Fine structure of giant resonances in Calcium isotopes

Iyabo Usman
University of the Witwatersrand

On behalf of
iThemba/Wits/UCT/RCNP/IKP-TU-Darmstadt K600 Group

*Project Funded By
South African National Research Foundation (Grant No: 85730)
German DFG under contracts SFB 634, NE 679/2-2

HST15 RCNP Osaka University 16 – 19 November 2015

Outline

- Fine structure of Giant Resonances
- High energy-resolution experiments with K600 Magnetic Spectrometer of iThemba LABS
- Isoscalar Giant Quadrupole Resonance in ^{40}Ca
- Isovector Giant Dipole Resonance in $^{40,42,44,48}Ca$
- Energy Scales and Comparison with Theoretical Calculations
- Level density extraction from (p,p′) data

Fine Structure of Giant Resonances

- Have been established as a Global phenomenon in

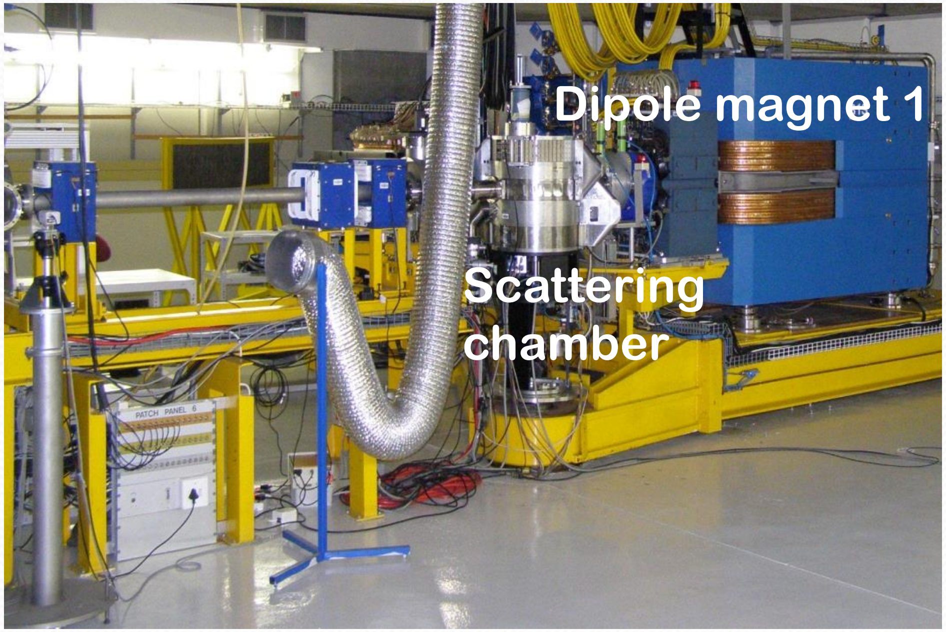
  - nuclei across the periodic table

  - other resonances

- Dominant processes of the decay?

- Spin- and parity-resolved level densities at energies above thresholds?

