A survey of the isoscalar giant monopole resonance from medium to heavy mass nuclei at iThemba LABS

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Outline

Introduction

- Giant resonances (GRs) are defined as collective, small amplitude excitation modes which occur at excitation energy of 10 MeV and above in nuclei across the periodic table. They are characterised by the three quantum numbers L, S and T.

- Inelastic α-particles scattering at energies of a few hundred MeV and very-forward scattering angles including 0° has been established as a best tool for the study of the isoscalar giant monopole strength distributions in nuclei across the periodic table.

- The present study describes a systematic investigation of the isoscalar giant monopole resonance in ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb.

Motivations

- The study of the ISGMR is important since knowledge of its excitation energy provides information relevant to the nuclear matter incompressibility coefficient which is crucial in the study of supernova collapse, neutron stars, etc.
- High energy-resolution light-ion inelastic scattering experiments at iThemba LABS (South Africa) revealed that giant resonances (ISGQR & IVGDR) carry fine structure. It is then of interest to know the mechanism leading to the fine structure in the case of the ISGMR in medium to heavy mass nuclei across the periodic table.
- Recent experiments show unexpected discrepancies between the results obtained by the Research Center for Nuclear Physics (RCNP), Osaka University, and the Texas A&M University Cyclotron Institute (TAMU) $\Rightarrow$ an independent survey becomes crucial.

Available GMR data from various experiments

Target	0° data	4° data
^{24}Mg*	Y	Y
^{28}Si*	Y	Y
^{40}Ca†	Y	Y
^{42}Ca†	Y	Y
^{44}Ca†	Y	Y
^{48}Ca†	Y	Y
^{58}Ni	Y	Y
^{90}Zr	Y	Y
^{120}Sn	Y	Y
^{208}Pb	Y	Y

*A. Bahini *et al*, Phys. Rev. C **105**, 024311 (2022)
†S. D. Olorunfunmi *et al*, Phys. Rev. C **105**, 054319 (2022)

Experimental setup

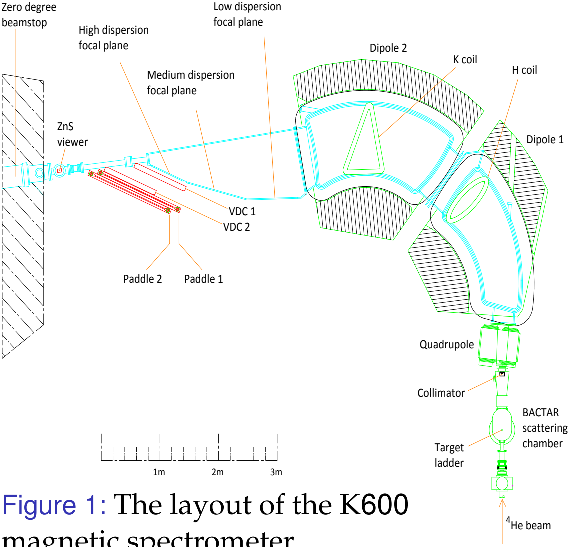
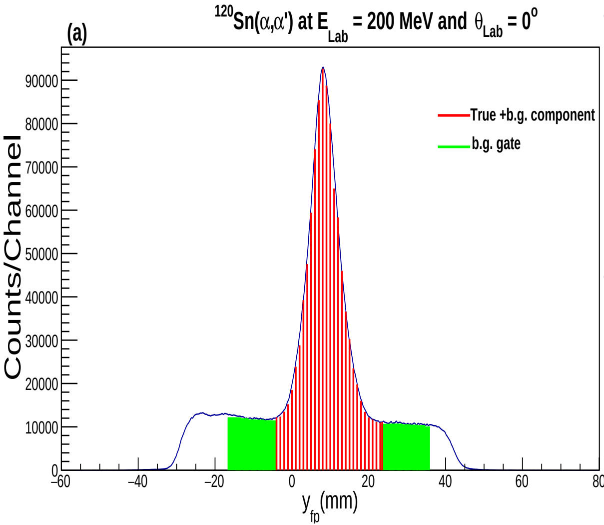


Figure 1: The layout of the K600 magnetic spectrometer.

