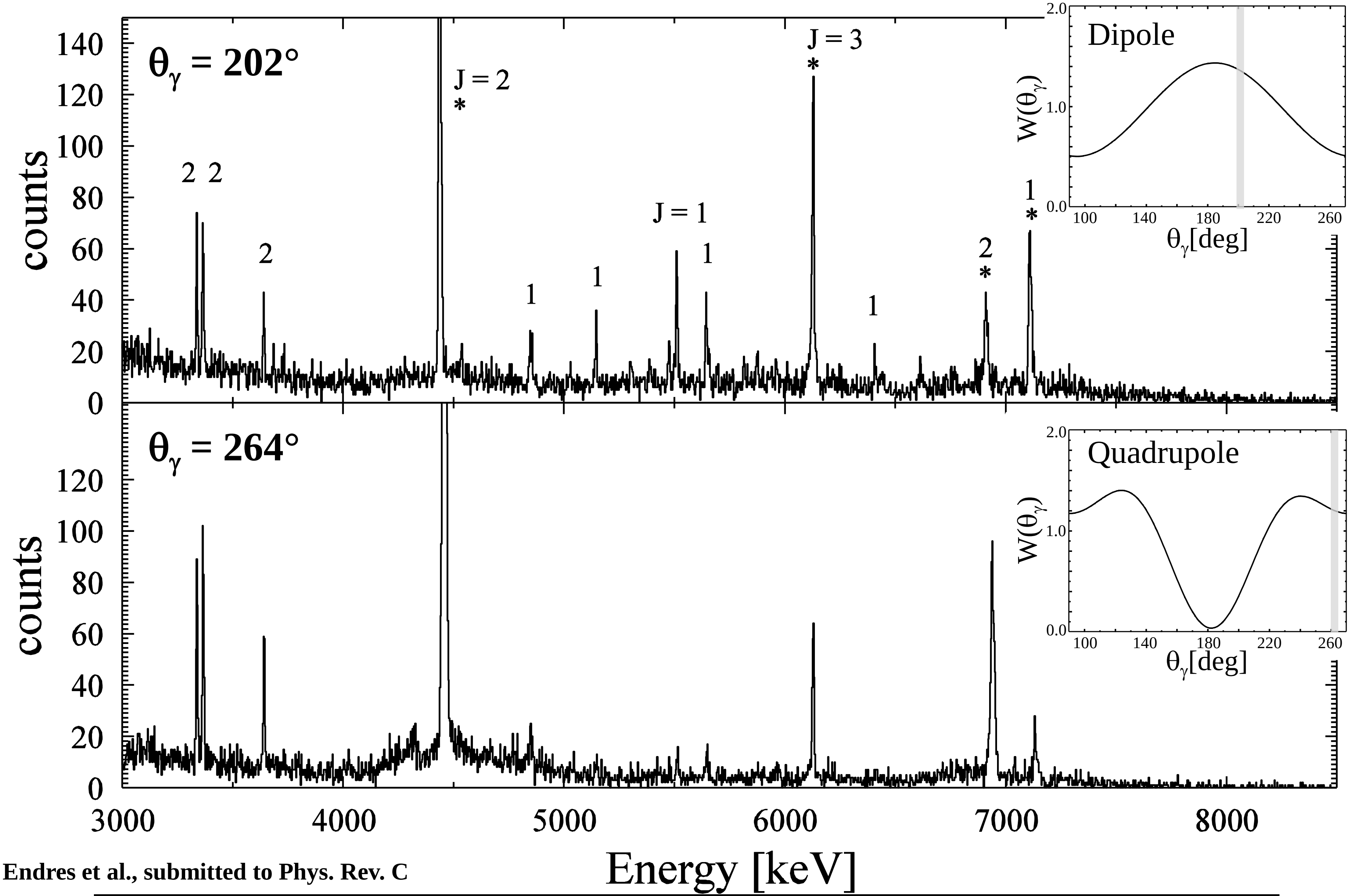
^{56}Ni: active target MAYA filled with deuterium gas
bombarding energy of 50A MeV

