Collective Excitations in Rare-Earth Nuclei: Insights from Isoscalar Giant Resonances

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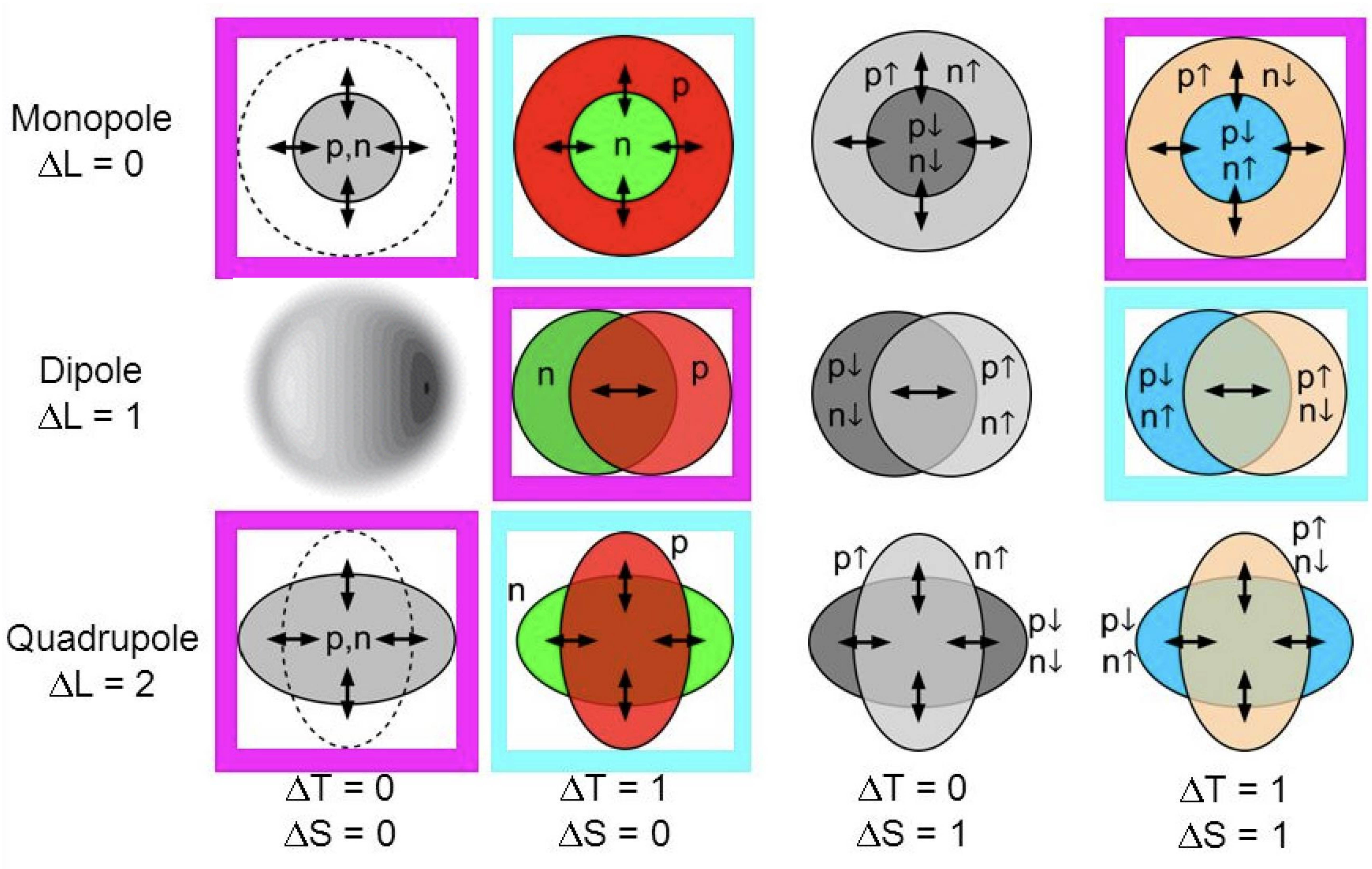
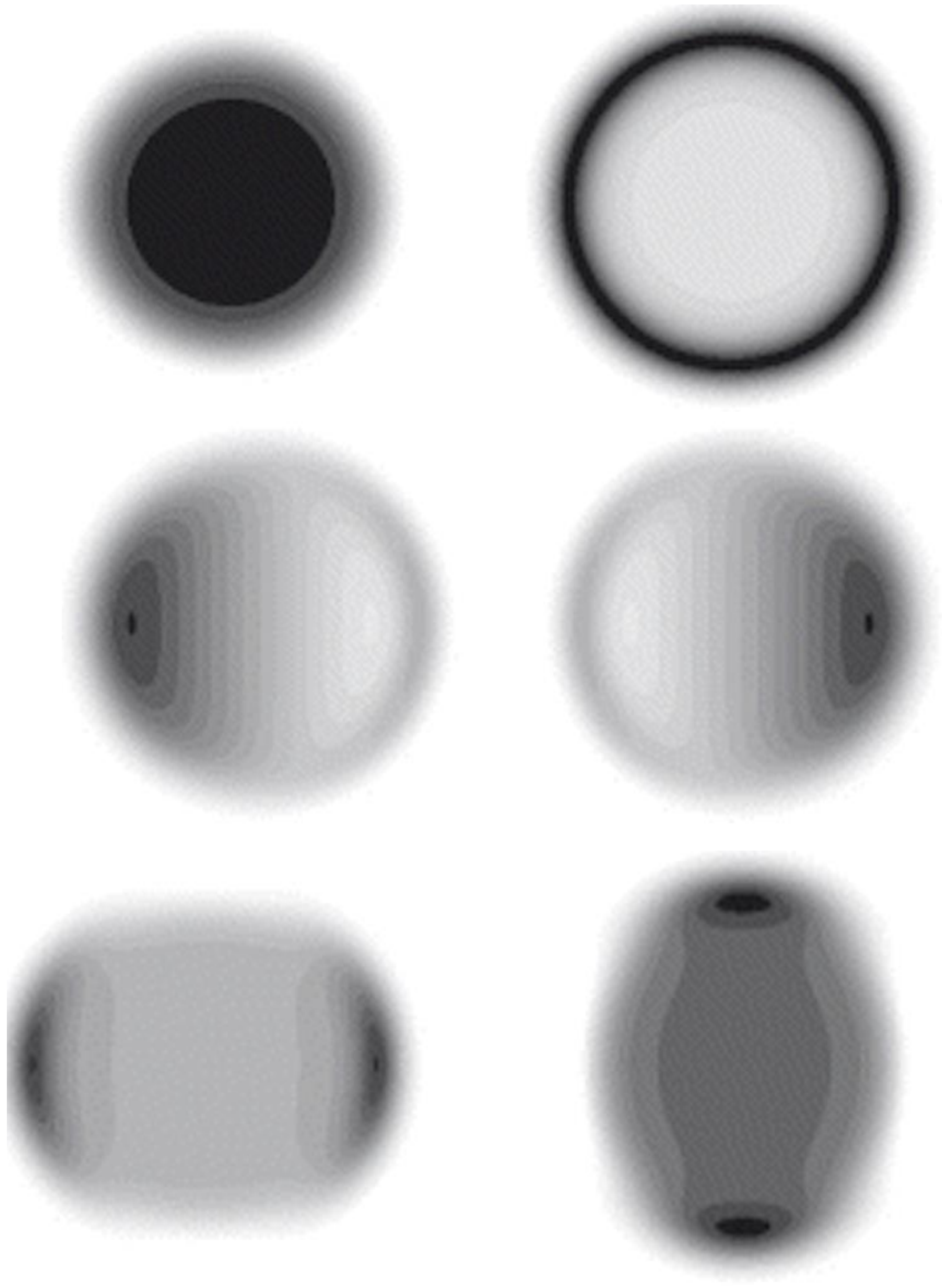


Outline

- What are giant resonances?
- Effect of ground-state deformation
- Experimental setup
- Recent results
- Summary

Operators for Giant Resonances

$$O^{L\mu} = \frac{Z}{A}\sum_k r_k^L Y_L^\mu(\hat{r}_k)$$



2ħω ISGMR
$\sum_i r_i^2 Y_{0\mu}(\Omega_i)$

1st order term (or maintone) is a constant. 2nd order term (overtone) is considered.

3ħω ISGDR
$\sum_i r_i^3 Y_{1\mu}(\Omega_i)$

1st order term (or maintone) is a translational motion of the center of mass of the nucleus. 2nd order term (overtone) is considered.

2ħω ISGQR
$\sum_i r_i^2 Y_{2\mu}(\Omega_i)$

1st order term (or maintone) is considered.

Strength distribution of Isoscalar/Isovector Giant Resonances

Y.-W. Lui et al., Phys. Rev. C 73, 014314 (2006)

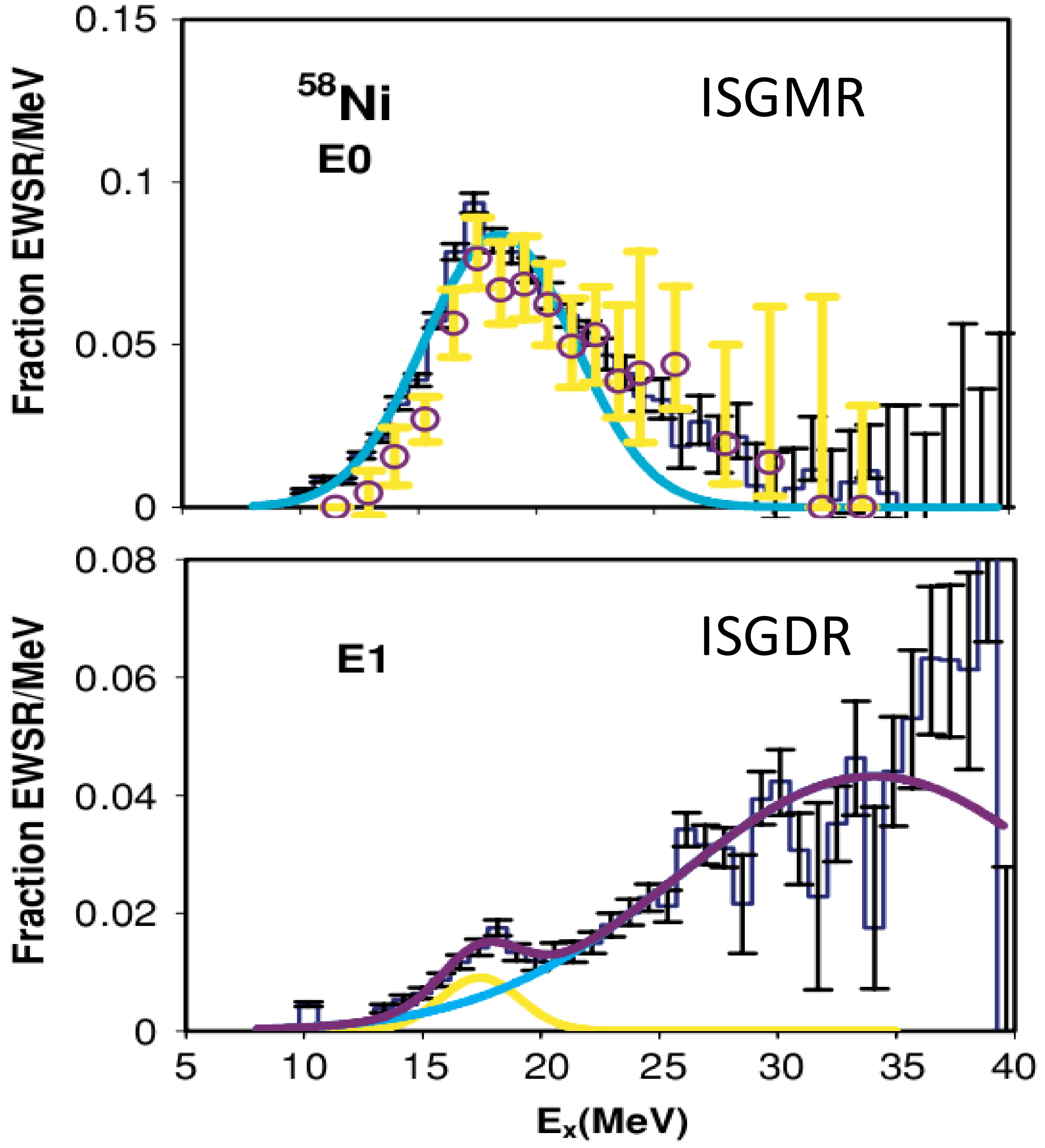
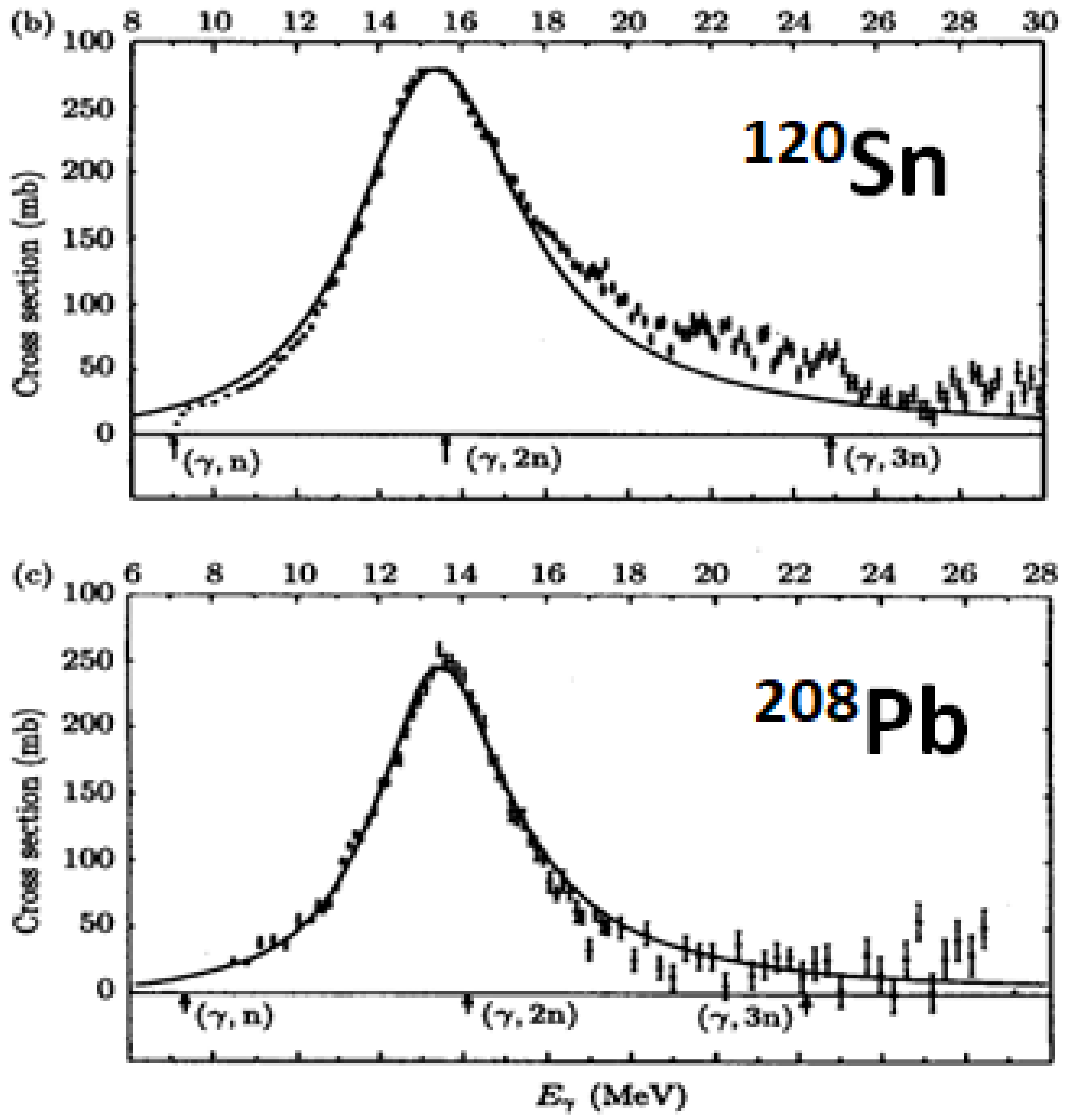


Photo neutron cross-sections (γ,n)



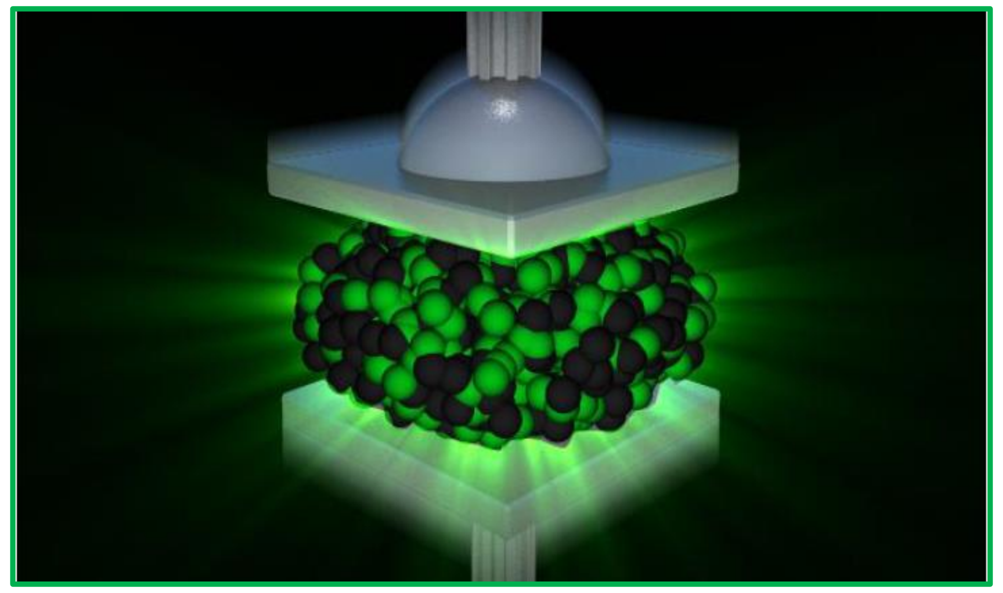
Berman and Fultz, Rev. Mod. Phys. 47, 713 (1975)

