Evolution to neutron rich isotopes in the fine structure of the Isoscalar Giant Monopole Resonance in $^{40,42,44,48}Ca$ using alpha inelastic scattering at zero degrees

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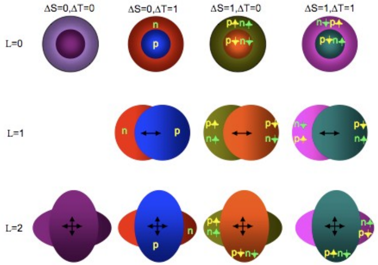
What are giant resonances?

- GRs are the collective motion of the nucleons within the nucleus
- Resonance typically occurs at excitation energies between 10 - 30 MeV
- Resonance can be isoscalar (i.e. the nucleons move in phase) or isovector (i.e. the nucleons move out of phase)
- The nucleus can take on monopole ($L = 0$), dipole ($L = 1$), quadrupole ($L = 2$), etc, structures
- ISGMR $\rightarrow \Delta L = 0$, $\Delta S = 0$, $\Delta T = 0$



Motivation

Fine structure

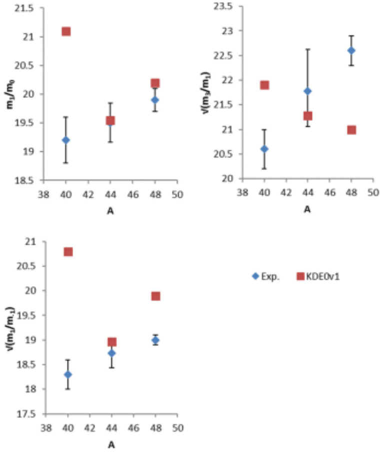
- GRs carry fine structure and experimental study of the GRs provides insight into the main mechanism leading to the fine structure phenomenon
- Fine structure observed in GRs:
  ISGQR $\rightarrow$ coupling of elementary 1p-1h states to low-energy surface vibrations
  IVGDR $\rightarrow$ fragmentation of 1p-1h strength (Landau damping)
  M1, M2, GTR $\rightarrow$ Mixing of 1p-1h with np-nh states
  ISGMR $\rightarrow$?
- Detailed study of the excitation and decay of ISGMR is imperative

- Giant resonances are important because they provide information about bulk properties of the nucleus e.g. compression modulus.
- Excitation energy of GMR is directly related to the incompressibility of the nucleaus, an important parameter in the EOS of nuclear matter.

$$E_{ISGMR} = \frac{\hbar\sqrt{K_A}}{m\langle r^2\rangle} \tag{1}$$

where E_{ISGMR} is the centroid energy of the GMR, m is the mass of the nucleus, $\langle r^2\rangle$ is the gs mean-square radius, and K_A is the incompressibility of the nucleus

- GR energies generally go roughly as $A^{-1/3}$.
- Contrary to expectations, J. Button *et al.* (PRC 96, 054330 (2017)) reported ISGMR energy in ^{48}Ca higher than in ^{40}Ca.



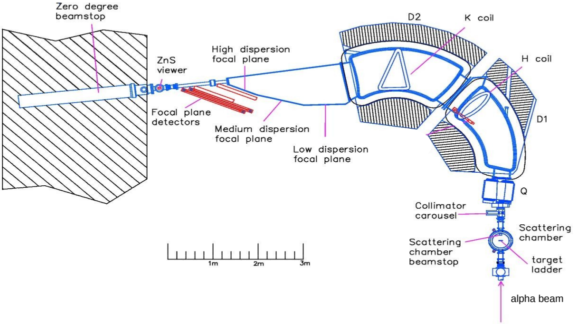
- It is imperative to examine this anomaly.

Objectives

- Obtain completely background-free inelastic scattering spectra for the ^{40,42,44,48}Ca isotopes
- Investigate the fine structure of the ISGMR as a function of neutron excess in the Ca isotopes and extract its characteristics energy scales
- Extract the $J^{\pi} = 0^{+}$ level densities
- Compare the value of the nuclear incompressibility K_A, based on the ISGMR results, with existing values

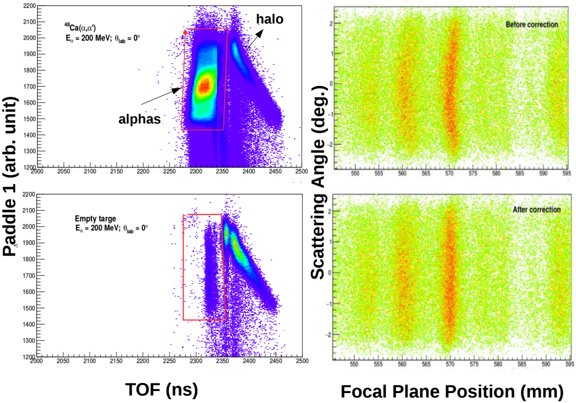
Measurements with the K600 Magnetic Spectrometer at iThemba LABS

