Progress in the study of electric giant and pygmy resonances over the last five decades

Muhsin N. Harakeh

University of Groningen, the Netherlands

Symposium in honor of Angela Bracco

Bormio, Italy

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Operators and Microscopic Structure

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

- **Excitation energy depends on**

  ***i*) multipole *L* (*Lħω*, 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:

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

Constant **Overtone**

***2ħω* excitation**

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

Spurious c.o.m. motion **Overtone**

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

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$$P_{0\mu} = \frac{1}{2}\sum_i r_i^2$$

$$\sum_n (E_n - E_0) \mathrm{B}(\mathrm{E}0, 0 \to n) = S_0 = \frac{\hbar^2}{2m} A < \mathrm{r}^2 >$$

$$P_{1\mu} = \frac{1}{2}\sum_i r_i^3 Y_{1\mu}(\hat{r}_i)$$

$$\sum_n (E_n - E_0) \mathrm{B}(\mathrm{E}1, 0 \to n) = S_1 = \frac{\hbar^2}{8\pi m} \frac{3}{4} A[11 < \mathrm{r}^4 > - \frac{25}{3} < \mathrm{r}^2 >^2 - 10\varepsilon < \mathrm{r}^2 >]$$

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

$$Q_{\lambda\mu} = \sum_i r_i^\lambda Y_{\lambda\mu}(\hat{r}_i)$$

$$\sum_n (E_n - E_0) \mathrm{B}(\mathrm{E}\lambda, 0 \to n) = S_\lambda = \frac{\hbar^2}{8\pi m} \lambda(2\lambda + 1)^2 A < \mathrm{r}^{2\lambda - 2} >$$

IVGDR

$\tau\, r Y_1$

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

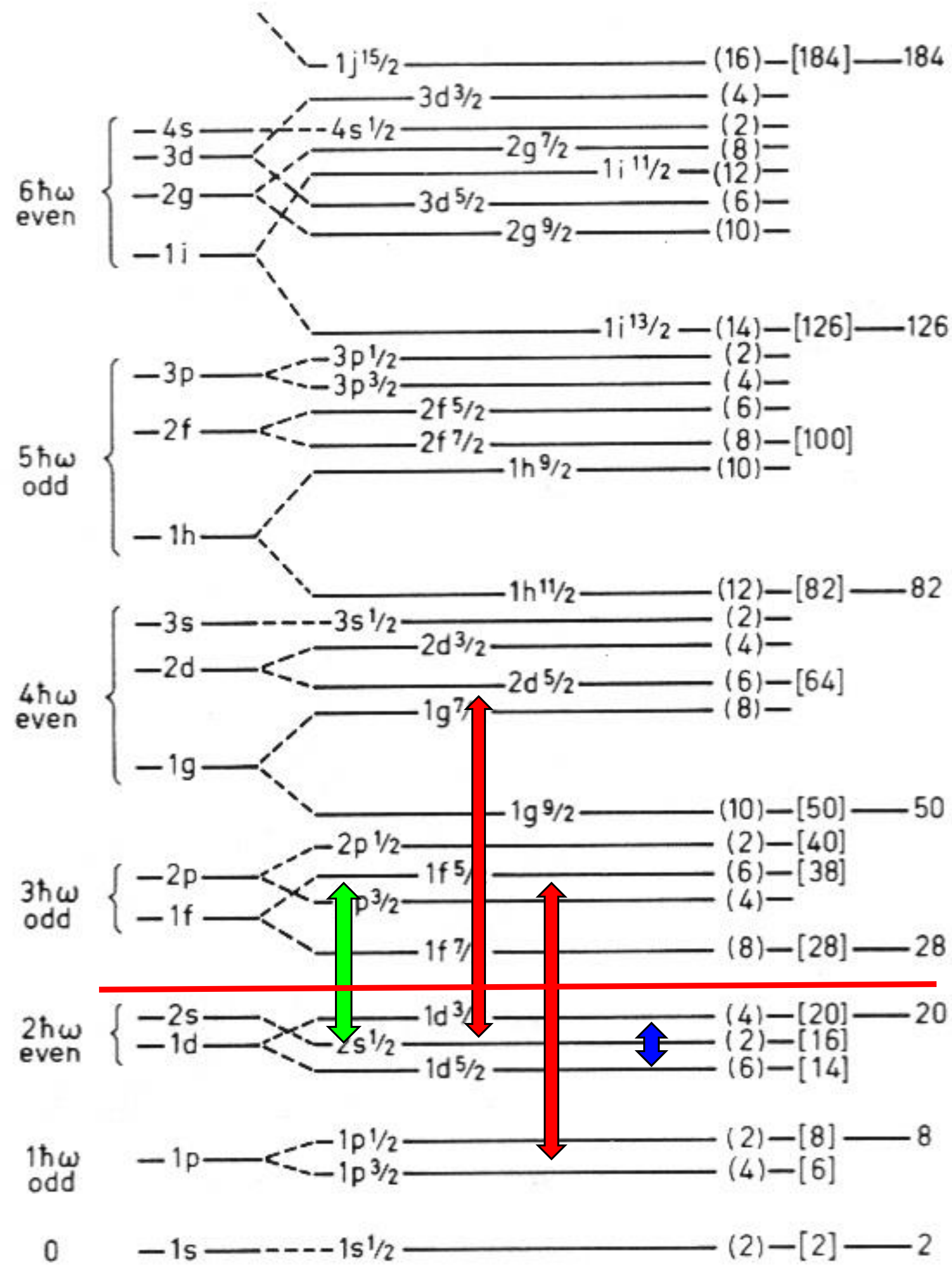
$\Delta N = 2$ **E2 (ISGQR)**

&

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

ISGMR $r^2 Y_0$

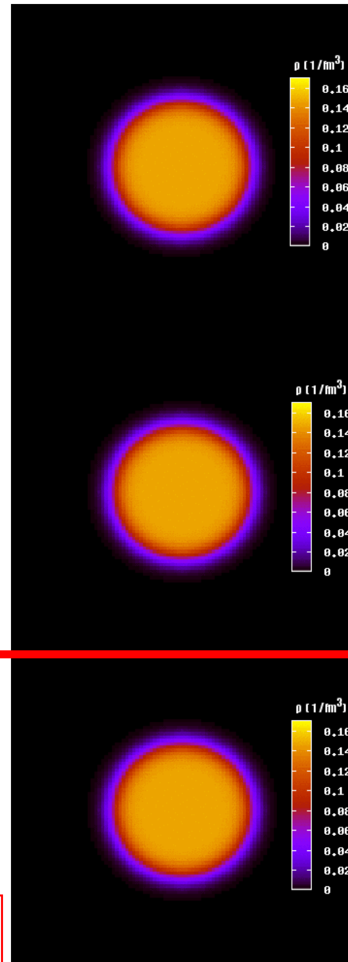
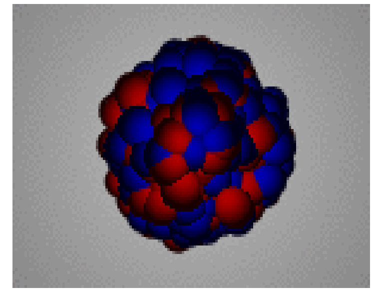
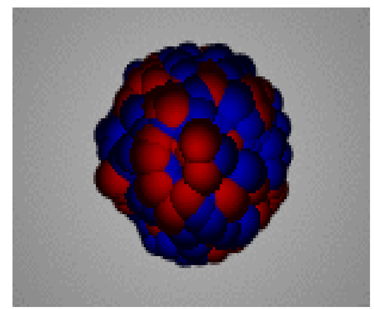
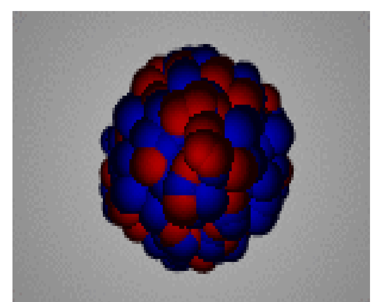
ISGQR $r^2 Y_2$



Compression Modes
ISGMR & ISGDR
Hydrodynamic Models

The Collective Response of the Nucleus: Giant Resonances

Compression modes

	Isoscalar (In phase) $\Delta T = 0$	*Isovector (Out of phase)* $\Delta T = 1$
Monopole $\Delta L = 0$ **(GMR)**		
Dipole $\Delta L = 1$ **(GDR)**		
Quadrupole $\Delta L = 2$ **(GQR)**		

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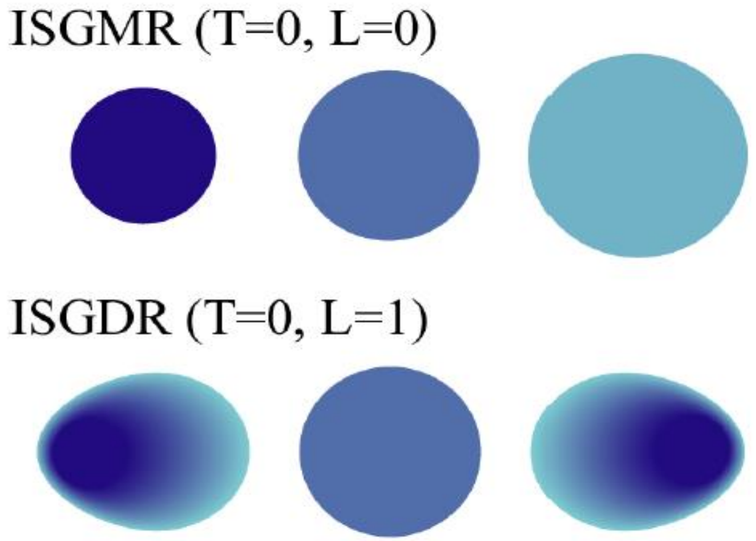
Compression Modes of Nuclei

Compression modes: ISGMR, ISGDR

In Constrained and Scaling Models:

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

$$E_{ISGDR} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\varepsilon_F}{m\langle r^2\rangle}}$$

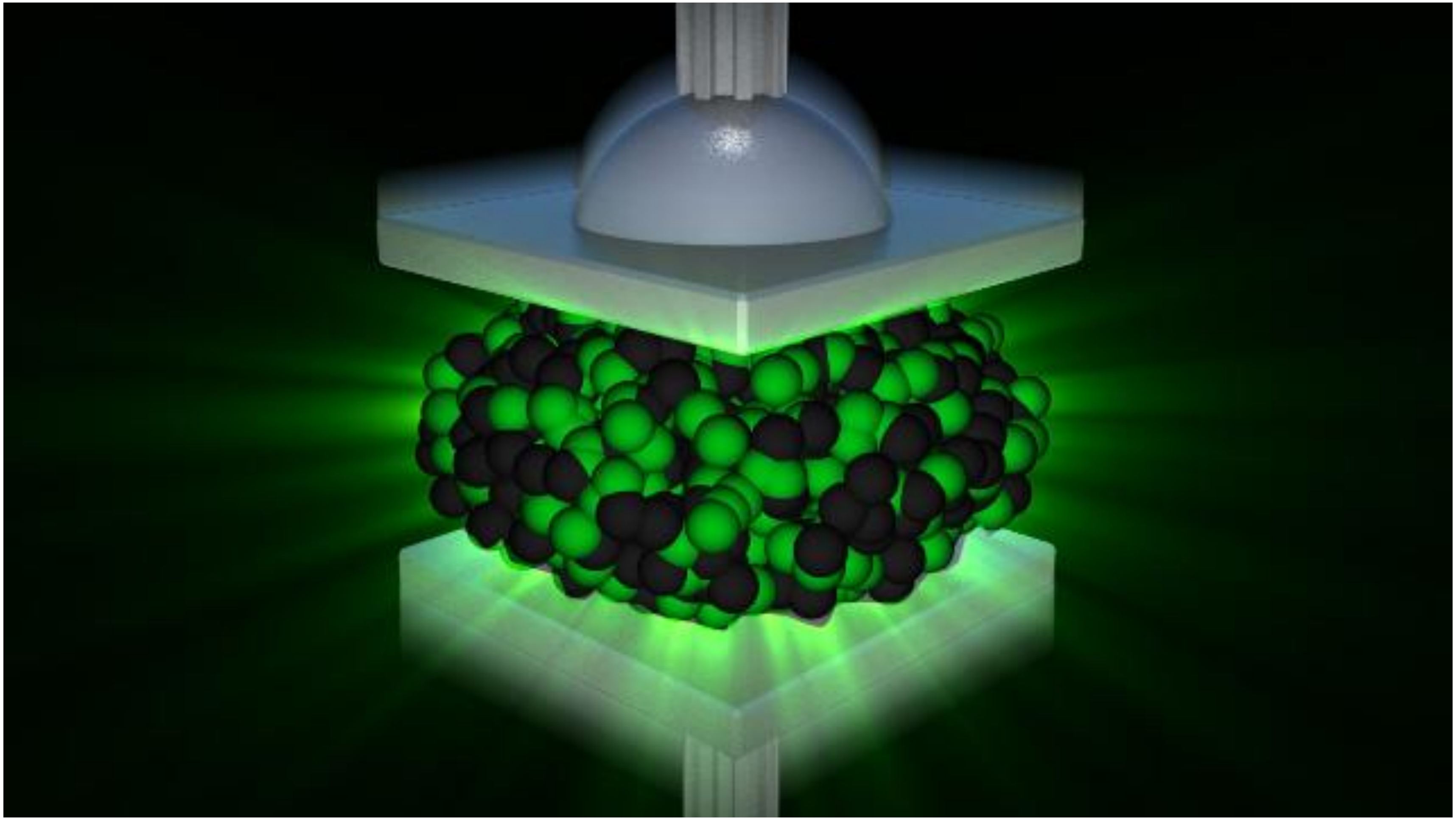


ε_F is the Fermi energy and K_A is the nucleus incompressibility

$$K_A = \left[r^2(d^2(E/A)/dr^2)\right]_{r=R_0}$$ **J.P. Blaizot, Phys. Rep. 64 (1980) 171**

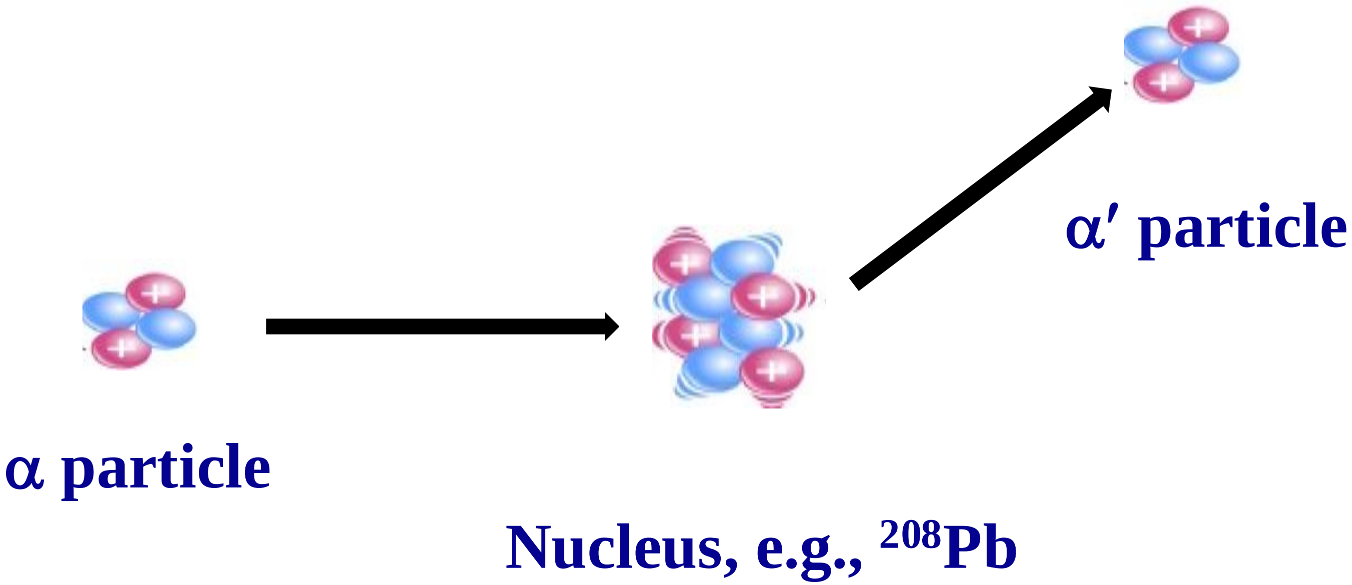
ISGMR, ISGDR ⇒ Incompressibility, symmetry energy

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



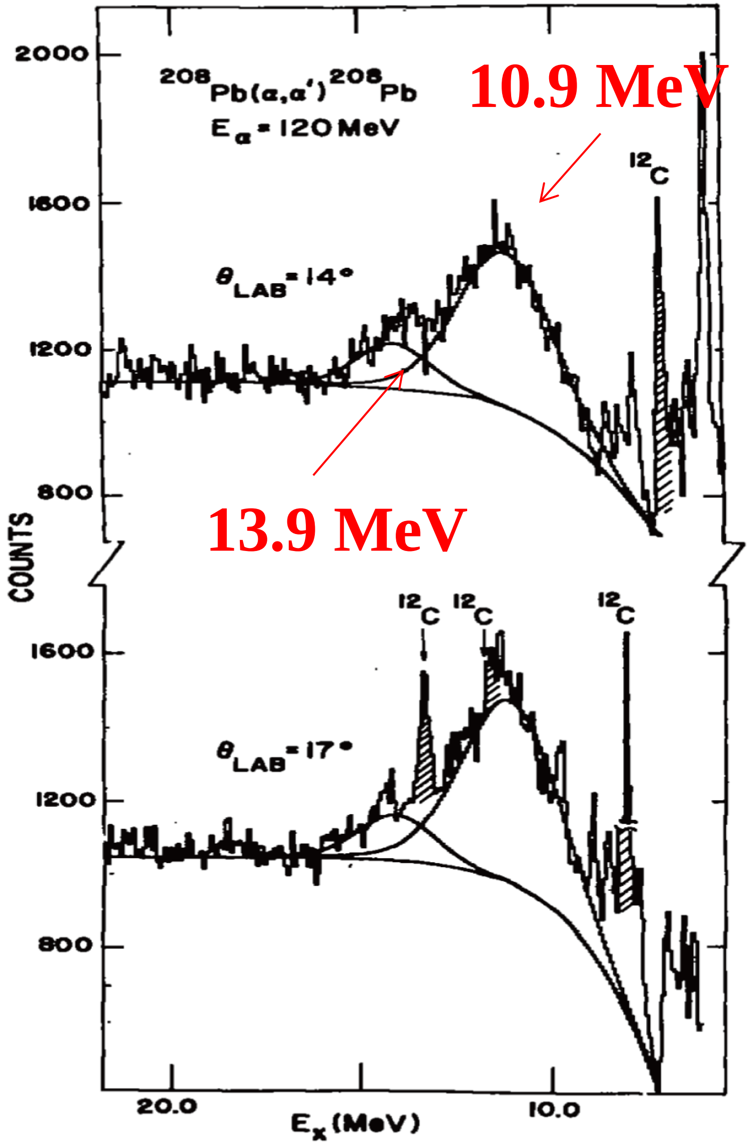
Thomas Flechel

Köln



Inelastic α scattering

ISGQR, ISGMR



⇐ ^{208}Pb(α,α') at E_α=120 MeV
Spectra obtained with solid-state detectors

Large instrumental background and nuclear continuum!

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

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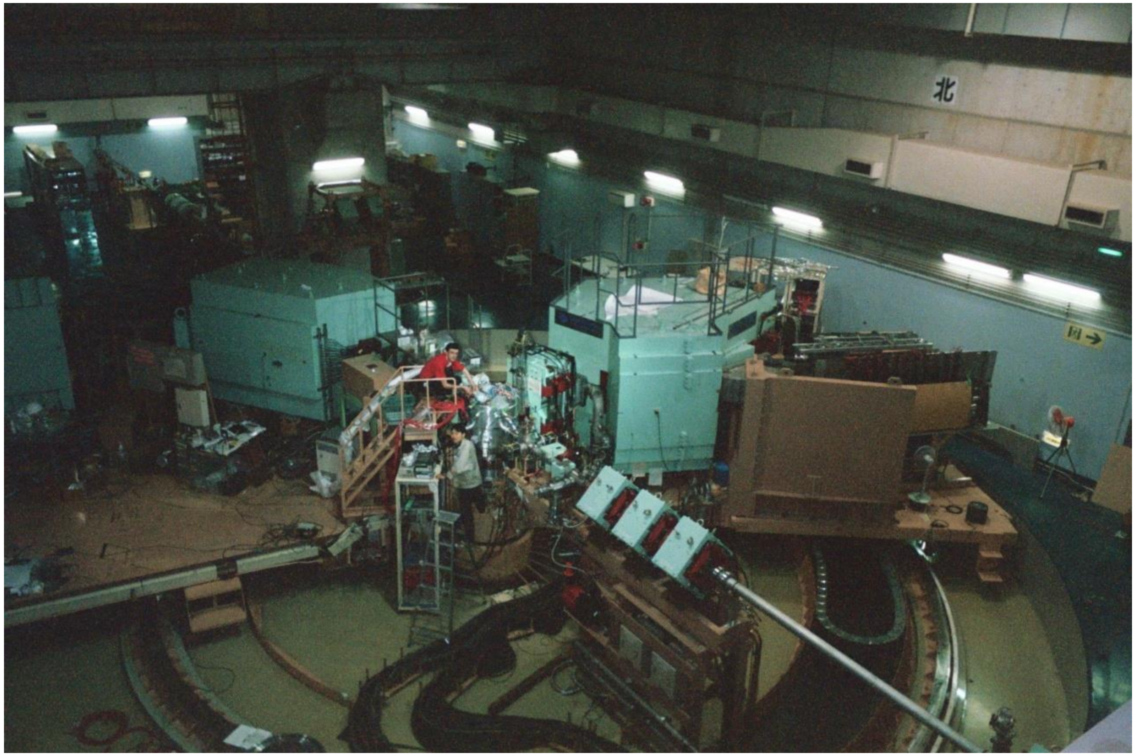
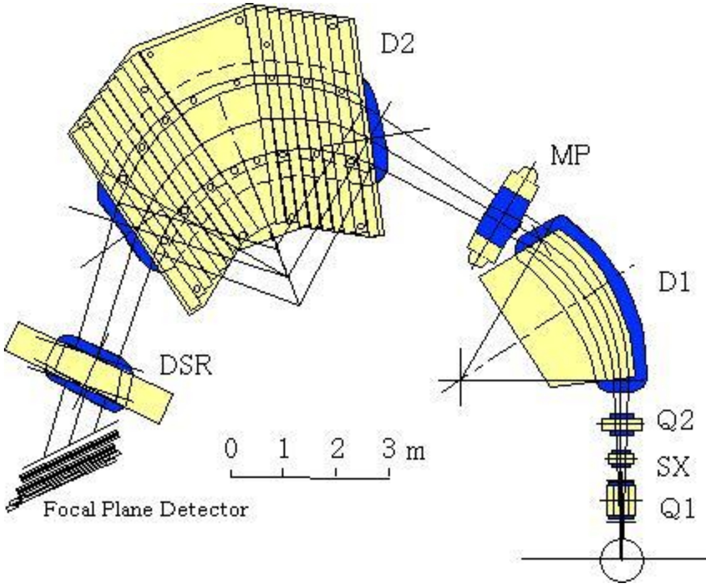
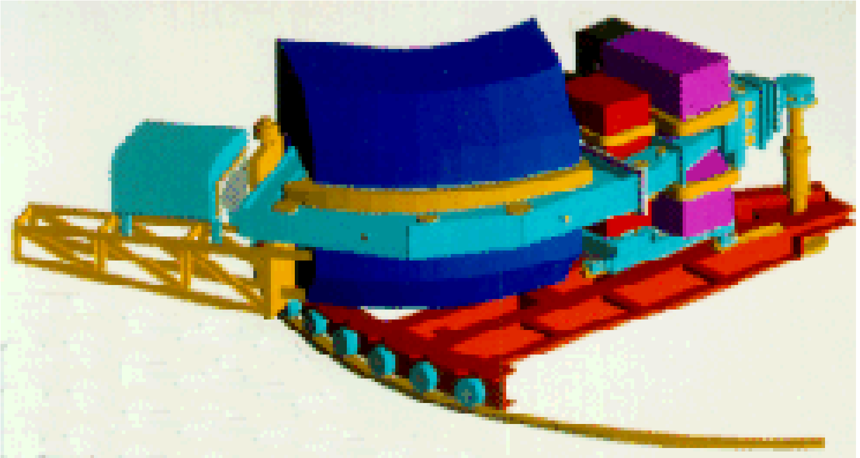