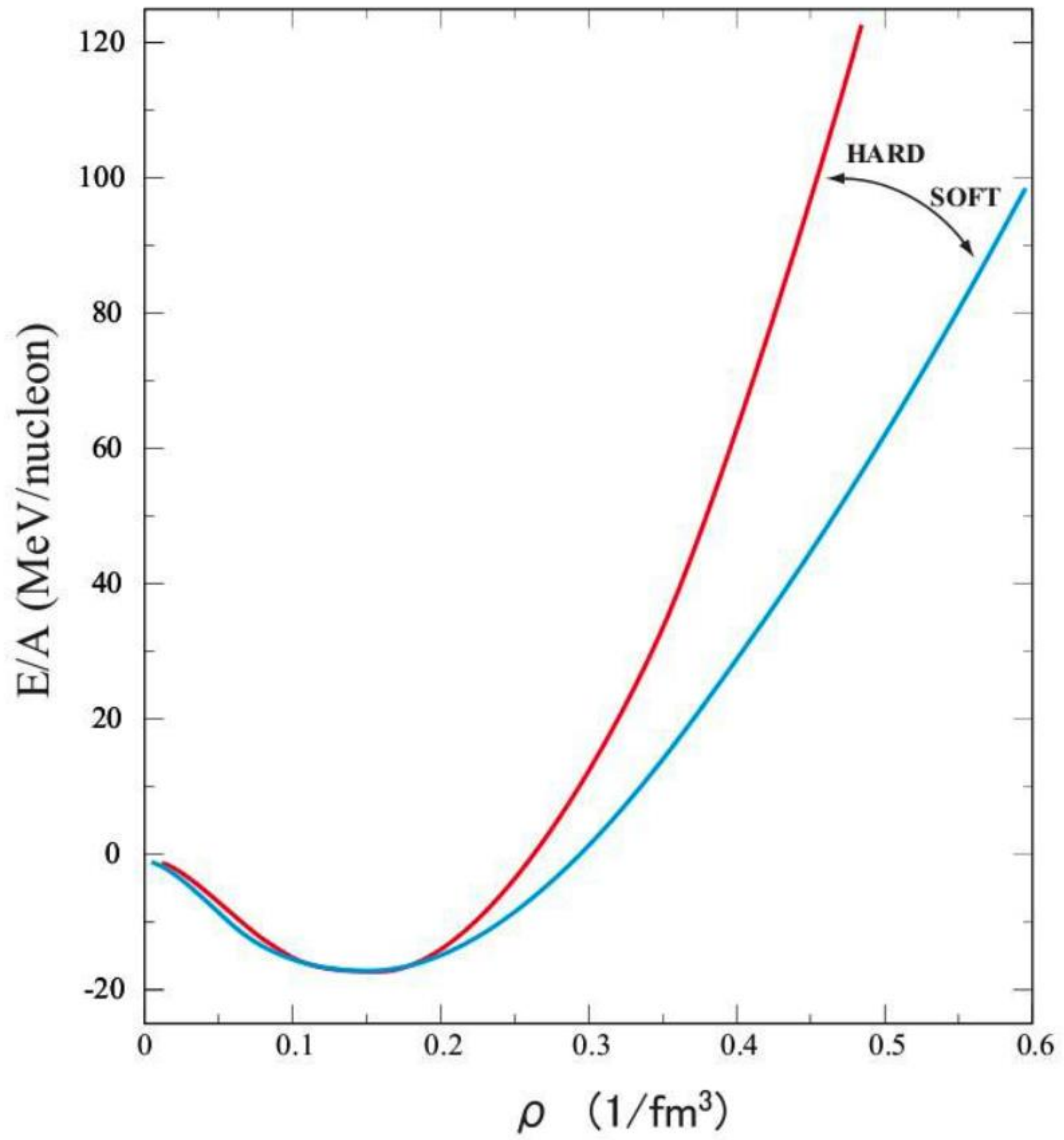
- Giant resonances are characterized by excitation energies higher than the particle-emission threshold (10 – 30 MeV)
- Broad resonance widths

Nuclear Incompressibility

Incompressibility:
A measure of the resistance of matter to uniform compression

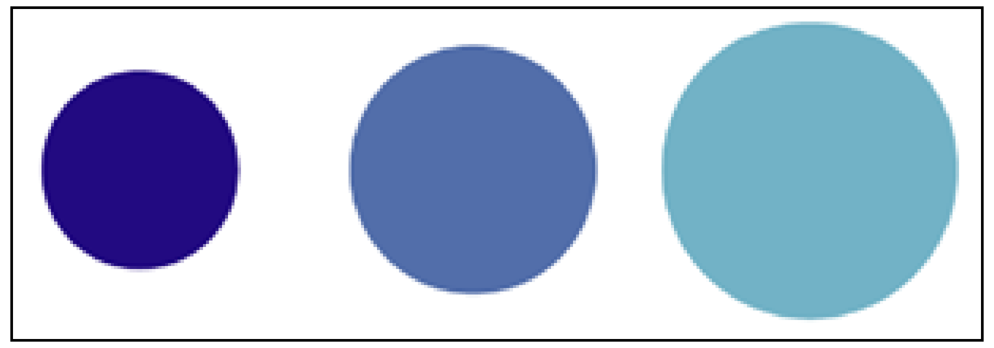
- Key input to the EoS of the nuclear matter





- Core collapse and supernovae explosion
- Formation of neutron star
- Collisions of heavy ions

Overtone mode



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

Overtone mode

$$E_{ISGDR} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\epsilon_F}{m < r^2 >}}$$

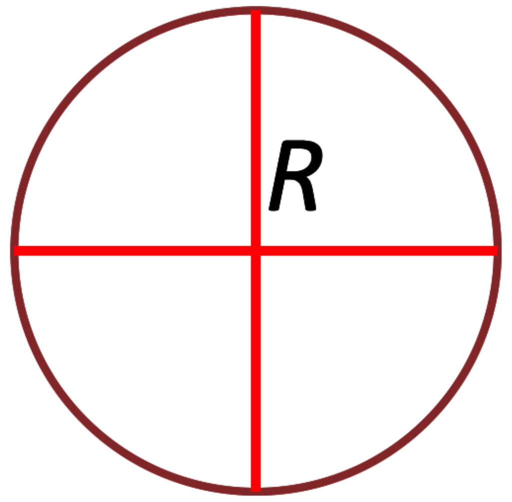
Incompressibility of finite nucleus $K_A \xrightarrow[\text{calculation}]{\text{RPA}} K_\infty$

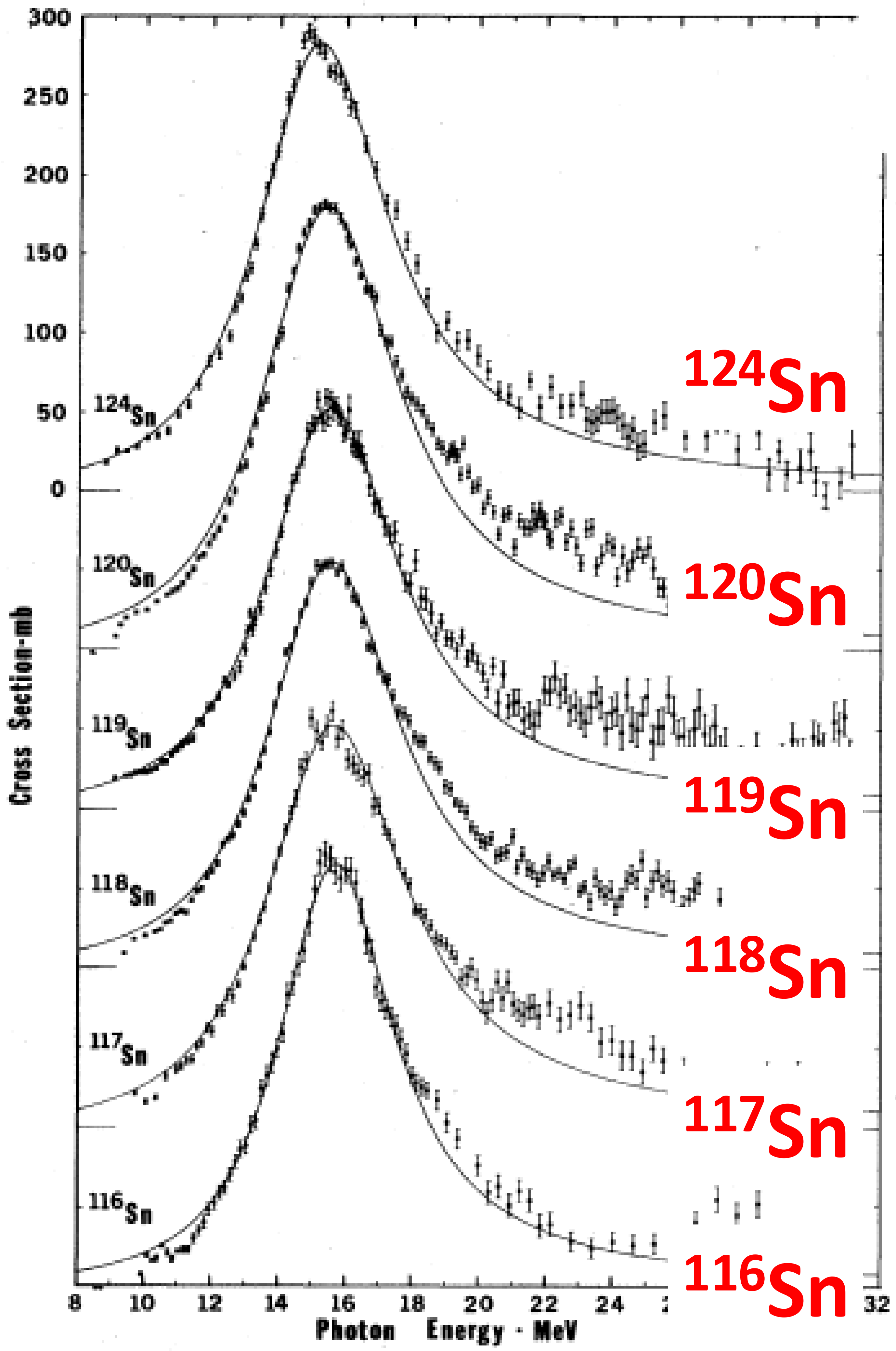
$$K_\infty = 9\rho_0^2 \left.\frac{d^2\epsilon}{d\rho^2}\right|_{\rho=\rho_0}$$

Incompressibility of infinite nuclear medium

IVGDR (Photoneutron cross section) in Spherical and Nearly Spherical and Deformed Nuclei

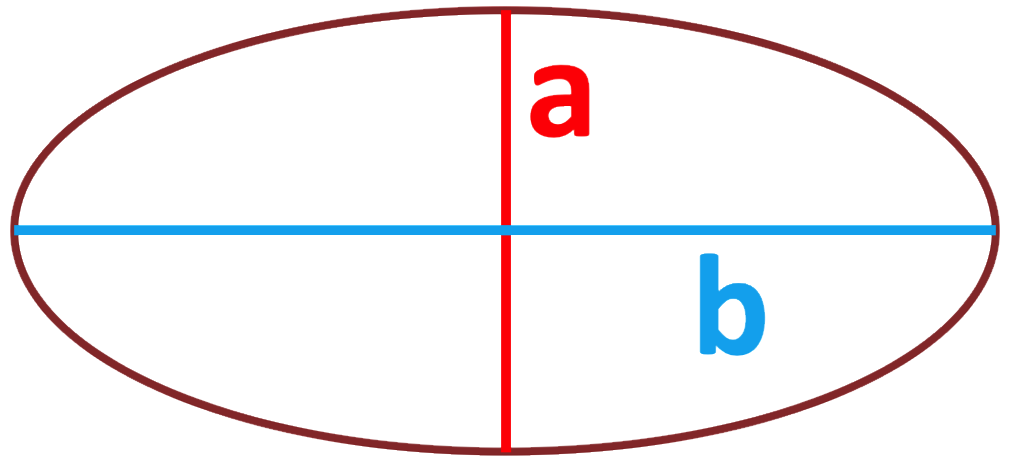
$$\omega \propto \frac{1}{R}$$

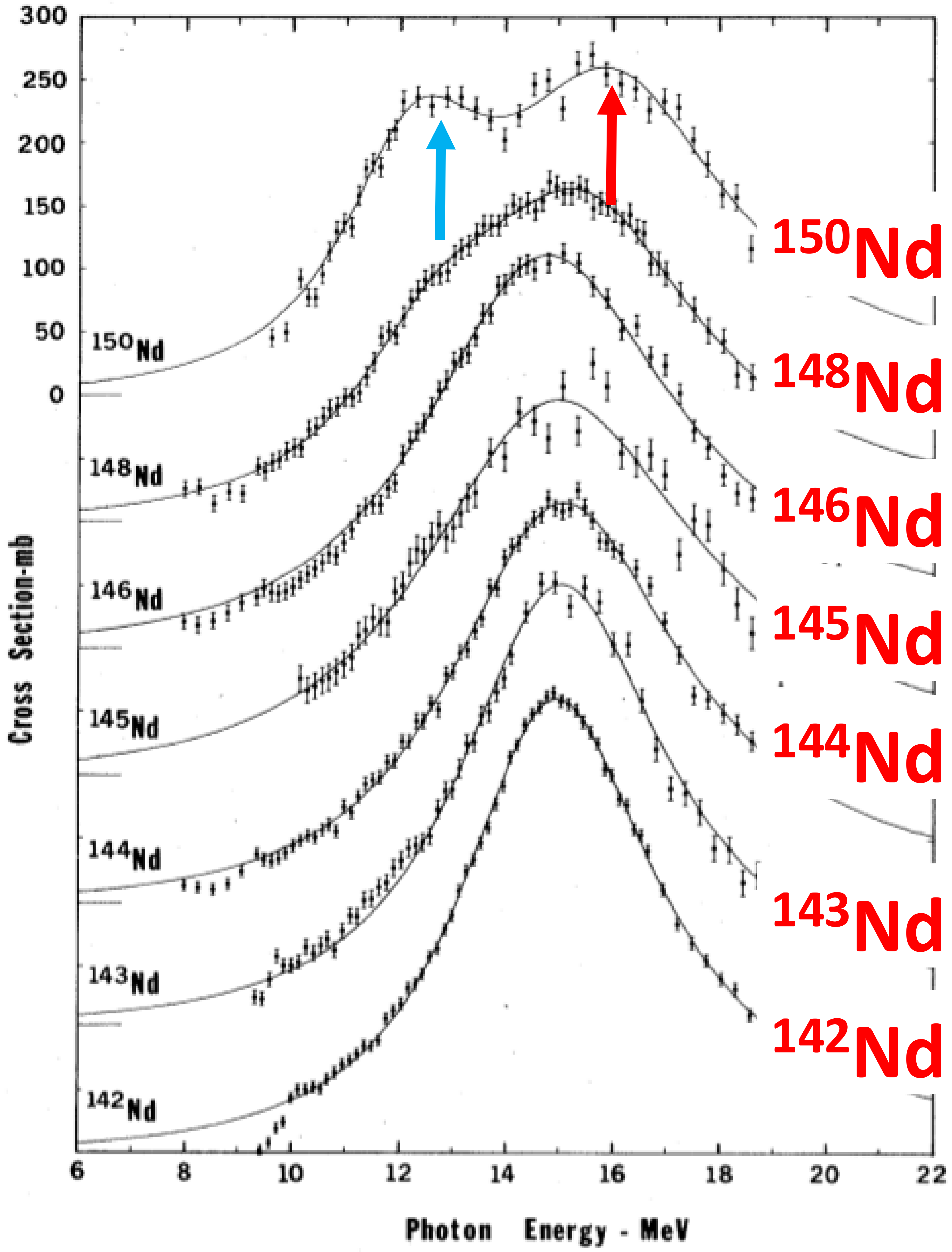




$$R(\theta,\varphi)=R_0(1+\beta_2 Y_{20}(\theta,\varphi))$$

$$\beta_2\ (^{150}\mathrm{Nd}) = 0.285(3)$$



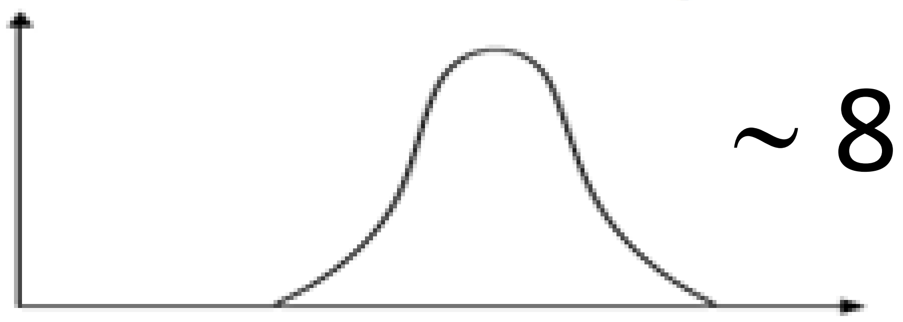


B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975)

