Isoscalar Giant Monopole Resonance (ISGMR) in ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb

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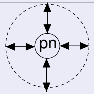
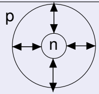
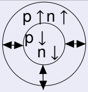
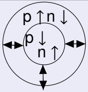
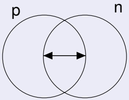
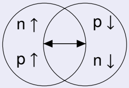
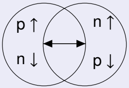
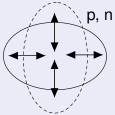
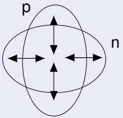
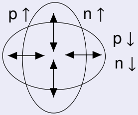
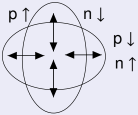
Introduction

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.

	Electric modes ($\Delta S = 0$)		Magnetic modes ($\Delta S = 1$)	
	Isoscalar ($\Delta T = 0$)	Isovector ($\Delta T = 1$)	Isoscalar ($\Delta T = 0$)	Isovector ($\Delta T = 1$)
$\Delta L = 0$				
$\Delta L = 1$	. . .			
$\Delta L = 2$				

Physical motivation

- The IsoScalar Giant Monopole Resonance (ISGMR) is a nuclear collective excitation that can provide information on the bulk properties of the nucleus and it helps constraining the incompressibility of uniform nuclear matter.

$$K_{\mathrm{A}} = K_{\infty} + K_{\mathrm{surf}} A^{-\frac{1}{3}} + K_{\tau} \left(\frac{N-Z}{A}\right)^{2} + K_{\mathrm{coul}} Z^{2} A^{-\frac{1}{3}} . \quad (1)$$

- The study of the ISGMR is considered as a mature field [a]. Yet there are, as we have seen recently, maybe more than a few questions about what is generally considered to be known in this field.

[a] U. Garg and G. Colò, Prog. Part. Nucl. Phys. 101 (2018) 55

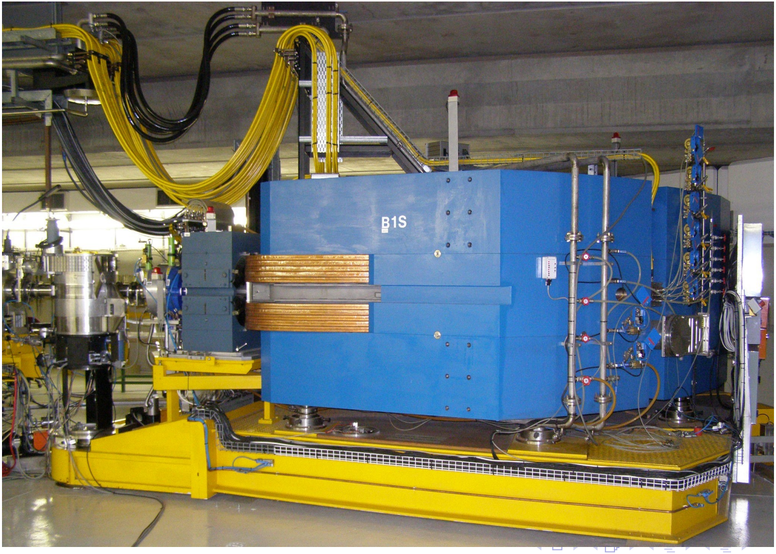
- Extraction of IS0 strength distributions for ^{58}Ni, ^{90}Zr, ^{120}Sn and ^{208}Pb are extracted in the excitation-energy region 9 – 25 MeV.

Available ISGMR data from iThemba LABS

Target	0° data	4° data
^{24}Mg*	✓	✓
^{28}Si*	✓	✓
^{40}Ca†	✓	✓
^{42}Ca†	✓	✓
^{44}Ca†	✓	✓
^{48}Ca†	✓	✓
^{58}Ni‡	✓	✓
^{90}Zr‡	✓	✓
^{120}Sn‡	✓	✓
^{208}Pb‡	✓	✓
^{144,154}Sm	Scheduled	Scheduled

*A. Bahini *et al*, Phys. Rev. C **105**, 024311 (2022)
†S. D. Olorunfunmi *et al*, Phys. Rev. C **105**, 054319 (2022)
‡A. Bahini *et al*, Phys. Rev. C **107**, 034312 (2023)