Grand Raiden@ RCNP



BBS@KVI

(p,p') at E_p~ 300 (α,α') at E_α~ 400 & 200 MeV at RCNP & KVI, respectively

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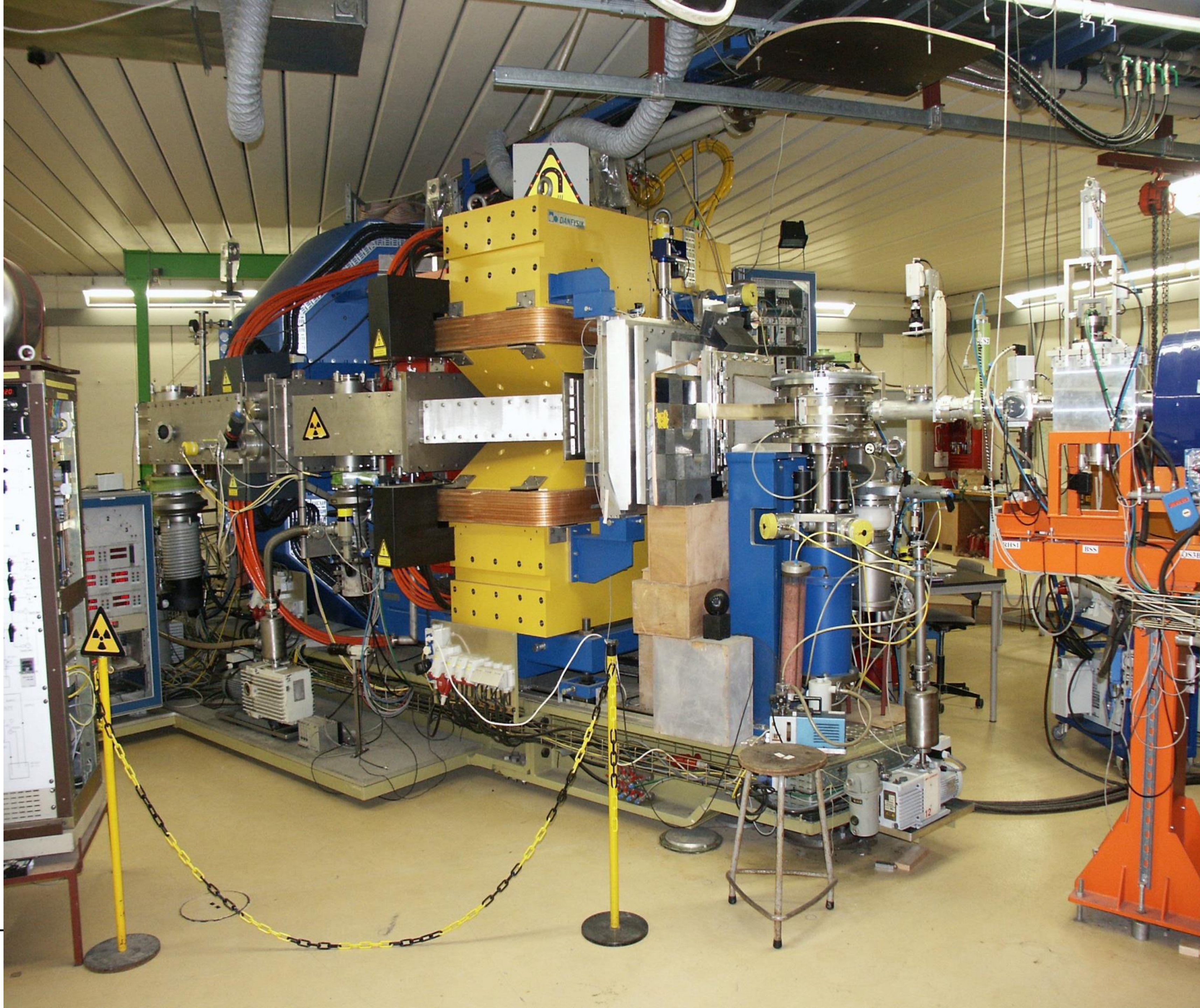
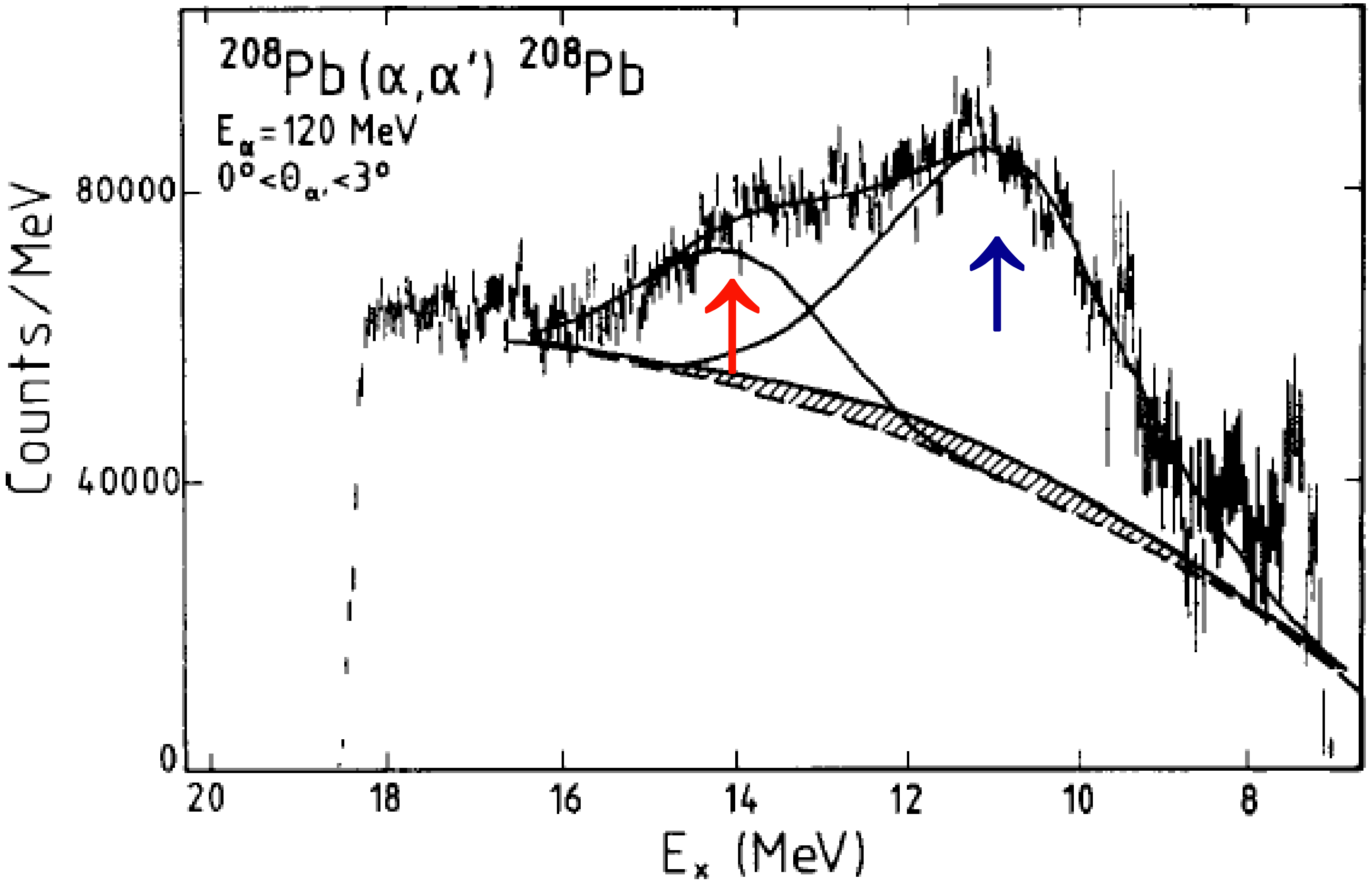

DANFYSIK

ISGQR at 10.9 MeV

ISGMR at 13.9 MeV



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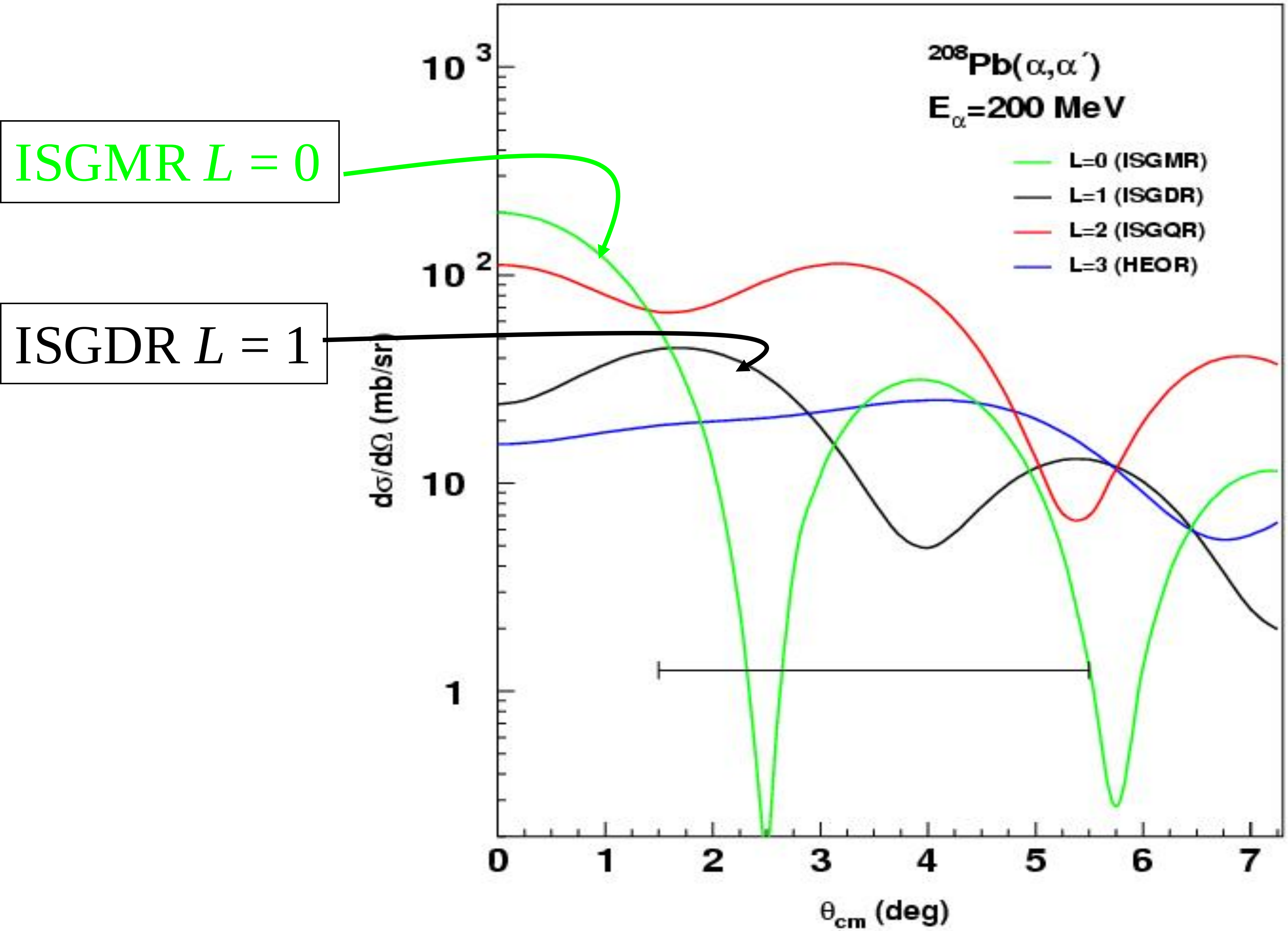

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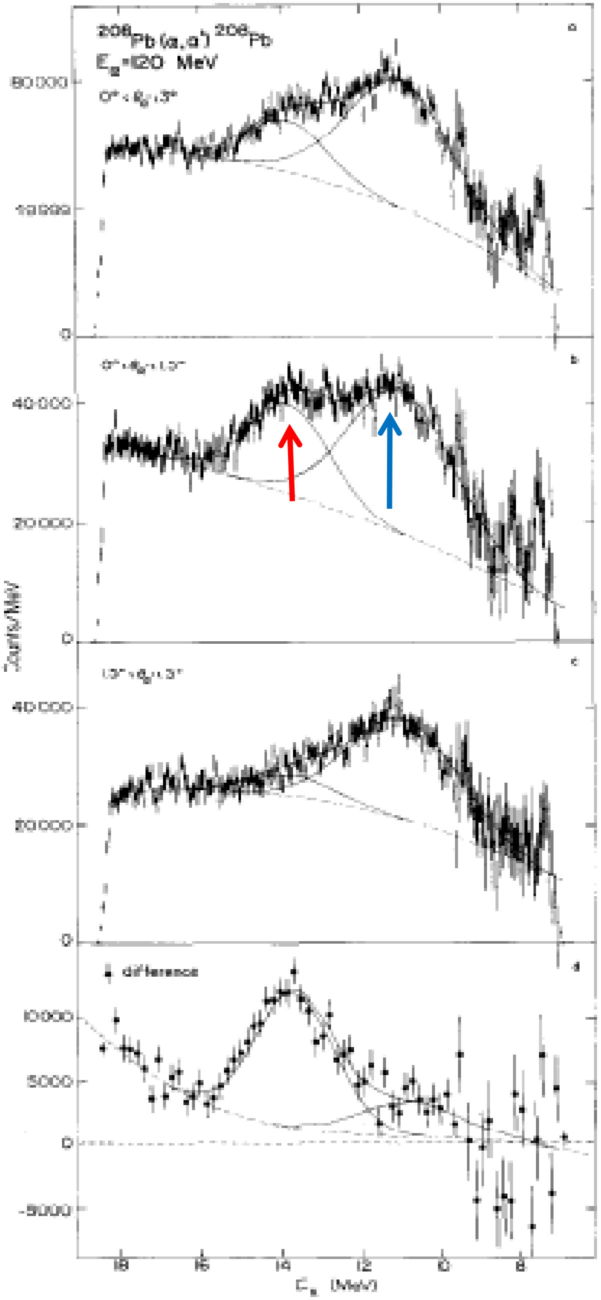
Difference of spectra

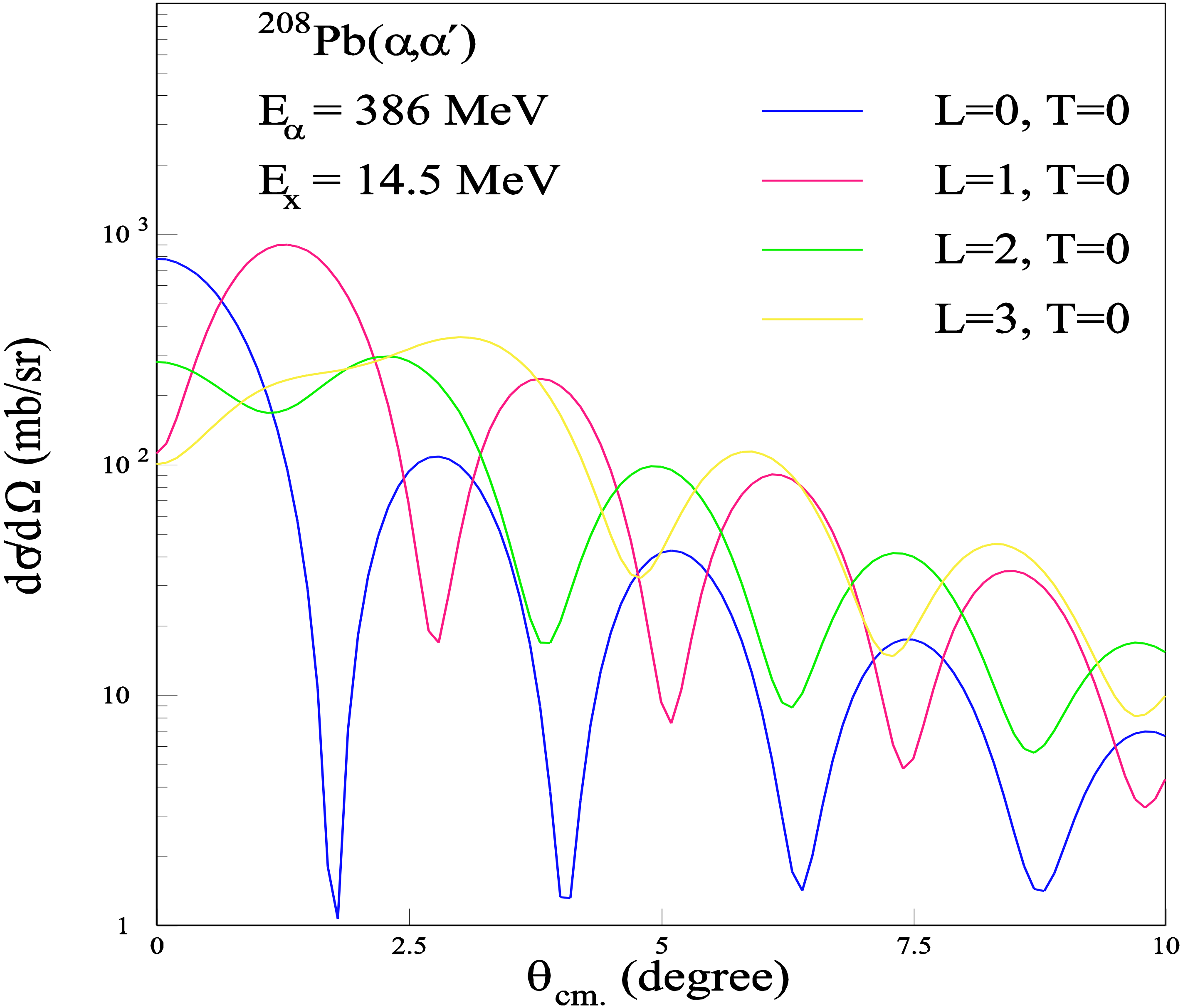
$0° < \theta_{\alpha'} < 3°$

$0° < \theta_{\alpha'} < 1.5°$

$1.5° < \theta_{\alpha'} < 3°$

Difference



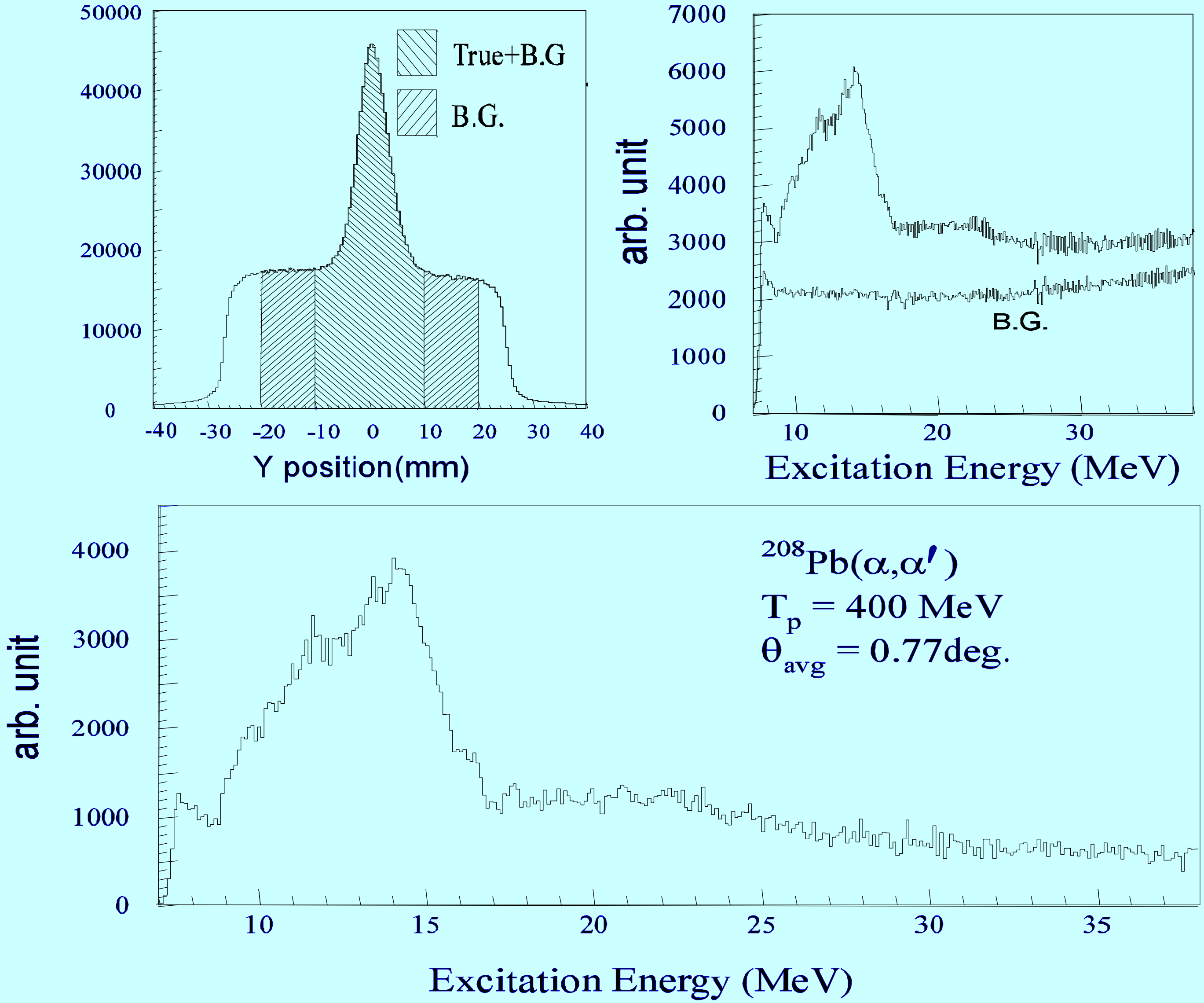


ISGMR, ISGDR

ISGQR, HEOR

100 % EWSR

At E_x= 14.5 MeV


True+B.G
B.G.
50000
40000
30000
20000
10000
0
-40
-30
-20
-10
0
10
20
30
40
Y position(mm)
7000
6000
5000
4000
3000
2000
1000
0
arb. unit
B.G.
10
20
30
Excitation Energy (MeV)
$^{208}Pb(\alpha,\alpha')$
T_p = 400 MeV
θ_{avg} = 0.77deg.
4000
3000
2000
1000
0
arb. unit
10
15
20
25
30
35
Excitation Energy (MeV)