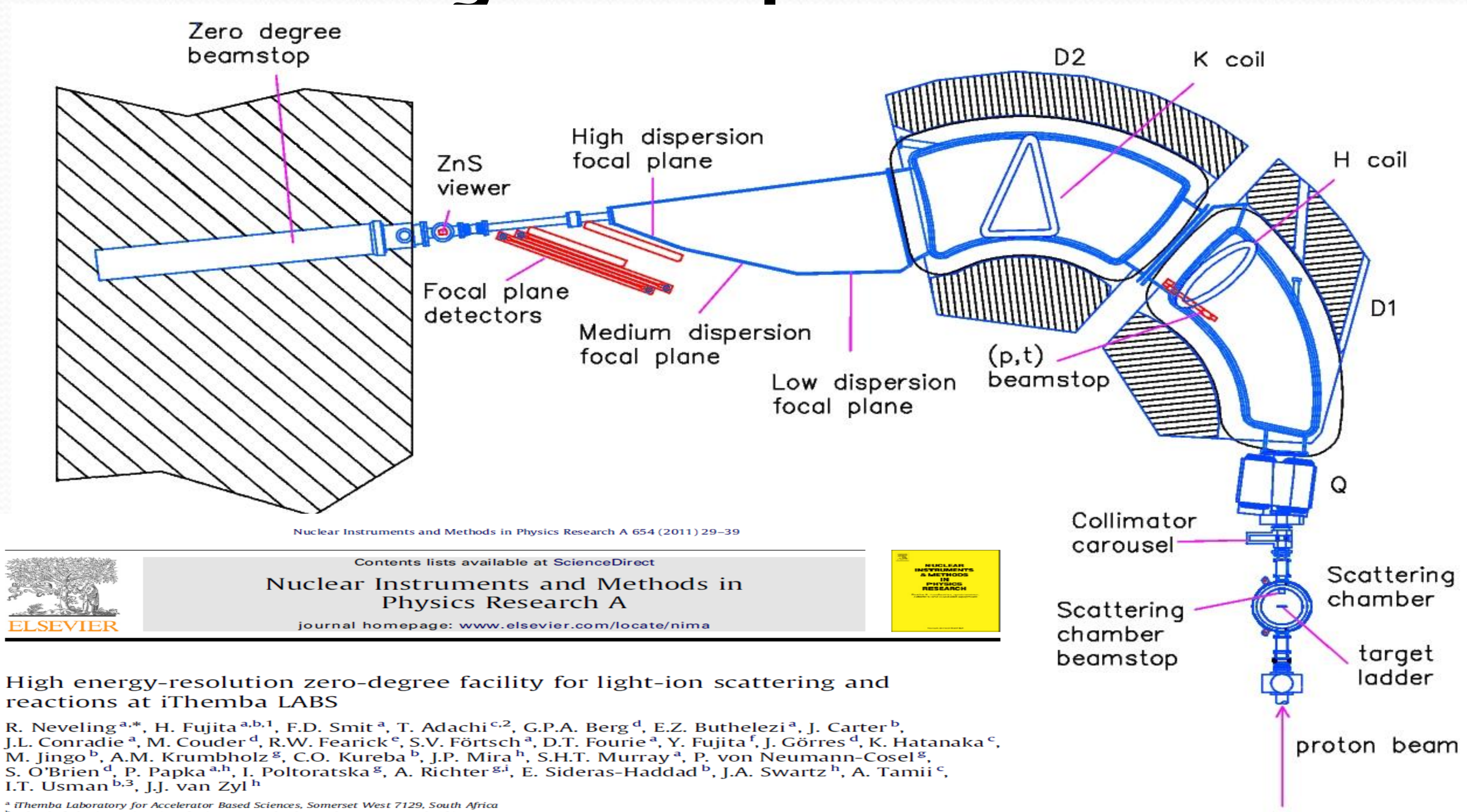
K600 Magnetic Spectrometer



Best resolution = 25 keV @ 200 MeV on Au target
Best resolution = 9 keV @ 66 MeV on Pb target
Largest angle so far = 87°
Smallest angle = 21° with external beamstop
Smallest angle = 7° with internal beamstop

- 2 VDC: high accuracy horizontal position determination in focal plane
- 1 HDC: high accuracy vertical position determination
- 2 plastic scintillators (BC-408) acting as trigger detectors for particle identification

K600 magnetic spectrometer at 0°



Nuclear Instruments and Methods in Physics Research A 654 (2011) 29–39

Contents lists available at ScienceDirect

ELSEVIER

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

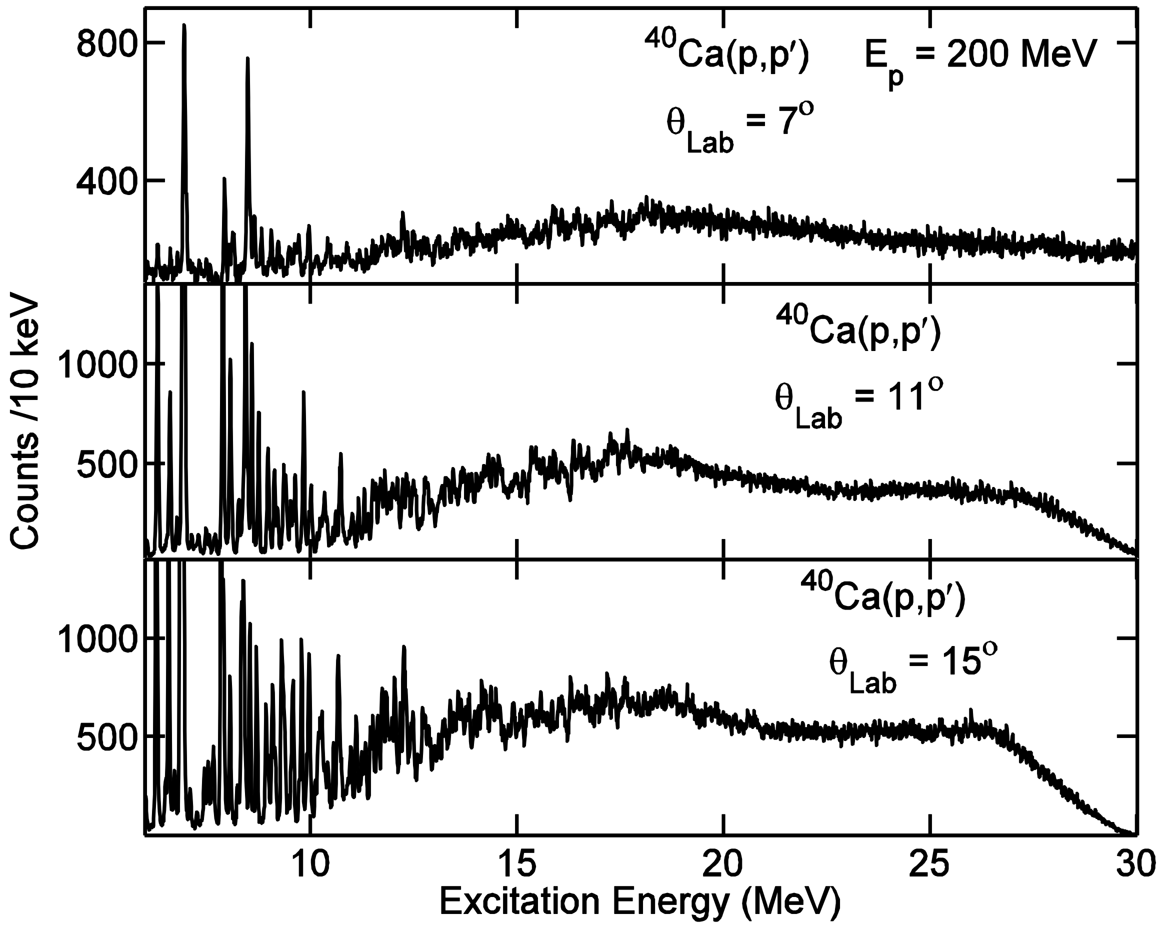
High energy-resolution zero-degree facility for light-ion scattering and reactions at iThemba LABS