The K600 Spectrometer at iThemba LABS



Experimental setup

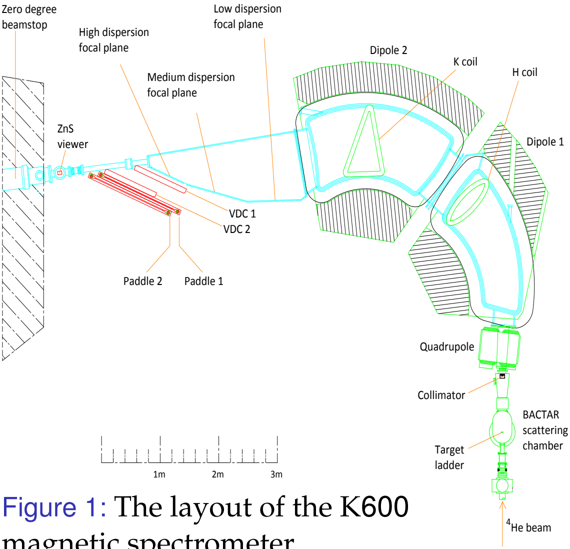
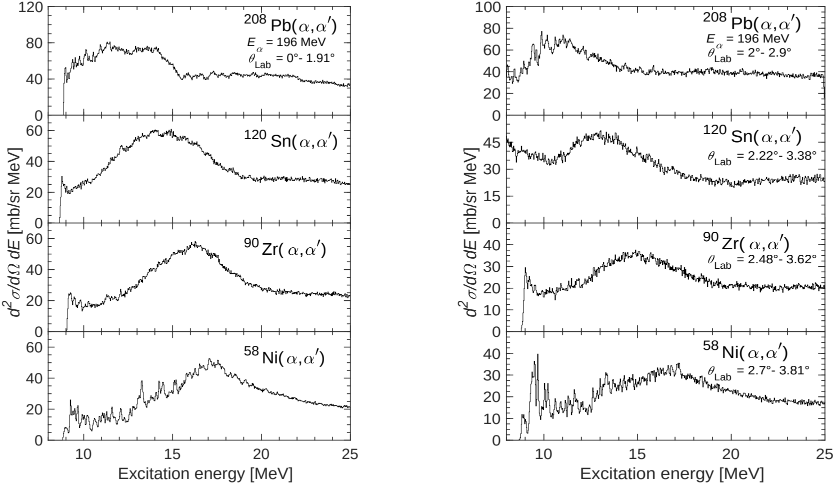


Figure 1: The layout of the K600 magnetic spectrometer.

- (α, α') scattering using the K600 magnetic spectrometer positioned at zero and four degrees (angular acceptance of ± 1.91°).
- 196 MeV α-particle 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.

Double-differential Cross sections



DWBA calculations

- The α-nucleus potential can be written as

$$U(r) = V_{\text{fold}}(r) + i\frac{W}{\{1 + \exp\left[(r - R_{\text{I}})/a_{\text{I}}\right]\}}\,.$$

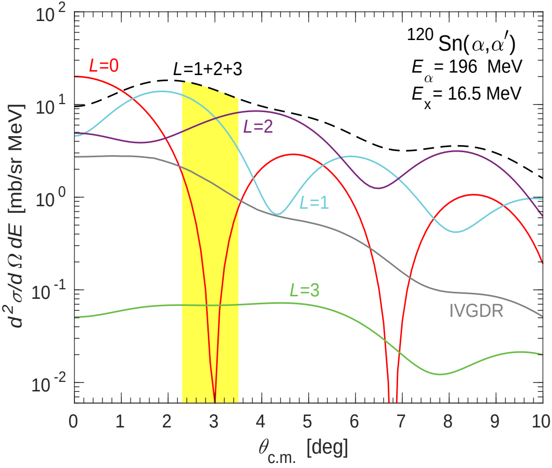
- The potential $V_{\text{fold}}(r)$ is obtained by folding the ground-state density with a density-dependent α-nucleon interaction

$$V_{\text{fold}}(r) = -V\int d^3r'\rho(r')\left[1 - \beta\rho(r')^{2/3}\right]\exp(-z^2/t^2)\,.$$

- The ground-state density $\rho(r)$ of the target nucleus at the position r is given by