Multipole decomposition analysis (MDA)

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

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

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

$$a_L(E) : \text{EWSR fraction}$$

a. ISGR (L<15)+ IVGDR (through Coulomb excitation)

b. DWBA formalism; single folding ⇒ transition potential

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

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

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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**

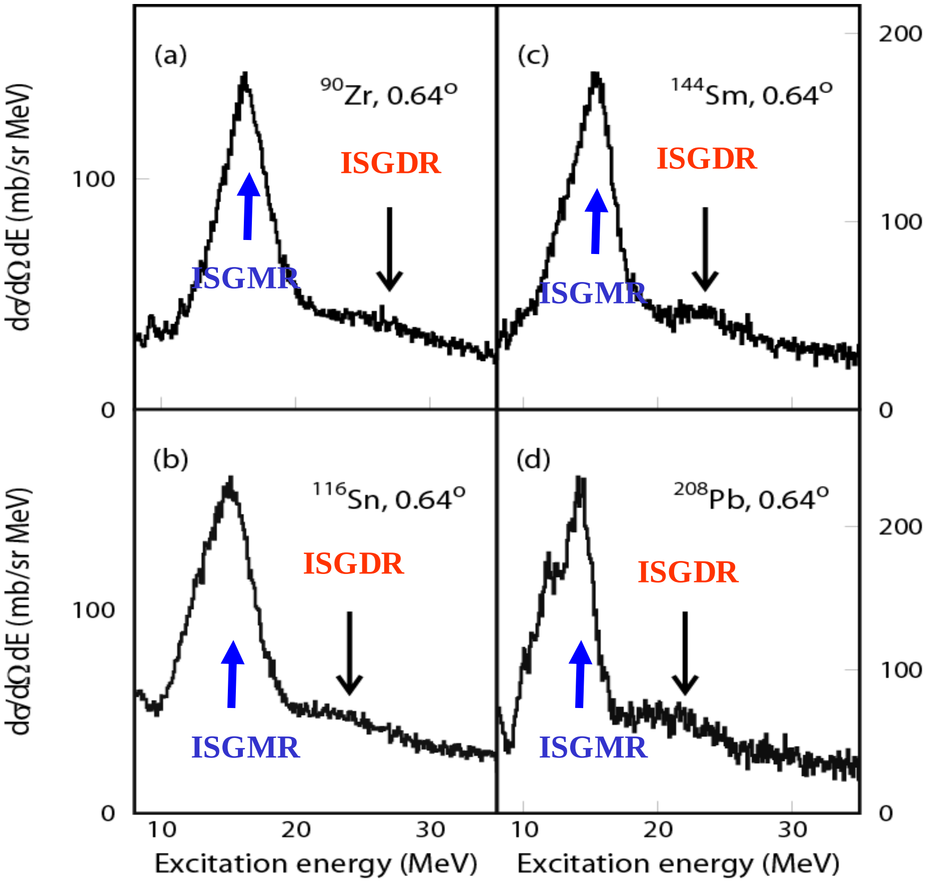
$$\delta\rho_L(r,E) = -\delta_L\frac{d}{dr}\rho_0(r)$$

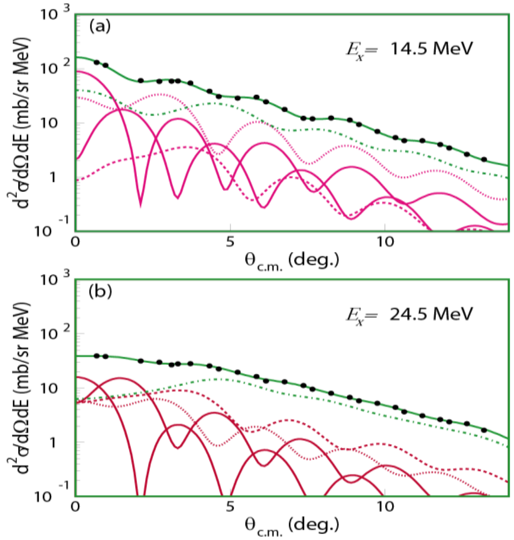
$$\delta_L^2 = (\beta_L c)^2 = \frac{L(2L+1)^2}{(L+2)^2}\frac{2\pi\hbar^2}{mAE}\frac{< r^{2L-2} >}{< r^{L-1} >^2}$$

Multipole Decomposition Analysis

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

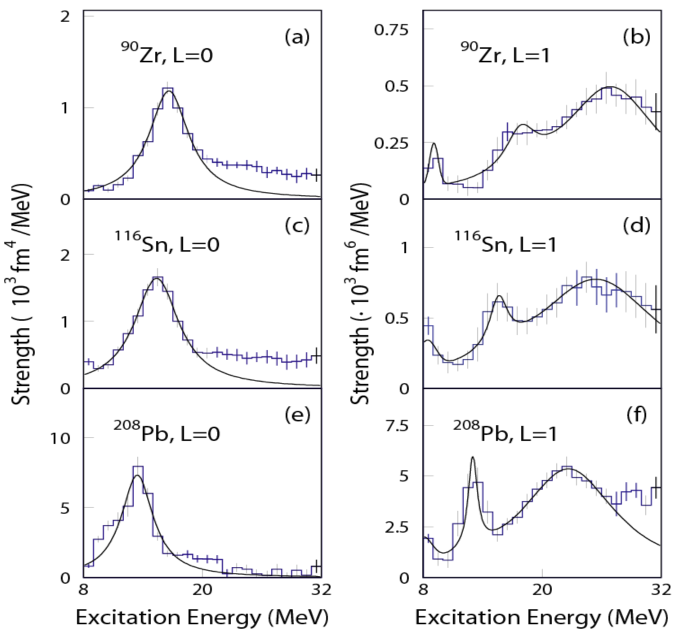
(α,α′) spectra at 386 MeV



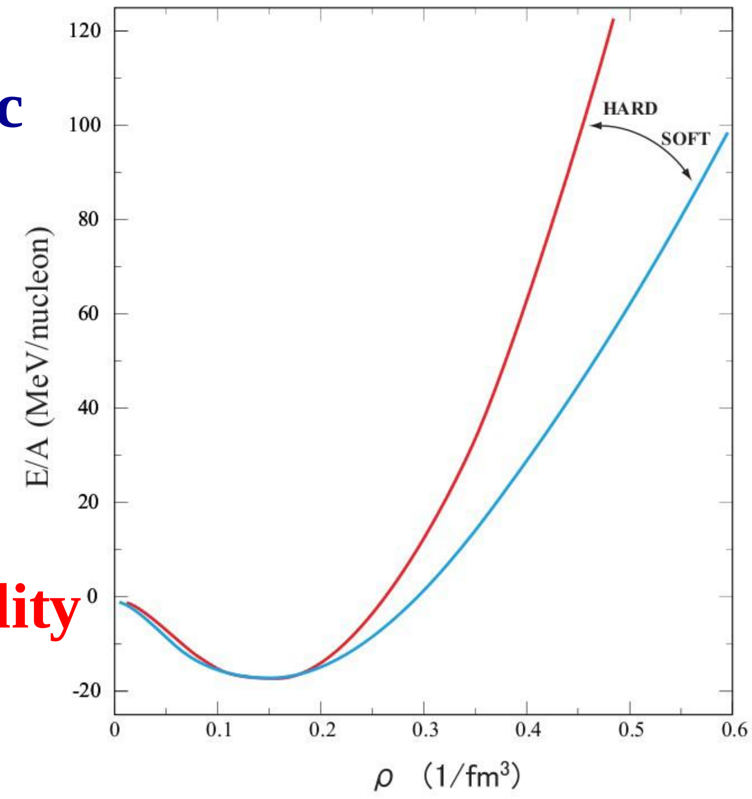


^{116}Sn

MDA results for *L=0* and *L=1*



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

ρ_0 : nuclear density at saturation

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

In HF+RPA calculations,

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

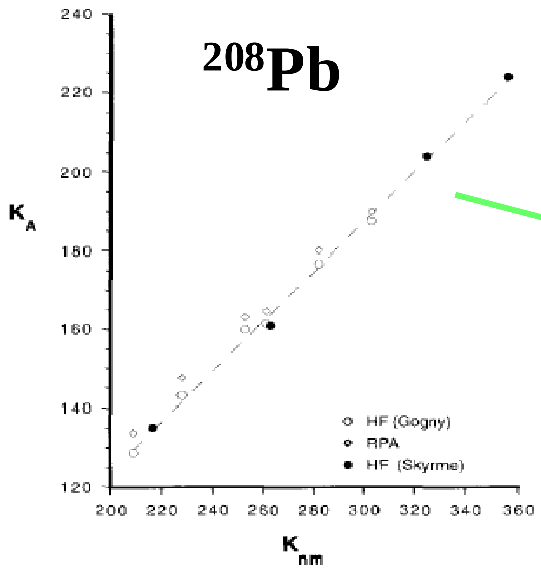
Nuclear matter

***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, Nucl. Phys. A591 (1995) 435

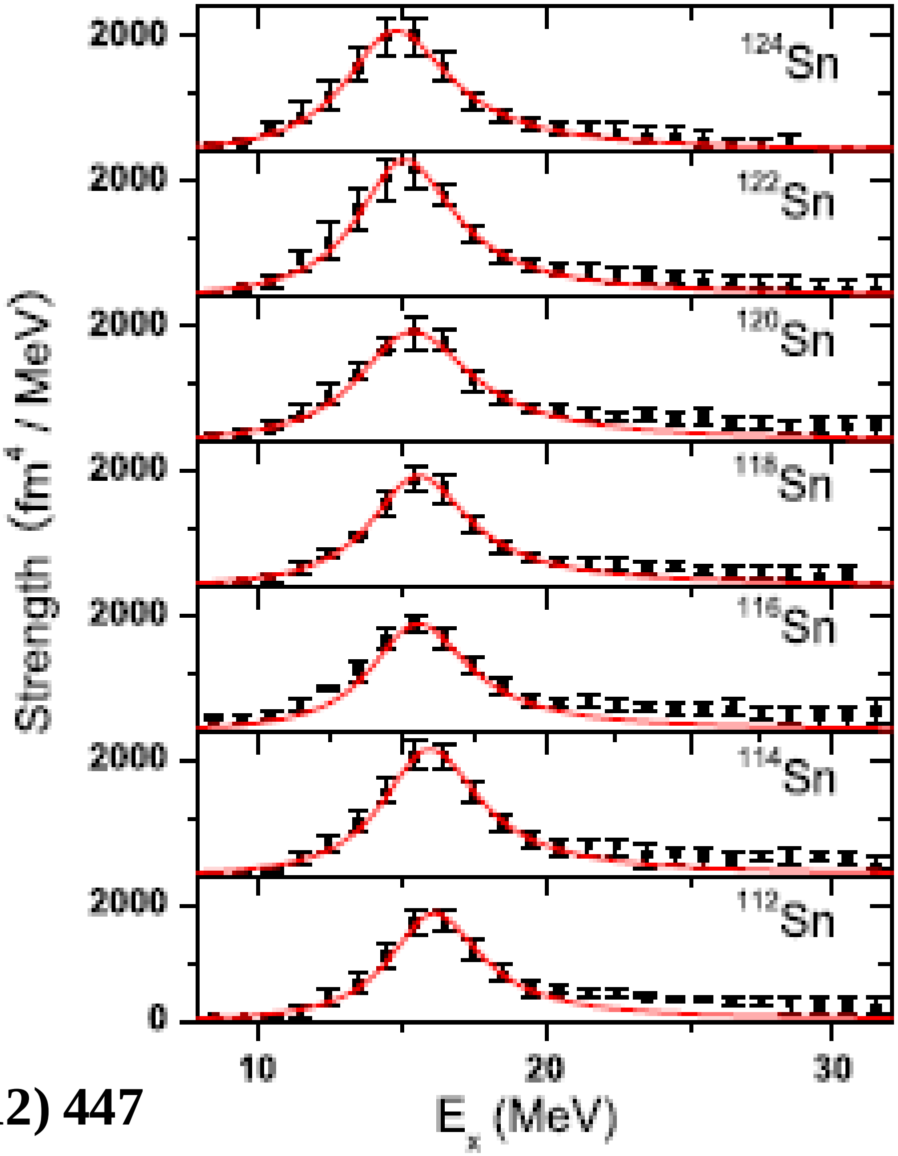
From GMR data on ^{208}Pb and ^{90}Zr,

K_∞ = 240 ± 10 (± 20) 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



D. Patel *et al.*, Phys. Lett. B718 (2012) 447

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

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

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

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

$(N - Z)/A$

^{112}Sn – ^{124}Sn: 0.107 – 0.194

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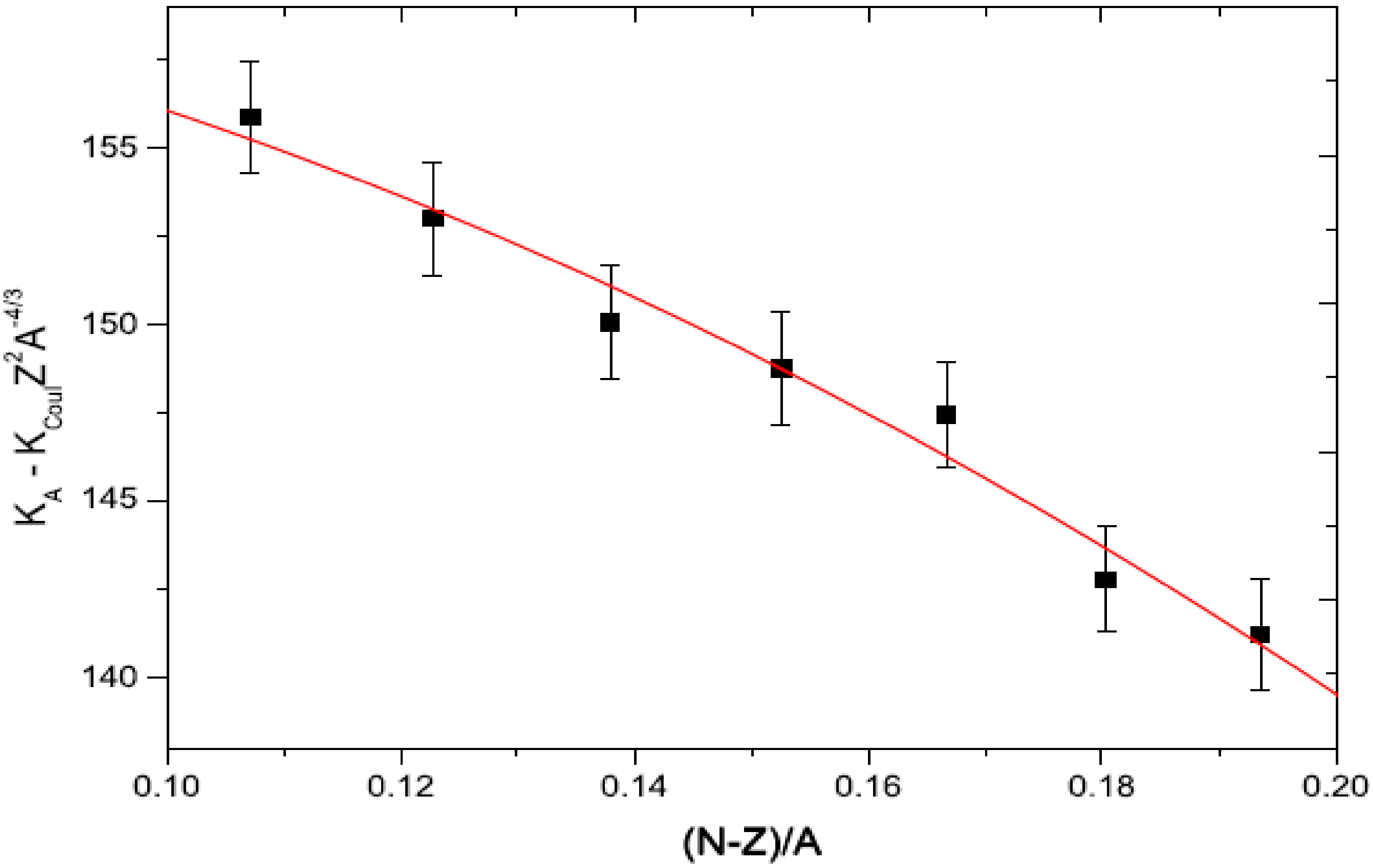
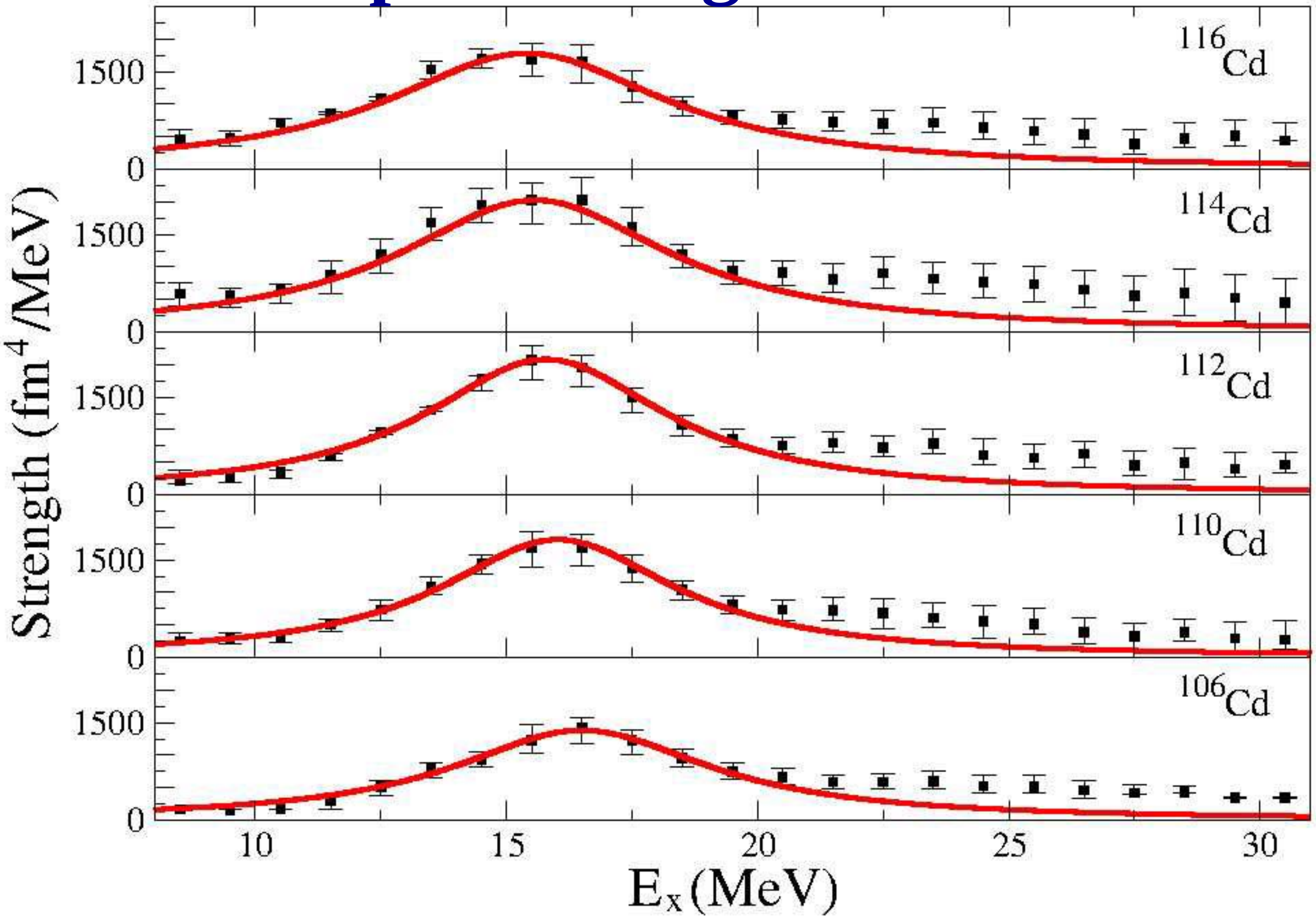


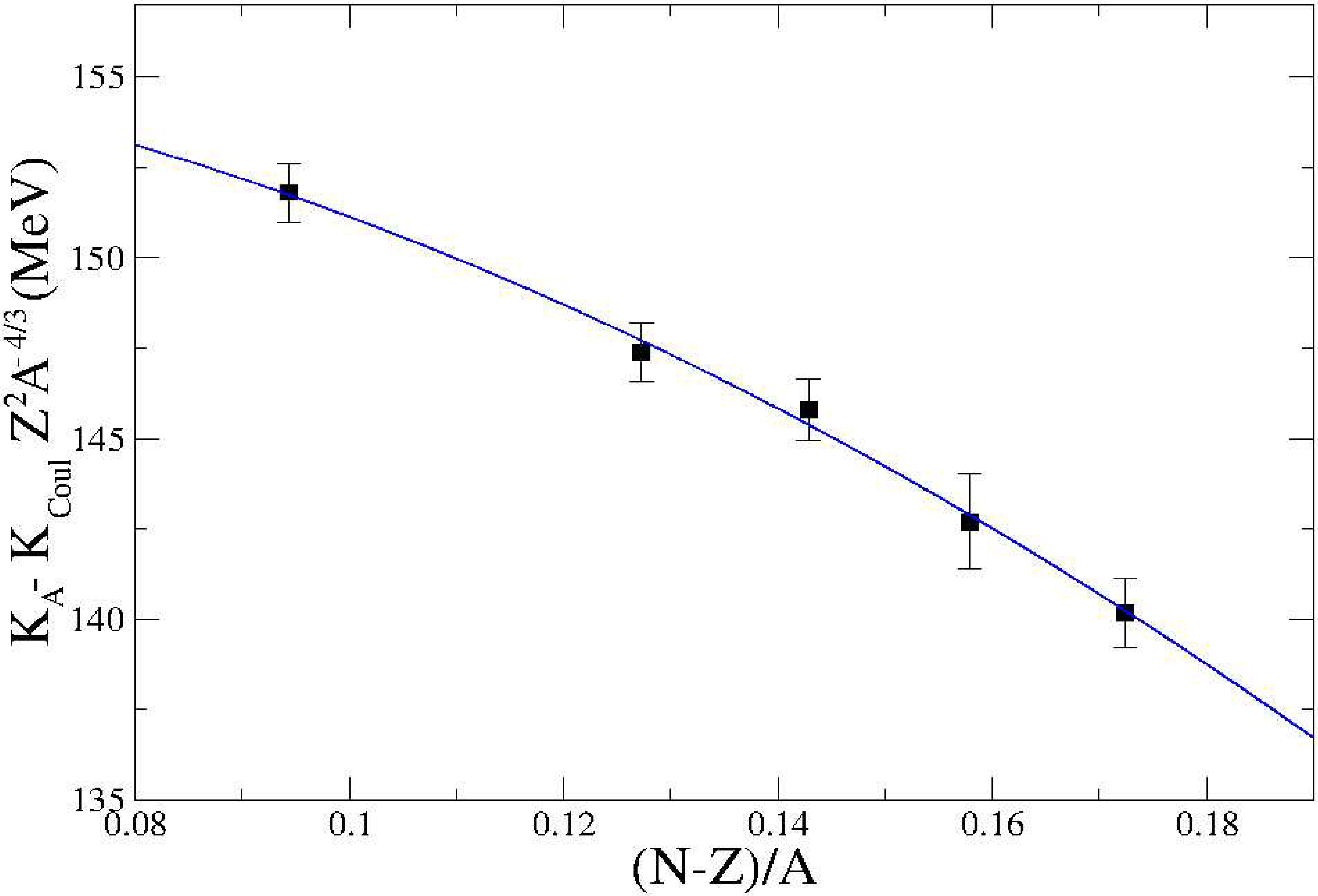
Sn isotopes $\Rightarrow K_\tau = -550 \pm 100$ MeV