R. Neveling[a,*], H. Fujita[a,b,1], F.D. Smit[a], T. Adachi[c,2], G.P.A. Berg[d], E.Z. Buthelezi[a], J. Carter[b], J.L. Conradie[a], M. Couder[d], R.W. Fearick[e], S.V. Förtsch[a], D.T. Fourie[a], Y. Fujita[f], J. Görres[d], K. Hatanaka[c], M. Jingo[b], A.M. Krumbholz[g], C.O. Kureba[b], J.P. Mira[h], S.H.T. Murray[a], P. von Neumann-Cosel[g], S. O'Brien[d], P. Papka[a,h], I. Poltoratska[g], A. Richter[g,i], E. Sideras-Haddad[b], J.A. Swartz[h], A. Tamii[c], I.T. Usman[b,3], J.J. van Zyl[h]

[a] iThemba Laboratory for Accelerator Based Sciences, Somerset West 7129, South Africa
[b] School of Physics, University of Witwatersrand, Johannesburg 2050, South Africa
[c] Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 560-0047, Japan
[d] Department of Physics and the Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, IN 46556, USA
[e] Physics Department, University of Cape Town, Rondebosch 7700, South Africa
[f] Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
[g] Institut für Kernphysik, Technische Universität Darmstadt, D-64829 Darmstadt, Germany
[h] Department of Physics, University of Stellenbosch, Matieland 7602, South Africa
[i] ECT*, Villa Tambosi, I-38123 Villazano (Trento), Italy

Contact person: neveling@tlabs.ac.za

Fine structure of ISGQR in ^{40}Ca

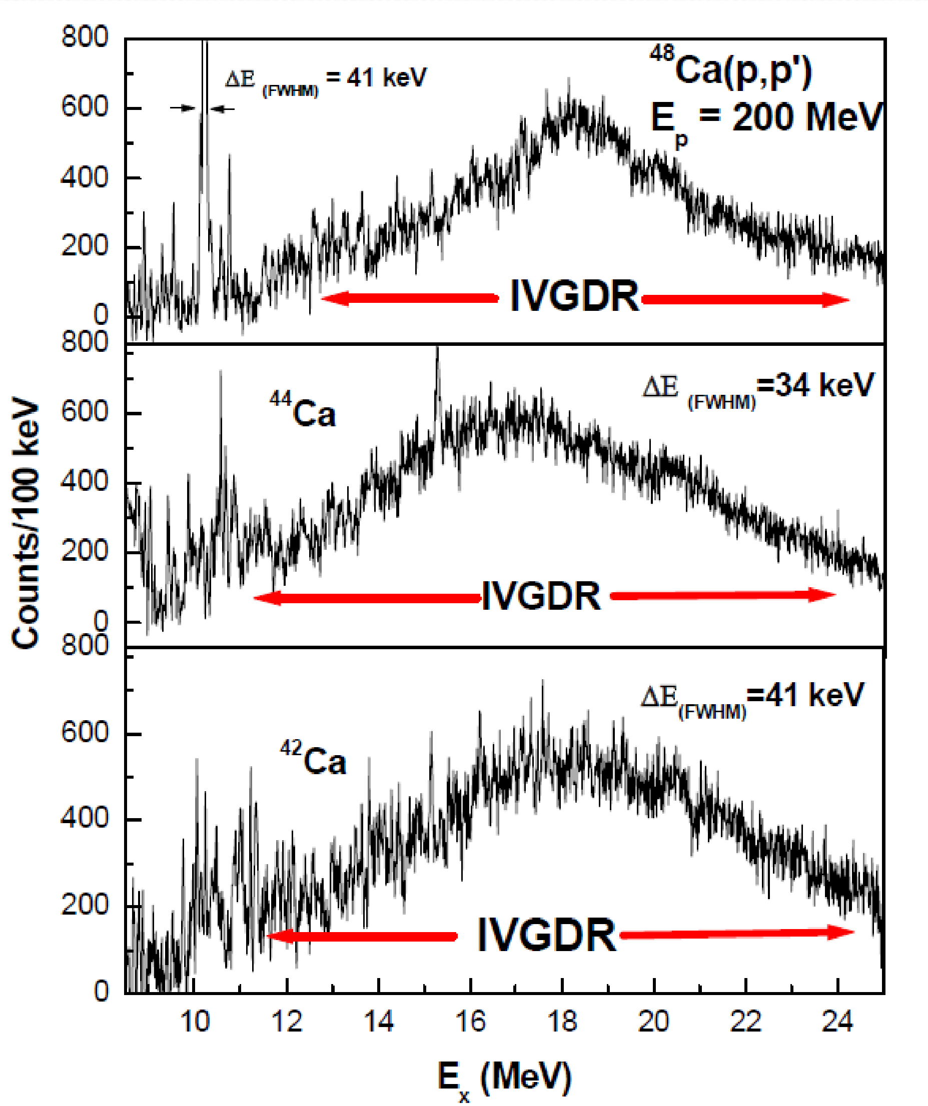


ΔE = 35 - 40 keV (FWHM)

Fine structures in the region of the ISGQR are clearly visible.