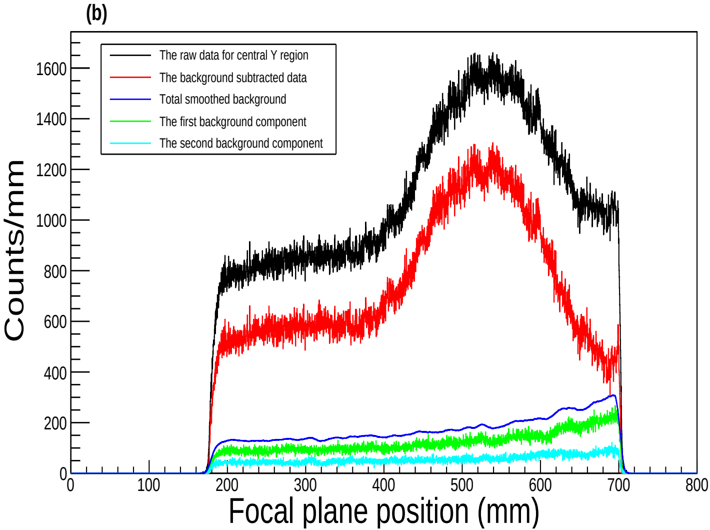
- (α, α') scattering using the K600 magnetic spectrometer positioned at zero and four degrees (angular acceptance of $\pm$ 1.91°).
- 200 MeV α-particles beam interacts with ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb targets with areal densities ranging from 0.9 to 1.43 mg/cm^2.
- "background-free" and high energy-resolution.

Background subtraction

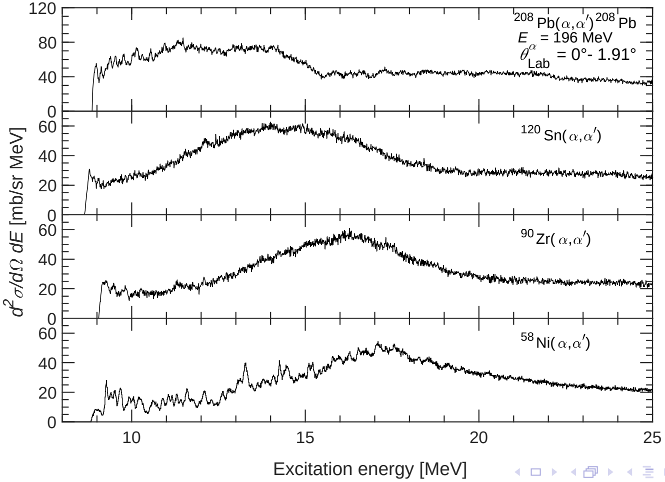


- The spectrometer was operated in vertical focus mode for 0° experiments in order to enable effective background subtraction.
- The events of interest are focused around y_{fp} = 5 mm while both background contributions are equally distributed.

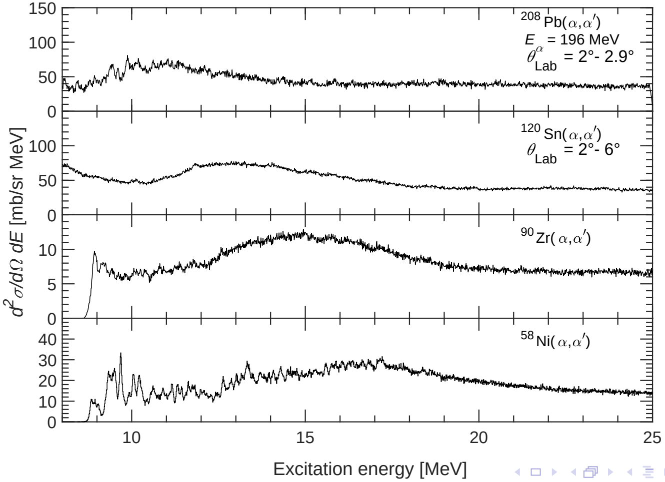
Background subtraction (Cont'd)