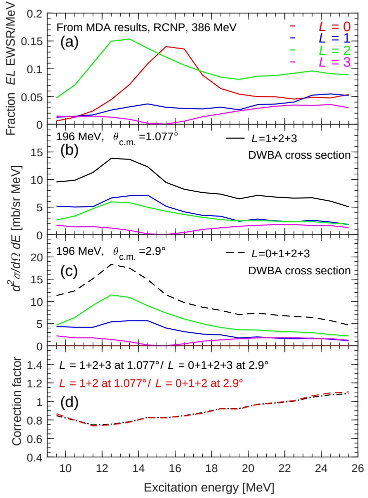
$$\rho(r) = \frac{\rho_0}{1 + \exp\left(\frac{r-c}{a}\right)}\,.$$

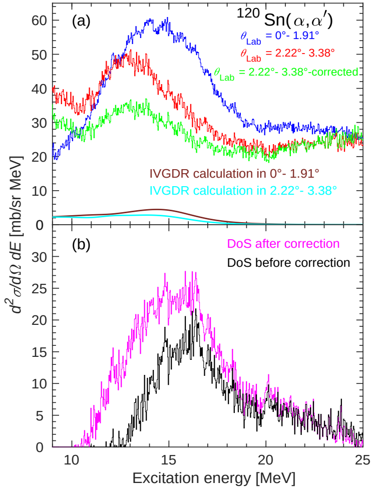
Difference-of-Spectra (DoS) technique



- 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°.

Correction procedure & DoS result





IS0 strength distributions determination

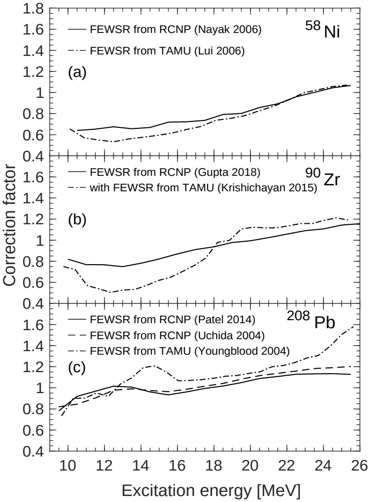
- The measured cross sections can be converted to fractions (a_0) of the EWSR(IS0)=$2\hbar^2/m \cdot A\langle r^2\rangle$ by comparing with DWBA calculations assuming 100% EWSR

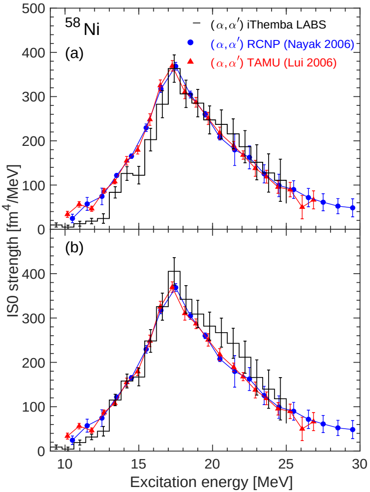
$$\frac{d^2\sigma^{\text{exp}}}{d\Omega dE}(\theta_{\text{c.m.}}, E_{\text{x}}) = a_0(E_{\text{x}}) \times \frac{d^2\sigma_L^{\text{DWBA}}}{d\Omega dE}(\theta_{\text{c.m.}}, E_{\text{x}}) .$$

- The IS0 strength $S_0(E_{\text{x}})$ is then calculated using the a_0 values and is expressed as

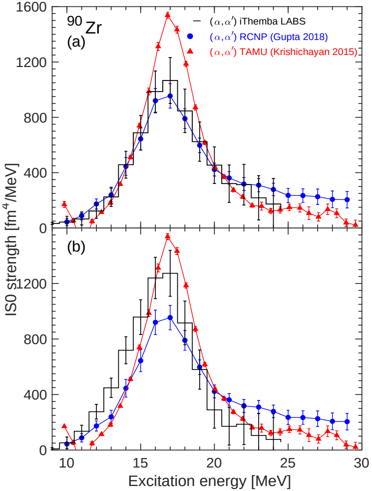
$$S_0(E_{\text{x}}) = \frac{\text{EWSR(IS0)}}{E_{\text{x}}} a_0(E_{\text{x}}) = \frac{2\hbar^2 A\langle r^2\rangle}{mE_{\text{x}}} a_0(E_{\text{x}}) .$$