- Reaction: inelastic scattering of 200 MeV α particles at 0° and 4°
- ISGMR partly overlaps with ISGQR, hence, 4° measurements were taken to remove ISGQR contribution from the 0° measurements
- Targets:^{24}Mg (2.1 mg/cm^2) and ^{42,44,48}Ca (1.35,1.43,1.09 mg/cm^2)



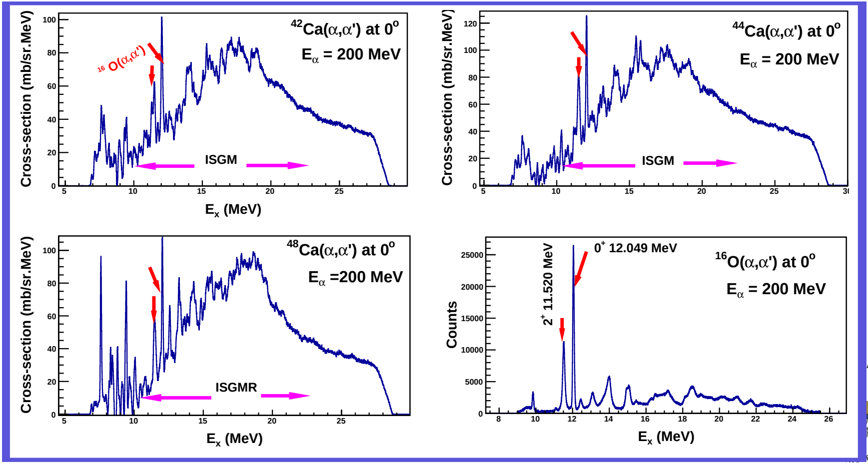
Background reduction and software correction

- Particle ID (PID) and time-of-flight (TOF) cuts were made to select alphas AND reduce background contributions from small angle scattering off the collimator lips.
- Lineshape correction was done to optimise the resolution.



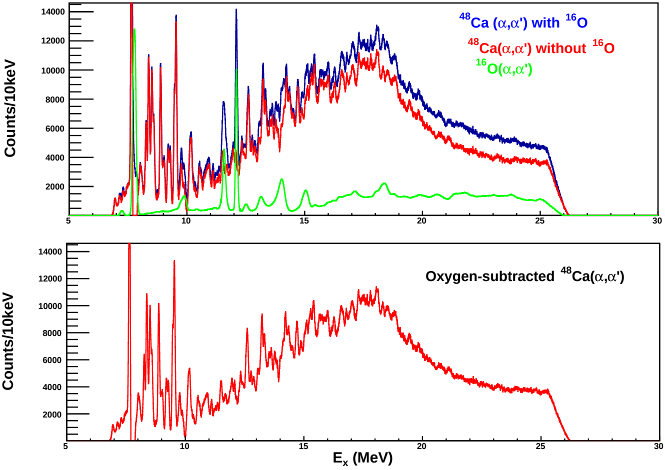
Excitation energies of Ca isotopes & ^{16}O

- The ^{16}O contamination peaks found on the lower edge of the ISGMR region

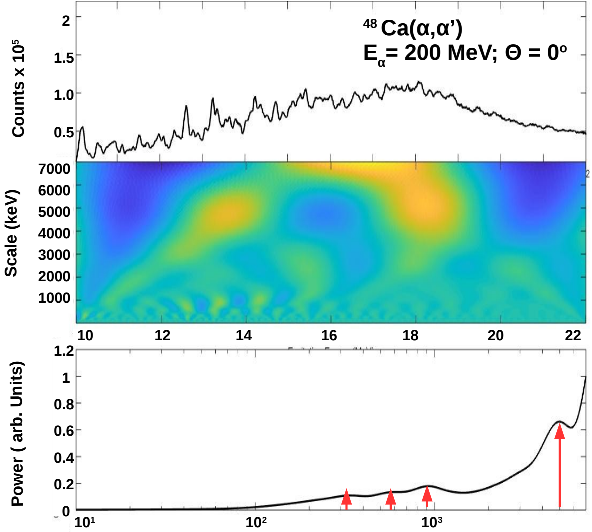


Removal of ^{16}O contamination

- The ^{16}O contamination was removed through a direct background subtraction.



Wavelet Analysis on ^{48}Ca without ^{16}O



Comparison of scales

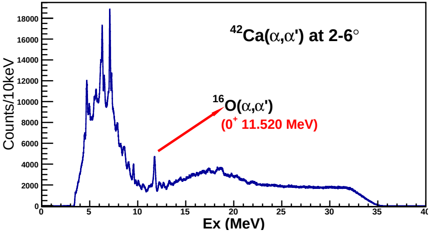
The excitation energy range considered is 10 – 22 MeV

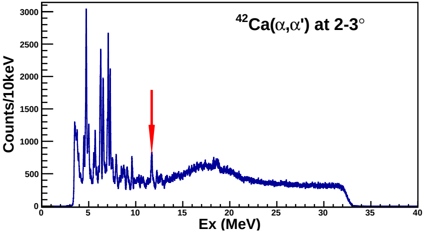
Target	Class I $\Delta E \leq 300$ (keV)	Class II $300 < \Delta E < 1000$ (keV)	Class III $1000 < \Delta E < 6000$ (keV)
^{16}O	- -	540 930	2390 5210
^{48}Ca (with ^{16}O)	290	560 960	3000 4970
^{48}Ca (without ^{16}O)	- -	340 610 930	- 4990

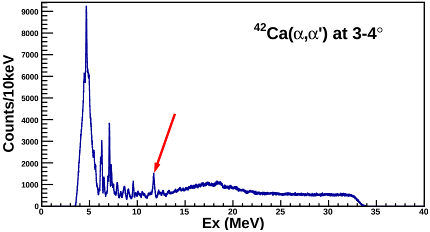
The removal of the ^{16}O has no significant effect on the structure of the target of interest.

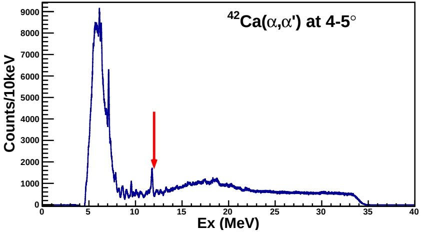
4° data

- ^{16}O contamination at around Ex =11.5 MeV.

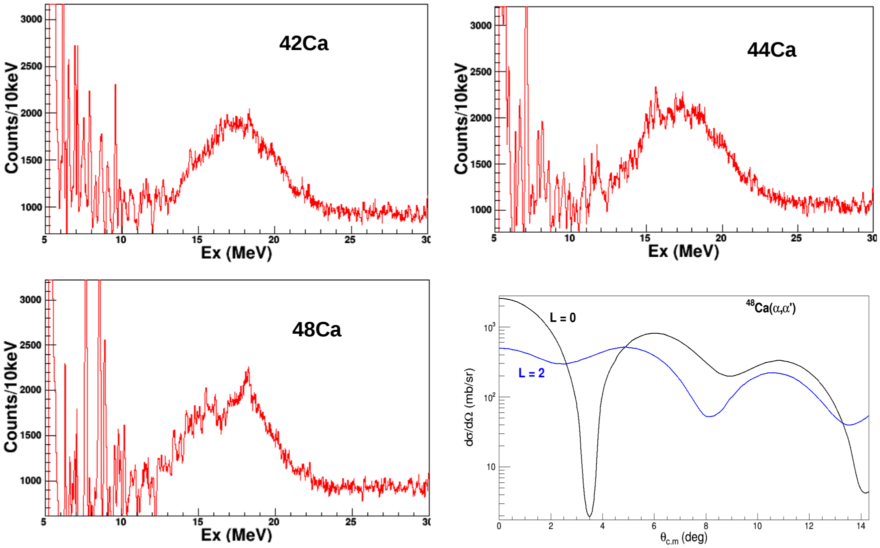




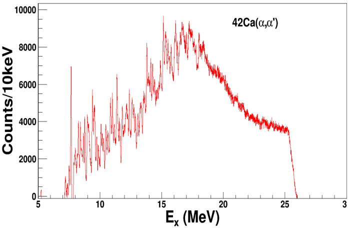


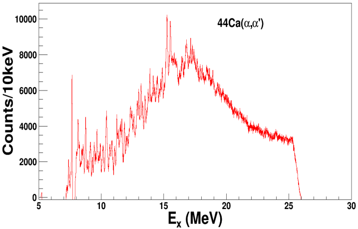


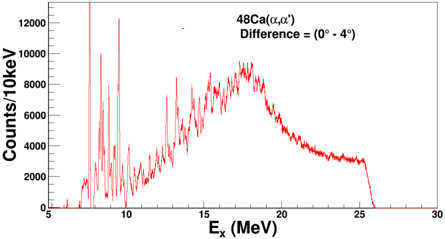
- DWBA plot: 1st minimum of ISGMR at 3-4°