Excitation energy spectra in ^{40}Ca at angles below, at and above the maximum of the ISGQR.

Fine structure of the IVGDR in $^{42,44,48}Ca$



M. Latif, PhD Thesis
(in preparation)
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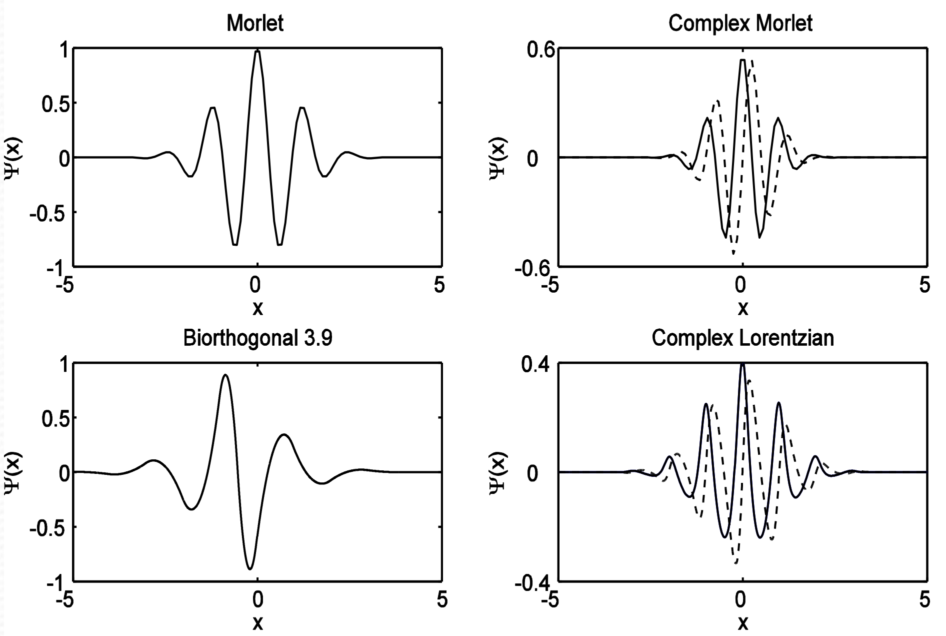
ΔE = 34 - 41 keV (FWHM)

Excitation energy spectra in $^{42,44,48}Ca$ at zero-degree

Wavelet Analysis

$$\int_{-\infty}^{\infty} \Psi(x)dx = 0$$

$$\int_{-\infty}^{\infty} |\Psi(x)|^2 dx < \infty$$



Wavelet coefficients

$$C(E_x, \delta E) = \frac{1}{\sqrt{\delta E}} \int \sigma(E) \Psi\left(\frac{E_x - E}{\delta E}\right) dE$$