C. Monrozeau *et al.* @ GANIL



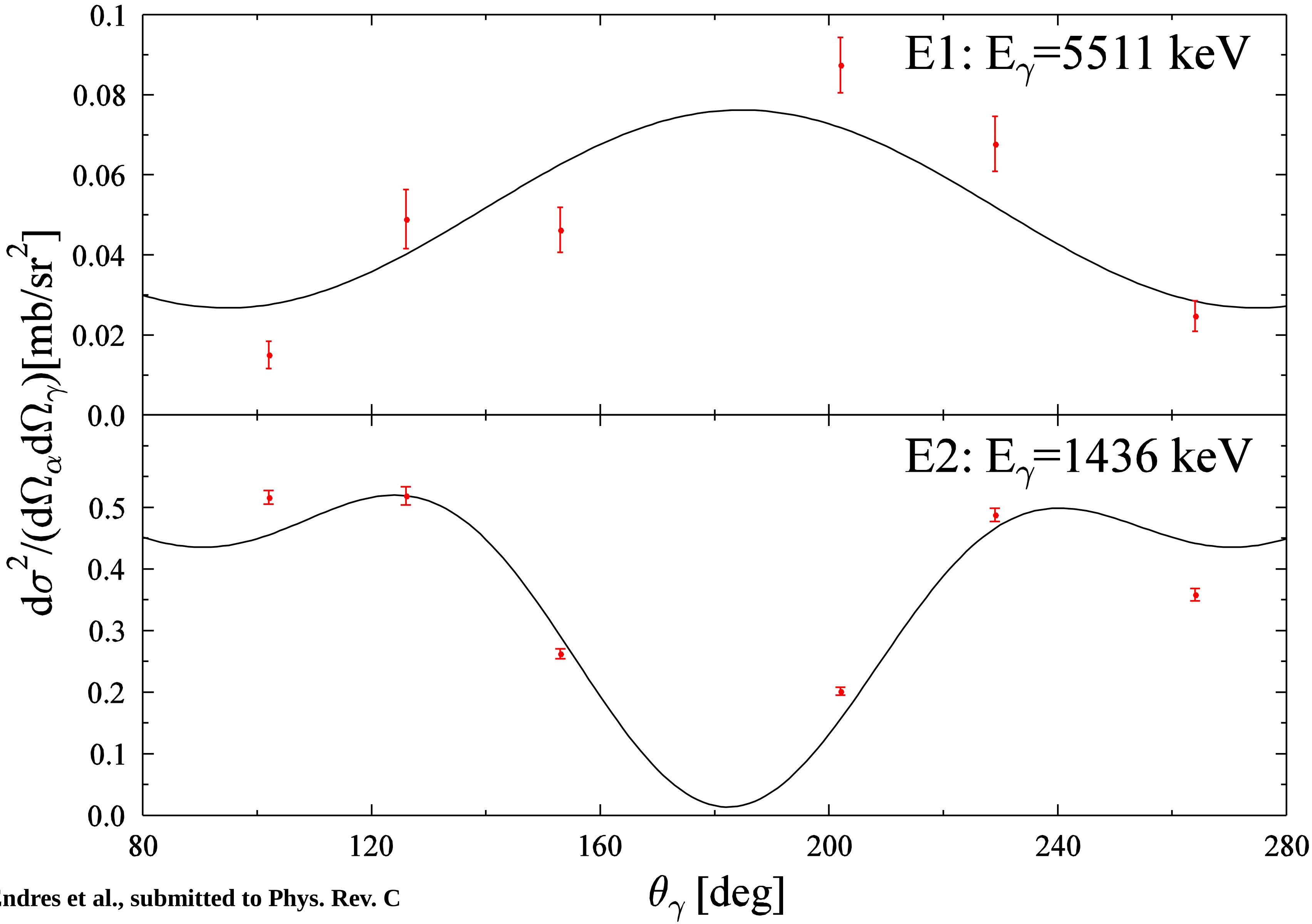


Multipole assignment with α–γ angular correlation



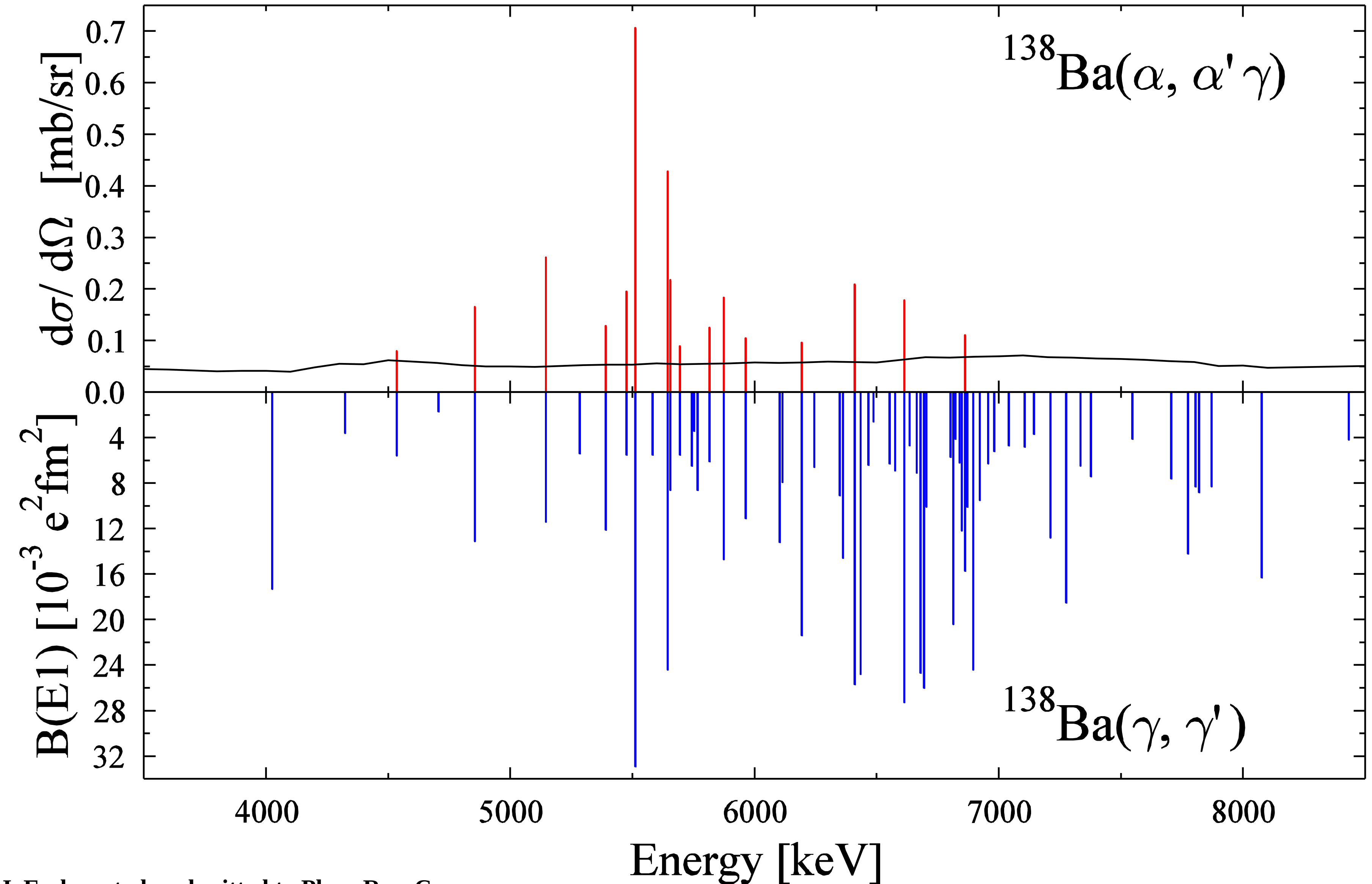
J. Endres et al., submitted to Phys. Rev. C