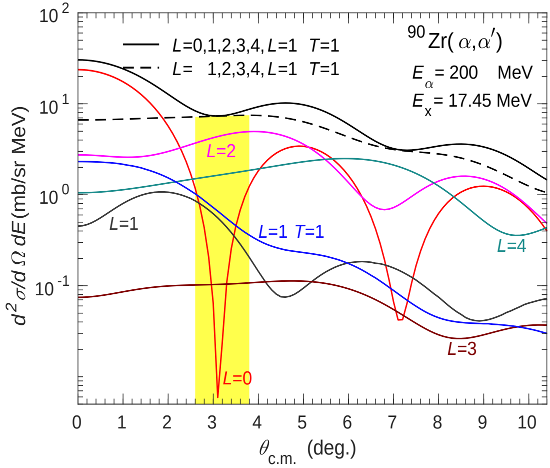
Double-differential cross sections



Double-differential cross sections

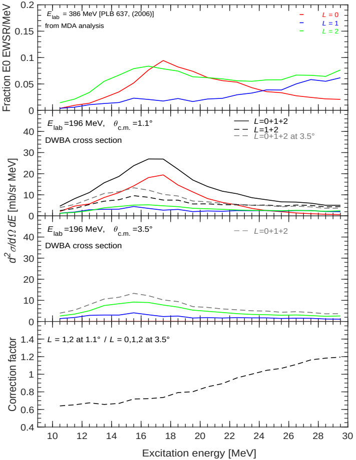


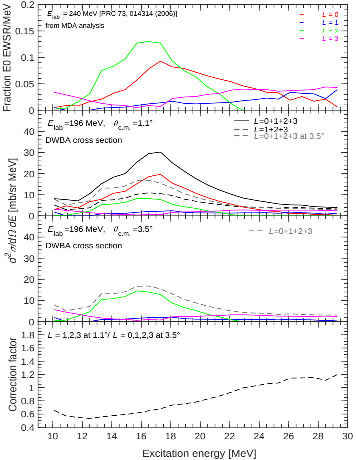
DWBA calculations for the application of the Difference-of-Spectra (DoS) technique.



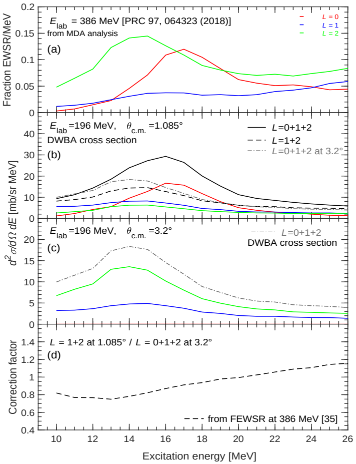
- The method consists of subtracting a spectrum obtained from an angle cut of the 4° data where the angular distributions for the other multipolarities except $L = 0$ are nearly flat, and that of GMR is at a minimum, from the spectrum obtained with data taken at 0°.

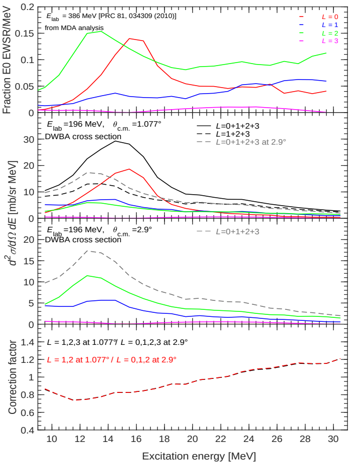
Excitation-energy-dependent correction factor for the finite-angle cross sections (^{58}Ni: a_L TAMU vs RCNP)