Effect of nuclear deformation on Isoscalar Giant Resonances

Spherical Nucleus

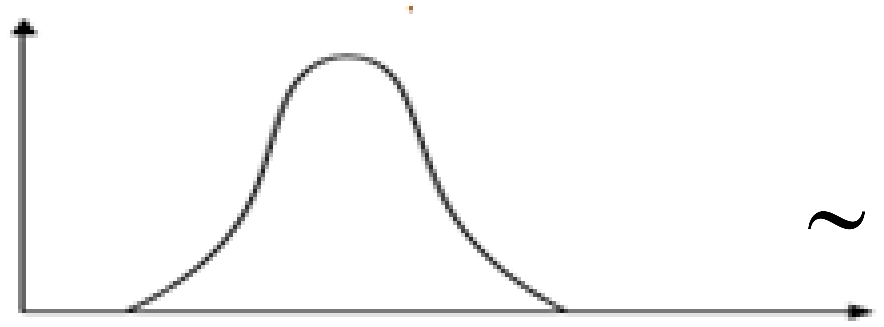
Monopole
$\Delta L = 0$



$\sim 80\ A^{-1/3}$ MeV

Ex

Quadrupole
$\Delta L = 2$

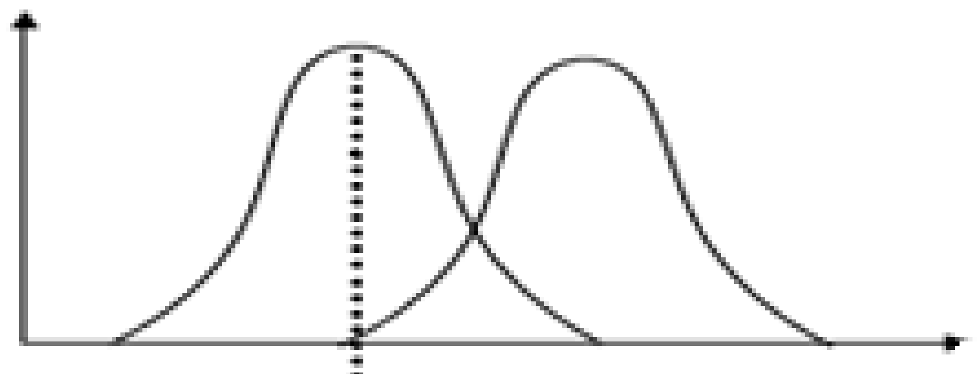


$\sim 60\ A^{-1/3}$ MeV

Ex

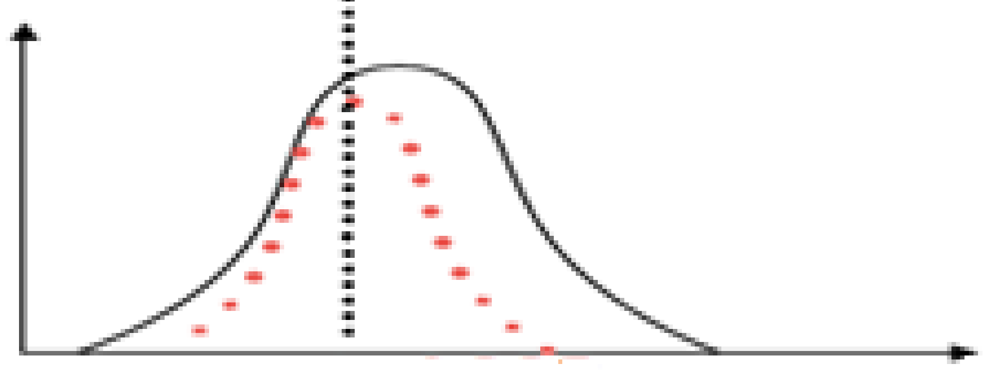
Adapted from U. Garg

Prolately Deformed Nucleus



Ex

Coupling between GMR and GQR due to deformation

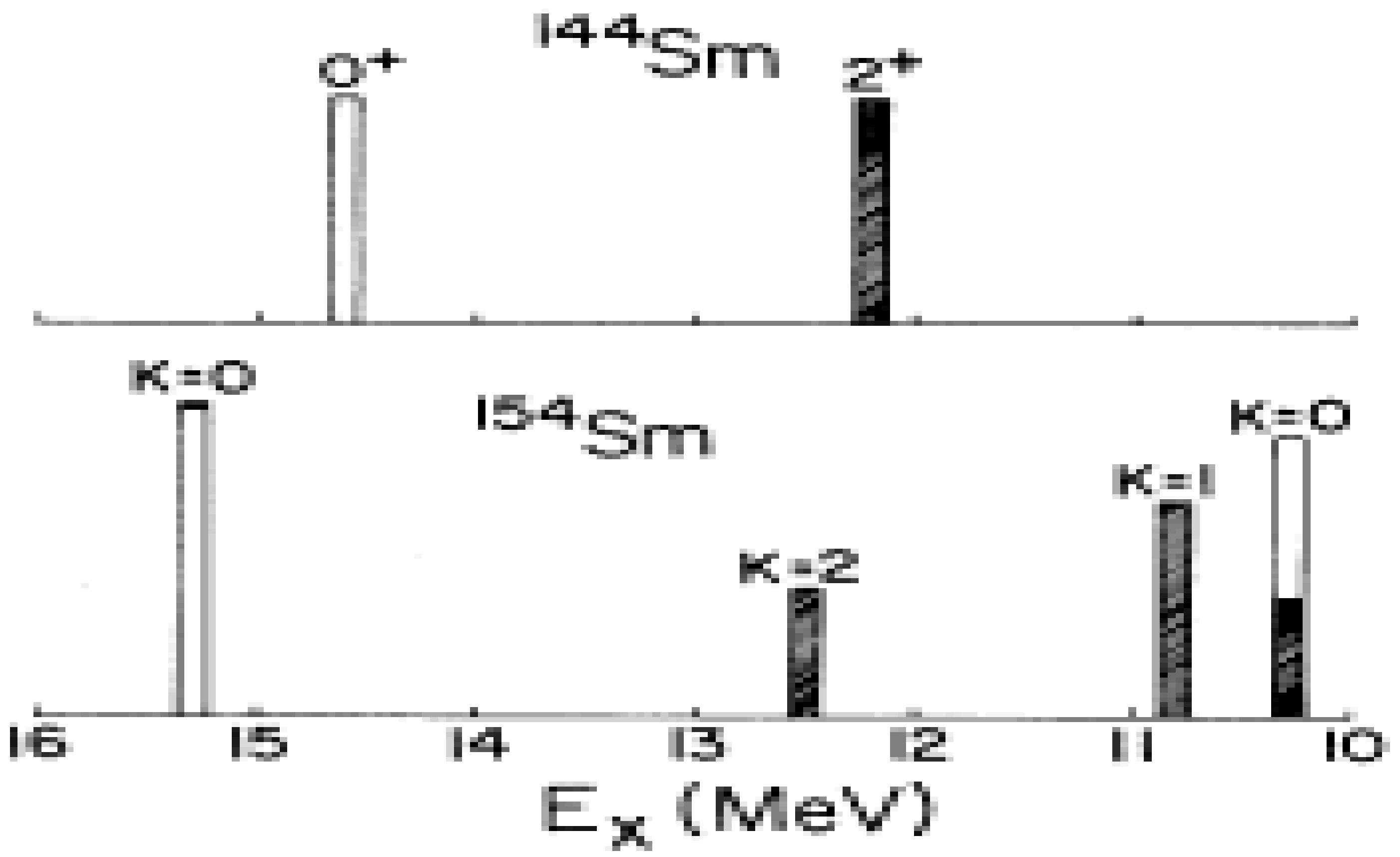


Ex

K = 0 component of GQR

Spherical Nucleus ^{144}Sm, $\beta_2 = 0.0881\ (13)$

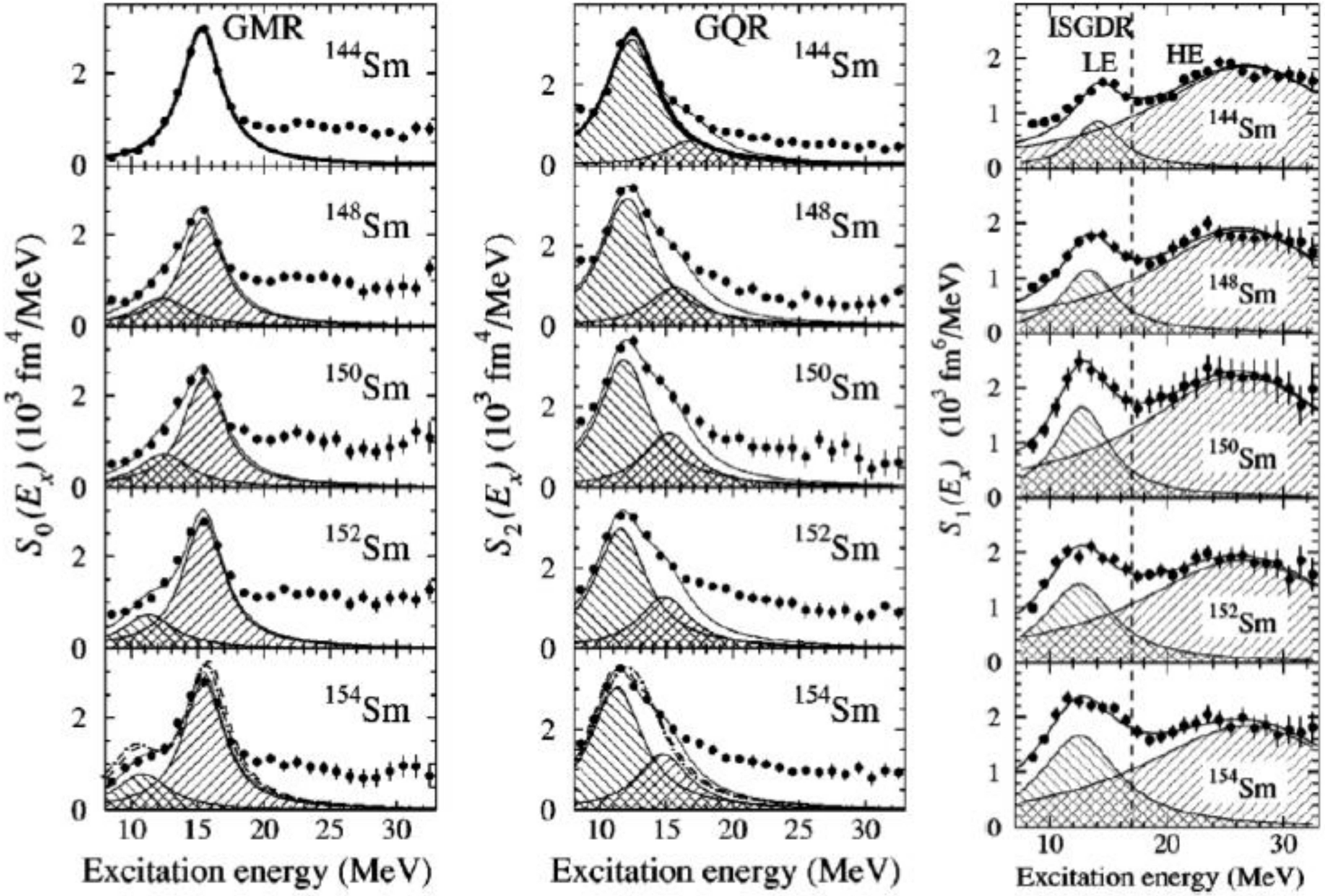
Deformed Nucleus ^{154}Sm, $\beta_2 = 0.339\ (3)$



Coupling between GMR and GQR due to deformation

Coupling between ISGDR and HEOR due to deformation

Effect of deformation on Isoscalar Giant Resonances: Sm isotopes



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

^{144}Sm
β_2 = 0.0881 (13)

^{148}Sm

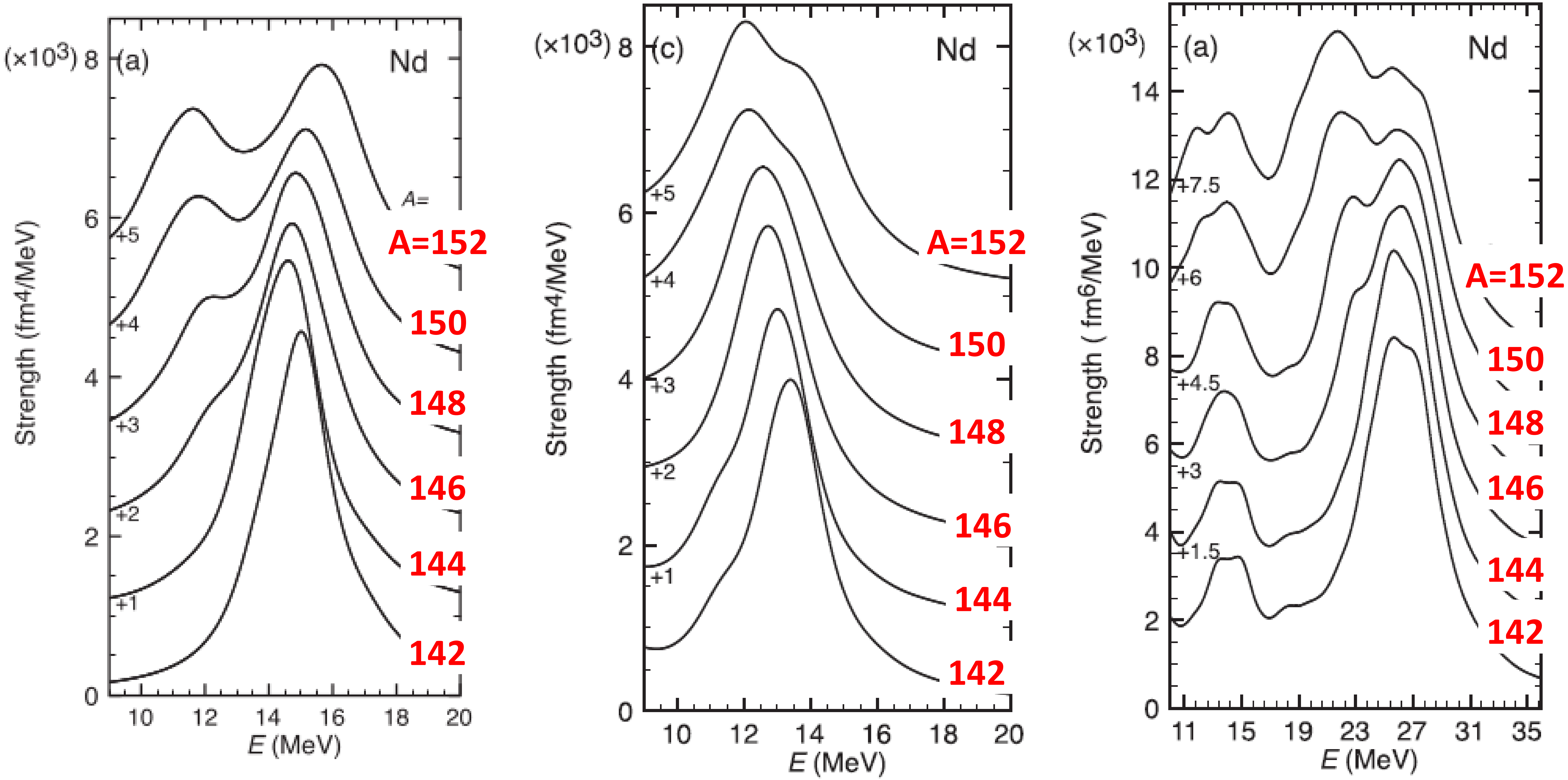
^{150}Sm

^{152}Sm

^{154}Sm
β_2 = 0.339 (3)

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

Isoscalar Giant Resonances in Nd isotopes: QRPA calculations



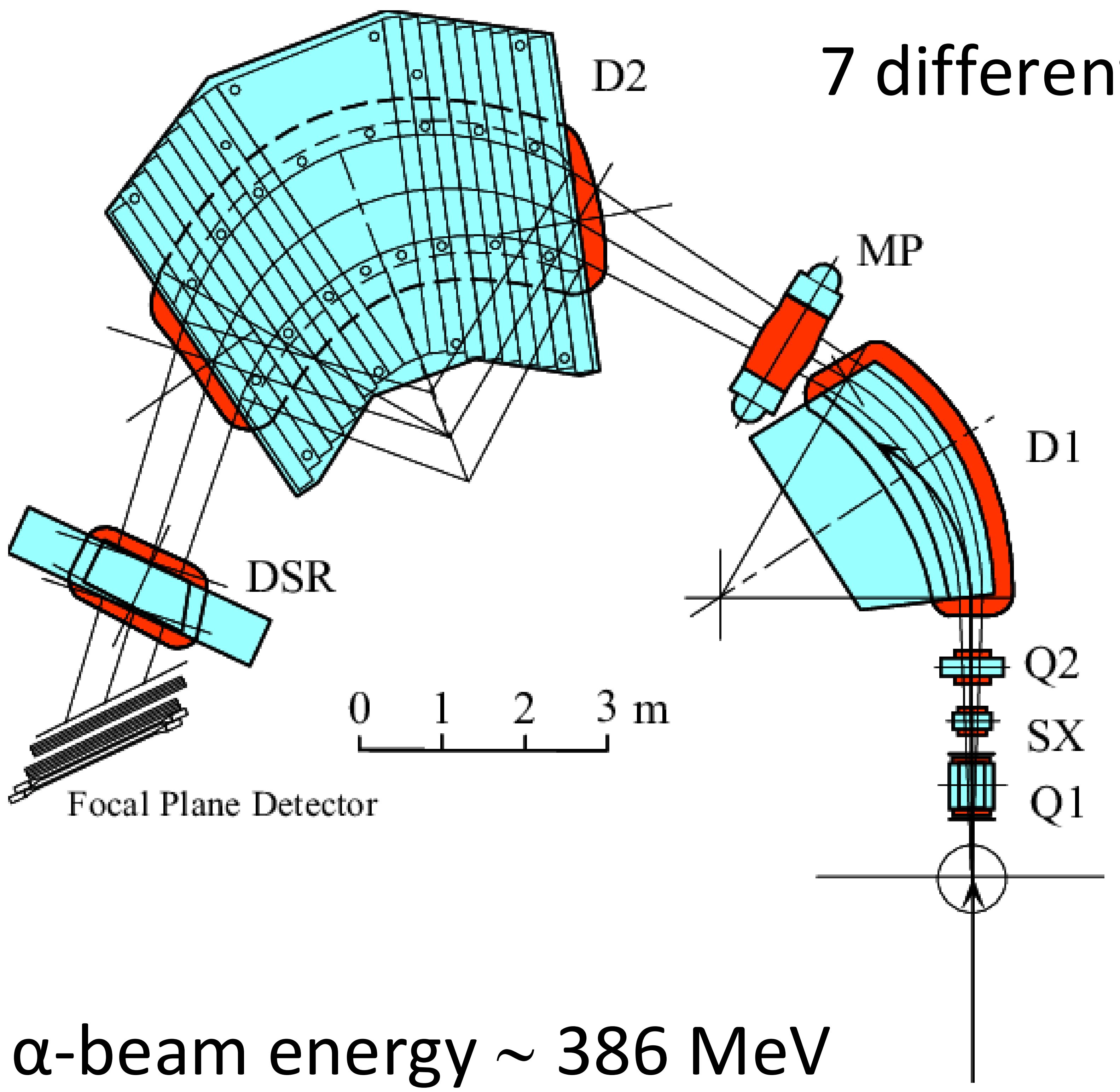
ΔL = 0; ISGMR

ΔL = 2; ISGQR

ΔL = 1; ISGDR

Kenichi Yoshida and Takashi Nakatsukasa, Phys. Rev. C 88, 034309 (2013)

Isoscalar Giant Resonance studies with inelastic α scattering at RCNP, Osaka, Japan



7 different angular settings of the spectrometer: 0°, 2.5°, 3.5°, 5°, 6.5°, 8°, and, 9.5°