T. Li *et al*., Phys. Rev. C81 (2010) 034309

Monopole strength Distribution

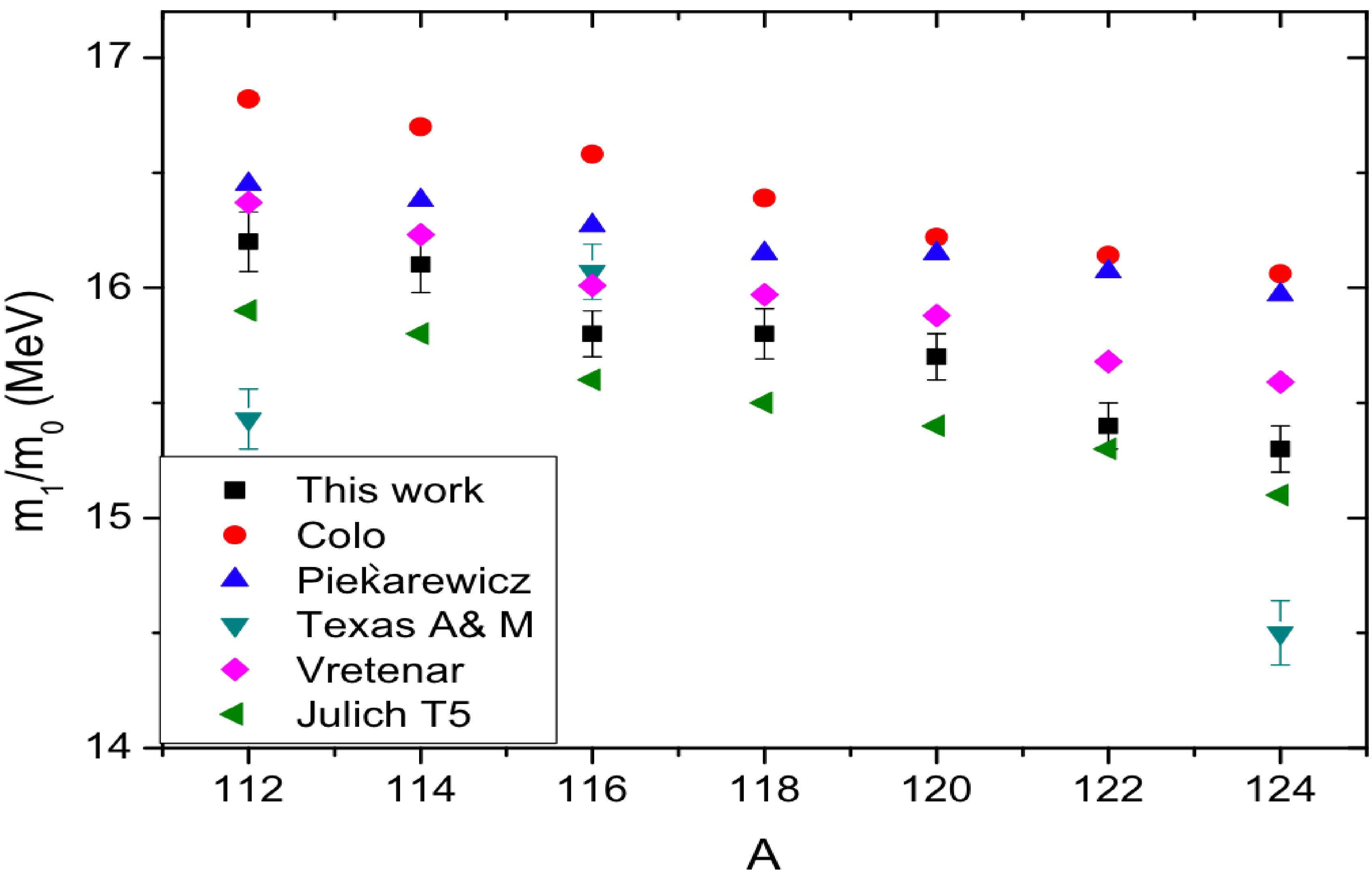


D. Patel *et al*., Phys. Lett. B718 (2012) 447



Cd isotopes ⇒ $K_\tau = -555 \pm 75$ MeV

D. Patel *et al*., Phys. Lett. B718 (2012) 447



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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]

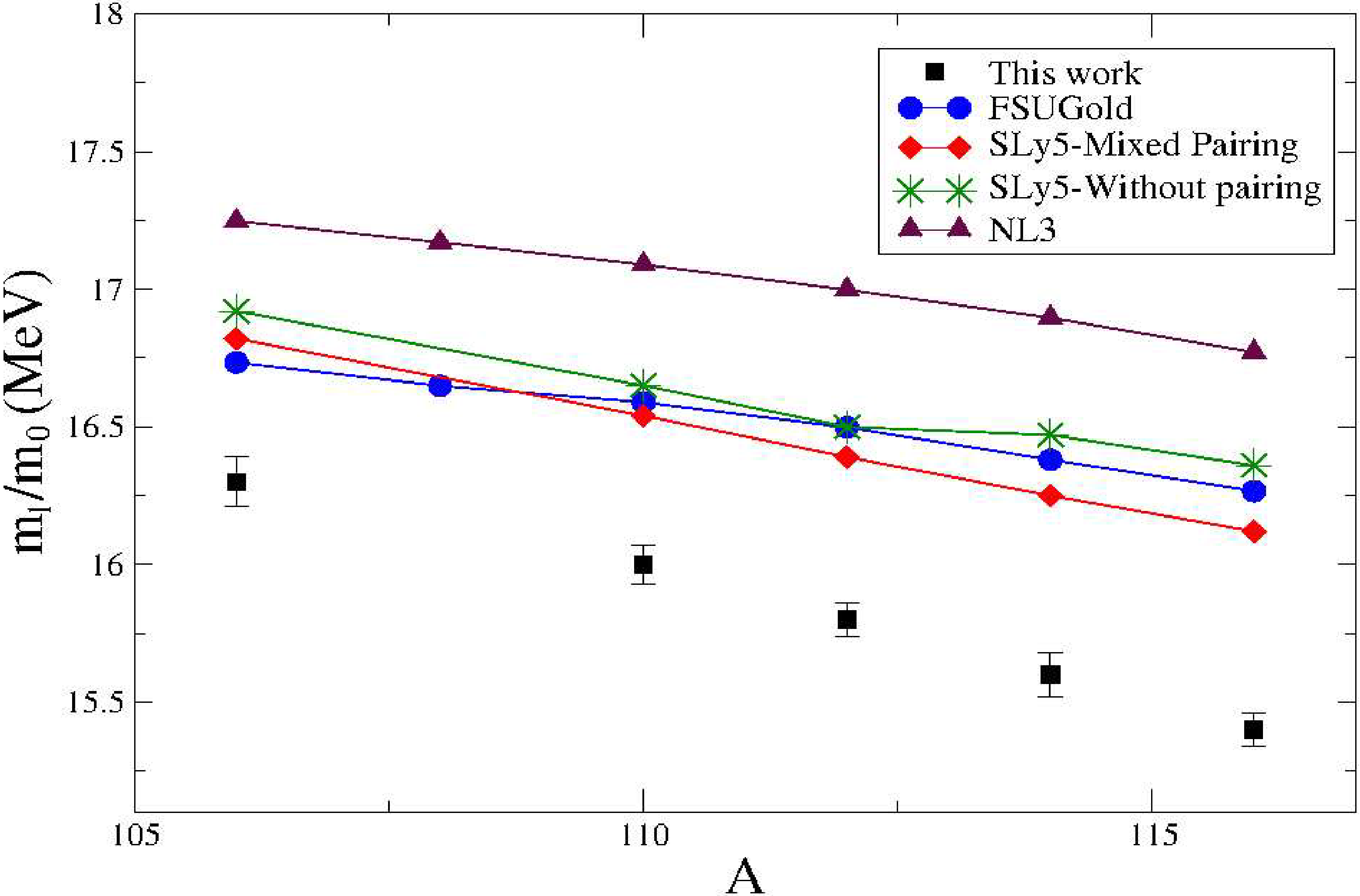
Vretenar: Relativistic mean field (DD-ME2: density-dependent mean-field effective interaction).

[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] B.G. Todd-Rutel and J. Piekarewicz

NL3 [K_∞ = 271 MeV] G.A. Lalazissis, J. Konig, and P. Ring

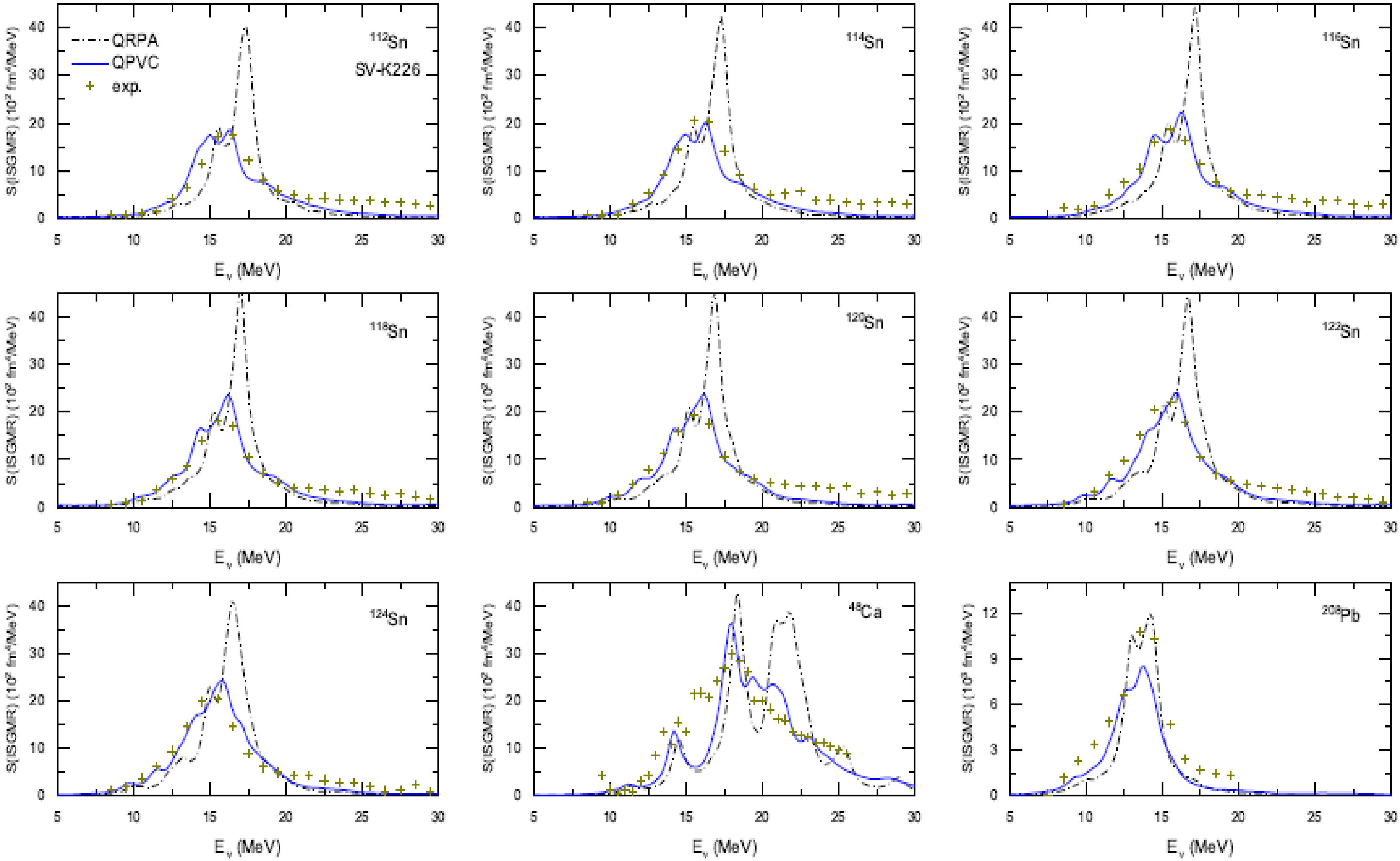
QRPA: SLy5 [K_∞ = 230 MeV] L-G. Cao, H. Sagawa, and G. Colò

Z.Z. Li, Y.F. Niu, and G. Colò, PRL 131 (2023) 082501

Fully self-consistent Quasiparticle Random-Phase Approximation plus Quasiparticle-Vibration Coupling model (QPVC) have been developed, based on the Skyrme-Hartree-Fock-Bogoliubov (SHFB) framework. Both QPVC effects and pairing effects are considered self-consistently.

Results suggest that QPVC effects are crucial in order to reach a unified description of the ISGMR in Ca, Sn, and Pb isotopes at the same time.

This conclusion has been corroborated by **Elena Litvinova [PRC 107 (2023) L041302]** in which the inclusion of beyond-mean-field correlations of QPVC type allowed for a simultaneous description of the ISGMR in nuclei of Pb, Sn, Zr, and Ni mass regions.



ISGMR strength functions in even-even $^{112\text{-}124}$Sn, ^{48}Ca, and ^{208}Pb isotopes, calculated either by (Q)RPA using a smoothing with Lorentzian having a width of 1 MeV (dash-dotted [black] line), or (Q)RPA+(Q)PVC (solid [blue] line). The SV-K226 Skyrme force is used. The experimental data are given by green crosses

Z.Z. Li, Y.F. Niu, and G. Colò

	SkP	SkM*	SV-K	KDE0	SV-bas	SV-K	SAMi
K_∞	201	217	226	229	233	241	245
				(Q)RPA			
^{48}Ca	0.11	0.89	1.09	1.17	1.40	1.70	1.72
^{120}Sn	0.22	0.43	0.78	0.76	1.05	1.31	1.34
^{208}Pb	0.74	0.14	0.14	0.20	0.37	0.60	0.76
				(Q)PVC			
^{48}Ca	0.70	0.25	0.36	0.51	0.67	0.90	1.07
^{120}Sn	0.67	0.14	0.02	0.18	0.36	0.68	0.82
^{208}Pb	0.94	0.37	0.25	0.06	0.08	0.31	0.48

The deviation of ISGMR energies from experimental data [$|E^{theo.} - E^{exp.}|$ (MeV)] in ^{48}Ca, ^{120}Sn, and ^{208}Pb, calculated by (Q)RPA and (Q)PVC using the Skyrme parameter sets SkP, SkM*, SV-K226, KDE0, SV-bas, SV-K241, and SAMi. The experimental data are taken from [1, 2, 3].

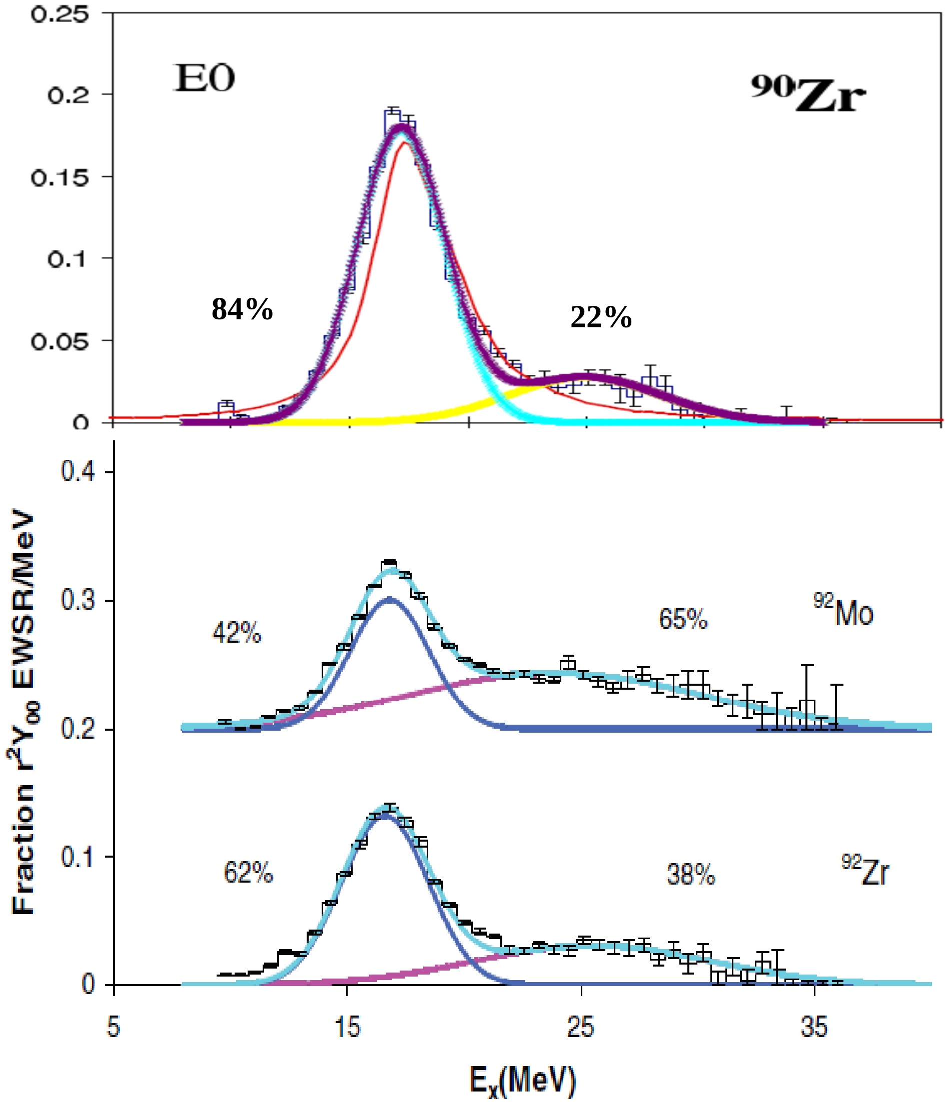
1- D. Patel, et al., Phys. Lett. **B 726**, 178 (2013). **-- Pb**

2- T. Li, et al., Phys. Rev. Lett. **99**, 162503 (2007). **-- Sn**

3- S. D. Olorunfunmi, et al., Phys. Rev. **C 105**, 054319 (2022). **-- Ca**

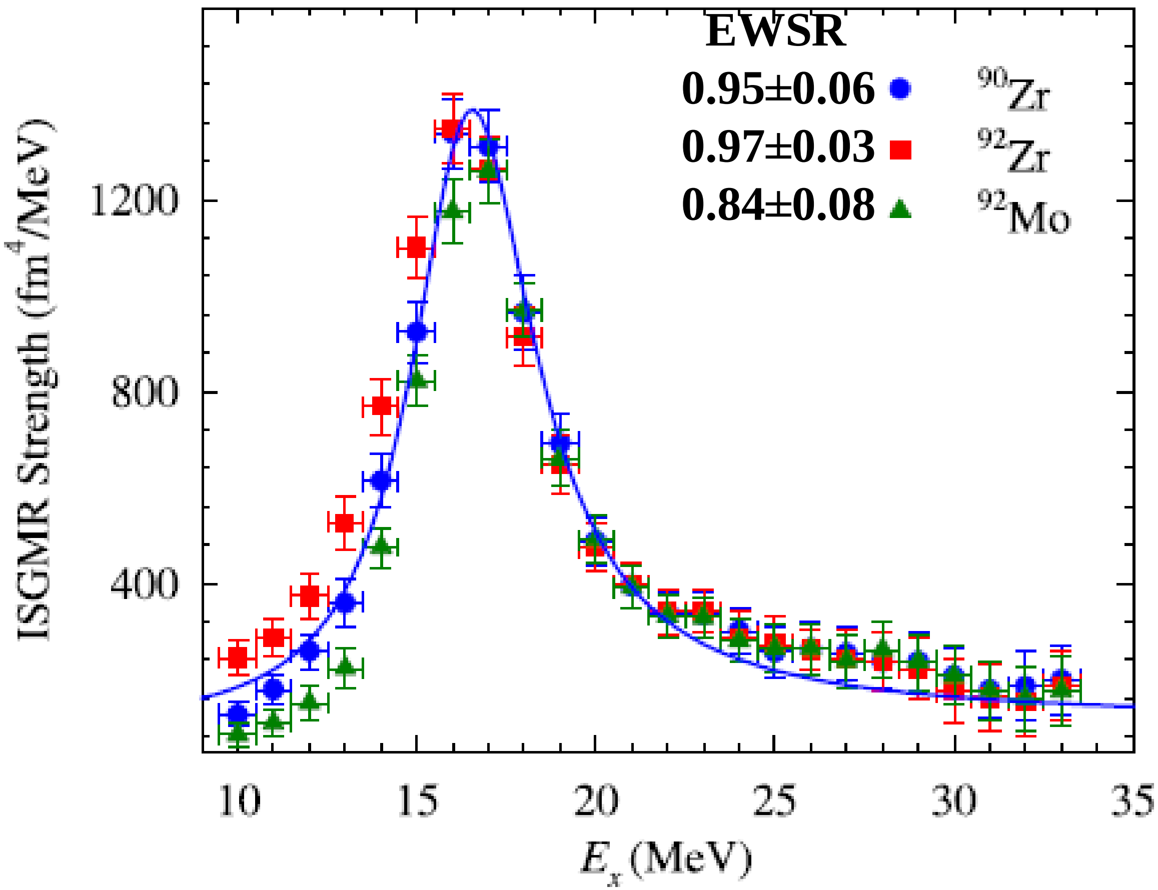
Inelastic scattering of 240-MeV α particles at small angles including 0°.

Lines in the distributions represent the individual peaks and their sum obtained from the Gaussian fits. The thin red line for ^{90}Zr represents the strength distribution obtained with the HF-RPA calculation.



Texas A&M
D.H. Youngblood *et al.*, PRC 88 (2013) 021301
PRC 92 (2015) 014318
PRC 92 (2015) 044323

Inelastic α scattering at E_α= 385MeV



EWSR errors are statistical. OMP parameters ⇒ 20% systematic error.