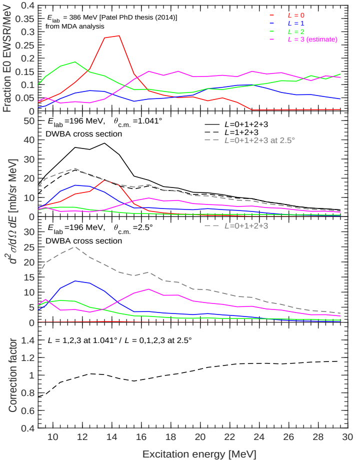


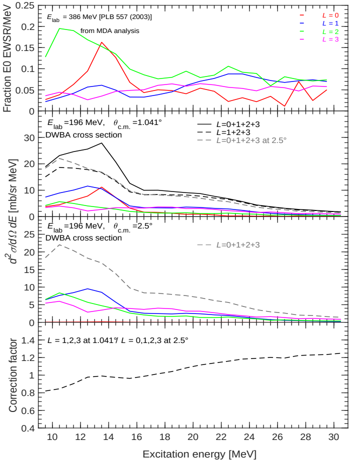
Excitation-energy-dependent correction factor for the finite-angle cross sections (^{90}Zr & ^{120}Sn: a_L RCNP)



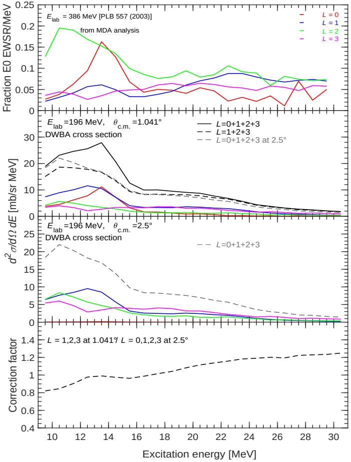


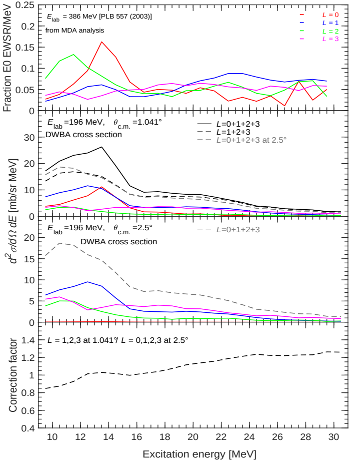
Excitation-energy-dependent correction factor for the finite-angle cross sections (^{208}Pb: a_L RCNP vs RCNP)



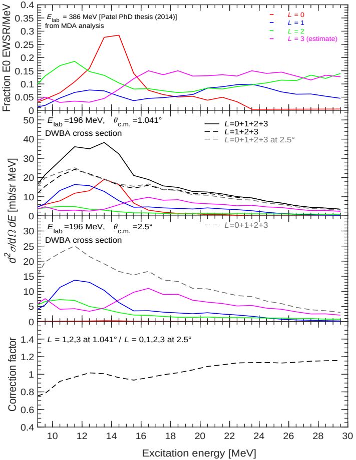


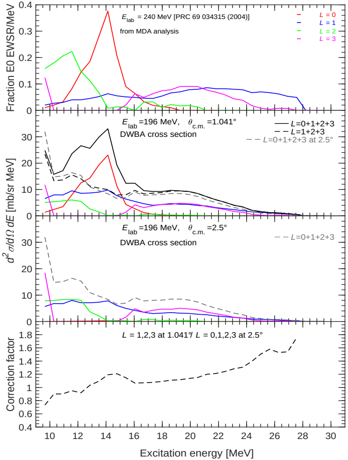
Excitation-energy-dependent correction factor for the finite-angle cross sections (^{208}Pb: a_L RCNP vs RCNP)



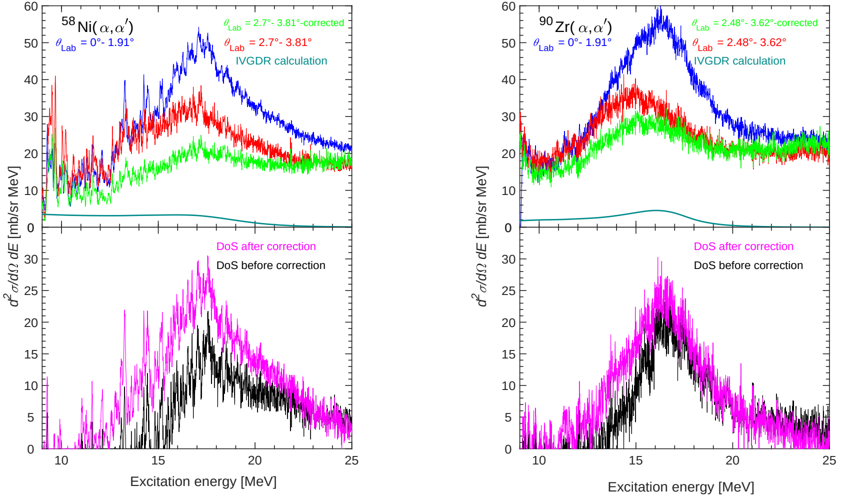


Excitation-energy-dependent correction factor for finite-angle cross-sections (^{208}Pb: RCNP vs TAMU)