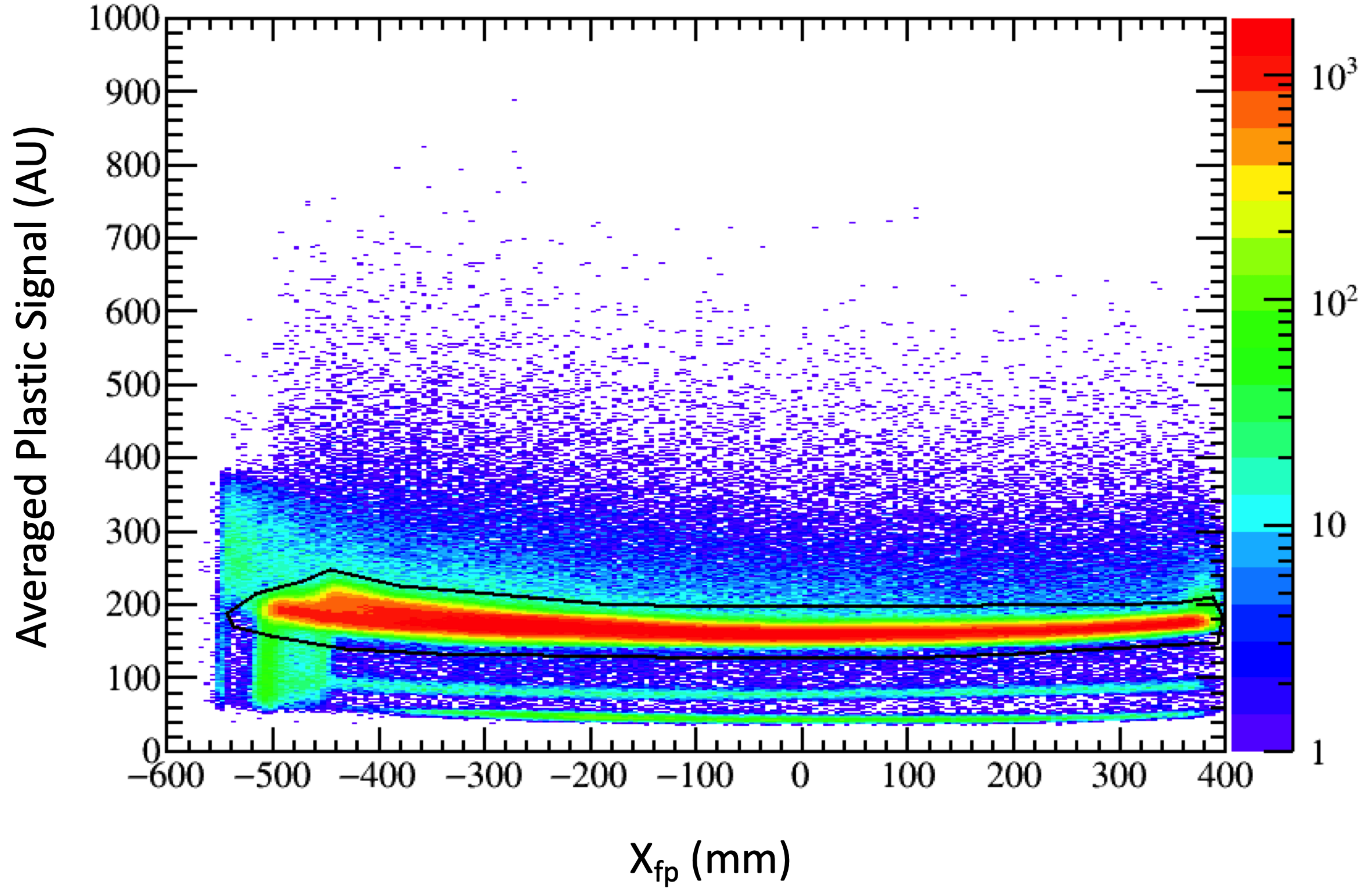
α-beam energy ~ 386 MeV

Grand Raiden spectrometer

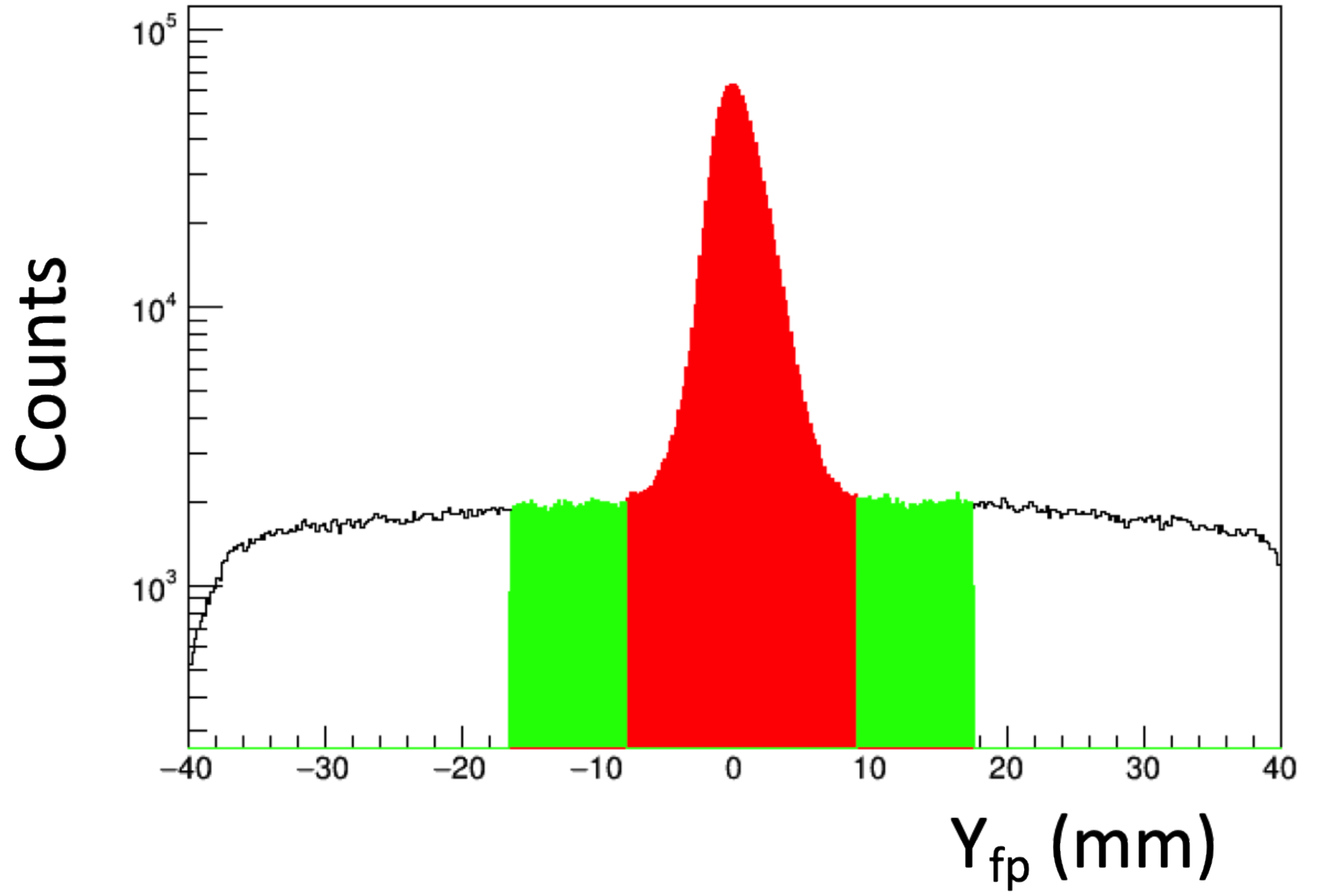
Enriched (> 95%) $^{142, 146, 148, 150}$Nd targets (~5 mg/cm^2)

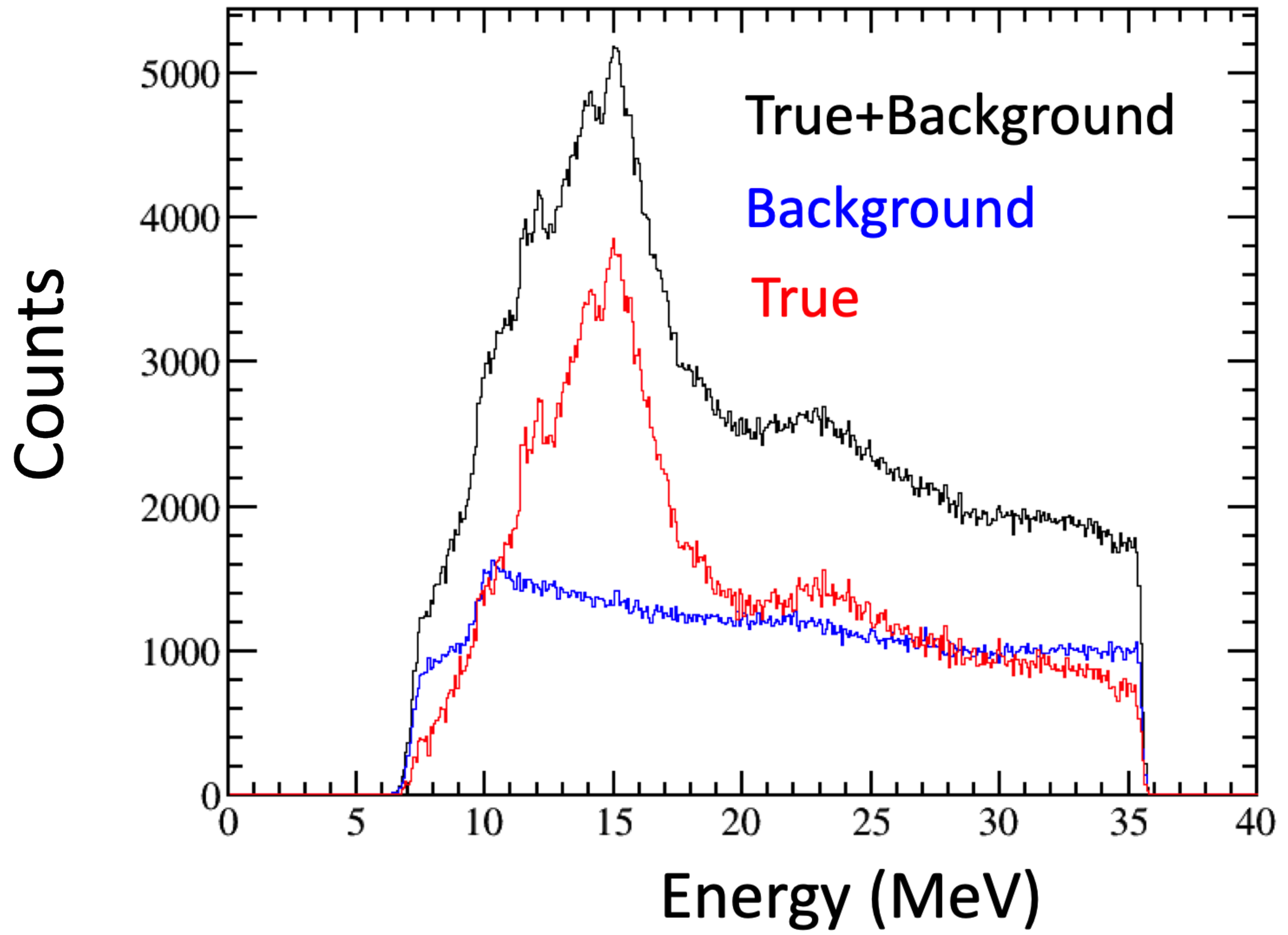
Focal plane: position-sensitive MWDCs and plastic scintillators for momentum analysis and particle identification.

Particle Identification and Instrumental background subtraction



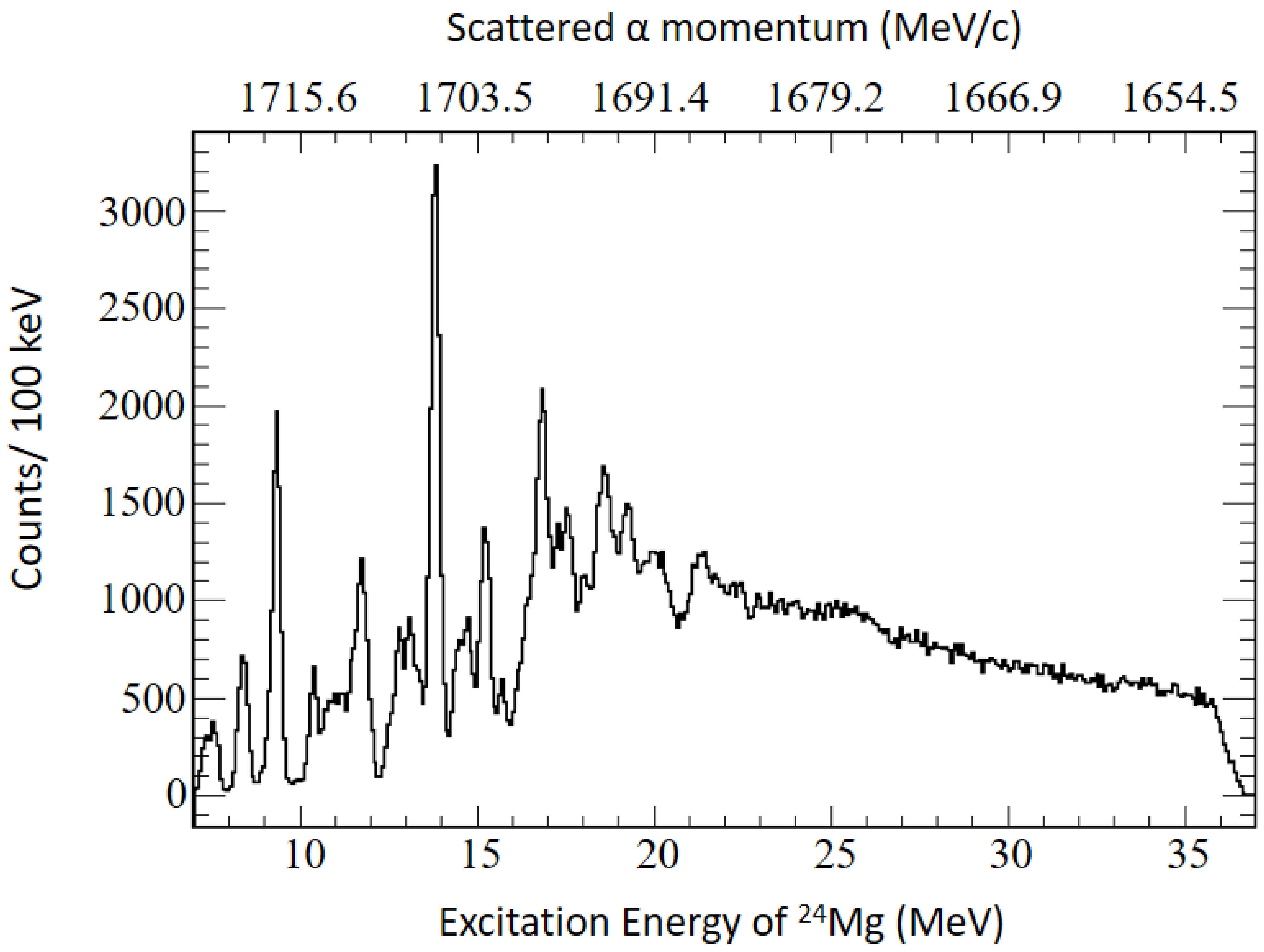
Double focusing mode of GR spectrometer



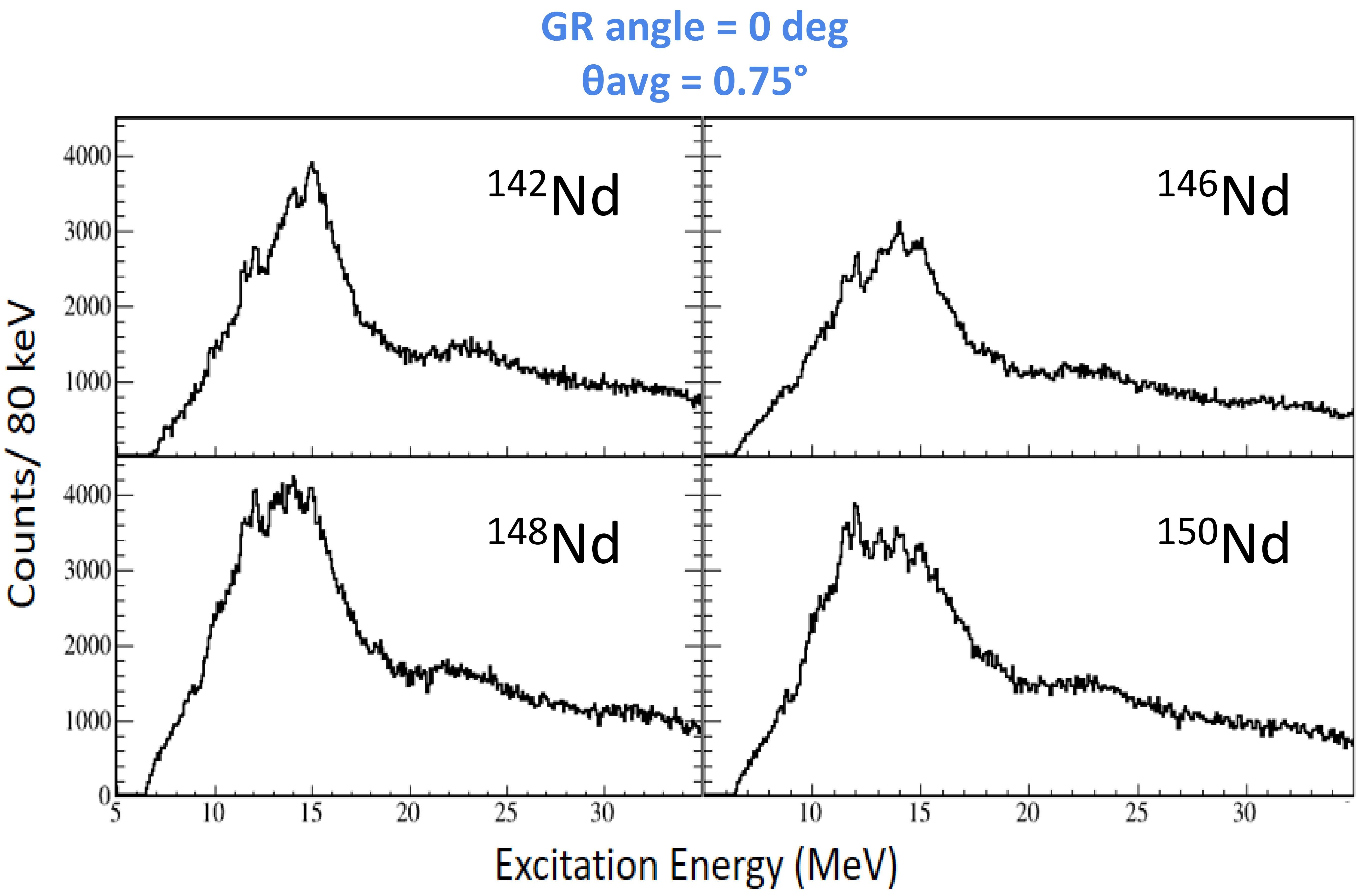


Pulse height from plastic scintillators mounted on the focal plane versus horizontal focal plane position obtained from MWDCs.