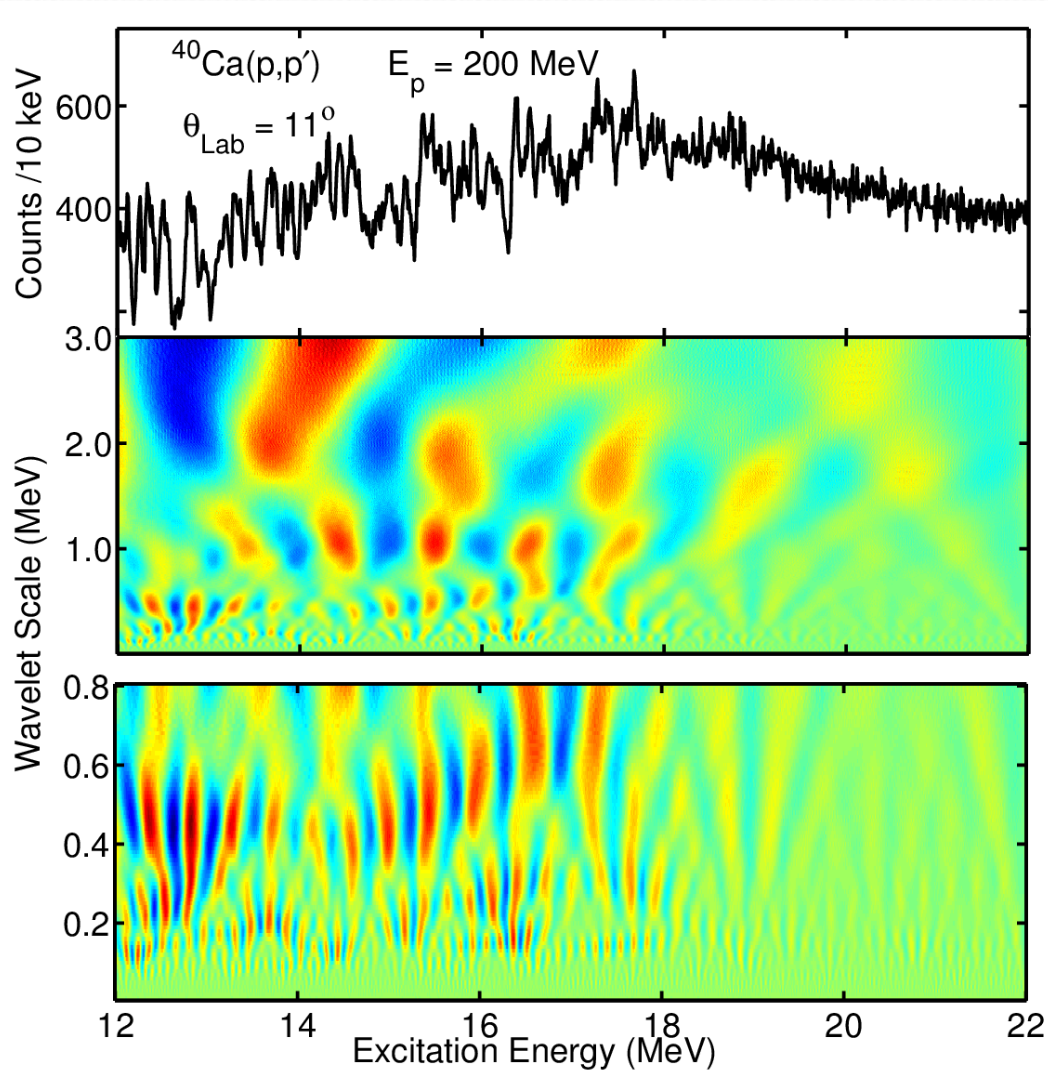
position scale spectrum wavelet

Morlet: $$\Psi(x) = \frac{1}{\pi^{1/4}} \cos(ikx) \exp\left(-\frac{x^2}{2}\right)$$

Complex Morlet: $$\Psi(x) = \frac{1}{\sqrt{\pi f_b}} \exp(2\pi i f_c) \exp\left(-\frac{x^2}{f_b}\right)$$

Complex Lorentzian: $$\Psi(x) = \sum_{n=-8}^{+8} \frac{(\Gamma/2)^2}{\left(x-(x_o+nf_c)\right)^2 + (\Gamma/2)^2} \exp\left(-\frac{x^2}{2f_b}\right)$$

Characteristic Energy Scales
^{40}Ca ISGQR



ISGQR is not mainly concentrated in a well-defined peak in light nuclei but completely fragmented e.g. ^{40}Ca, ^{28}Si & ^{12}C

Wavelet Coefficients

Pronounced fine structure is observed up to

Comparison with Theoretical Calculations

- To understand the origin and physical nature of different scales, comparison of experimental results with model calculations is important.

- Theoretical models for ISGQR and IVGDR in $^{40,42,44,48}Ca$

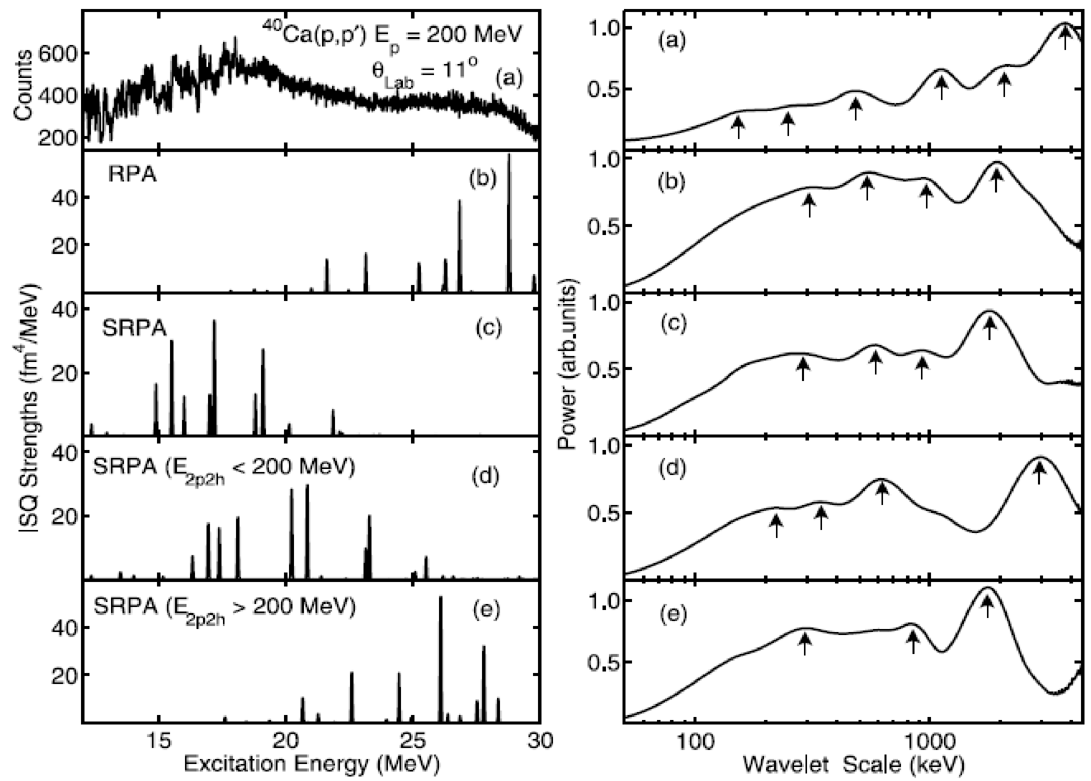
  - Random Phase Approximation (RPA)