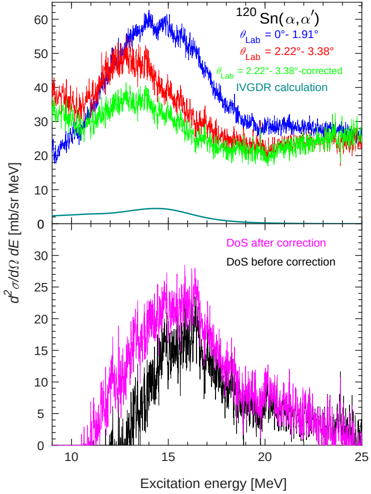


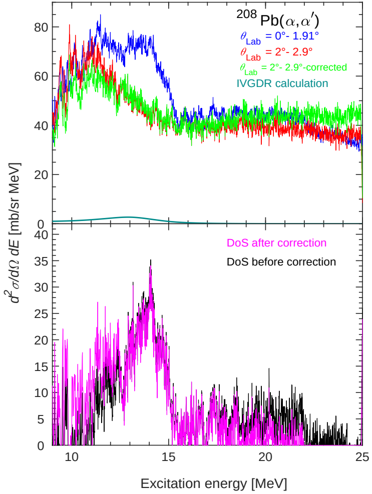


Difference-of-Spectra (DoS) results: ^{58}Ni & ^{90}Zr



Difference-of-Spectra (DoS) results: ^{120}Sn & ^{208}Pb





IS0 strength distributions determination

- The measured cross sections can be converted to fractions (a_0) of the EWSR(IS0)=$2\hbar^2/m \cdot A\langle r^2\rangle$ by comparing with DWBA calculations assuming 100% EWSR

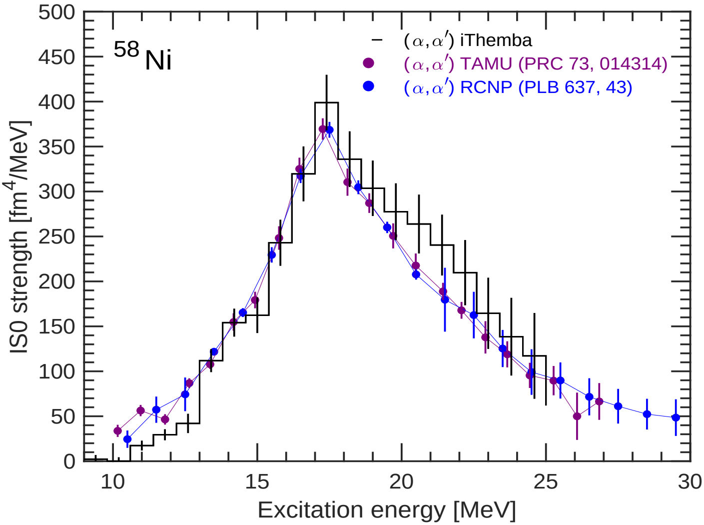
$$\frac{d^2\sigma^{\text{exp}}}{d\Omega dE}(\theta_{\text{c.m.}}, E_{\text{x}}) = \sum_{L=0}^{n} a_L(E_{\text{x}}) \times \frac{d^2\sigma_L^{\text{DWBA}}}{d\Omega dE}(\theta_{\text{c.m.}}, E_{\text{x}}) .$$

The coefficients $a_L(E_{\text{x}})$ represent the fractional EWSR contribution.