Calibration with ^{24}Mg (α,α')

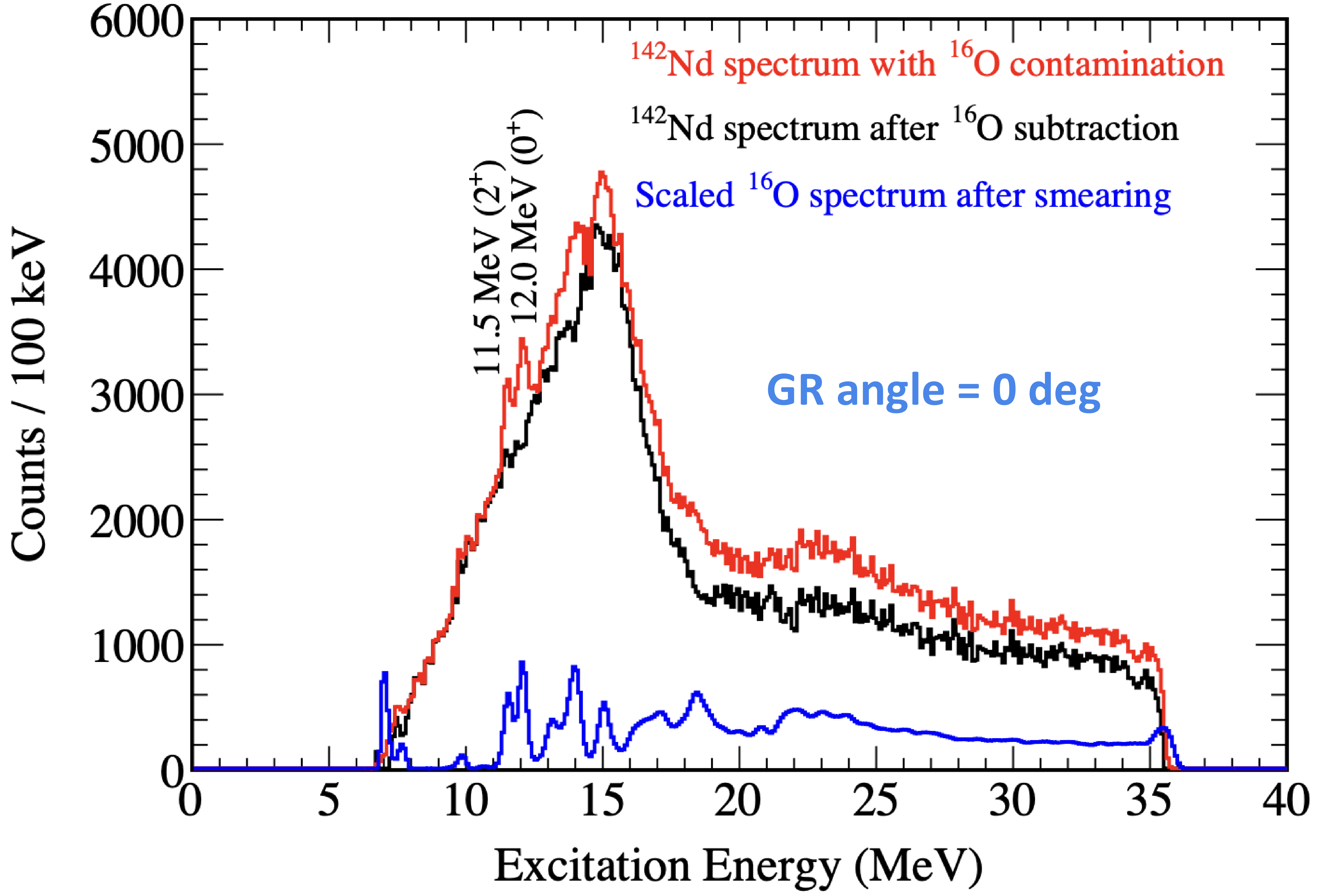


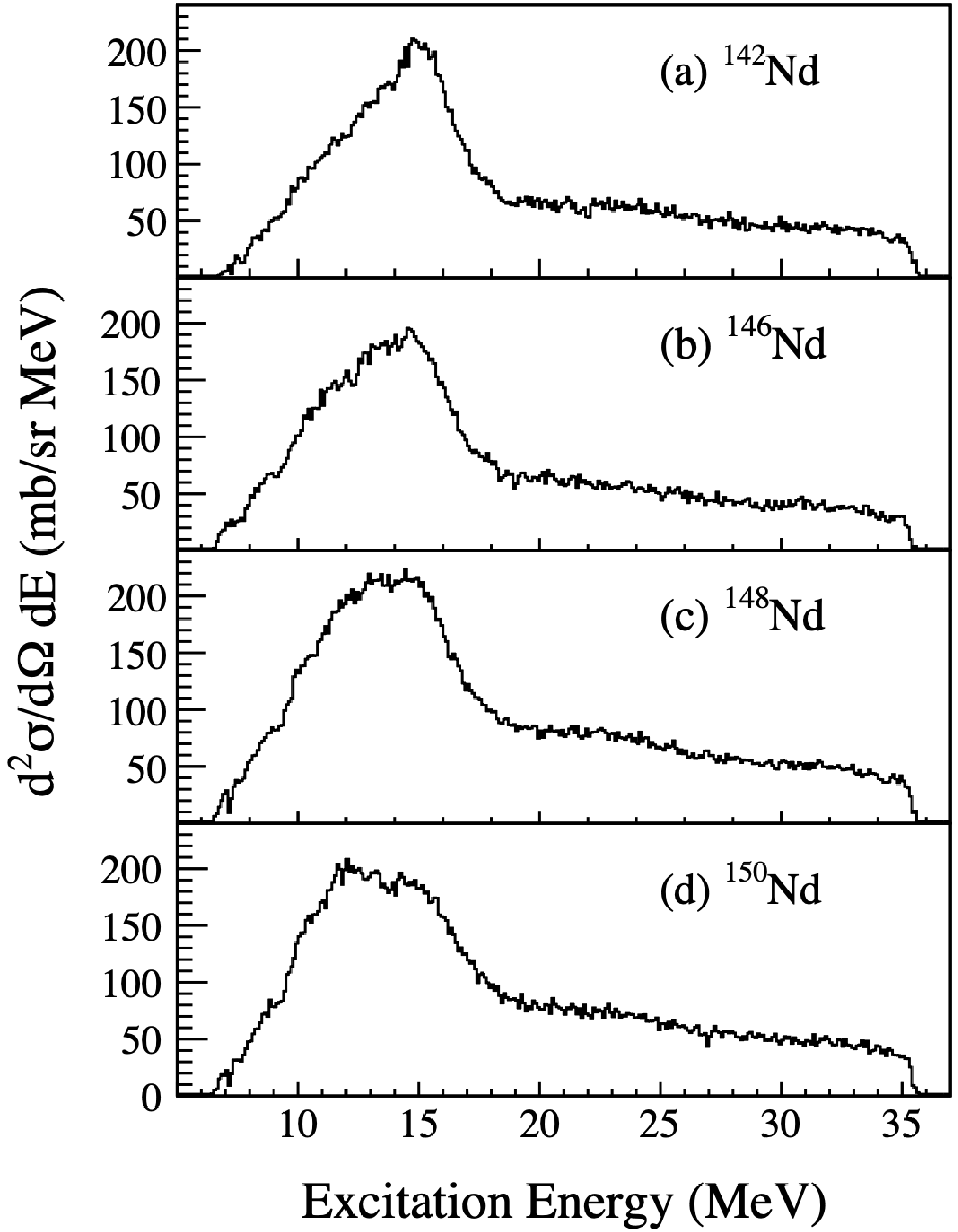
Calibration parameters were obtained using the kinematical relations between the incident particle, the target nucleus, and the scattered α particle.



Contamination in the excitation energy spectrum

- Contamination: H and O contamination

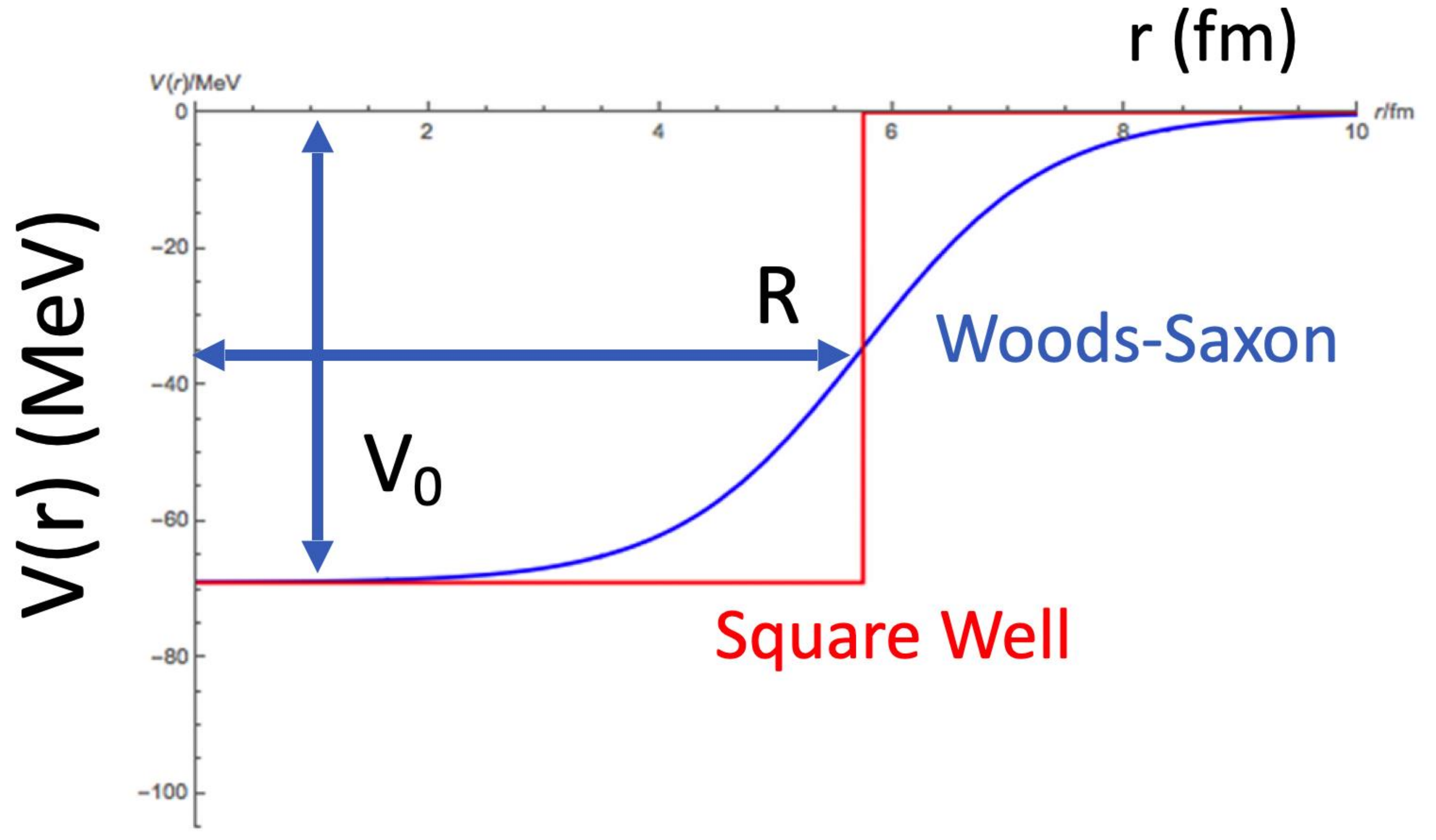




- Inelastic alpha scattering data off ^{16}O (SiO_2 target), (courtesy M. Itoh)
- Beam energy is the same

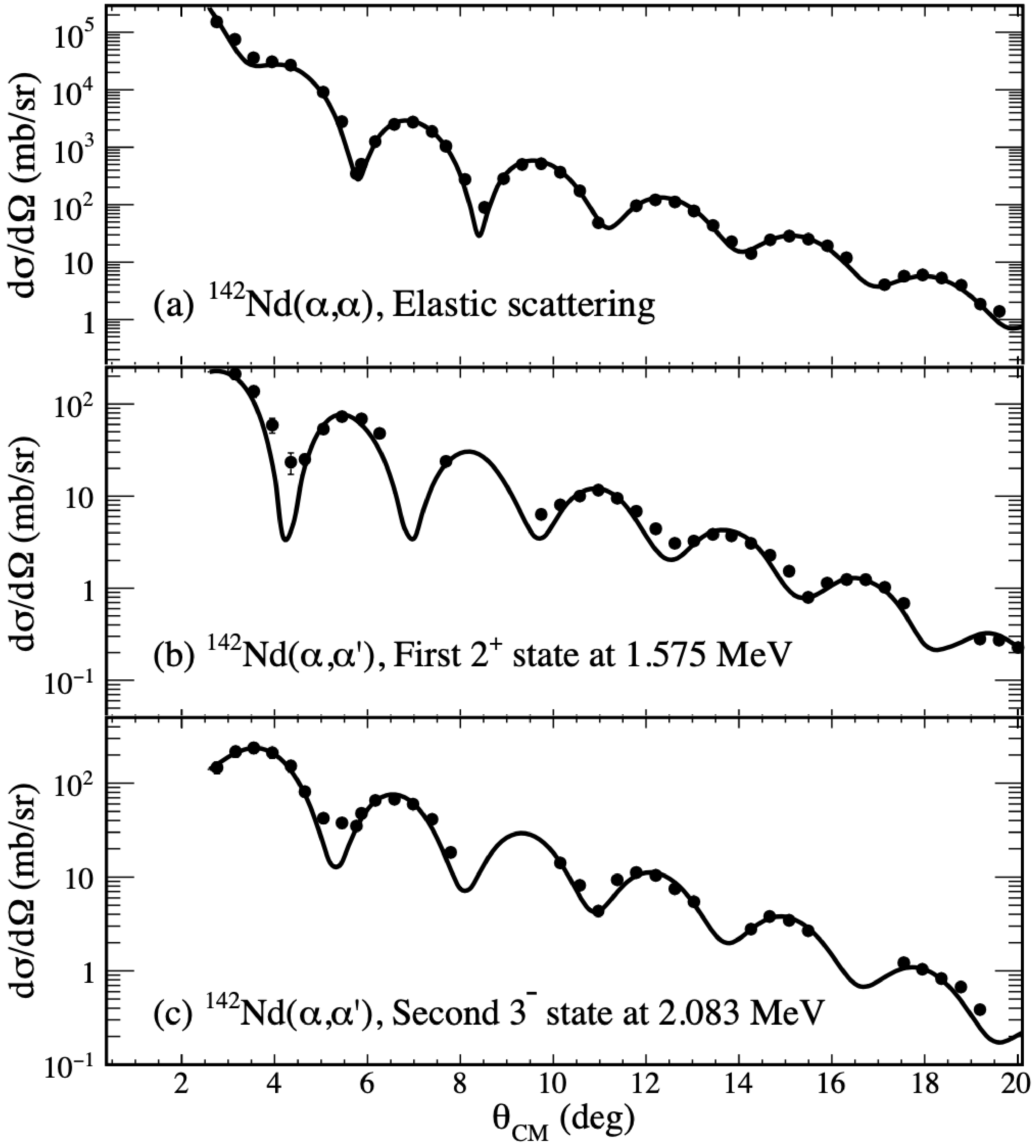
M. Abdullah, K. Khokhar, SB et al., Phys. Rev. C 112, 044316 (2025)

Determination of Optical Potential Parameters



$$V(r) = -\frac{V_0}{1+\exp(\frac{r-R}{a})}$$

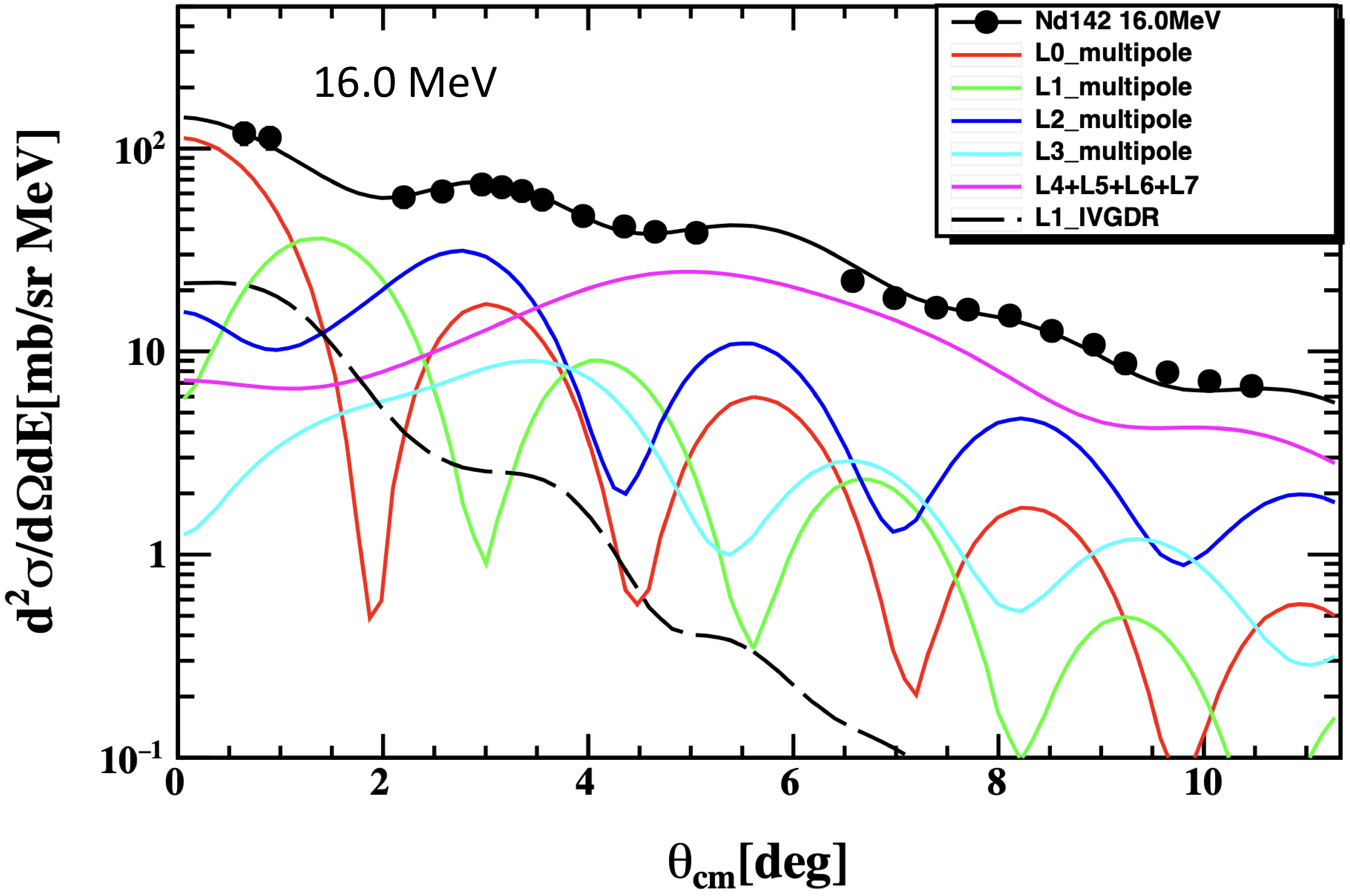
Total 6 parameters :
$\{V_R, R_R, a_R\}$ and $\{V_I, R_I, a_I\}$