  - Second-RPA (SRPA)

  - (R-QRPA)

  - Relativistic Quasiparticle Time Blocking Approximation (RQTBA)

Comparison with Theoretical Calculations RPA and SRPA in ^{40}Ca ISGQR



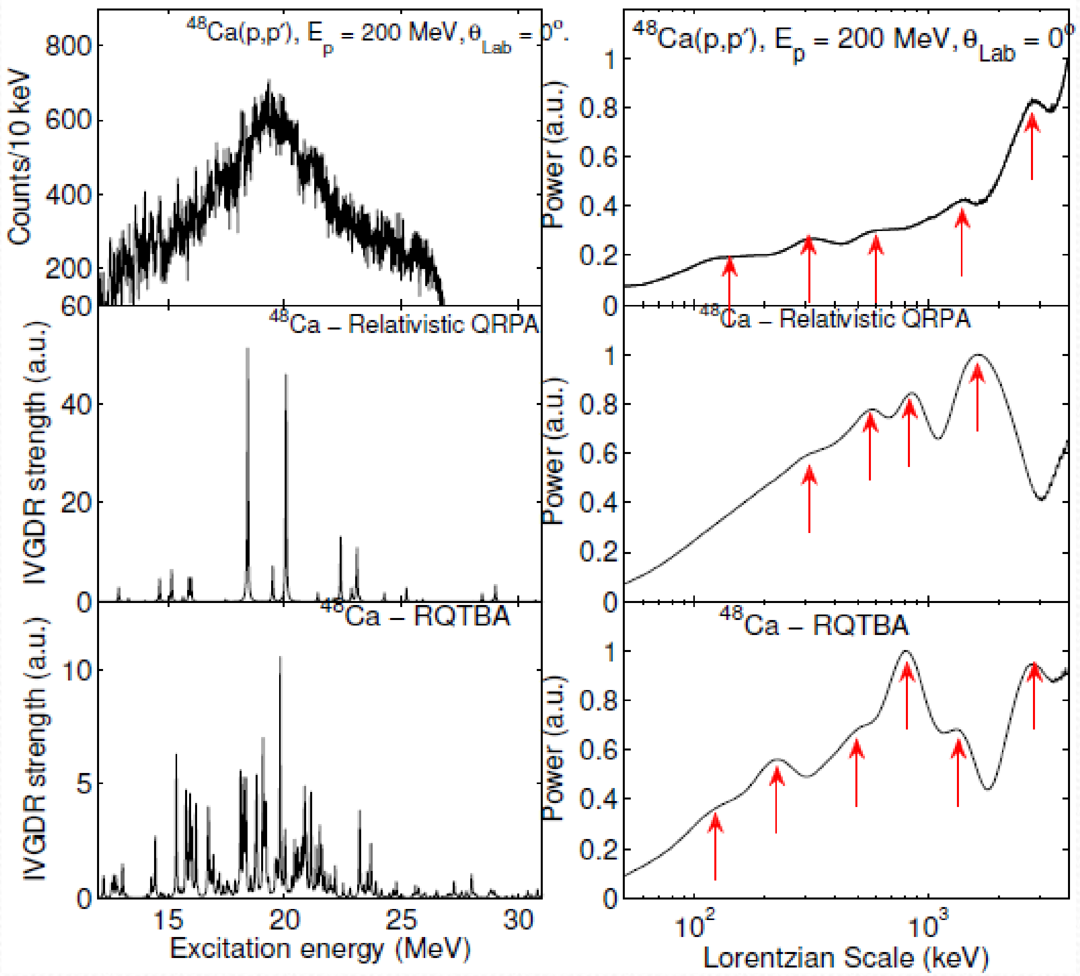
Experimental Scales (150, 240, 460) keV; (1.05, 2.0, 3.9) MeV;

Observed fragmentation is attributed to mixing of the 1p–1h states with more complex configurations, including collective phonons

RPA only accounts for Landau damping

I. Usman, Z. Buthelezi, J. Carter, G. R. J. Cooper, R. W. Fearick, S. V. Fortsch, H. Fujita, Y. Fujita, Y. Kalmykov, P. von Neuman-Cosel, R. Neveling, P. Papakonstantinou, A. Richter, R. Roth, A. Shevchenko, E. Sideras-Haddad, F.D. Smit, Physics Letters B 698 (2011) 191-195.

Comparison with Theoretical Calculations QRPA and RQTBA ^{48}Ca IVGDR



M. Latif, PhD Thesis
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Model	Class I	Class II	Class III
Experiment	150	320, 680	1400, 2820
RQRPA	–	310, 550, 860	1640
RQTBA	130, 230	480, 810	1340, 2820

E. Litvinova, P. Ring and V. Tselyaev, Phys. Rev. C 78 (2008) 014312.

E. Litvinova, Phys. Rev. C 91 (2015) 034332.

Extraction of spin- and parity-dependent Level densities

- Level densities of $J^{\pi} = 2^{+}$ and 1^{-} states extracted from high energy-resolution (p,p′) experiments in the region above particle thresholds

- Continuum background determination using Quasi-free calculations and model-independent method of Discrete Wavelet Transform (DWT)

- Self consistent procedure to extract level densities based on fluctuation analysis and Autocorrelation functions

Fluctuation Analysis

Measure of cross section fluctuations with respect to a stationary mean value.