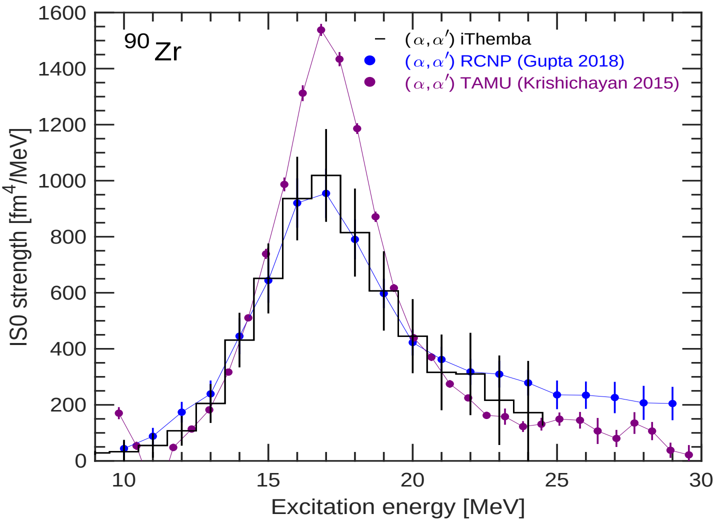
- The IS0 strength is then calculated using the a_0 values and is expressed as

$$S_0(E_{\text{x}}) = \frac{\text{EWSR(IS0)}}{E_{\text{x}}} a_0(E_{\text{x}}) = \frac{2\hbar^2 A\langle r^2\rangle}{mE_{\text{x}}} a_0(E_{\text{x}}) ,$$

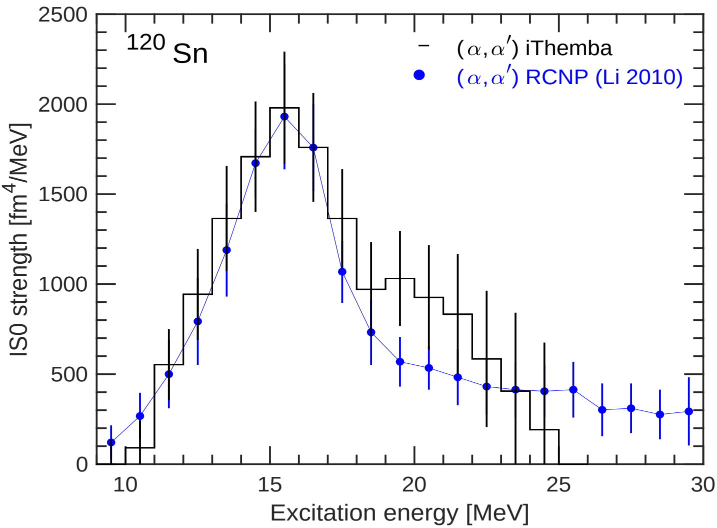
IS0 strength distributions results: ^{58}Ni



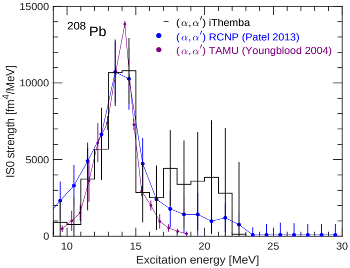
IS0 strength distributions results: ^{90}Zr

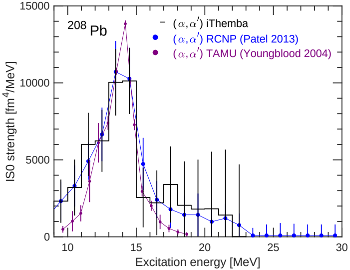


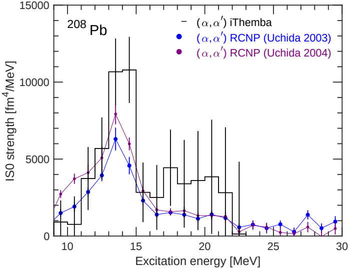
IS0 strength distributions results: ^{120}Sn