M. Abdullah, K. Khokhar, SB et al., Phys. Rev. C 112, 044316 (2025)

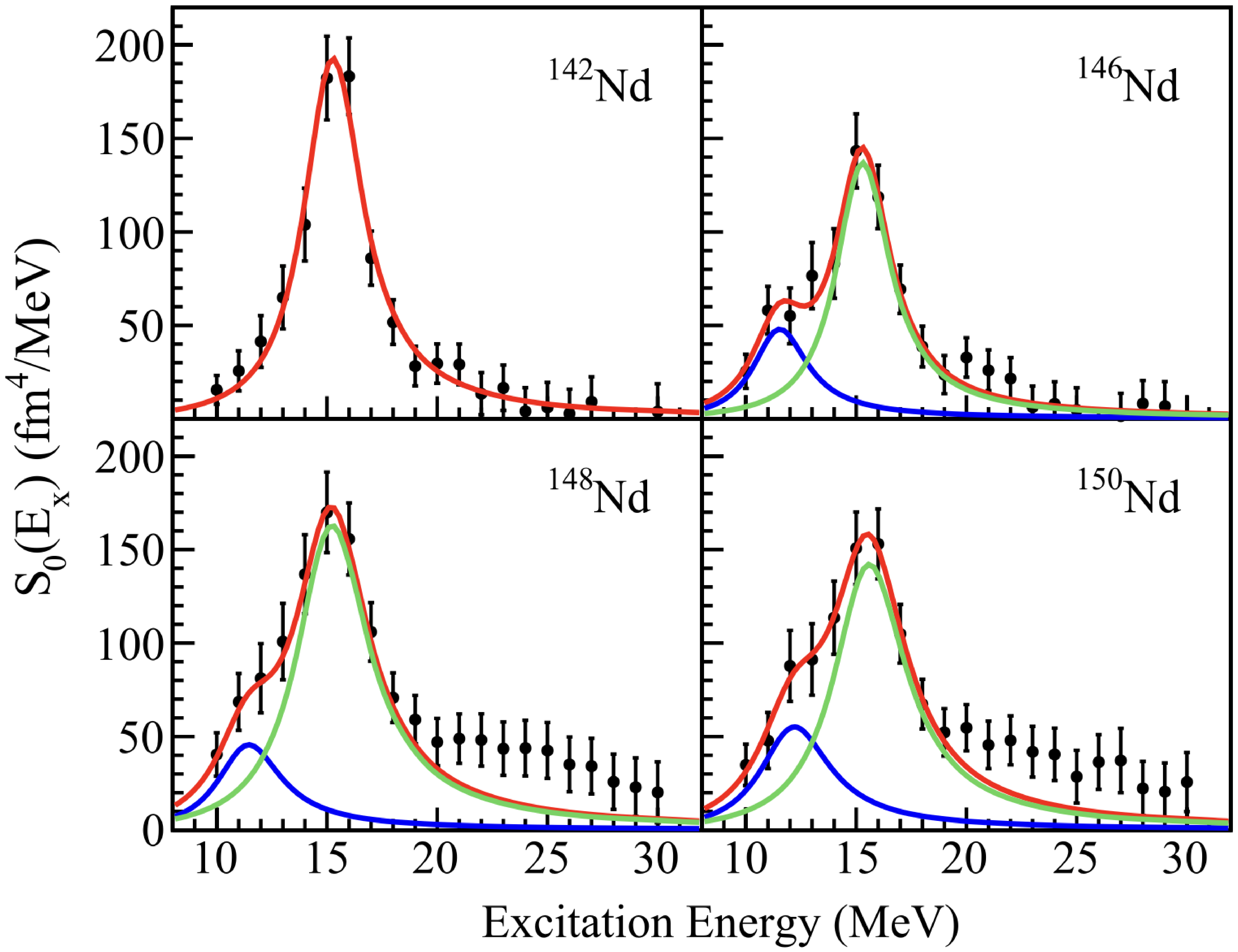
Extraction of strength of Isoscalar Resonances: Multipole Decomposition Analysis

$$\frac{d^2\sigma^{\exp}(\theta_{\mathrm{CM}}, E_{\mathrm{x}})}{d\Omega dE} = \sum_{L=0}^{7} A_L(E_{\mathrm{x}}) \frac{d^2\sigma_L^{\mathrm{DWBA}}(\theta_{\mathrm{CM}}, E_{\mathrm{x}})}{d\Omega dE}$$



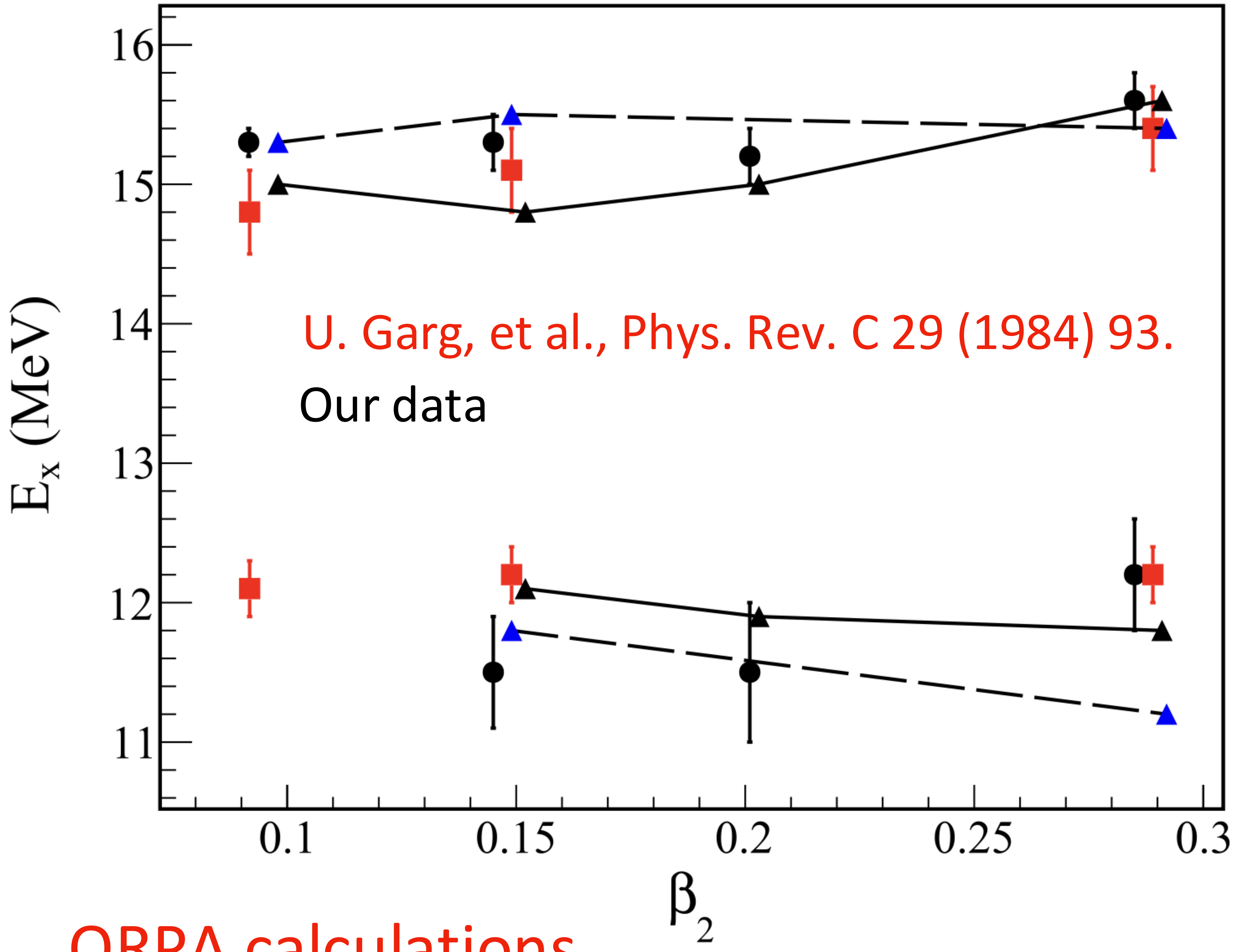
- Optical parameters used from the elastic scattering data
- Coupled channel code was used to calculate the theoretical angular distribution at a particular energy
- Energy bins used 1 MeV

Monopole Strength Distribution



M. Abdullah, SB et al., Phys. Lett. B 855, 138852 (2024)

$$S_0(E_x) = \frac{\hbar^2}{2m}\frac{Z^2}{A}\frac{<r^2>}{E_x}A_0(E_x)$$

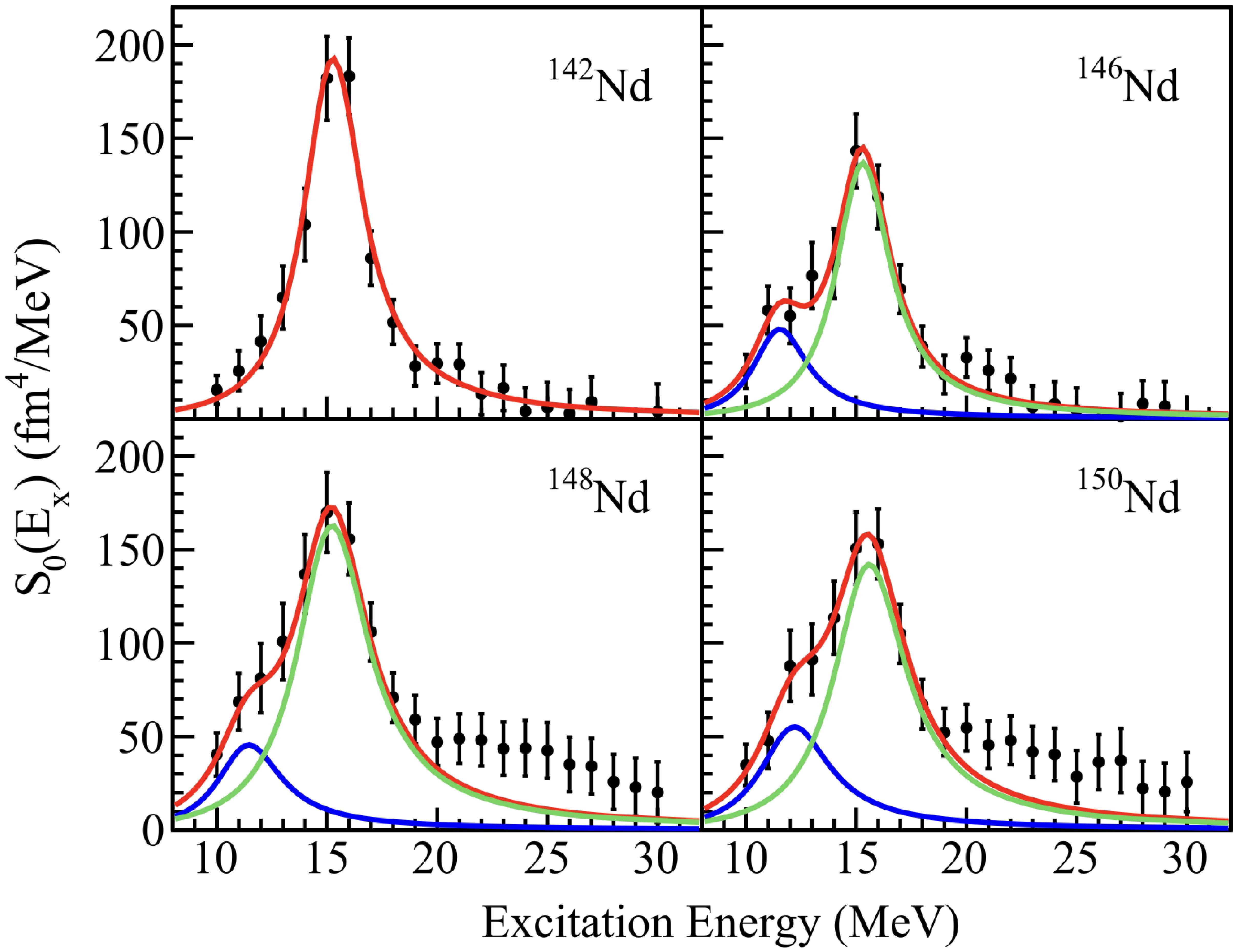


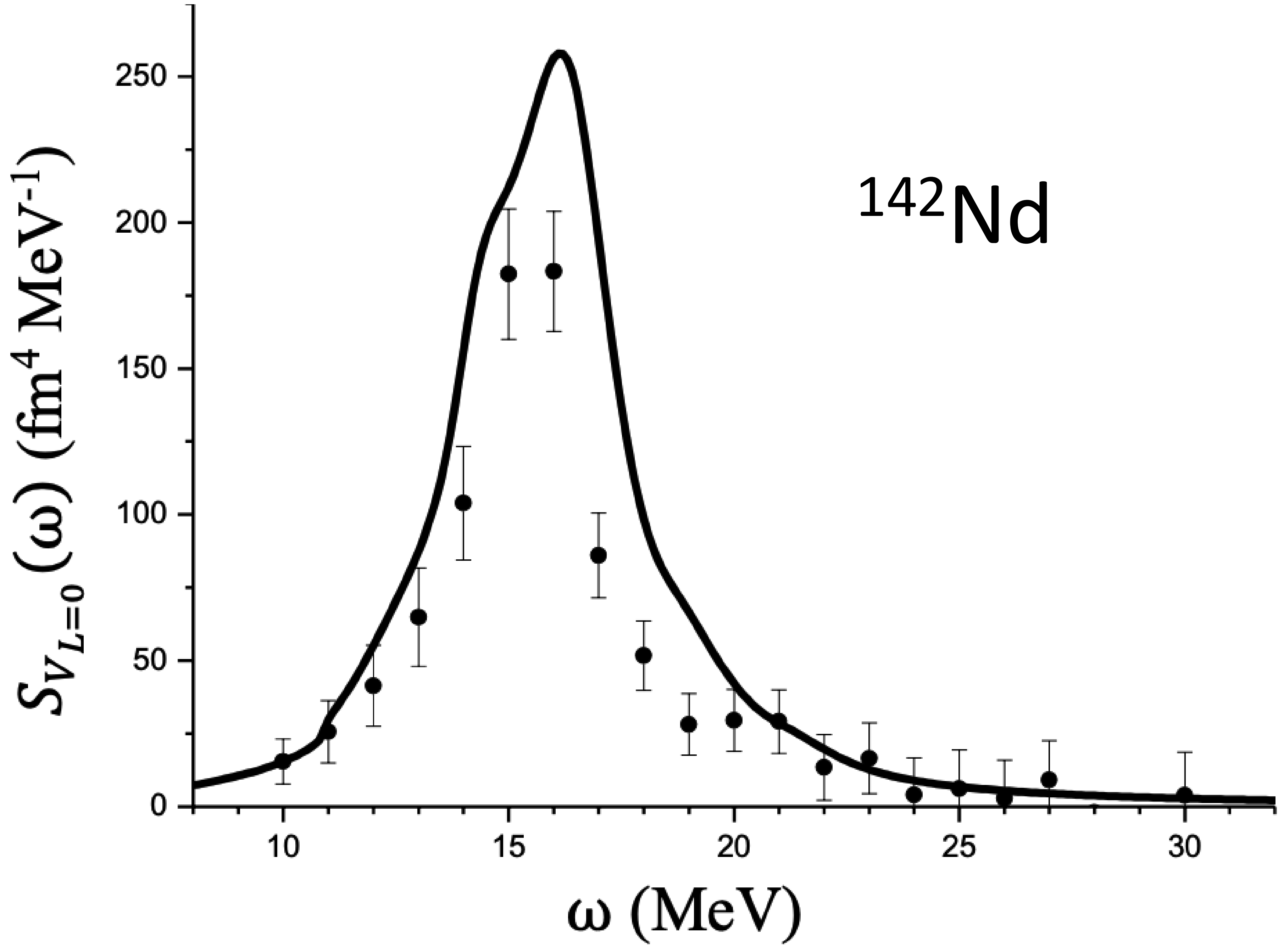
QRPA calculations

J. Kvasil, et al., Phys. Rev. C 94, 064302 (2016)

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

Monopole Strength Distribution





semi-microscopic Particle-Hole Dispersive Optical Model (PHDOM)

M. Abdullah, SB et al., Phys. Lett. B 855, 138852 (2024)

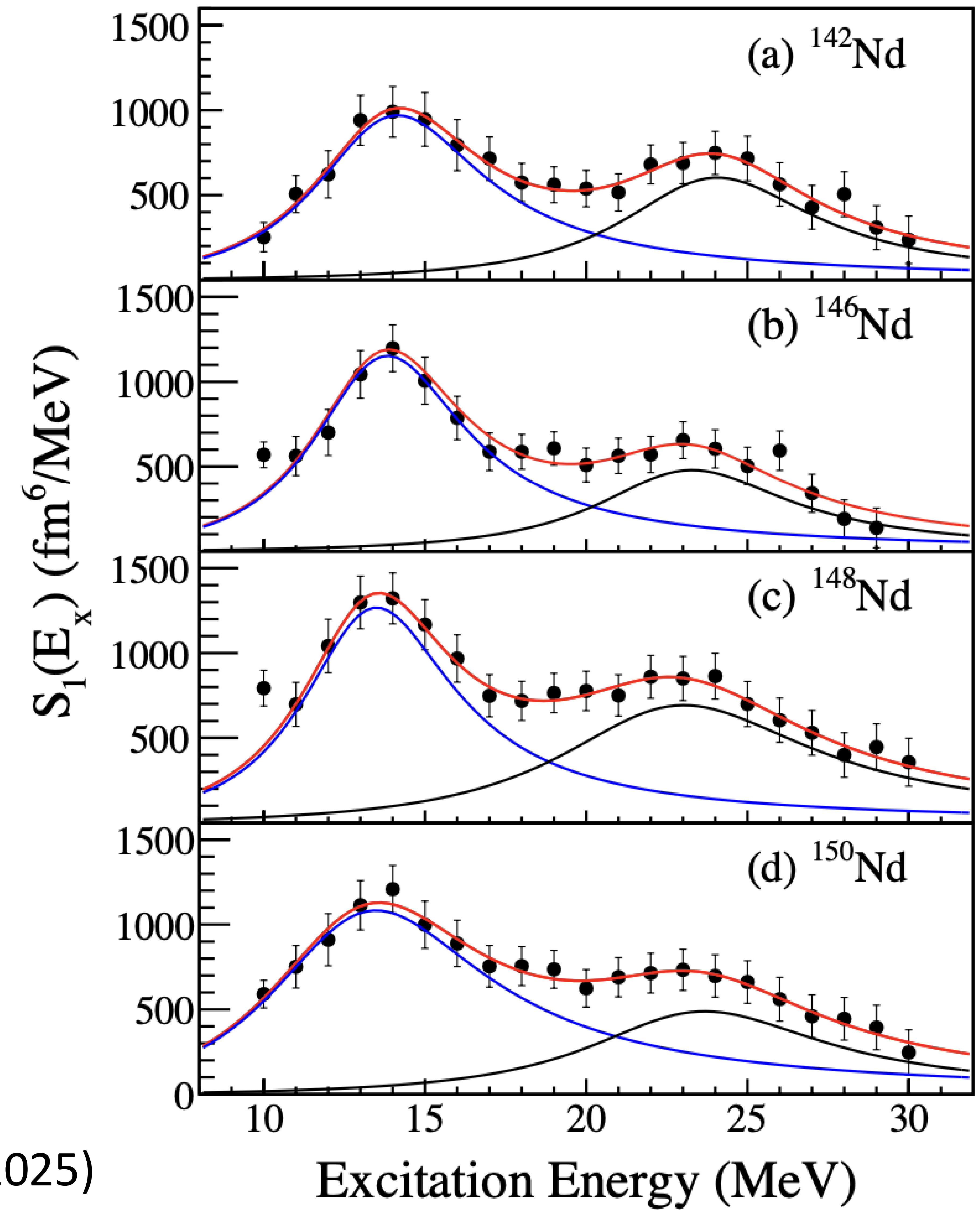
M. Abdullah, K. Khokhar, SB et al., Phys. Rev. C 112, 044316 (2025)