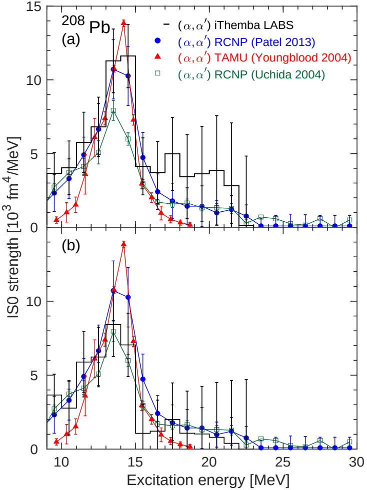
Correction procedure & IS0 strength





IS0 strength distribution in ^{90}Zr and ^{208}Pb





Parameters extracted from the ISGMR strength distributions from previous (α, α') measurements

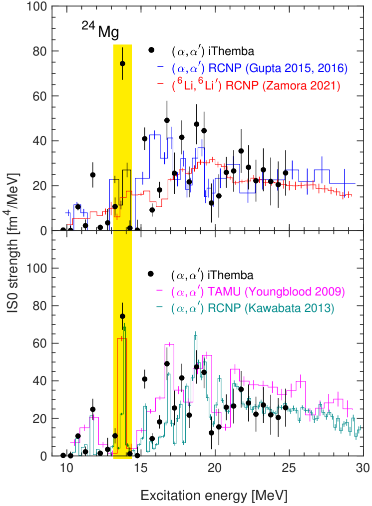
Nucleus	Centroid (MeV)	Width (MeV)	m_1/m_0 (MeV)	$\sqrt{m_1/m_{-1}}$ (MeV)	$\sqrt{m_3/m_1}$ (MeV)	Energy range (MeV)	Reference
^{58}Ni	—	—	$19.9^{+0.7}_{-0.8}$	—	—	10.5 – 32.5	RCNP
	18.43 ± 0.15	7.41 ± 0.13	$19.20^{+0.44}_{-0.19}$	$18.70^{+0.34}_{-0.17}$	$20.81^{+0.90}_{-0.28}$	10 – 35	TAMU §
^{90}Zr	16.76 ± 0.12	$4.96^{+0.31}_{-0.32}$	$19.17^{+0.21}_{-0.20}$	18.65 ± 0.17	$20.87^{+0.34}_{-0.33}$	10 – 30	RCNP ¶
	17.1	4.4	$17.88^{+0.13}_{-0.11}$	$17.58^{+0.06}_{-0.04}$	$18.86^{+0.23}_{-0.14}$	10 – 35	TAMU[a]
^{120}Sn	15.4 ± 0.2	4.9 ± 0.5	15.7 ± 0.1	15.5 ± 0.1	16.2 ± 0.2	10.5 – 20.5	RCNP [b]
^{208}Pb	13.7 ± 0.1	3.3 ± 0.2	—	13.5 ± 0.1	—	9.5 – 19.5	RCNP [b]
	13.4 ± 0.2	4.0 ± 0.4	—	—	—	8 – 33	RCNP
	—	2.88 ± 0.20‖	13.96 ± 0.20	—	—	10 – 35	TAMU

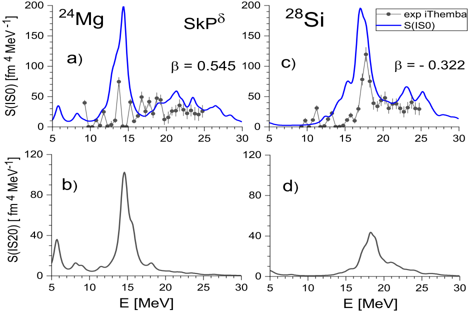
§Peak positions and widths (FWHM) from Gaussian fits.
¶Peak positions and widths (FWHM) from Lorentzian fits.
‖The equivalent Gaussian FWHM.