Multipole assignment with α–γ angular correlation



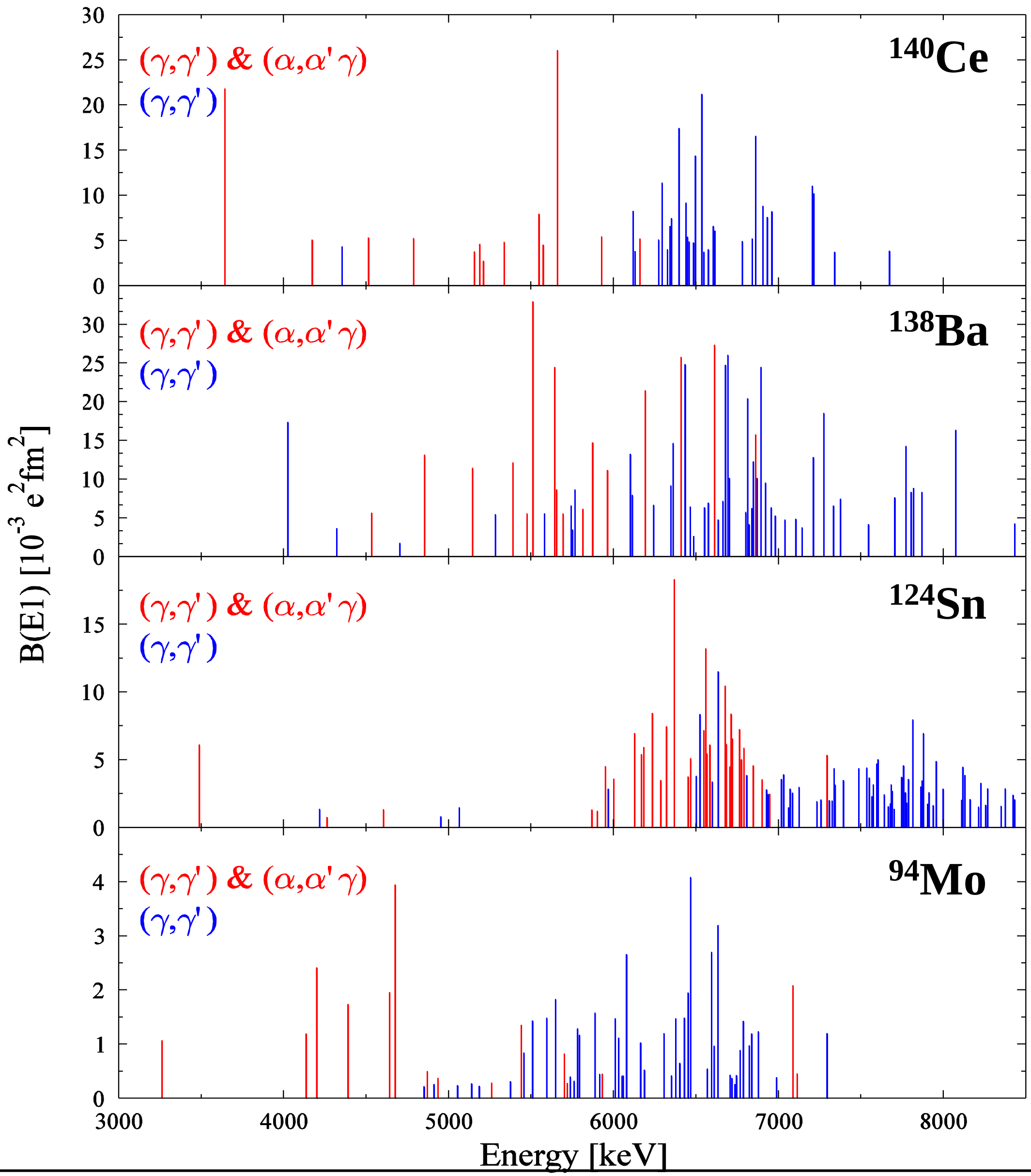
J. Endres et al., submitted to Phys. Rev. C

Comparison of $(\alpha,\alpha'\gamma)$ with (γ,γ') on ^{138}Ba



J. Endres et al., submitted to Phys. Rev. C

E1 strength distribution in ^{140}Ce, ^{138}Ba, ^{124}Sn, and ^{94}Mo



— (γ,γ′) & (α,α′γ)

— (γ,γ′) only