Assumptions:

$$\langle \Gamma \rangle \leq \langle D \rangle \leq \Delta E$$

$$\alpha = \alpha_w + \alpha_{PT}$$

$\langle \Gamma \rangle$ Mean level width

$\langle D \rangle$ Mean level spacing

ΔE Energy resolution

α Sum of normalised variances

Procedure:

- Background subtraction from the experimental spectrum
- Smoothing by convolution with a Gaussian function of width larger than ΔE $\longrightarrow$ $g_>(E_x)$
- Folding with a Gaussian function with a width smaller than ΔE $\longrightarrow$ $g(E_x)$
- Create a stationary spectrum $\longrightarrow$ $\langle d(E_x) \rangle = \left\langle \frac{g(E_x)}{g_>(E_x)} \right\rangle = 1$

Autocorrelation Function

- Mean level spacing $\langle D \rangle = \dfrac{1}{\langle \rho \rangle}$

  proportional to the variance of $\langle d(E_x) \rangle$

- Intensity fluctuations in $\langle d(E_x) \rangle$ can be autocorrelated at energies E and $E + \varepsilon$

$$C(\varepsilon) = \frac{\langle d(E_x) d(E_x + \varepsilon) \rangle}{\langle d(E_x) \rangle \langle d(E_x + \varepsilon) \rangle}$$

- $\langle D \rangle$ can be extracted from $C(\varepsilon) - 1 = \dfrac{\alpha \langle D \rangle}{2\Delta E \sqrt{\pi}} f(\varepsilon, \Delta E)$

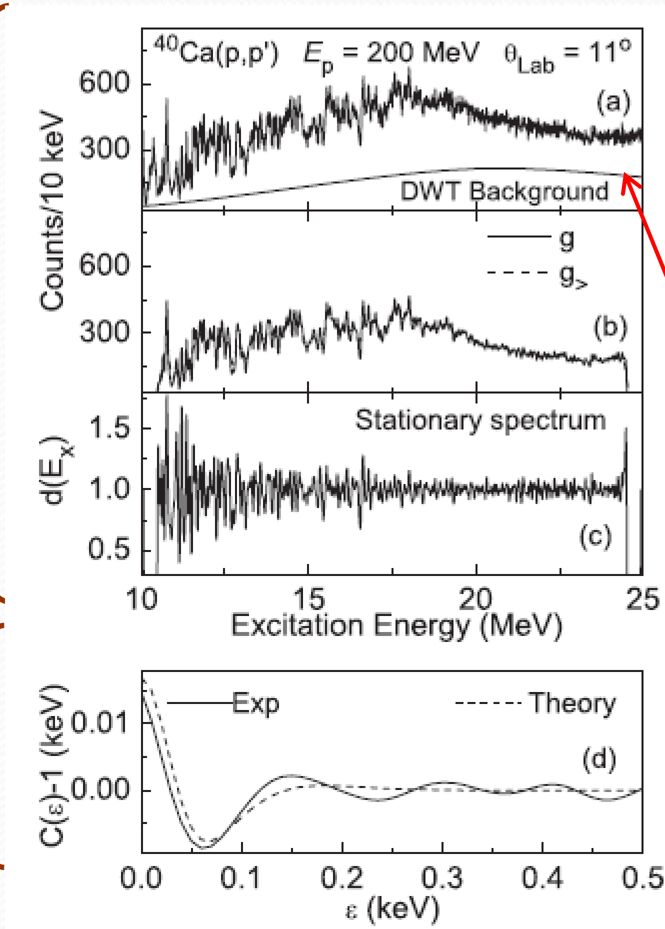
  ε = *energy increment*

  $C(\varepsilon)$ = *Autocorrelation function*

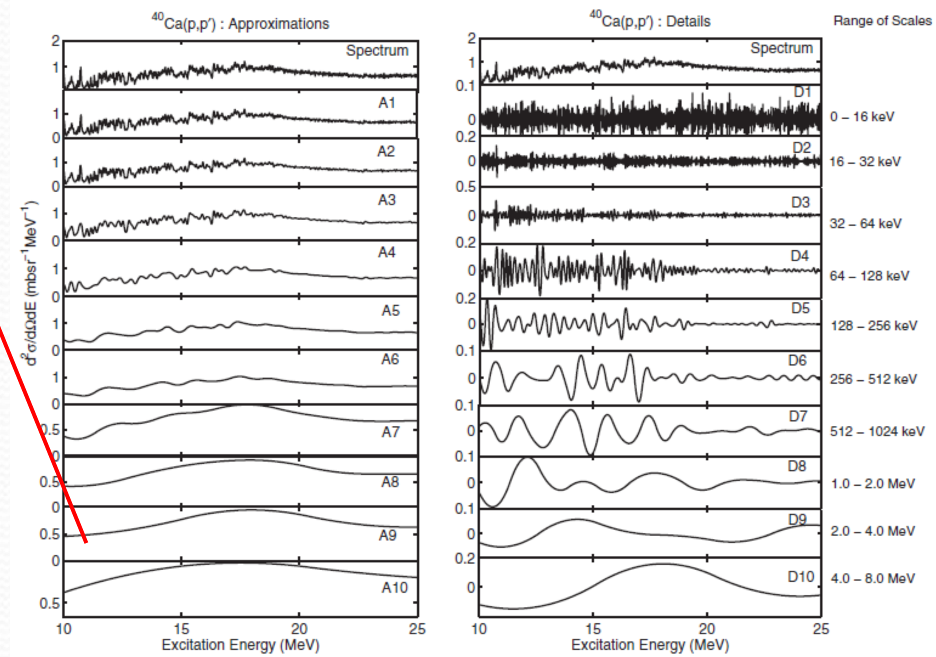
Level density: Background Subtraction and Autocorrelation Function