- Difference-spectrum is essentially monopole monopole

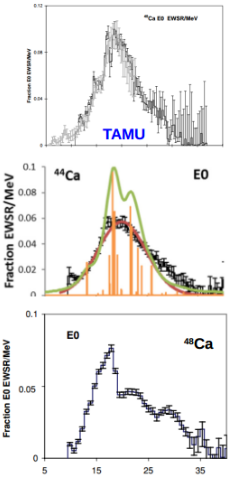


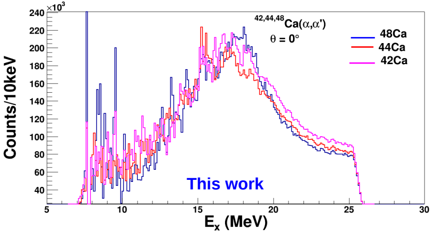


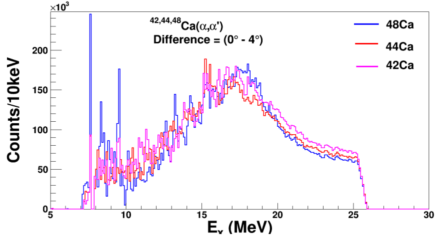


Structure effects in Ca isotopes

- TAMU recommends the need to consider nuclear structure effects in order to understand the systematics of Ca isotopes.







Outlook

- Continuous Wavelet Analysis on the (α, α') data to extract characteristics energy scales from fine structure of ISGMR
- Comparison of scales from experimental data with those from theoretical calculations
- Autocorrelation function analysis to extract $J^{\pi} = 0^{+}$ level densities

Collaborators...

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NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

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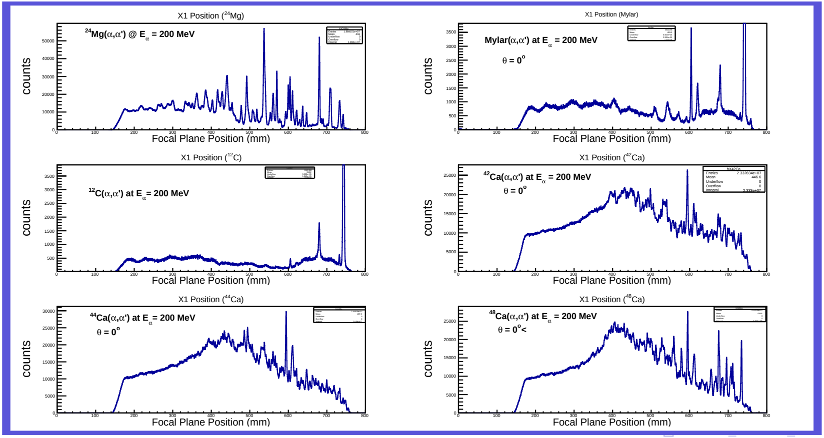
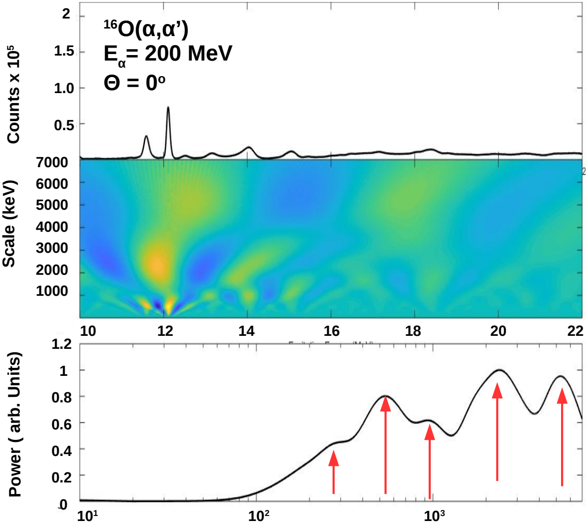
Backup Slides