The centroid energy and width of ISGMR

Nucleus	Centroid (MeV)	Width (MeV)	m_1/m_0 (MeV)	$\sqrt{m_1/m_{-1}}$ (MeV)	$\sqrt{m_3/m_1}$ (MeV)	Reference
^{58}Ni	17.8 ± 0.4	5.4 ± 0.4	18.40 ± 0.15	18.14 ± 0.14	19.12 ± 0.17	Present
	17.8 ± 0.4	5.4 ± 0.4	18.22 ± 0.13	17.94 ± 0.13	18.98 ± 0.15	Present
	17.9 ± 0.3	5.3 ± 0.3	18.15 ± 0.11	17.85 ± 0.11	19.00 ± 0.12	RCNP
	17.9 ± 0.3	5.3 ± 0.3	18.14 ± 0.06	17.81 ± 0.06	19.00 ± 0.06	TAMU
^{90}Zr	16.7 ± 0.2	4.4 ± 0.2	17.06 ± 0.35	16.80 ± 0.32	17.84 ± 0.48	Present
	16.2 ± 0.2	4.2 ± 0.2	16.02 ± 0.36	15.79 ± 0.32	16.69 ± 0.57	Present
	16.8 ± 0.2	4.8 ± 0.3	17.59 ± 0.11	17.31 ± 0.11	18.41 ± 0.11	RCNP
	16.9 ± 0.2	3.9 ± 0.3	17.23 ± 0.03	17.03 ± 0.03	17.81 ± 0.04	TAMU
^{120}Sn	15.5 ± 0.4	5.6 ± 0.4	16.24 ± 0.39	15.92 ± 0.35	17.21 ± 0.54	Present
	15.4 ± 0.2	4.6 ± 0.3	16.54 ± 0.23	16.20 ± 0.22	17.61 ± 0.25	RCNP
^{208}Pb	13.8 ± 0.3	3.1 ± 0.2	13.39 ± 0.27	13.25 ± 0.26	13.80 ± 0.29	Present
	13.3 ± 0.3	3.2 ± 0.3	12.44 ± 0.45	12.29 ± 0.42	12.90 ± 0.57	Present
	13.7 ± 0.2	3.4 ± 0.2	13.47 ± 0.22	13.32 ± 0.22	13.86 ± 0.22	RCNP
	13.4 ± 0.2	4.0 ± 0.3	13.78 ± 0.29	13.59 ± 0.27	14.32 ± 0.35	RCNP
	13.9 ± 0.3	2.3 ± 0.4	13.64 ± 0.08	13.56 ± 0.08	13.85 ± 0.07	TAMU

Discrepancies in results: iTL vs RCNP for ^{24}Mg

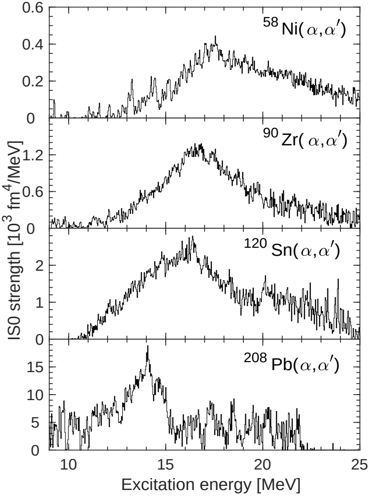


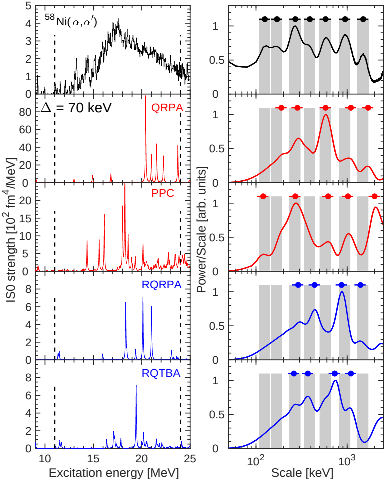


see Phys. Rev. C **105**, 024311 (2022)

	SV-bas	SkM*	SkP$^{\delta}$	SkT6	SV-mas10
K_∞ (MeV)	234	217	202	236	234
m_0^*/m	0.9	0.79	1	1	1

Fine structure in ISGMR (upcoming next!)





Conclusions

- The isoscalar monopole strength has been investigated using α-particle inelastic scattering with a 196 MeV beam at scattering angles $\theta_{\text{Lab}} = 0^\circ$ and 4°.

- Previous measurements show significant differences in the IS0 strength distributions of ^{90}Zr and ^{208}Pb. This work demonstrates clear structural differences in the energy region of the main resonance peaks with possible impact on the determination of the nuclear matter incompressibility presently based on the IS0 centroid energies of these two nuclei.

- The results also suggest that for an improved determination of the incompressibility, theoretical approaches should aim at a description of the full strength distributions rather than the centroid energy only.

COMEX7

7th International Conference on
Collective Motion in Nuclei under Extreme Conditions

Catania 11-16 June 2023

NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

Thank for your attention.

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