Y.K. Gupta et al., Phys. Lett. B 760 (2016) 482

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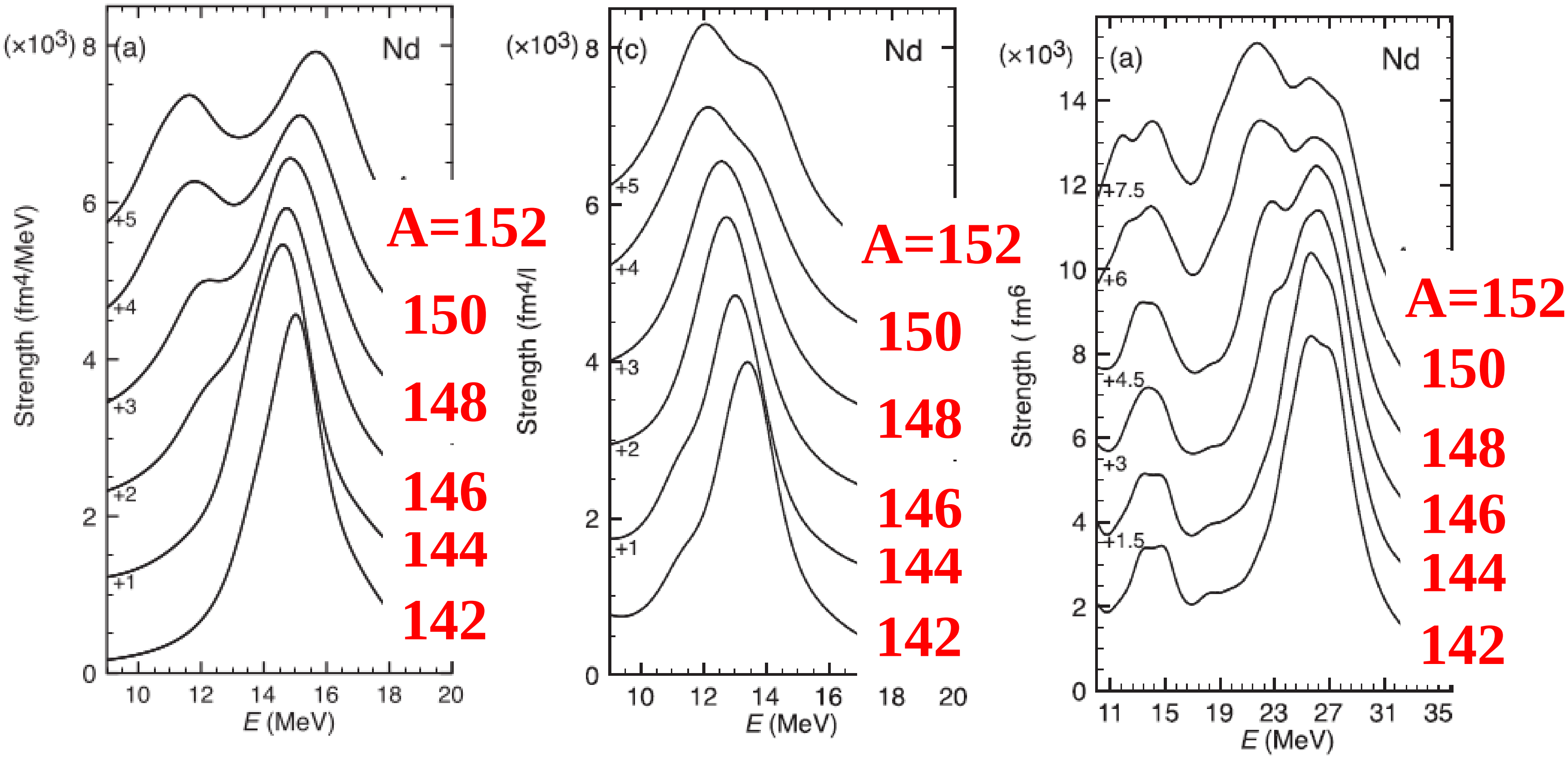
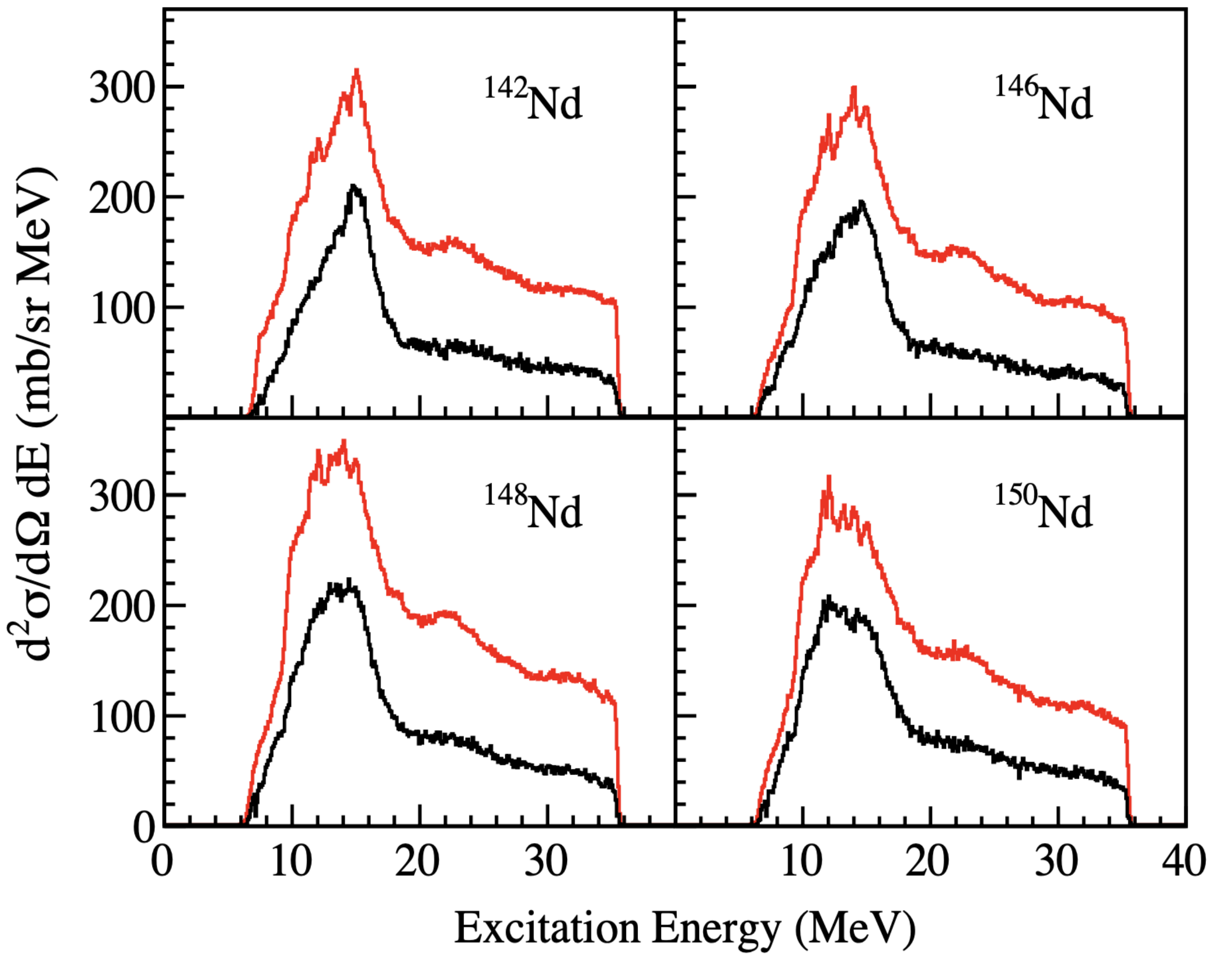
Isoscalar Giant Resonances in Nd isotopes: QRPA calculations



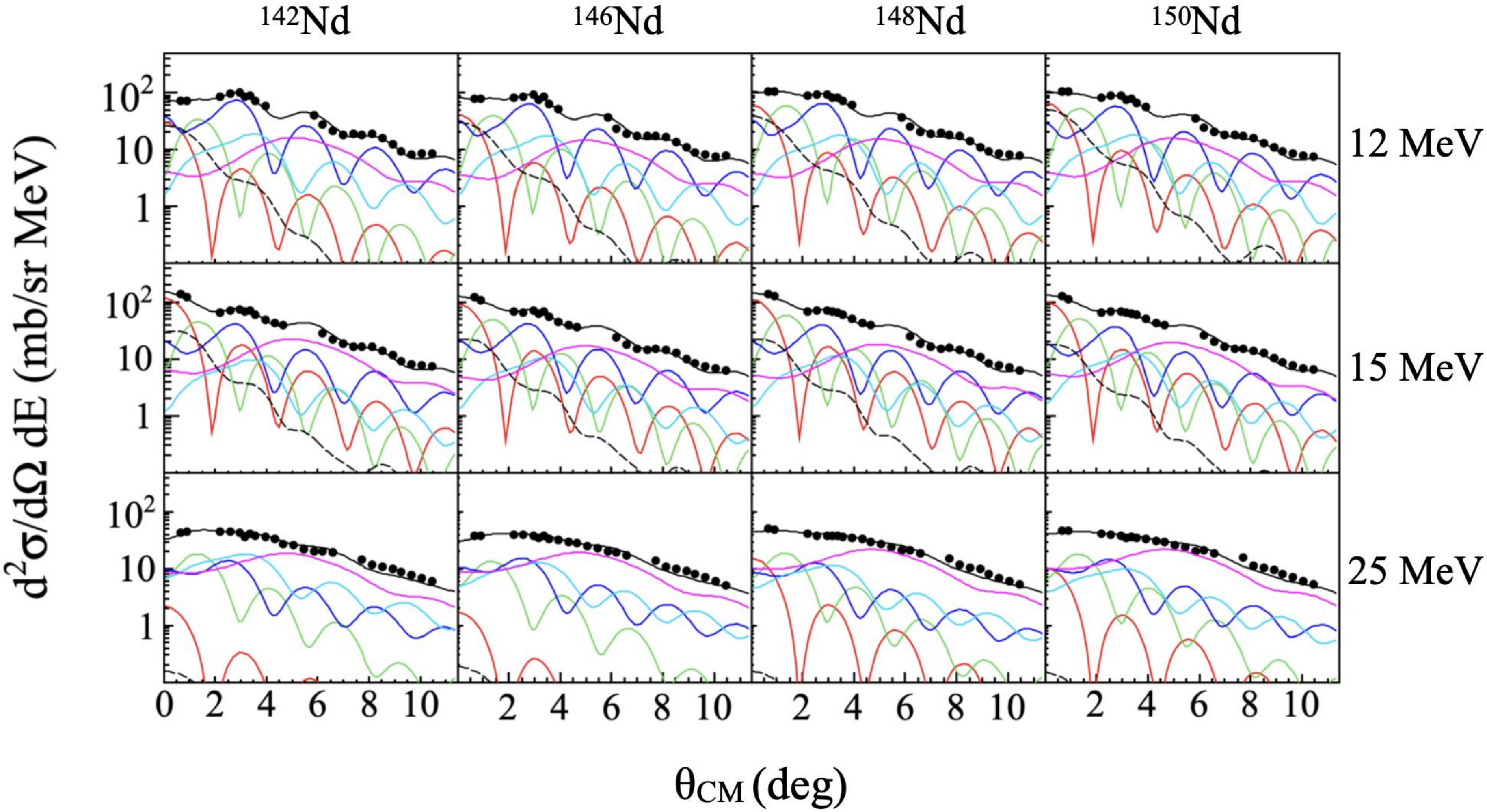
ΔL = 0; ISGMR **ΔL = 2; ISGQR** **ΔL = 1; ISGDR**

K. Yoshida and T. Nakatsukasa, Phys. Rev. C 88 (2013) 034309

^{142,146,148,150}Nd(α,α') spectra at θ_{Lab} = 0.75° after particle identification, subtraction of the instrumental background, and of contaminants are shown in black histograms. The red histograms show the spectra before instrumental-background and contaminants subtraction.



M. Abdullah *et al.*, Phys. Lett. B855 (2024) 138852



Multipole-decomposition analyses for ^{142,146,148,150}Nd

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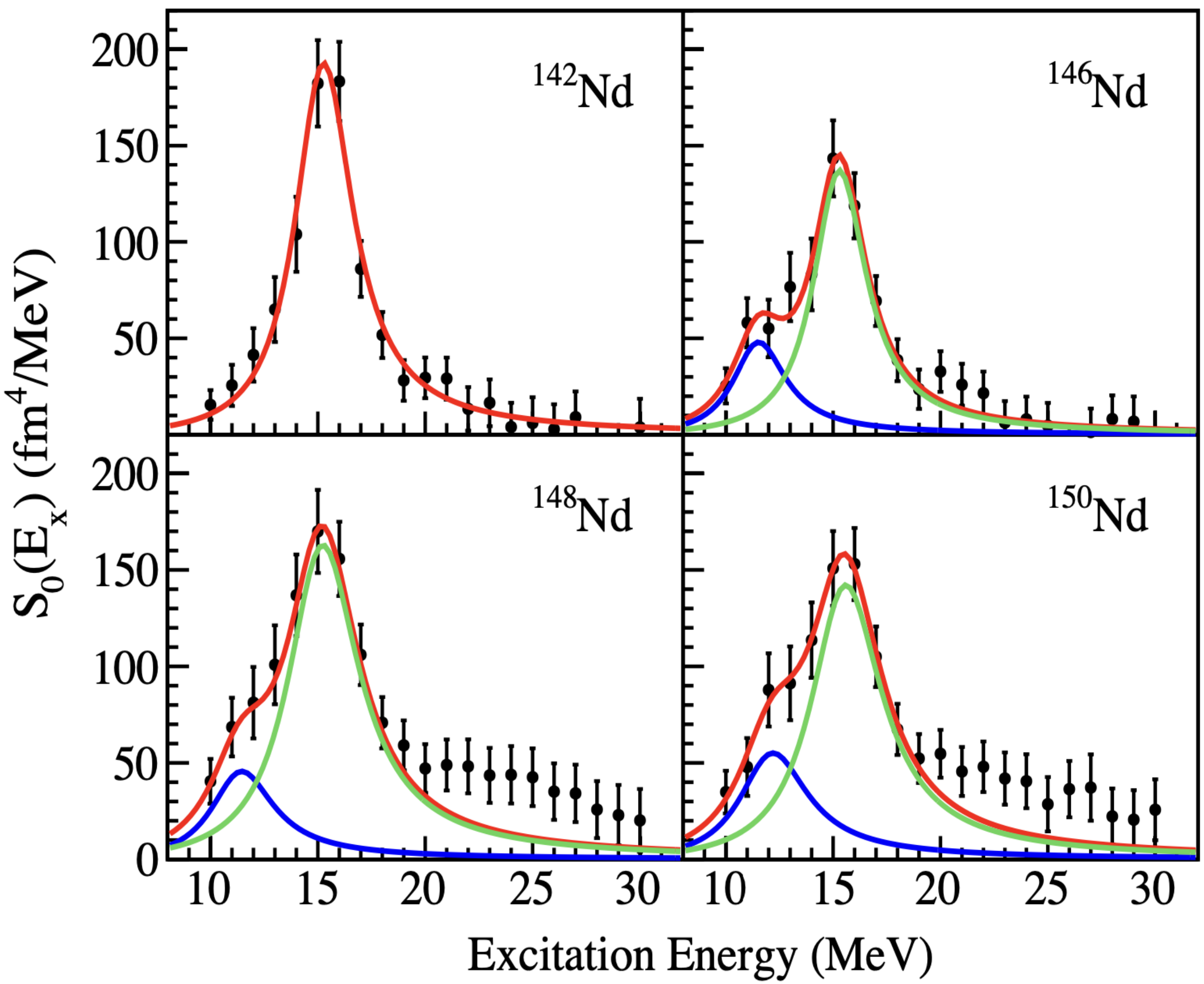
The monopole strength distributions for $^{142-150}$Nd obtained from MDA. The red lines show the results of single-Lorentzian fitting in ^{142}Nd (upper left) and of double-Lorentzian fitting in ^{146}Nd (upper right), ^{148}Nd (lower left), and ^{150}Nd (lower right). In deformed Nd isotopes, the low- and high-energy components of the ISGMR are indicated by blue and green lines, respectively.



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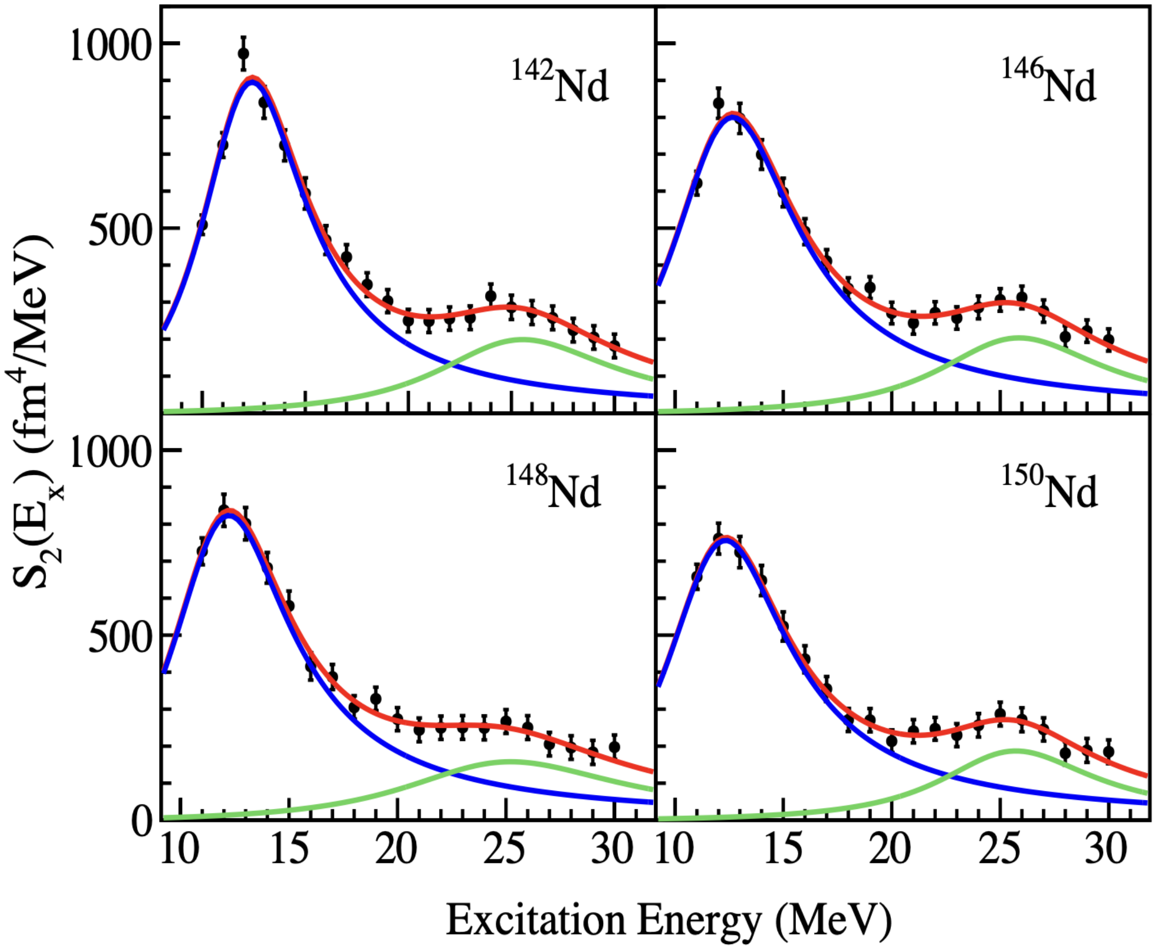
The quadrupole strength distributions for $^{142-150}$Nd isotopes obtained from MDA. The overall fits, employing a double-Lorentzian function, are represented by red lines. The main-tone modes ($\sum r_i^2 Y_2$, $2\hbar\omega$) of the quadrupole resonances are depicted using blue lines, while the overtone compression modes ($\sum r_i^4 Y_2$, $4\hbar\omega$) are illustrated with green lines.



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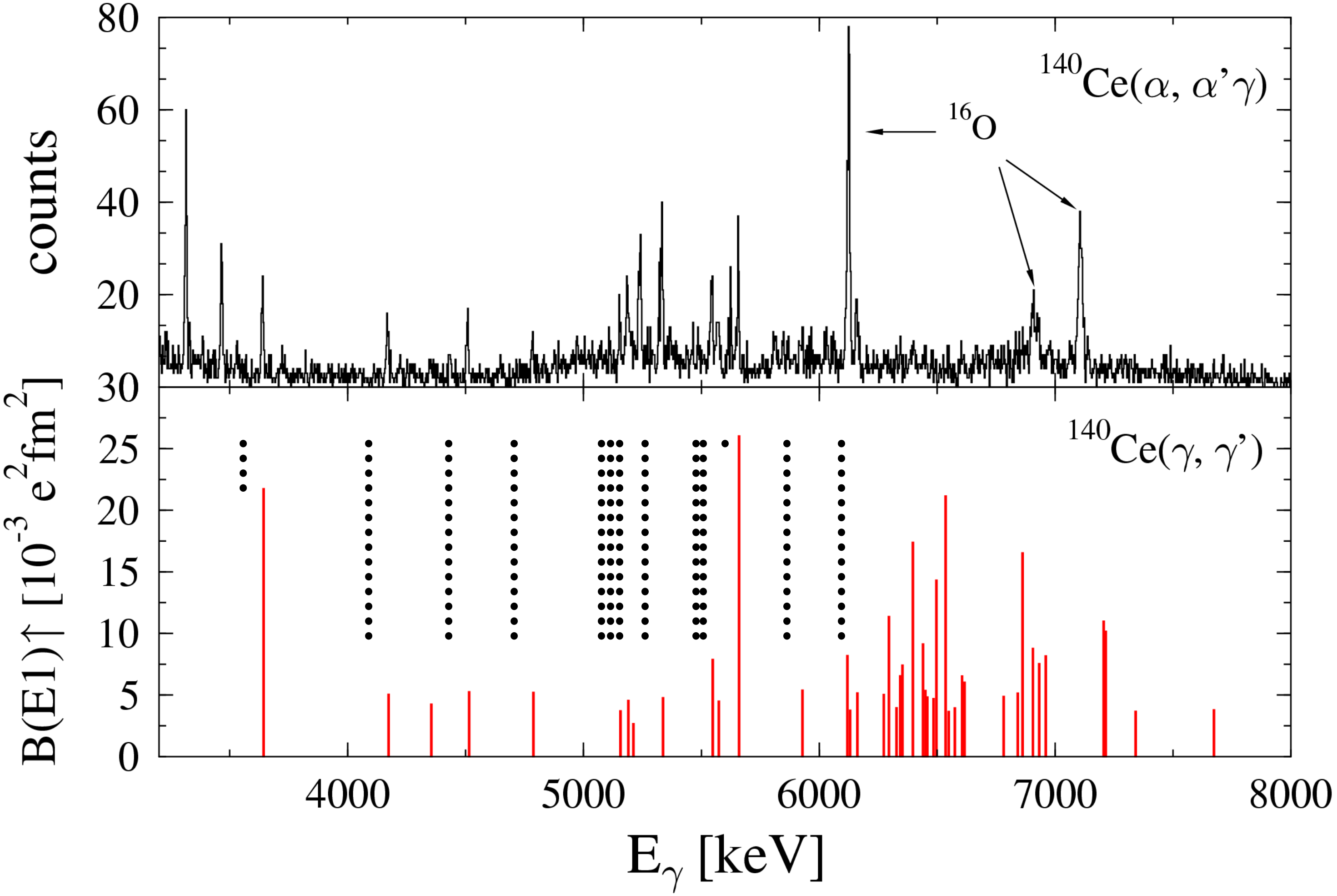
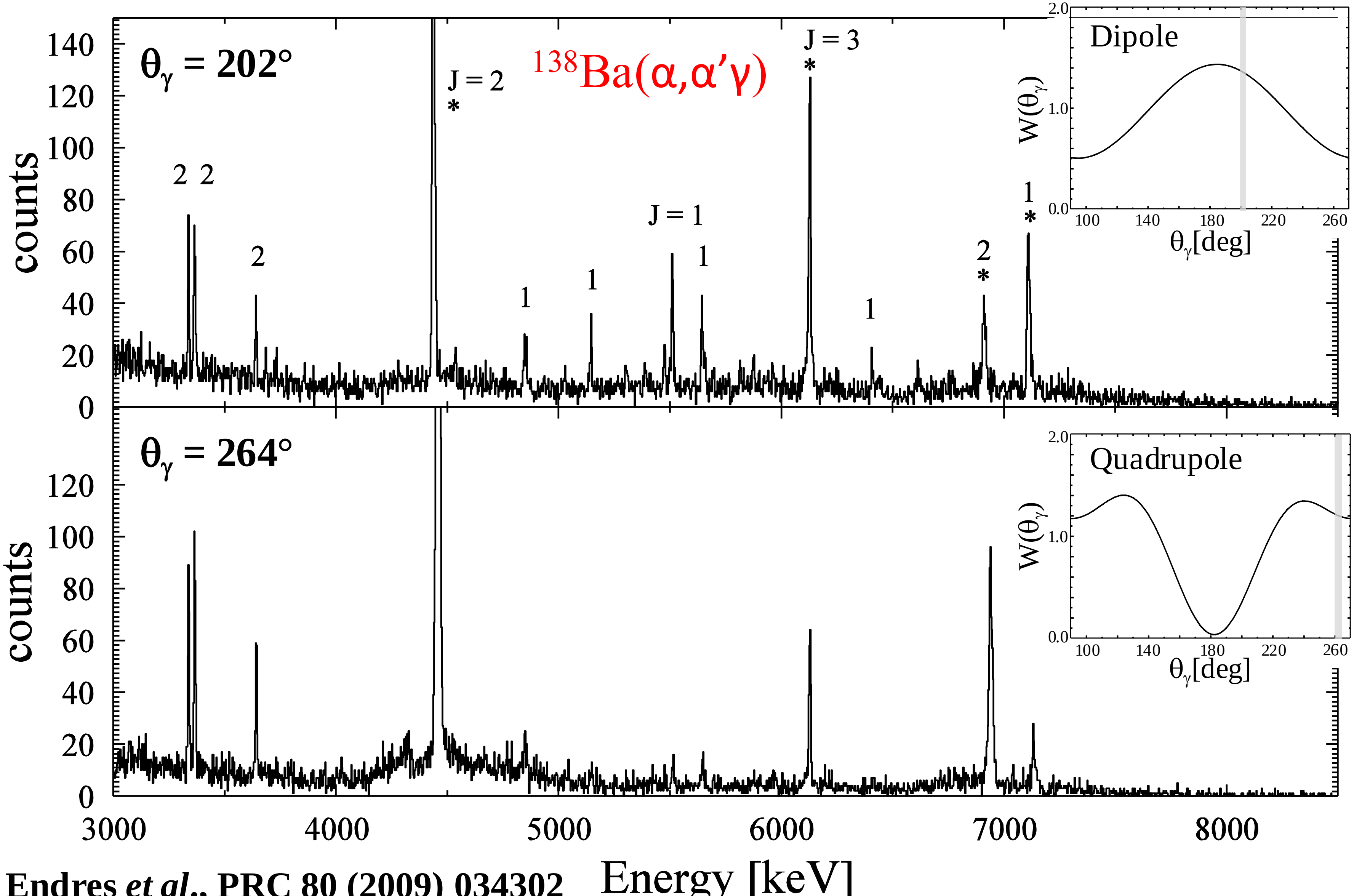
^{140}Ce(α,α′γ) vs. ^{140}Ce(γ,γ′)