M.L. Gorelik, M.H. Urin, arXiv:2508.17046

Dipole Strength Distribution

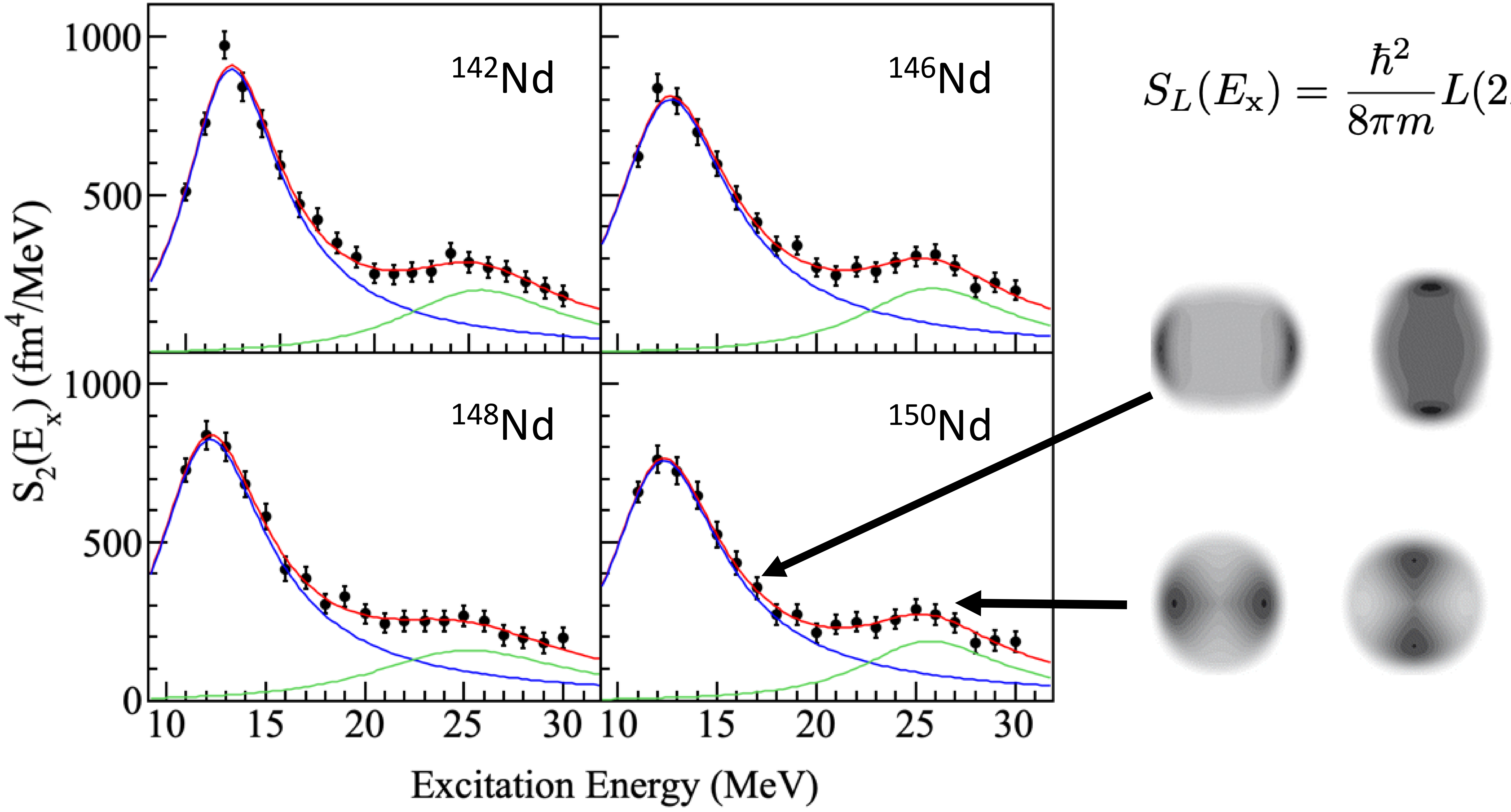
- The strength distribution displays a clear "bi-modal" behavior.
- The HE component, observed around the 3ħω excitation energy and it is related to the nuclear incompressibility.
- The LE component is related to the vortex or toroidal mode.

$$S_1(E_x) = \frac{\hbar^2}{8\pi m}\frac{3}{4}\frac{Z^2}{A}\left(\frac{11\langle r^4\rangle - \frac{25}{3}\langle r^2\rangle^2 - 10\epsilon\langle r^2\rangle}{E_x}\right) A_1(E_x)$$



M. Abdullah, K. Khokhar, SB et al., Phys. Rev. C 112, 044316 (2025)

Quadrupole Strength Distribution



$$S_L(E_\mathrm{x}) = \frac{\hbar^2}{8\pi m} L(2L+1)^2 \frac{Z^2}{A} \frac{< r^{2L-2} >}{E_\mathrm{x}} A_L(E_\mathrm{x})$$

2ħω ISGQR

$\sum_i r_i^2 Y_{2\mu}(\Omega_i)$

Maintone mode

ISGQR

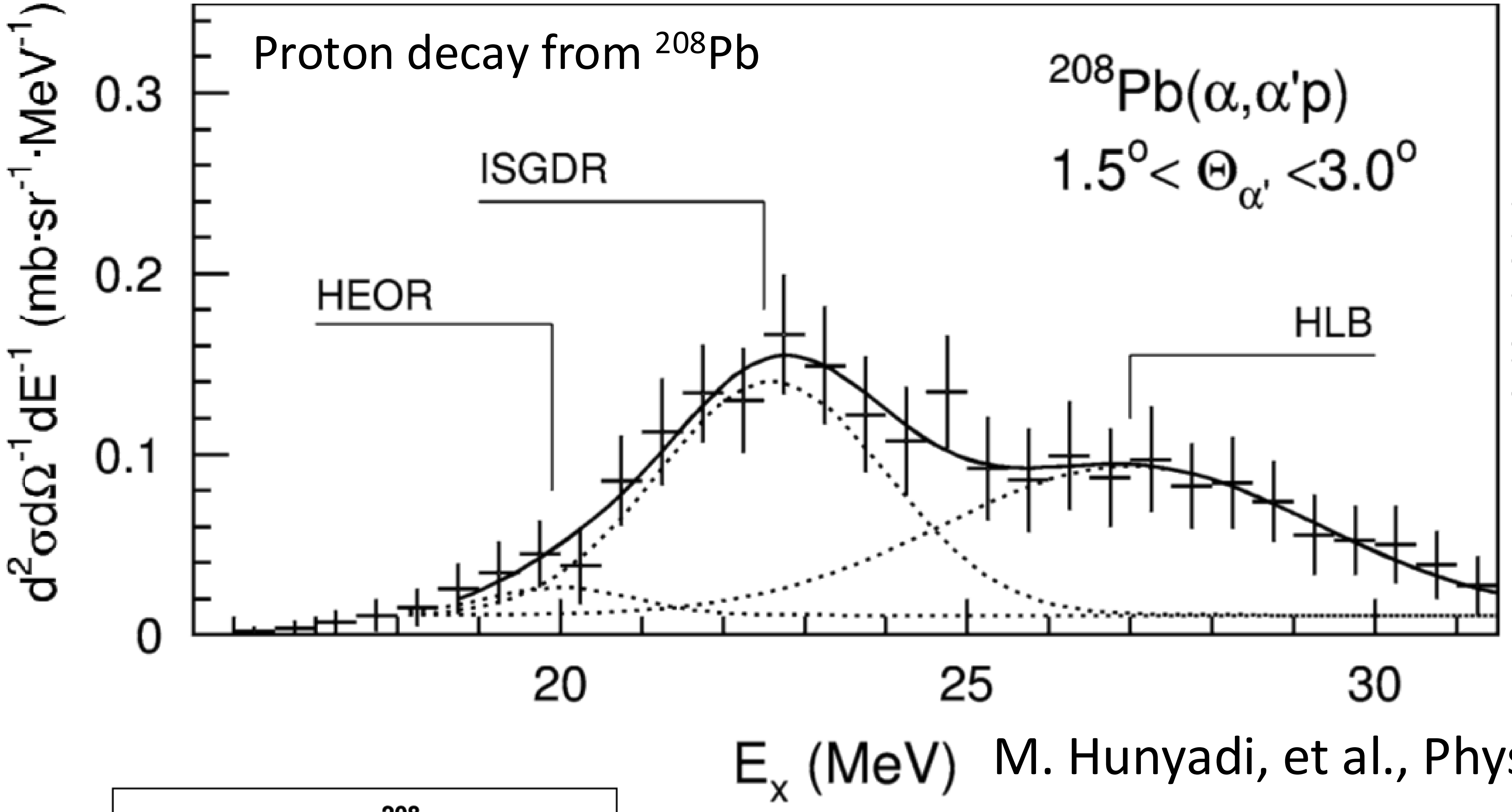
$\boxed{\text{4ħω ISGQR2} \quad \sum_i r_i^4 Y_{2\mu}(\Omega_i)}$

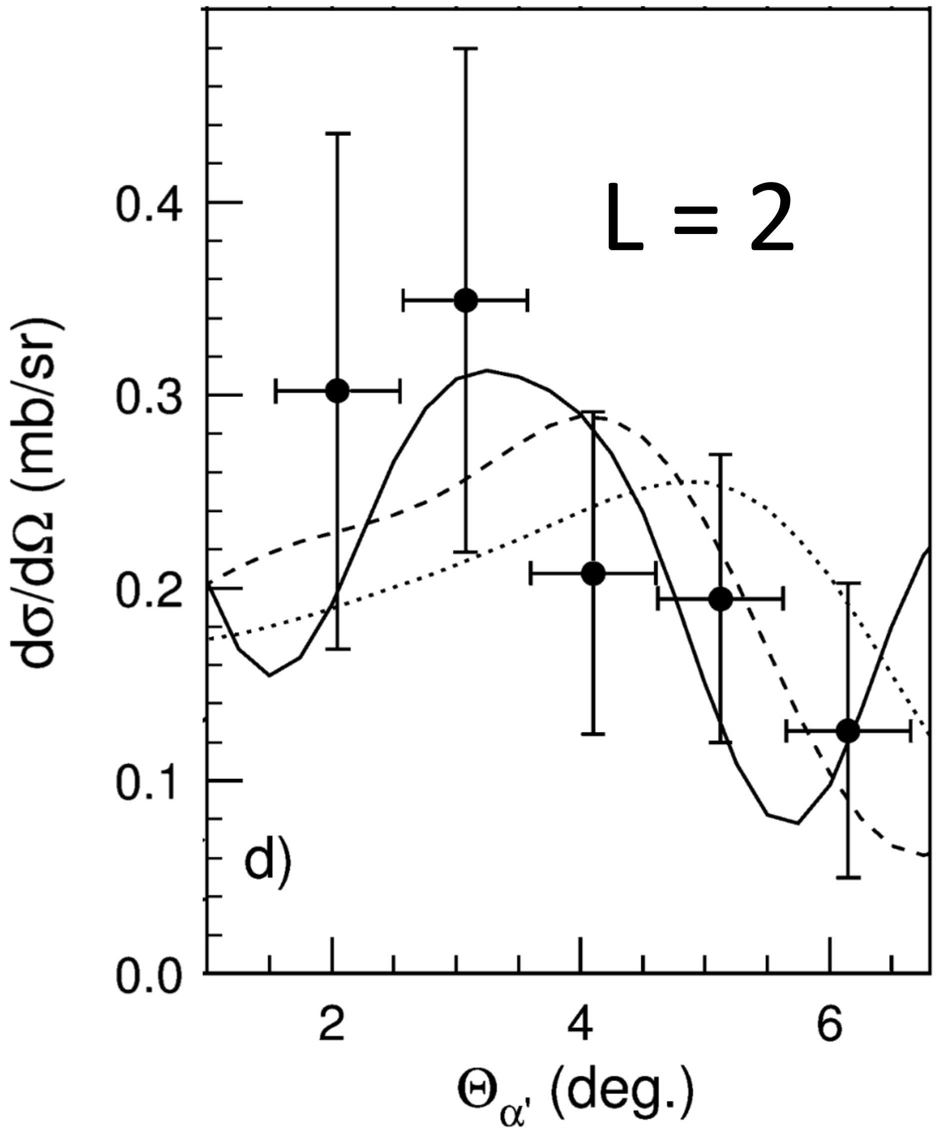
Overtone mode

ISGQR2

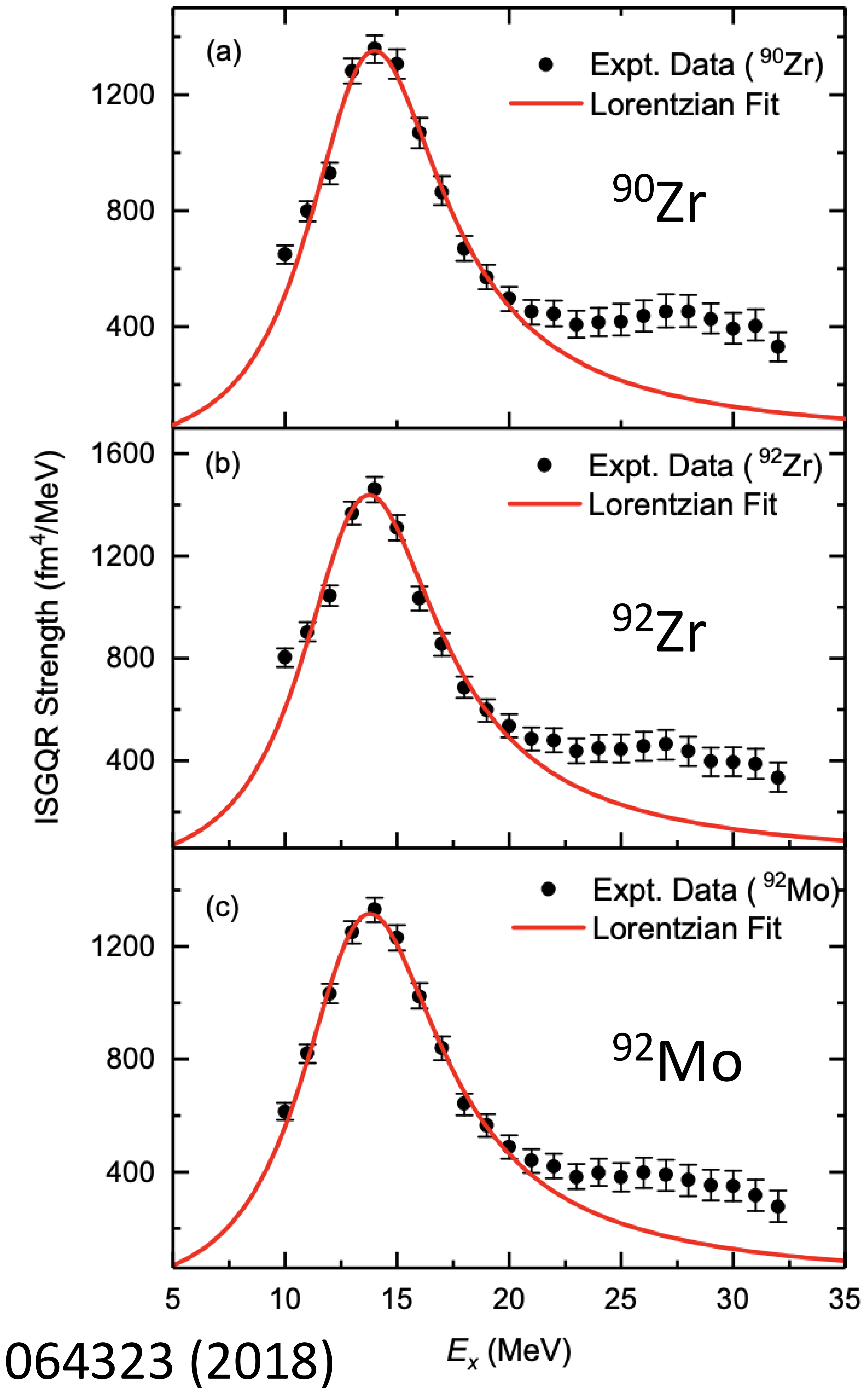
M. Abdullah, SB et al., Phys. Lett. B 855, 138852 (2024)