Position spectra

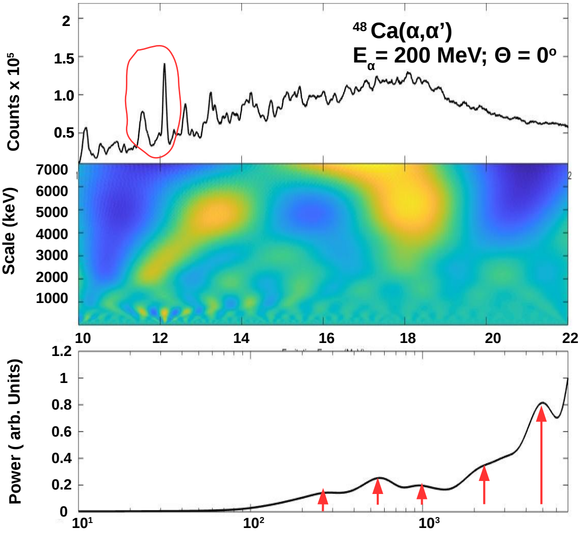
- Excitation energy calibration was done using the ^{24}Mg(α, α'), whose spectrum exhibited well-known excited states
- Mylar target was used to check/reveal the presence of structures due to ^{16}O contamination



Wavelet Analysis on ^{16}O

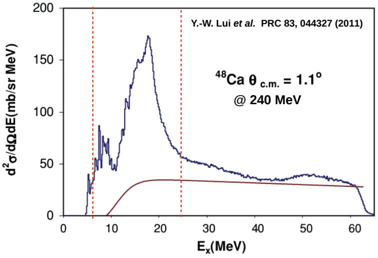


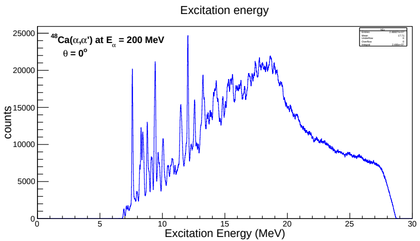
Wavelet Analysis on ^{48}Ca with ^{16}O



Comparison with previous measurements

- Texas A&M has data for only ^{40,48}Ca isotopes while this work presents data for ^{40,42,44,48}Ca with better resolution
- Texas A&M data on Ca isotopes does not allow for fine structure analysis





Example

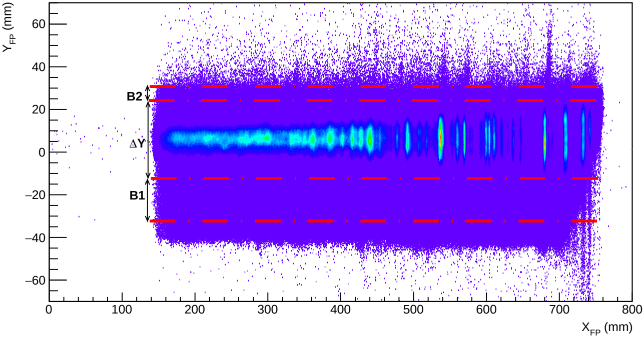
$$K_A = K_V + K_{surf} A^{-1/3} + K_{sym}(\frac{N-Z}{A})^2 + K_{Coul}\frac{Z^2}{A^{4/3}} + ...$$

Volume term, $K_V = K_{(A \longrightarrow \infty)} = K_{nm}$, where K_{nm} compressibility of the nuclear matter. Let $\delta = (N-Z)/A$

- In recent years, studies of the symmetry term K_{sym} are mostly on heavy nuclei, especially on Sn isotopes, yielding varying results (T. Li *et al.*, Phys. Rev. C 81, 034309 (2010)).
  $\delta(^{124}Sn) - \delta(^{112}Sn) = 0.194 - 0.107 = 0.087$
- However, in the Ca isotopes,
  $\delta(^{48}Ca) - \delta(^{40}Ca) = 0.167 - 0 = 0.167$
- Thus, studies of $^{40-48}$Ca might provide a more precise determination of K_{sym}

- Comparison of ^{24}Mg excited states obtained in this work with the ones reported in NNDC and by Kawabata *et al.* 2010. The last column shows the difference between calibrated excited states and assigned excited states.

J^{π}	NNDC (MeV)	Kawabata (MeV)	This work (MeV)	Difference (MeV)
2^+	9.00334	-	9.004	0.0006
1^-	9.14599	-	9.148	0.002
0^+	9.30539	-	9.304	-0.0014
2^+	10.3605	-	10.364	0.0035
0^+	10.6797	-	10.684	0.0043
2^+	11.5182	-	11.517	-0.0012
0^+	11.7281	-	11.724	-0.0041
1^-	11.8649	-	11.864	-0.0009
0^+	13.8500	-	13.854	0.004
4^+	-	15.2500	15.260	0.010
2^+	-	17.6400	17.634	-0.006


Y_FP (mm)
60
40
20
0
−20
−40
−60
B2
ΔY
B1
0
100
200
300
400
500
600
700
800
X_FP (mm)