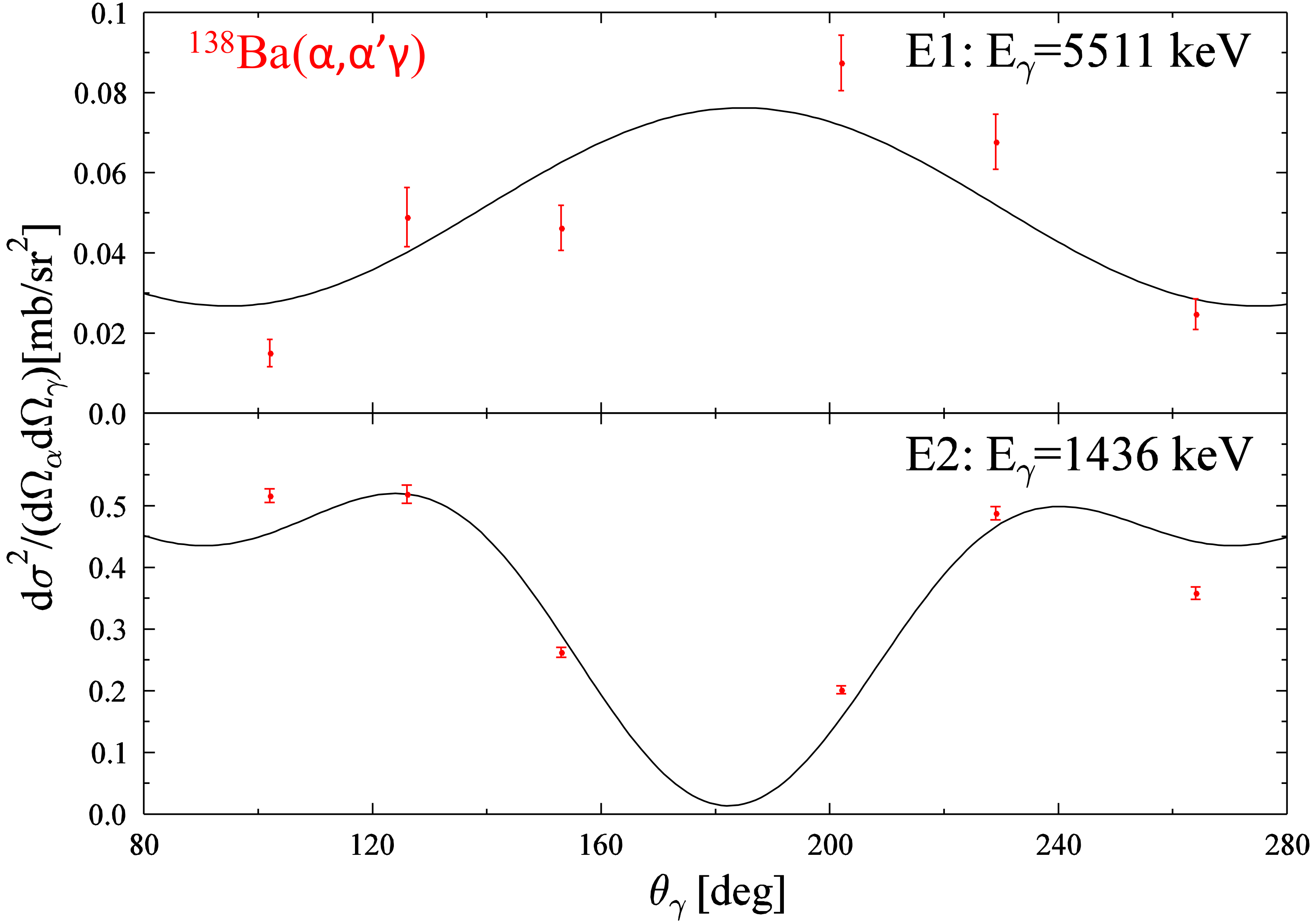
D. Savran *et al.*, Phys. Rev. Lett. 97 (2006) 172502

Multipole assignment with α–γ angular correlation



J. Endres *et al*., PRC 80 (2009) 034302

Multipole assignment with α-γ angular correlation



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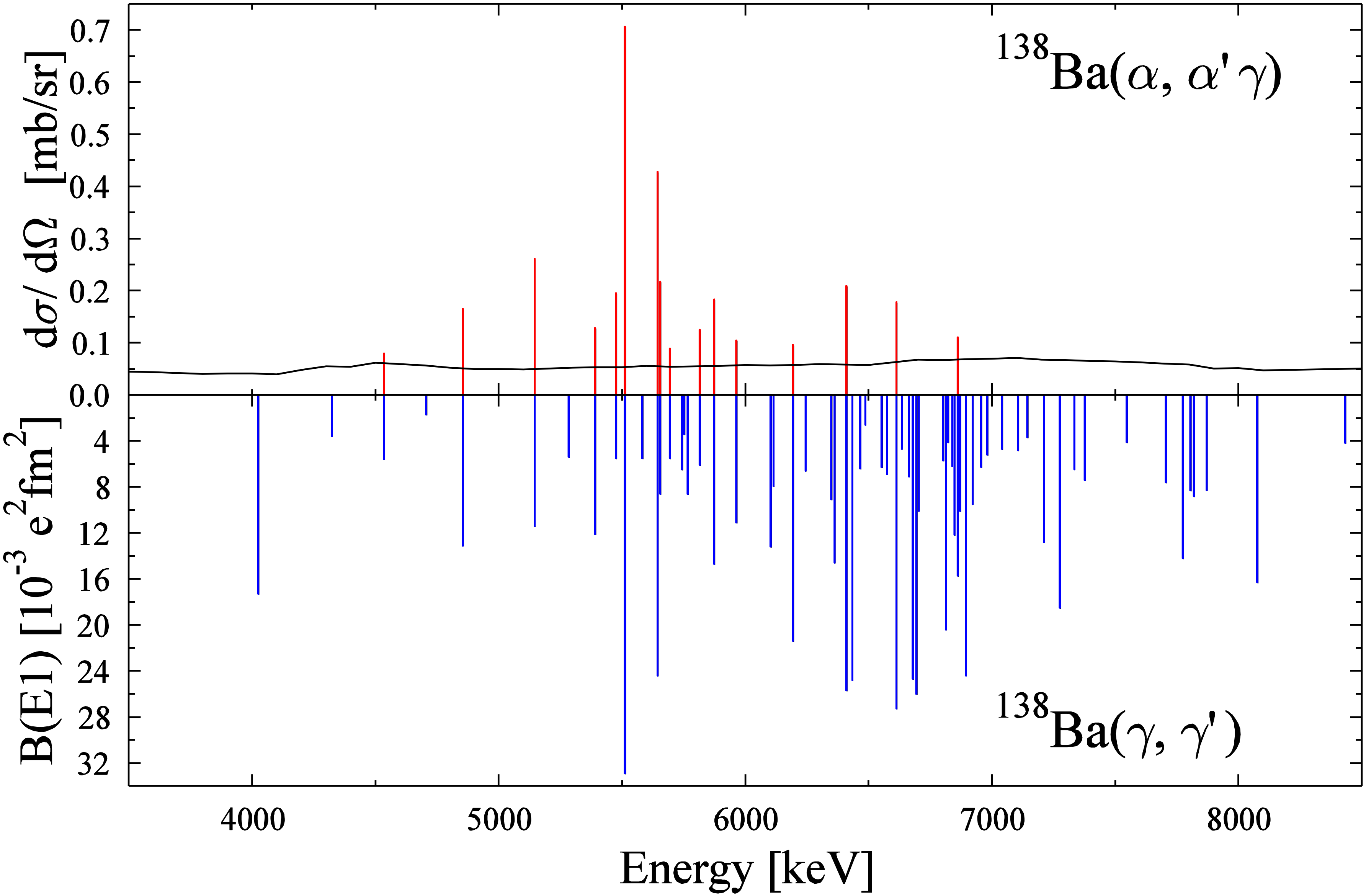
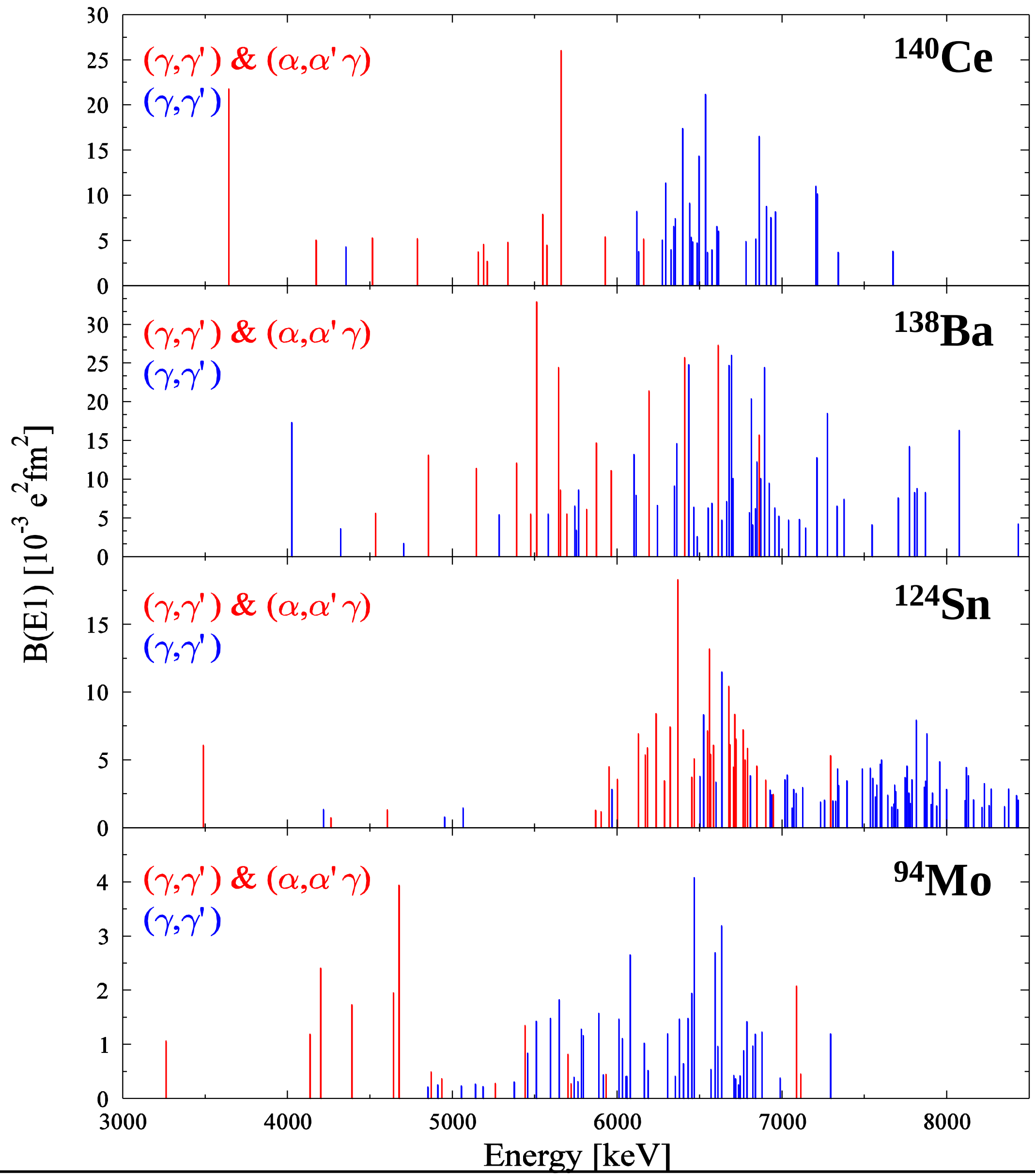
Comparison of (α,α′γ) with (γ,γ′) on ^{138}Ba



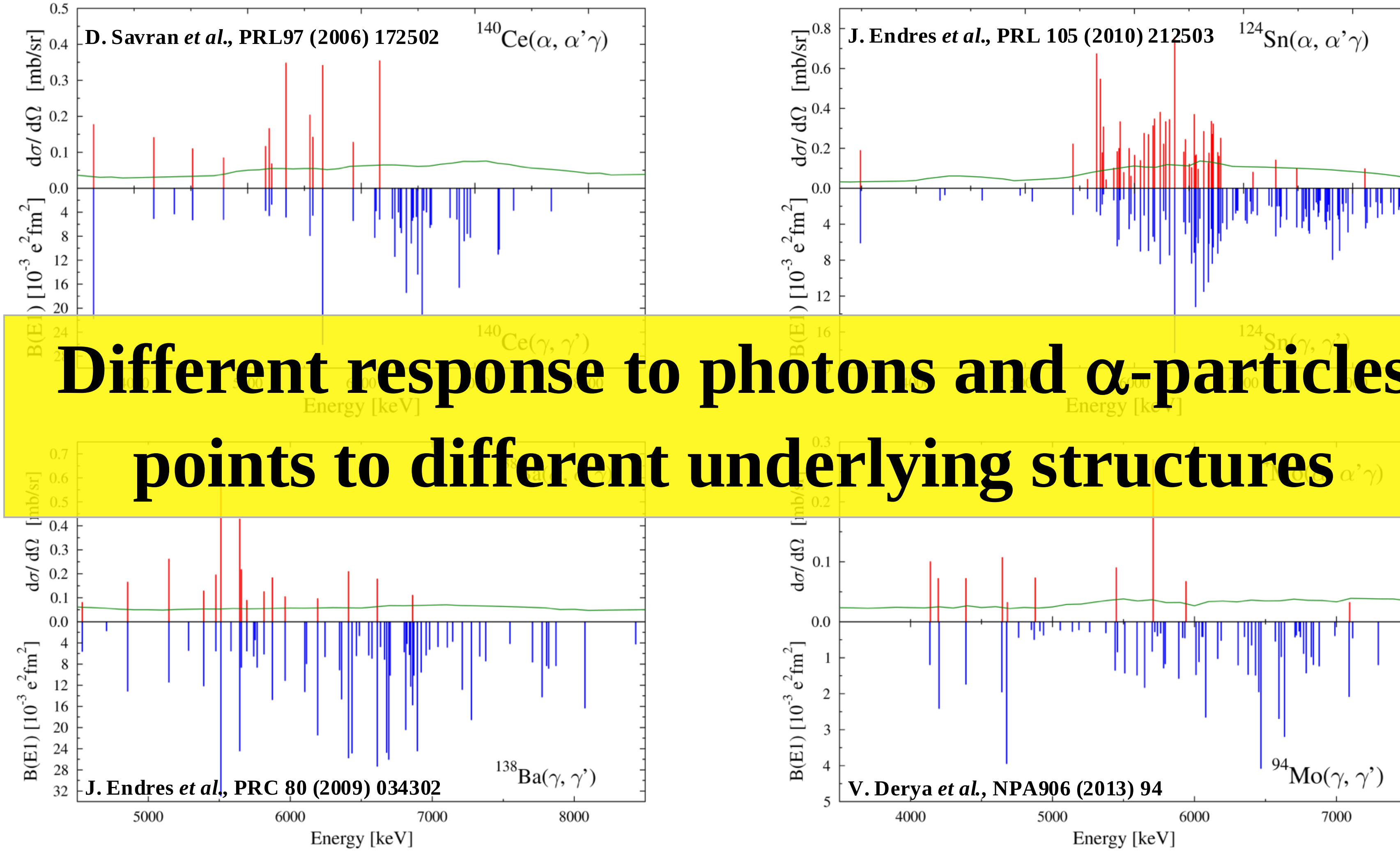
E1 strength distribution in ^{140}Ce, ^{138}Ba, ^{124}Sn, and ^{94}Mo



— (γ,γ′) & (α,α′γ)

— (γ,γ′) only

Systematics



Different response to photons and α-particles points to different underlying structures

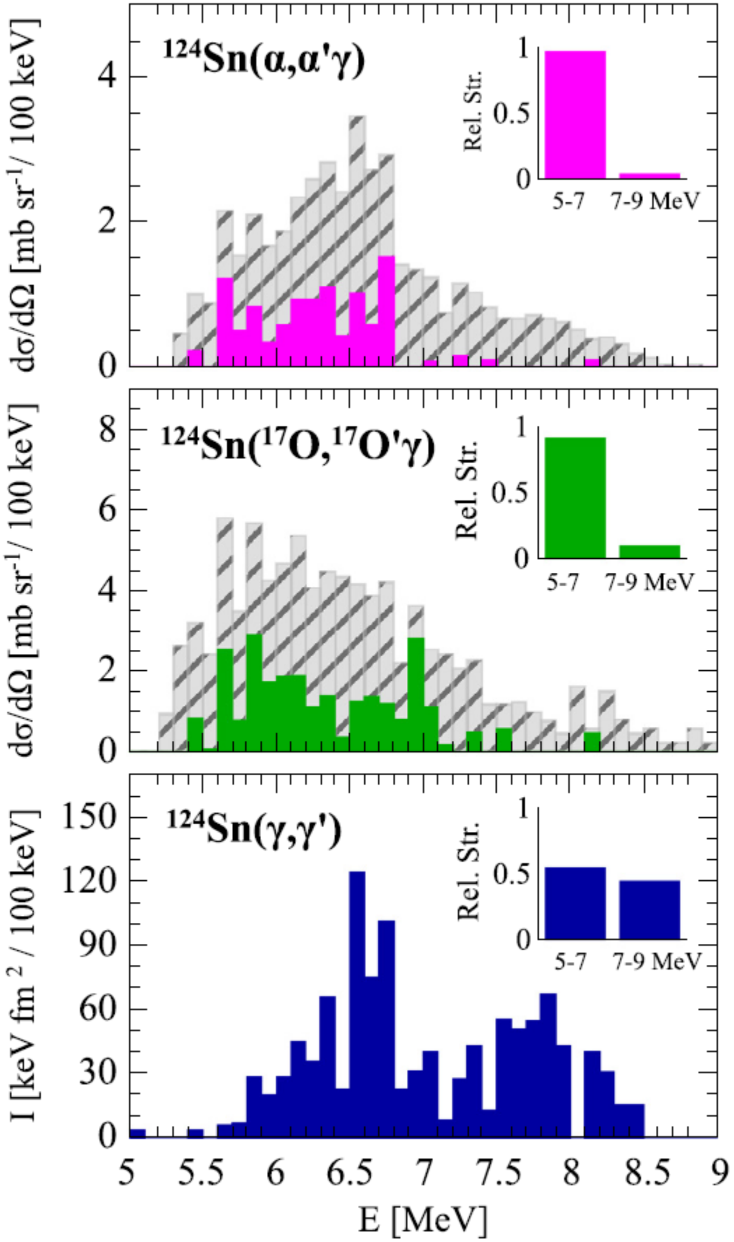
The grey histogram corresponds to the total unresolved strength.