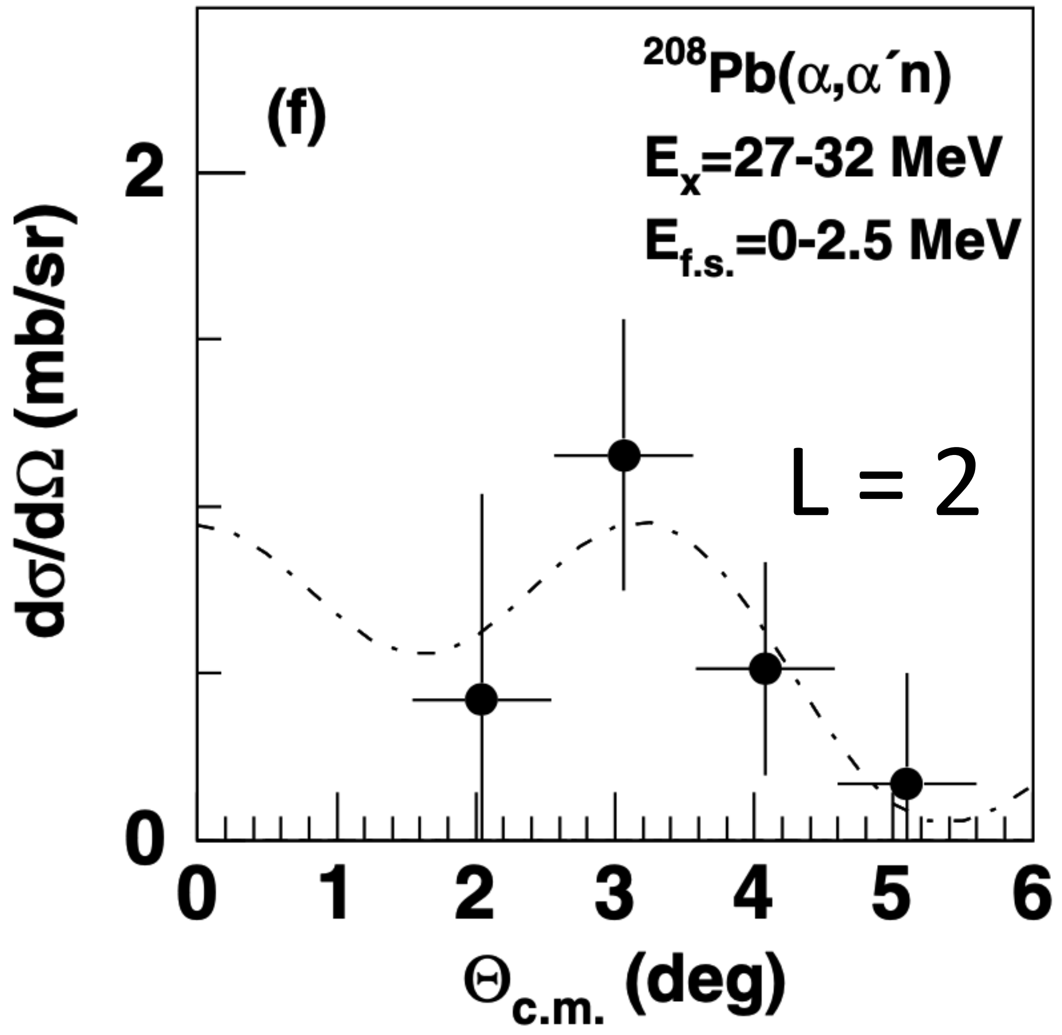
Quadrupole Strength Distribution: Signature of ISGQR2





M. Hunyadi, et al., Phys. Lett. B 576, 253 (2003)



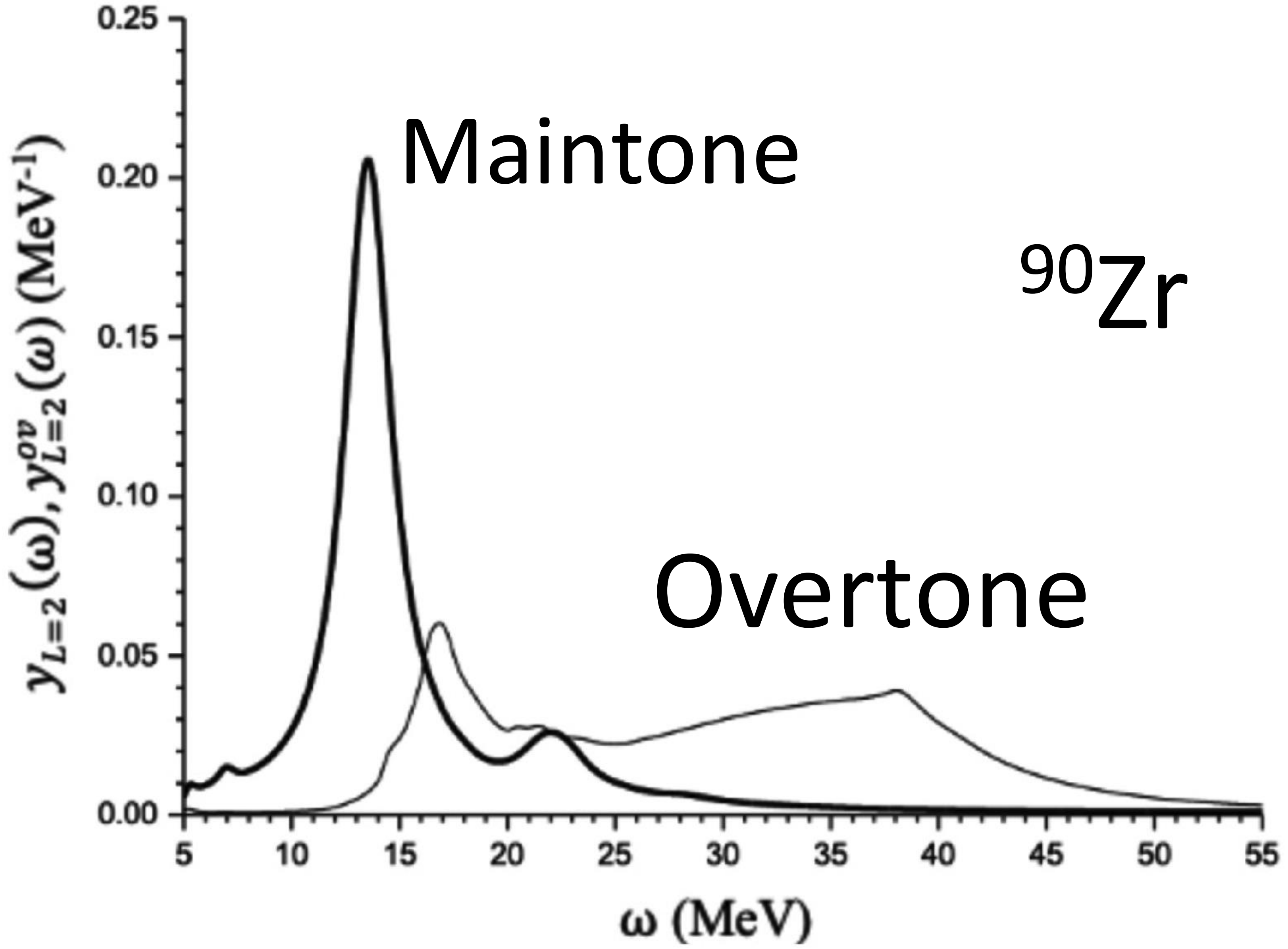


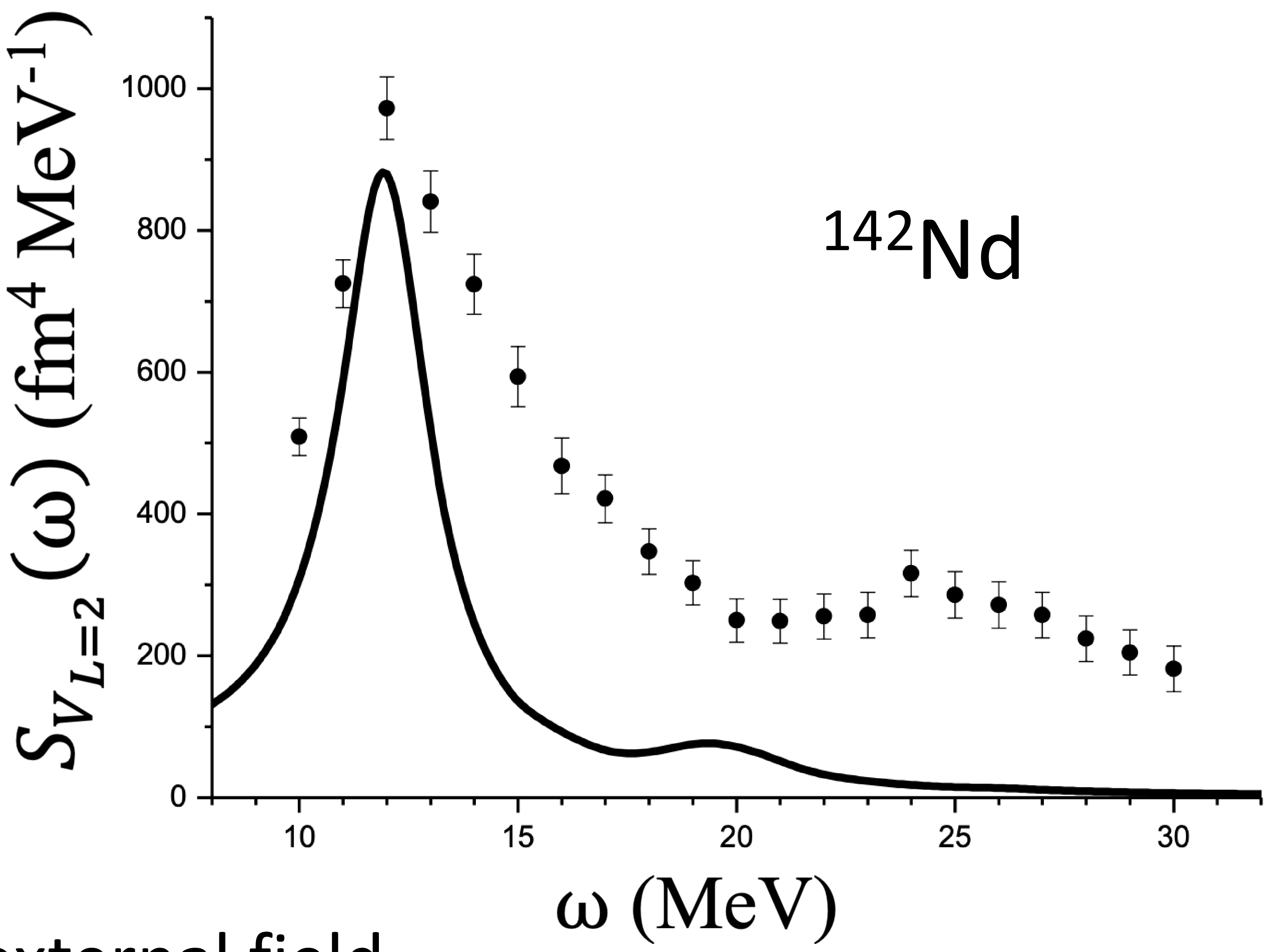
Neutron decay from ^{208}Pb

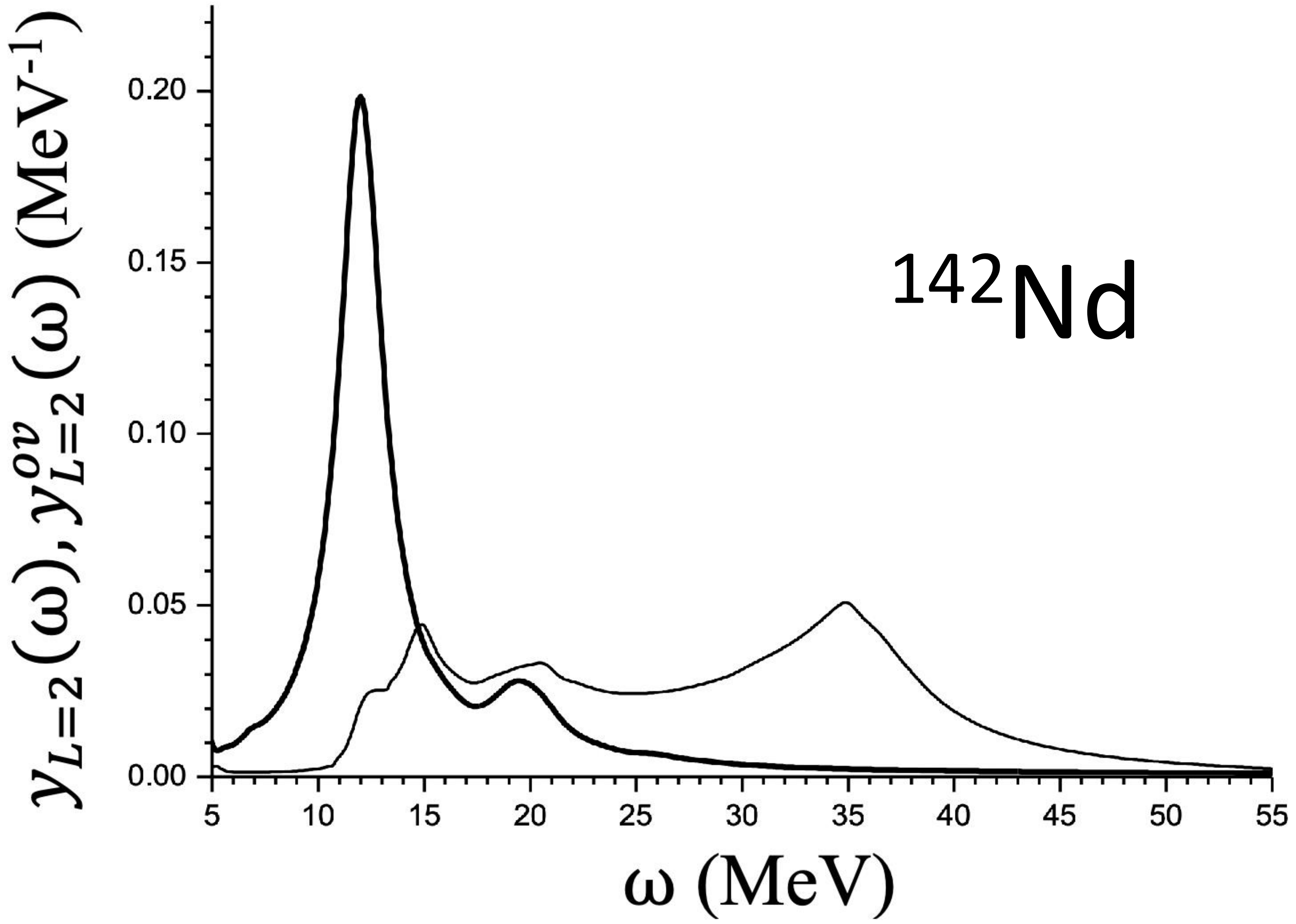
M. Hunyadi et al., Phys. Rev. C 75, 014606 (2007)

Y.K. Gupta, et al., Phys. Rev. C 97, 064323 (2018)

Overtones in Quadrupole Resonance (ISGQR2): PHDOM approach







Radial part of the external field

$$V_L^{\text{ov}}(r) = r^2(r^2 - \eta_L^{\text{ov}} \langle r^2 \rangle)$$

M.L. Gorelik et al., Phys. Rev. C 108, 014328 (2023)

M.L. Gorelik, M.H. Urin, arXiv:2508.17046

Summary

- Isoscalar Giant Resonances in Nd isotopes are shown.
- Effect of deformation on isoscalar resonances are illustrated.
- A novel compression mode in the ISGQR has been identified in Nd isotopes.
- PHDOM calculations are hint the overtone modes of quadrupole resonances but at higher energies.

Collaboration

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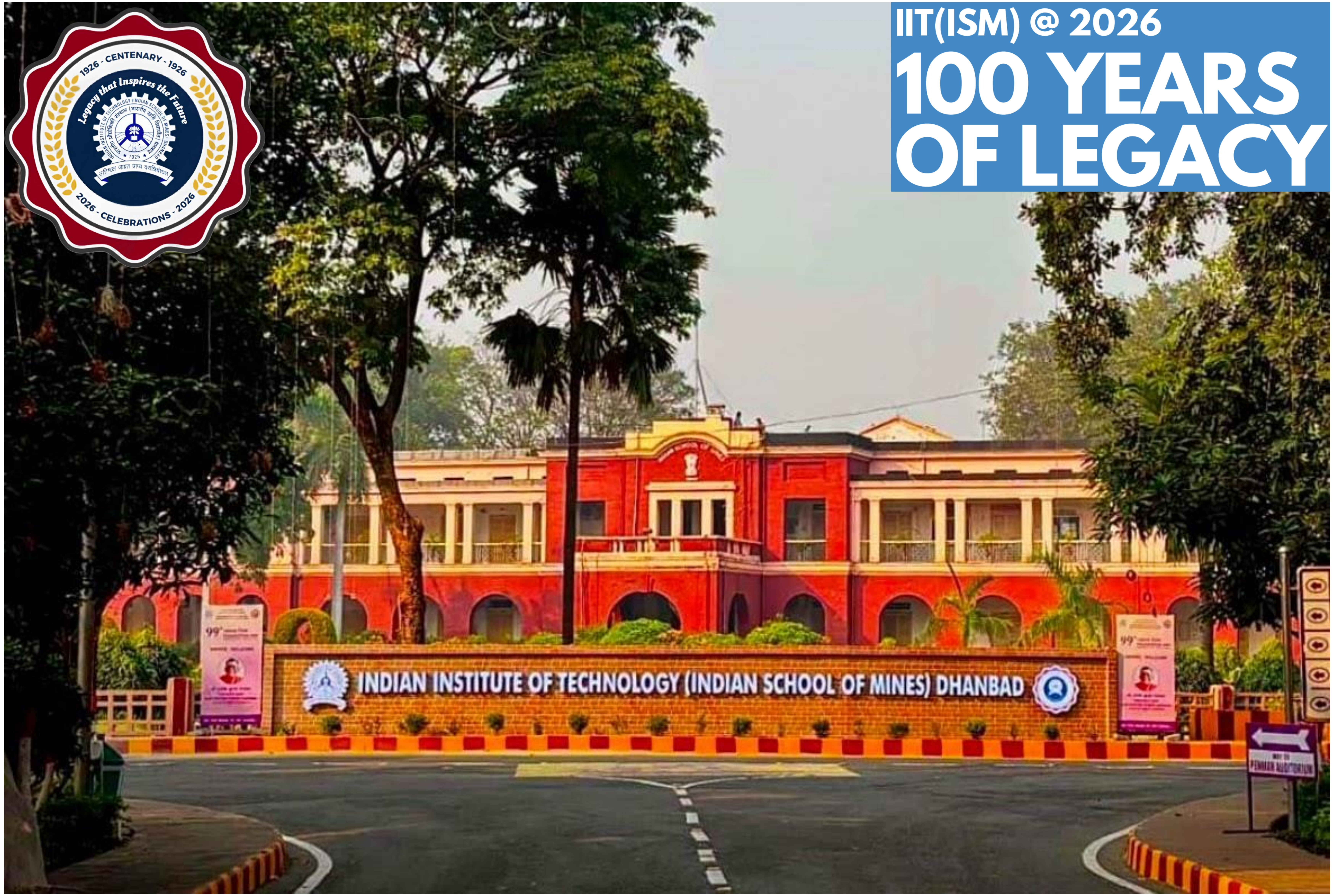

Thank you for your kind attention