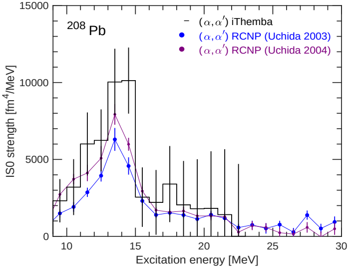


IS0 strength distributions results: ^{208}Pb

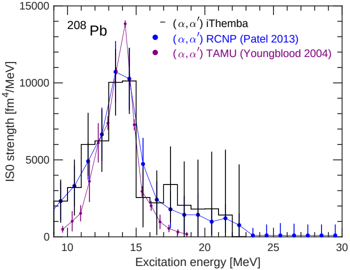


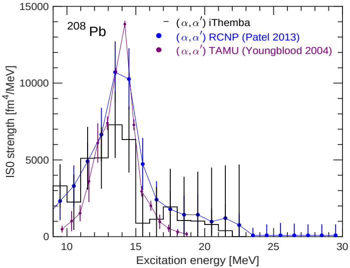


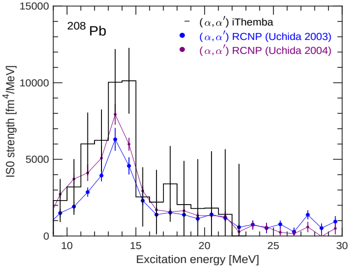


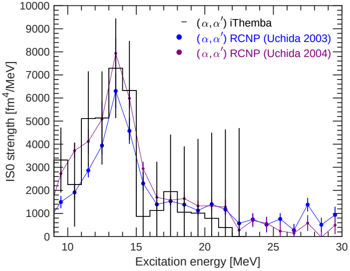


IS0 strength distributions results: ^{208}Pb (cont'd)









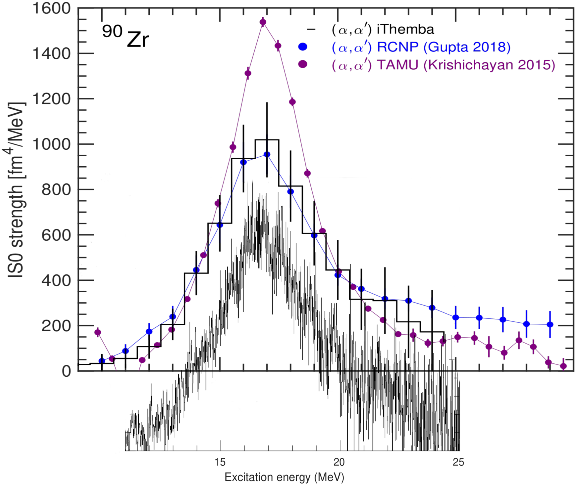
The centroid energy and width of ISGMR

Nucleus	Centroid (MeV)	Width (MeV)	EWSR (%)	References
^{208}Pb	13.60 ± 0.20	2.85 ± 0.20	119 ± 14‡	Present work
	13.70 ± 0.10	3.30 ± 0.20	149 ± 18	RCNP, Phys. Lett. B **726**, 178 (2013)
	13.96 ± 0.20	2.88 ± 0.20	99 ± 15	TAMU, Phys. Rev. C **69**, 034315 (2004)
^{120}Sn	15.70 ± 0.40	5.00 ± 0.40	111 ± 11§	Present work
	15.40 ± 0.20	4.90 ± 0.50	108 ± 7	RCNP, Phys. Rev. C **81**, 034309 (2010)
^{90}Zr	16.90 ± 0.20	4.05 ± 0.20	86 ± 7	Present work
	16.76 ± 0.12	4.96 ± 0.32	74.7 ± 9	RCNP, Phys. Rev. C **97**, 064323 (2018)
	17.10	4.4	106 ± 12	TAMU, Phys. Rev. C **92**, 044323 (2015)
^{58}Ni	17.80 ± 0.50	4.00 ± 0.60	65 ± 17	Present work
	19.90 ± 0.70	—	92 ± 4	RCNP, Phys. Lett. B **637**, 43 (2006)
	18.14 ± 0.14	7.40 ± 0.13	85 ± 13	TAMU, Phys. Rev. C **73**, 014314 (2006)

‡For the excitation-energy region 9 to 17 MeV.

§For the excitation-energy region 9 to 25 MeV. No access to higher Ex values.