Top panel: Discrete level in α scattering

Centre panel: Discrete levels in ^{17}O scattering

Bottom panel: photon scattering

L. Pellegri *et al.*, Phys. Lett. B738 (2014) 519



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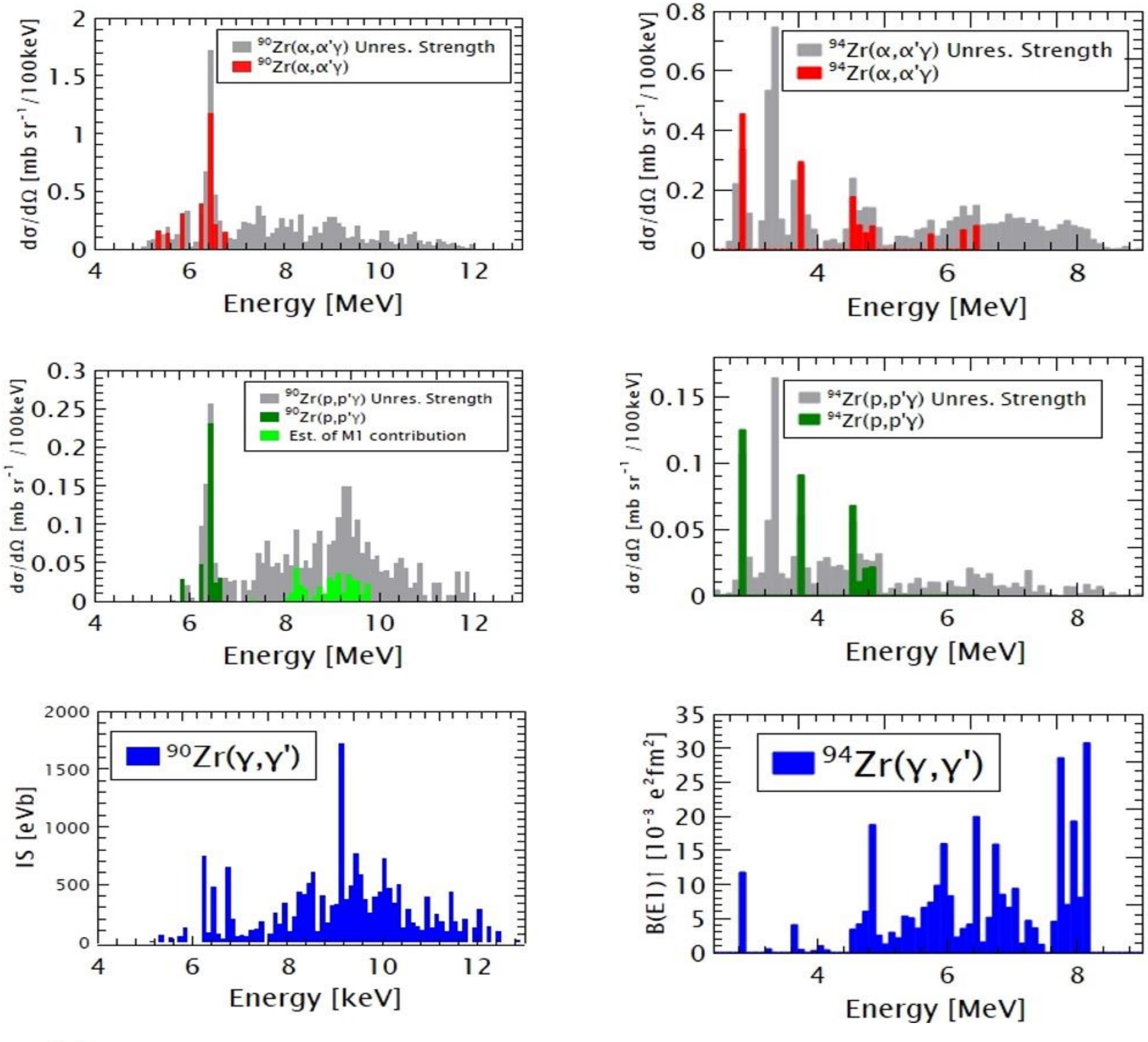
Panels (a) and (b) are for the (α,α′γ) reaction at 130 MeV, panels (c) and (d) are for the (*p*,*p*′γ) reaction at 80 MeV, while panels (e) and (f) show (γ,γ′) measurements.
The coloured bars correspond to discrete transitions while the grey bars correspond to the continuum regions in the present measurements.



F.C.L. Crespi, A. Bracco *et al*., Phys. Lett. B 816 (2021) 136210

“Study of the breathing mode of ^{208}Pb through neutron decay”
A. Bracco, J.R. Beene *et al*., PRL 60 (1988) 2603

“The direct neutron decay of giant resonances in ^{208}Pb”
A. Bracco, NPA 482 (1988) c421

“Neutron decay from the giant-resonance region in ^{208}Pb”
A. Bracco, J.R. Beene *et al*., PRC 39 (1989) 725 (R)
⇒ ^{17}O scattering at 378 MeV (22.24 MeV/u) at 13°

“Decay of the isoscalar giant monopole resonance in ^{208}Pb”
S. Brandenburg *et al*., NPA 466 (1987) 29

“Evidence for a (semi) direct component in the decay of the isoscalar giant monopole in ^{208}Pb”
S. Brandenburg *et al*., PRC 39 (1989) 2448

We both worked separately on the topic of hot GDR and we both have many publications on that.

“Pygmy dipole resonance in ^{124}Sn populated by inelastic scattering of ^{17}O”
L. Pellegri, A. Bracco *et al*., Phys. Lett. B738 (2014) 519

“Isospin character of low-lying pygmy dipole states in ^{208}Pb via inelastic scattering of ^{17}O ions”
F.C.L. Crespi, A. Bracco *et al*., PRL 113 (2014) 012501

“Low-energy isoscalar dipole strength in ^{40}Ca, ^{58}Ni, ^{90}Zr and ^{208}Pb”
T.D. Poelhekken, …, M.N. Harakeh
Phys. Lett. B278 (1992) 423-427

“Splitting of the pygmy dipole resonance in ^{138}Ba and ^{140}Ce observed in the $(\alpha,\alpha'\gamma)$ reaction”
J. Endres *et al*., PRC 80 (2009) 034302

“Isospin character of the pygmy dipole resonance in ^{124}Sn”
J. Endres *et al*., PRL 105 (2010) 212503

“Structure of the pygmy dipole resonance in ^{124}Sn”
J. Endres *et al*., PRC 85 (2012) 064331

Angela and I were working on several topics in parallel for almost four decades. We started Since more than 10 years collaborating on experiments at GSI, GANIL, RCNP and at Cyclotron Centre Bronowice at IFJ-PAN.

Since 2012, I have counted that we have 25 publications in common. I mention a recent one here, which I used in my talk:

"The structure of low-lying 1^- states in ^{90,94}Zr from (α,$\alpha'\gamma$) and (p,$p'\gamma$) reactions"
F.C.L. Crespi et al., Phys. Lett. B 816 (2021) 136210

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PhD Ceremony of Soumya Bagchi Rijksuniversiteit Groningen, May 2015

Finally I wish Angela active retirement (as I do not expect otherwise from her) with many years of good health and energy to keep doing the excellent work.

Thank you for your attention

$$P_{0\mu} = \frac{1}{2}\sum_i r_i^2$$

$$\sum_n (E_n - E_0)\,\tilde{P}_{0n}^{(0)} = S_0 = \frac{\hbar^2}{2m} A < \mathrm{r}^2 >$$

$$P_{1\mu} = \frac{1}{2}\sum_i r_i^3\, Y_{1\mu}(\hat{r}_i)$$

$$\sum_n (E_n - E_0)\,\tilde{P}_{0n}^{(1)} = S_1 = \frac{\hbar^2}{8\pi m}\frac{3}{4} A[11 < \mathrm{r}^4 > - \frac{25}{3} < \mathrm{r}^2 >^2 - 10\varepsilon < \mathrm{r}^2 >]$$

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

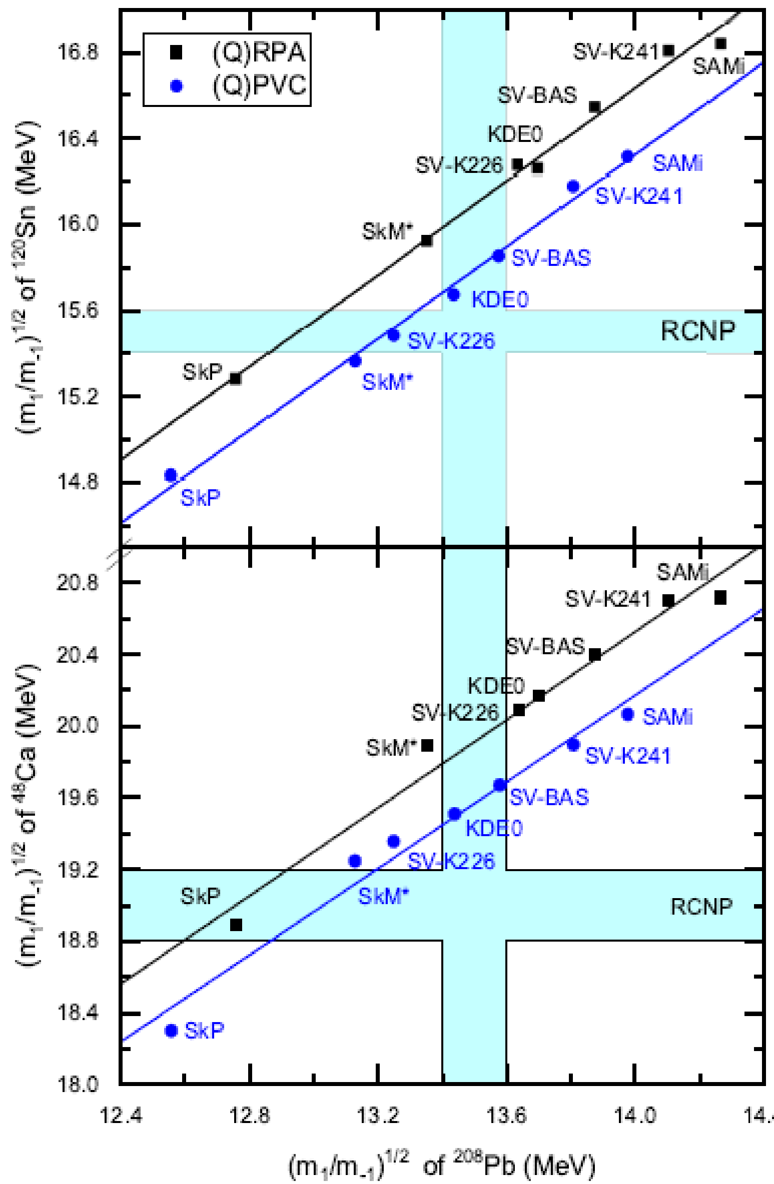
$$Q_{\lambda\mu} = \sum_i r_i^{\lambda}\, Y_{\lambda\mu}(\hat{r}_i)$$

$$\sum_n (E_n - E_0)\,\tilde{Q}_{0n}^{(\lambda)} = S_\lambda = \frac{\hbar^2}{8\pi m}\lambda(2\lambda+1)^2 A < \mathrm{r}^{2\lambda-2} >$$

Including (Q)PVC effects, ^{48}Ca prefers SkM* and SV-K226, ^{120}Sn prefers SkM*, SV-K226, and KDE0, while ^{208}Pb prefers SVK226, KDE0, and SV-bas.

=>, SV-K226 and KDE0 describe all three nuclei very well at the same time, **with K_∞ = 226 MeV and 229 MeV respectively: this is consistent with the constraint 240±20 MeV**, obtained previously from the ISGMR of ^{208}Pb in QRPA .

The ISGMR energies in ^{208}Pb vs. the ones in ^{120}Sn (upper panel), and ^{48}Ca (lower panel), calculated by (Q)RPA (black squares), and by (Q)RPA+(Q)PVC (blue circles) using 7 different Skyrme parameters. The regression lines are obtained from the (Q)RPA results and (Q)RPA+(Q)PVC results, respectively. The experimental data and their uncertainties, taken from [1, 2, 3], are displayed by means of cyan-coloured bands.



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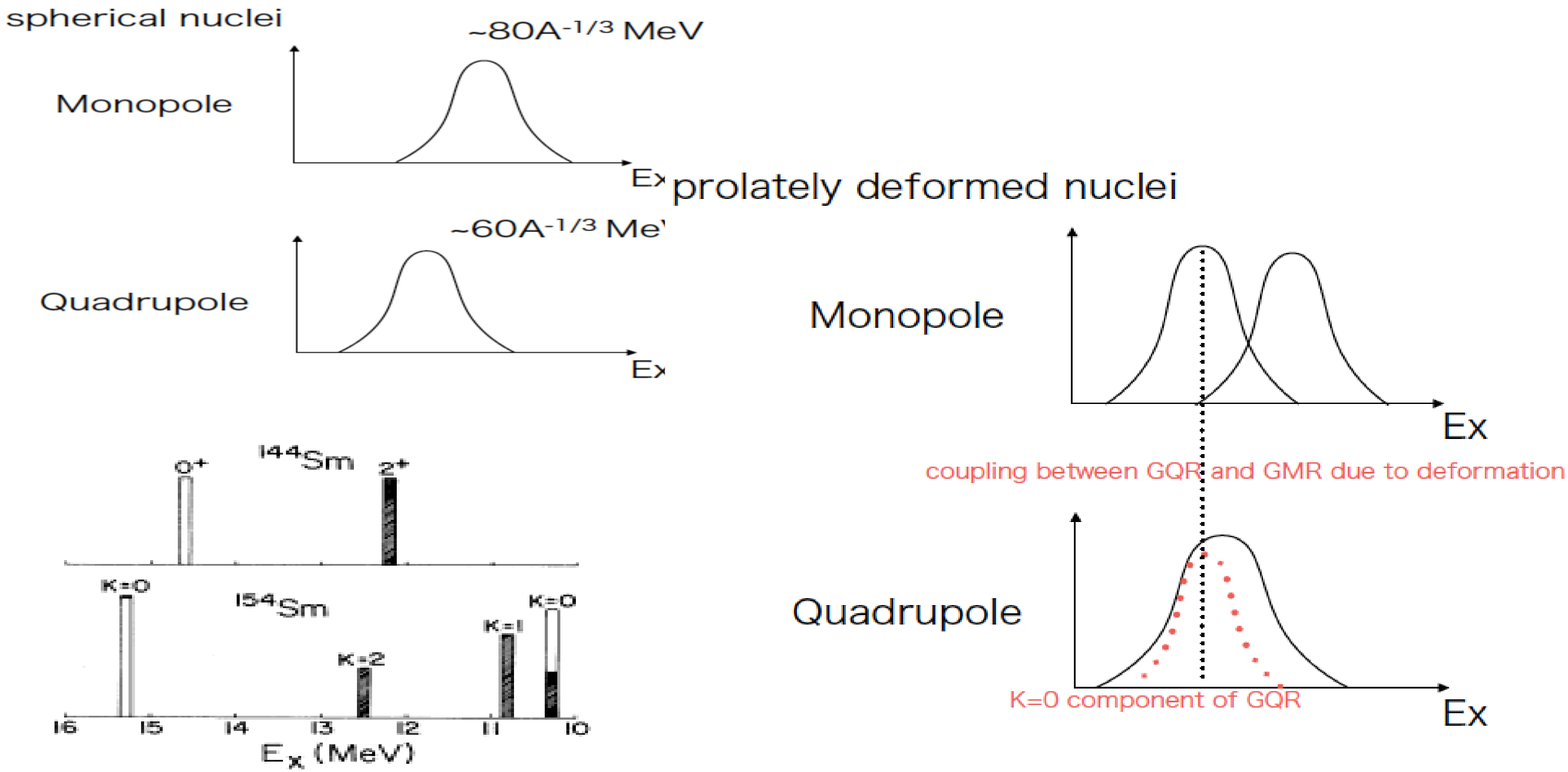
Splitting of the ISGMR under deformation

K projection of *J* on symmetry axis is good quantum number in deformed nuclei

Coupling of ISGMR with *K*=0 component of ISGQR



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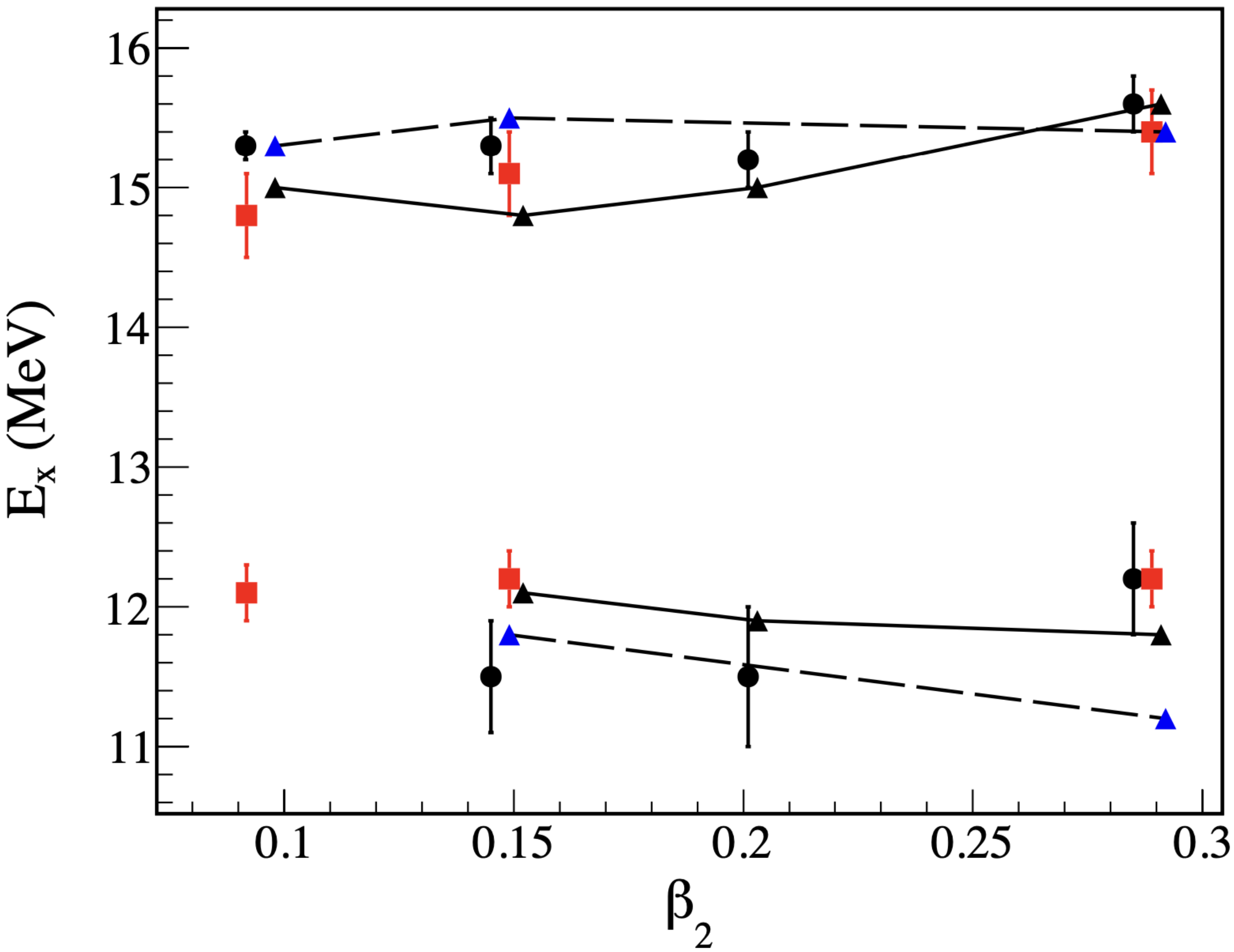
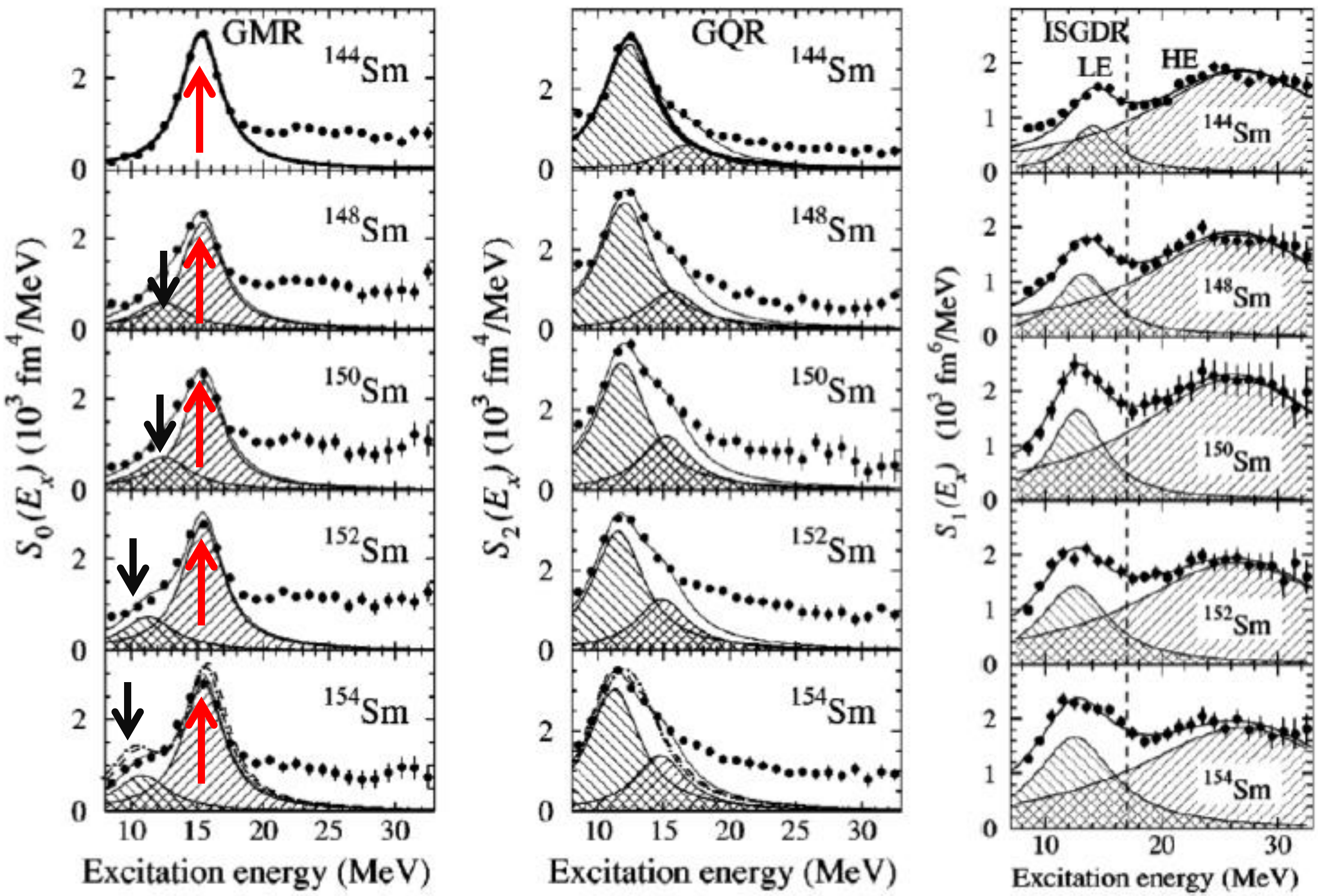


16
15
14
13
12
11
E_x (MeV)
0.1
0.15
0.2
0.25
0.3
β_2

Effect of deformation on Isoscalar Giant Resonances: Sm isotopes



^{144}Sm

$\beta_2 = 0.0881$ (13)

^{148}Sm

^{150}Sm

^{152}Sm

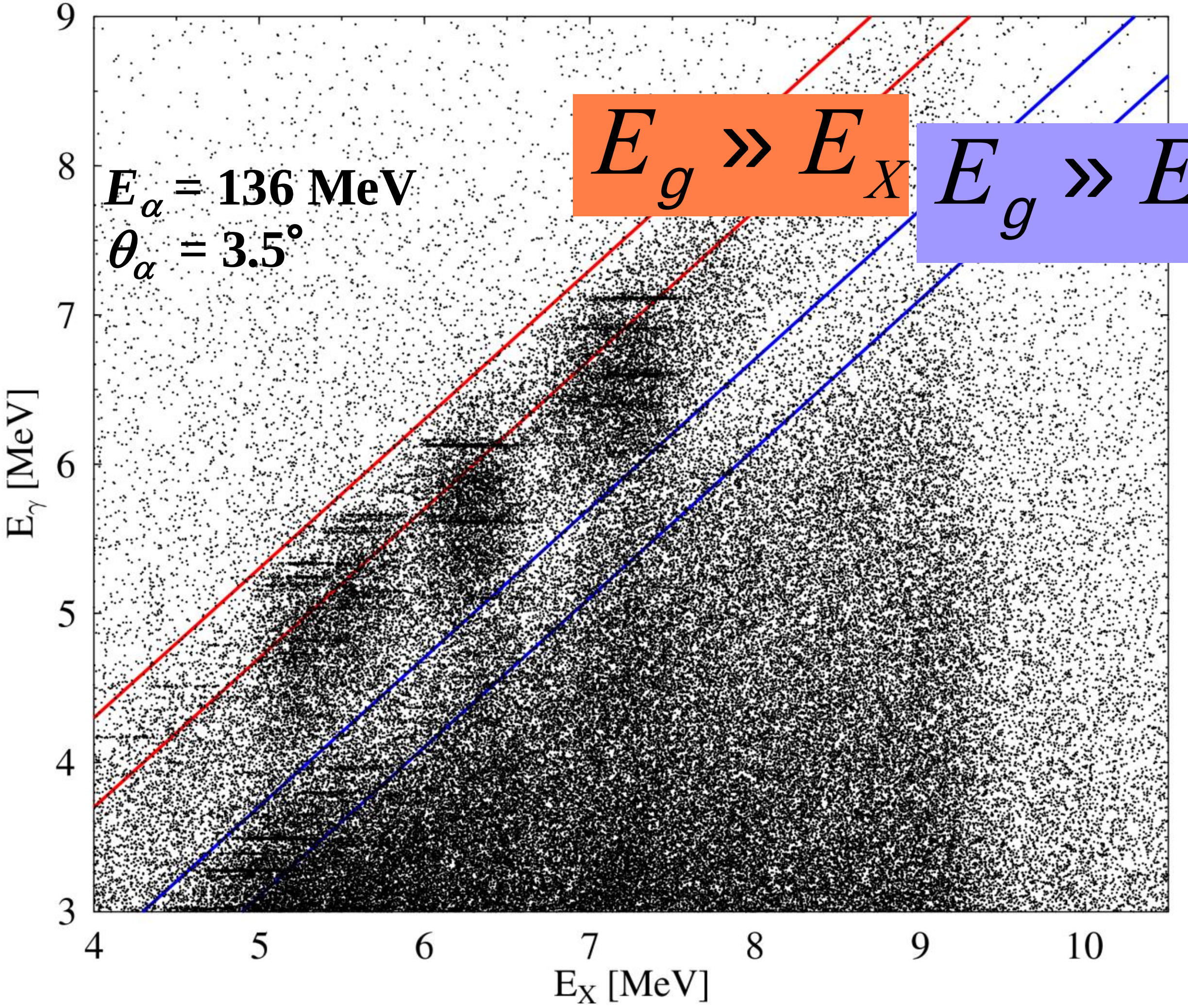
^{154}Sm

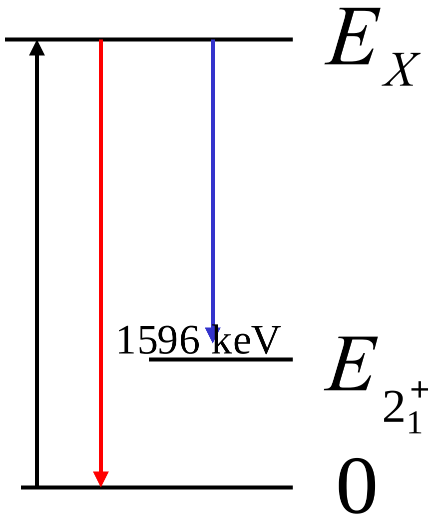
$\beta_2 = 0.339$ (3)

ΔL = 0; ISGMR *ΔL* = 2; ISGQR *ΔL* = 1; ISGDR

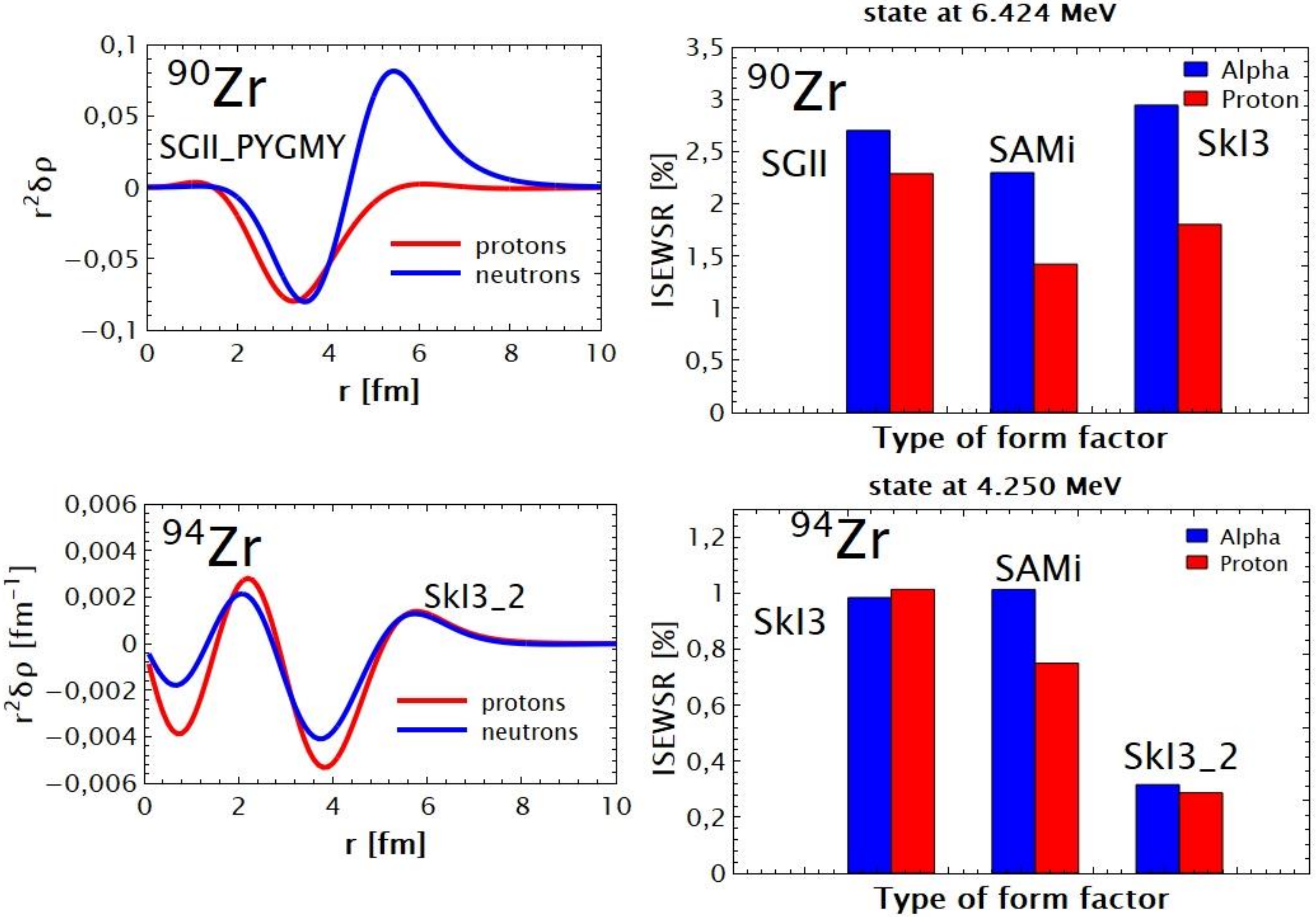
M. Itoh *et al*., Phys. Rev. C 68 (2003) 064602

^{140}Ce(α,α′γ) - coincidence matrix





D. Savran *et al.*, PRL97 (2006) 172502


state at 6.424 MeV
90Zr
SGII_PYGMY
r²δρ
r [fm]
protons
neutrons
SGII
SAMi
SkI3
Alpha
Proton
ISEWSR [%]
Type of form factor
state at 4.250 MeV
94Zr
SkI3_2
r²δρ [fm⁻¹]
r [fm]
protons
neutrons
SkI3
SAMi
SkI3_2
Alpha
Proton
ISEWSR [%]
Type of form factor

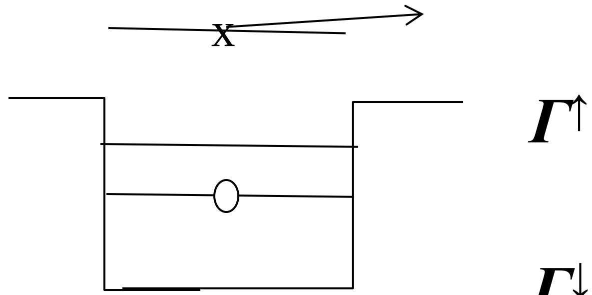
Decay of giant resonances

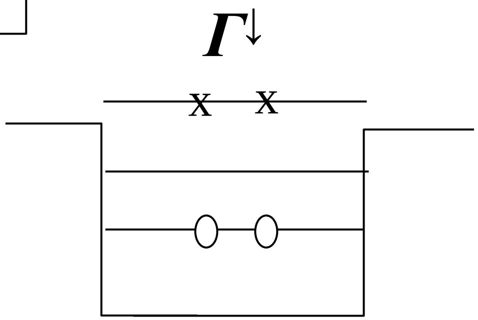
- **Width of resonance**

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

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

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

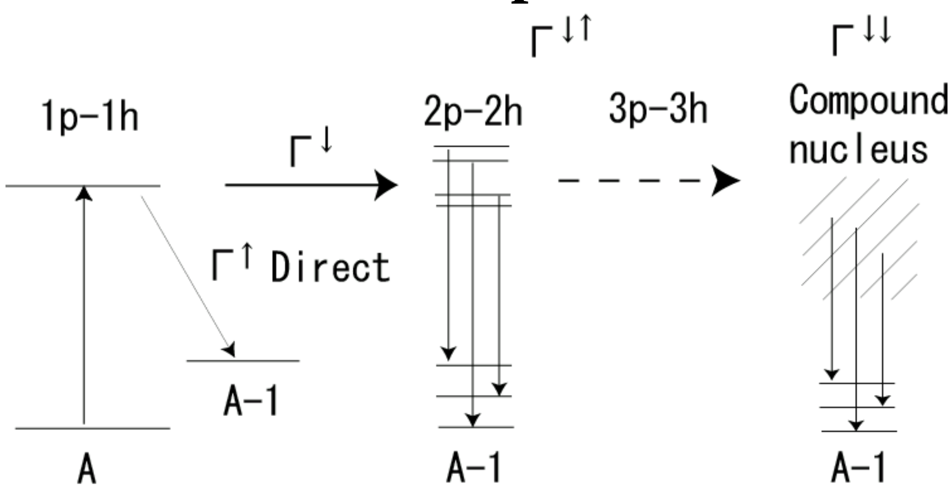




- **Decay measurements**

  ⇒ **Direct reflection of damping processes**

  Allows detailed comparison with theoretical calculations



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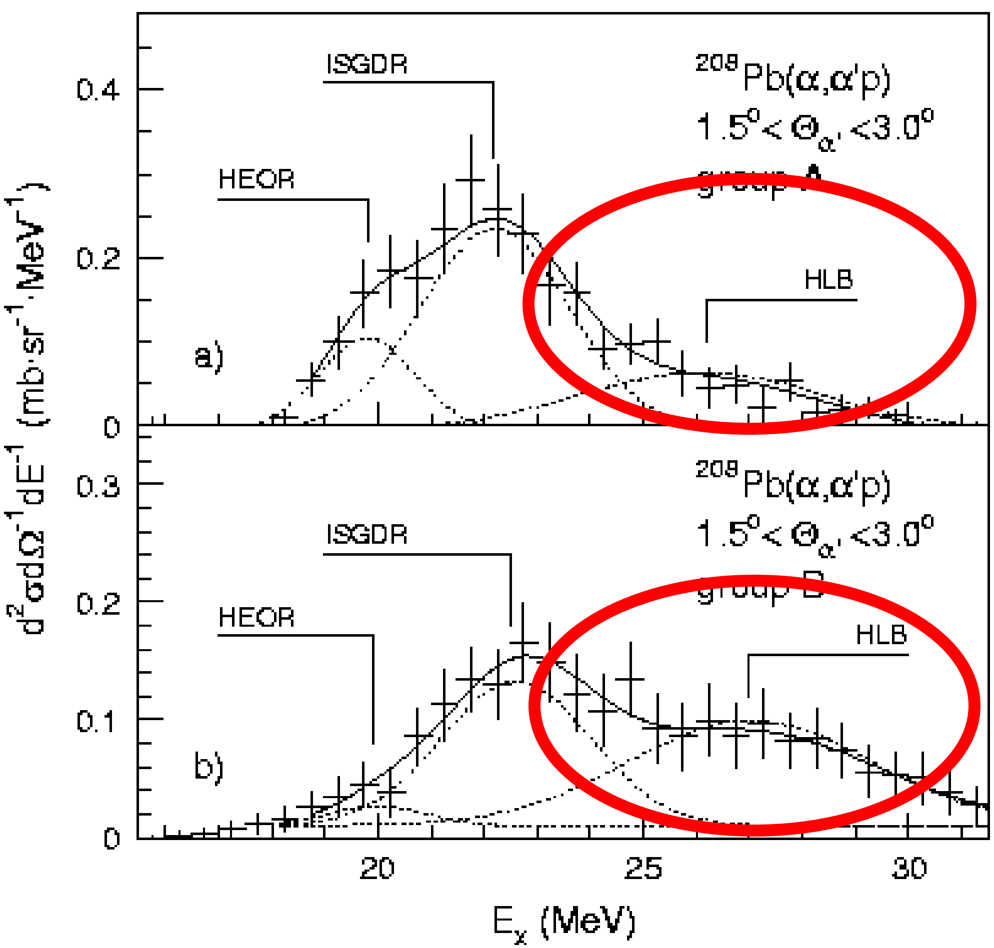
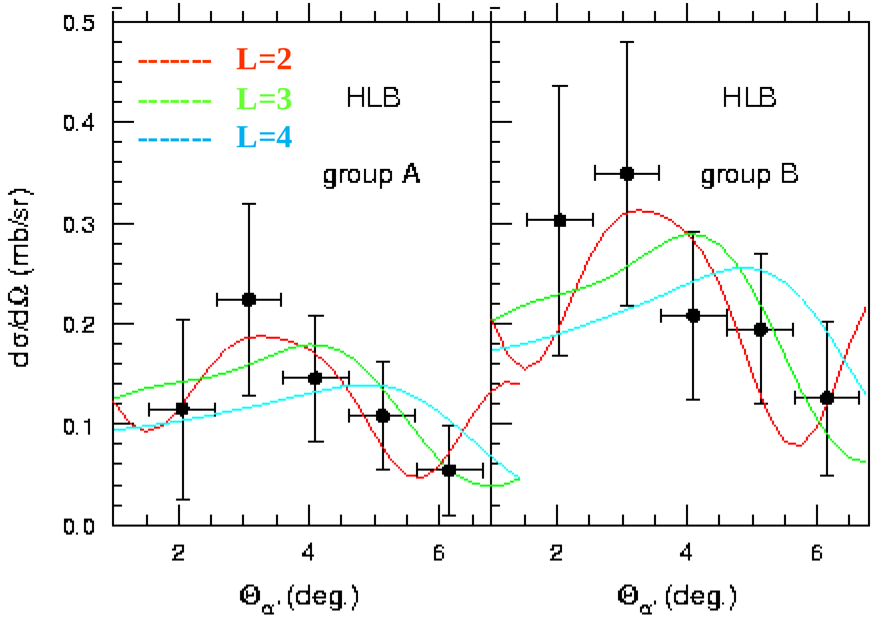
Overtone of the ISGQR? [$r^4 Y_2$]



E_x = 26.9 ± 0.7 MeV

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



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Conclusions!

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

  Systematics: E_x, Γ, %EWSR

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

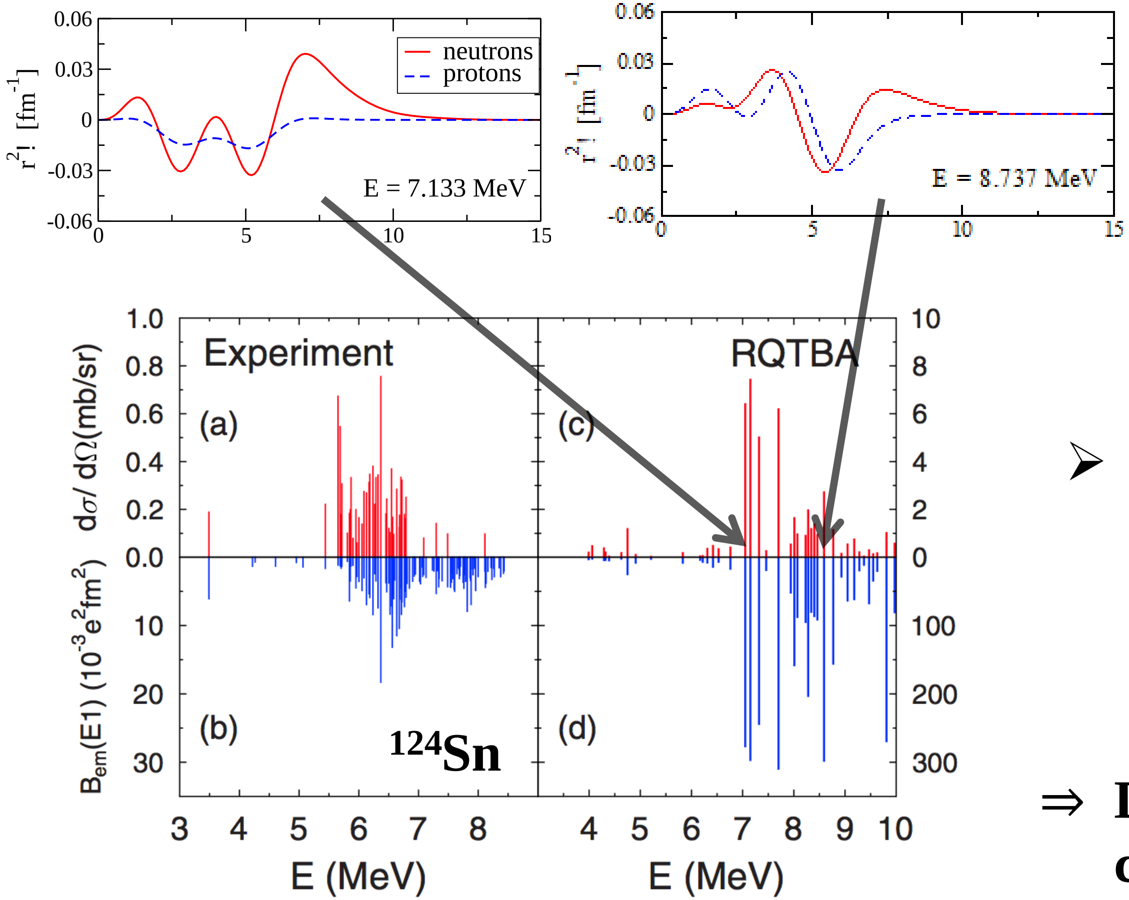
  $\Rightarrow K_{\tau} \approx -500$ MeV

- **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**

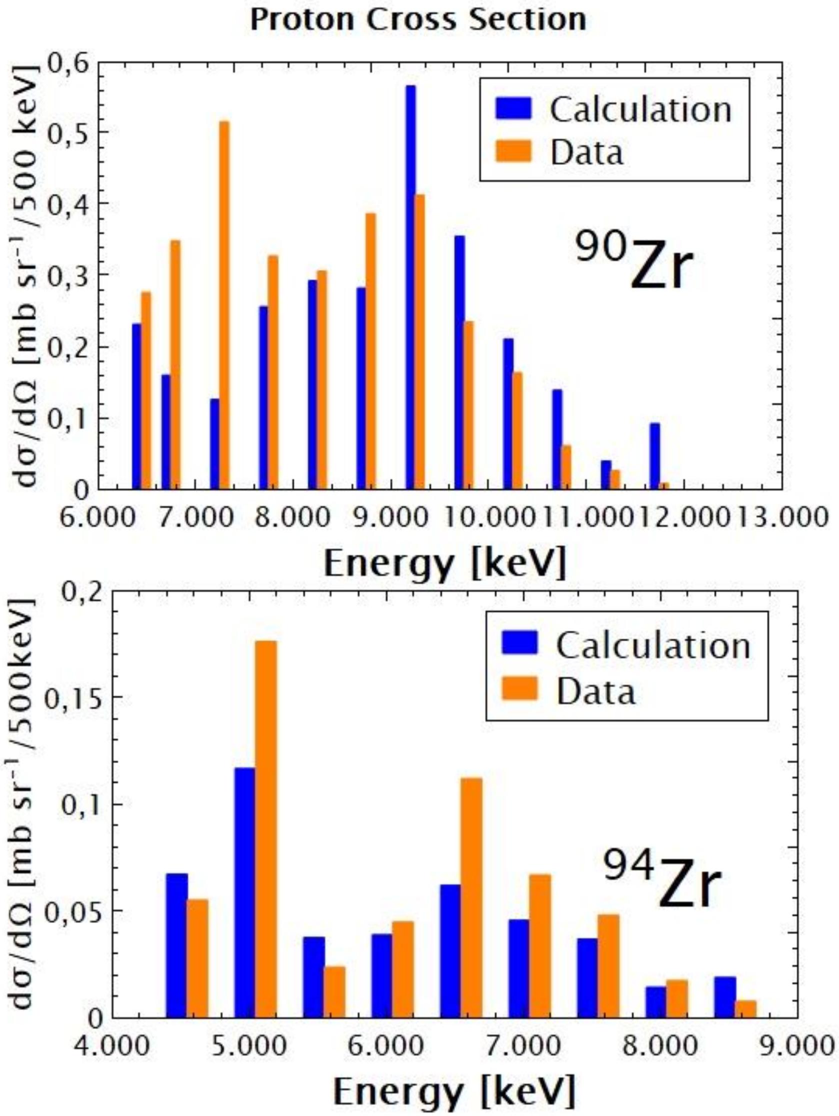
Identification of PDR structure in (α,α′γ)



- ➢ **Good reproduction of experimental results using RQTBA transition densities + semi-classical reaction model**

⇒ **Different response to complementary probes allows identification of PDR structure**

J. Endres *et al.*, PRL 105 (2010) 212503
E. Lanza *et al.*, PRC 89 (2014) 041601(R)


Proton Cross Section
dσ/dΩ [mb sr⁻¹/500 keV]
Calculation
Data
90Zr
0
0,1
0,2
0,3
0,4
0,5
0,6
6.000 7.000 8.000 9.000 10.000 11.000 12.000 13.000
Energy [keV]
dσ/dΩ [mb sr⁻¹/500keV]
Calculation
Data
94Zr
0
0,05
0,1
0,15
0,2
4.000 5.000 6.000 7.000 8.000 9.000
Energy [keV]