Difference-of-Spectra (DoS) results: Significant fine structure is clearly observed in the ISGMR region.



Fine structure analysis: ^{90}Zr as an example!!!

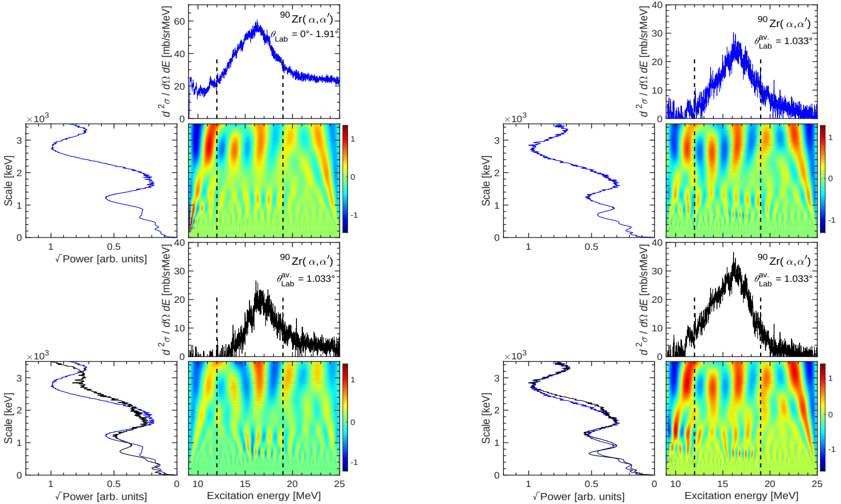
- Characteristic wavelet length-like energy scales from measured excitation energy spectra were extracted using wavelet analysis.

- The difference spectrum obtained via the subtraction of the small angle cut spectrum from the 0° spectrum represents the extracted IS0 strength used in the process.

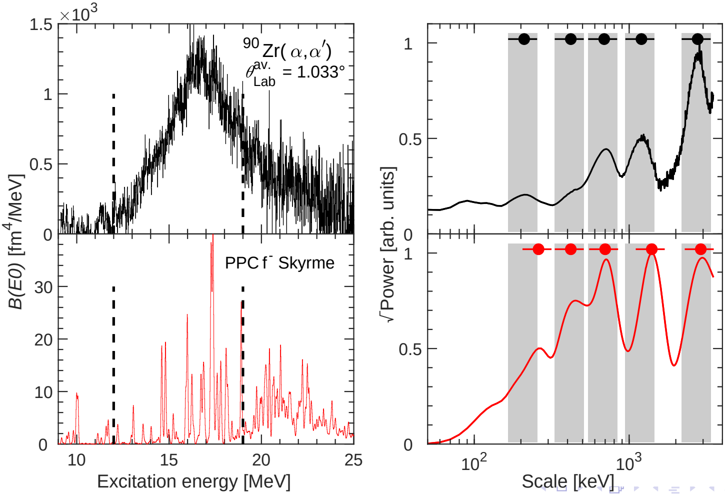
- The theoretical comparison is based on the phonon-phonon coupling (PPC) model where the calculation of the single spectrum and the parameters of the residual interaction are done with the Skyrme forces f^-.

- The PPC formalism is fully self-consistent i.e. both the mean field and residual interaction are derived from the same initial Skyrme functional.

Do the DoS method and the small-angle correction procedure have an impact on fine structure analysis?



Extraction of characteristic energy scales in ^{90}Zr



Conclusions and Outlook

- The isoscalar monopole strength in the energy interval $9 \leq E_x \leq 25$ MeV in ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb has been investigated using α-particle inelastic scattering with a 196 MeV beam at scattering angles $\theta_{\mathrm{Lab}} = 0^\circ$ and 4°.
- The DoS technique was applied in order to extract the IS0 strength distributions. Overall, the strength distributions obtained in this study show a reasonable agreement with results from the RCNP and TAMU groups.
- The extracted experimental energy scales are well reproduced by the model where in most cases a number of scales can be reproduced, but the one-to-one correspondence varies.
- The present study could be extended by attempting a MDA analysis.

Thanks for your attention.

Results of the ISGMR in ^{40,42,44,48}Ca