Fluctuation Analysis

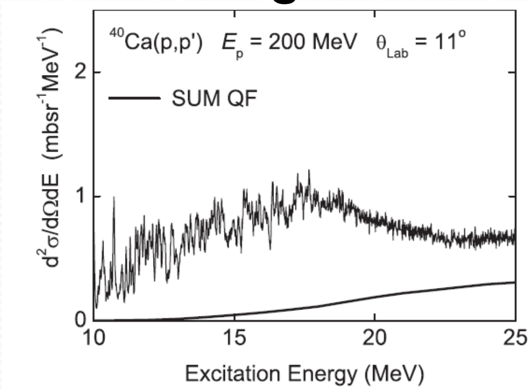
Autocorrelation



DWT Background subtraction

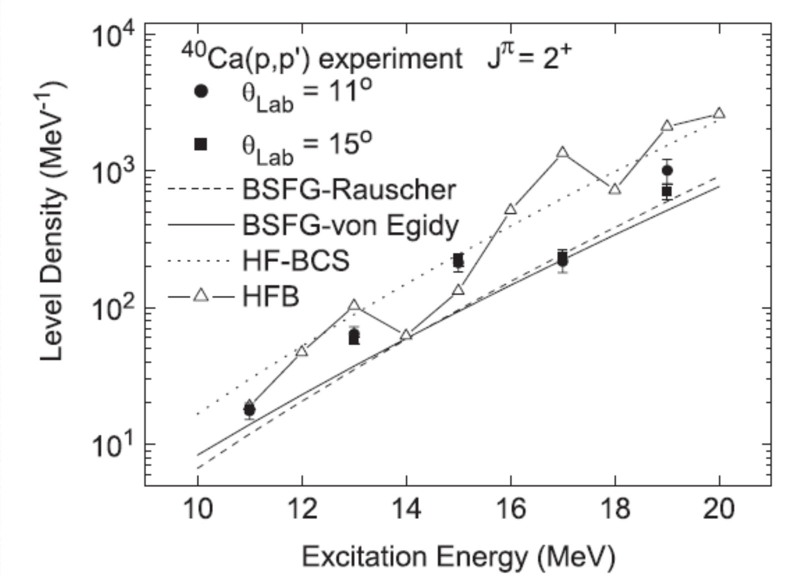


Quasi-free Background subtraction



Limited contribution from quasi-free in the ISGQR region

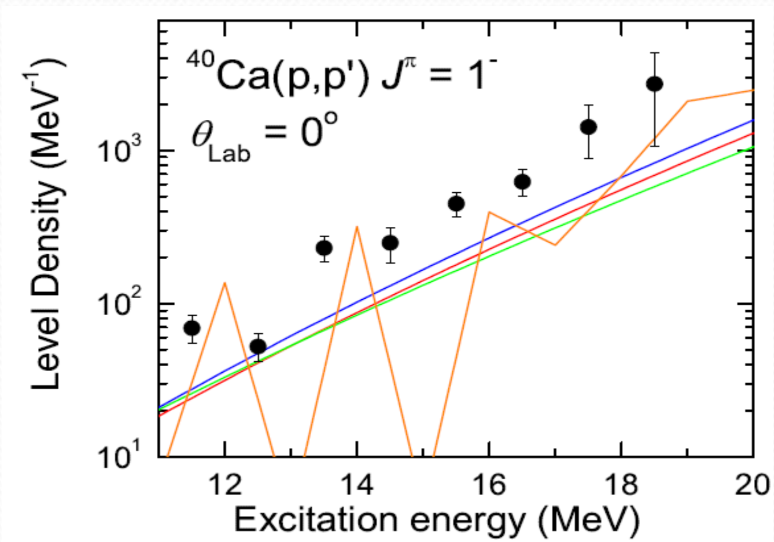
Spin-parity-resolved Level Densities



I. Usman *et.al.*, PRC 84 (2011) 054322

TABLE I. Level density of 2^{+} states in ^{40}Ca at various excitation energies E_x extracted from the (p, p') data at scattering angles $\theta_{Lab} = 11°$ and 15 °.

E_x (MeV)	Level density (MeV^{-1})	
	11°	15°
11	$17.5^{+2.9}_{-3.1}$	$18.1^{+3.0}_{-1.9}$
13	$64.1^{+10.6}_{-10.7}$	$57.3^{+9.5}_{-6.6}$
15	213^{+35}_{-38}	224^{+37}_{-32}
17	217^{+36}_{-43}	236^{+39}_{-37}
19	1007^{+166}_{-226}	705^{+116}_{-122}

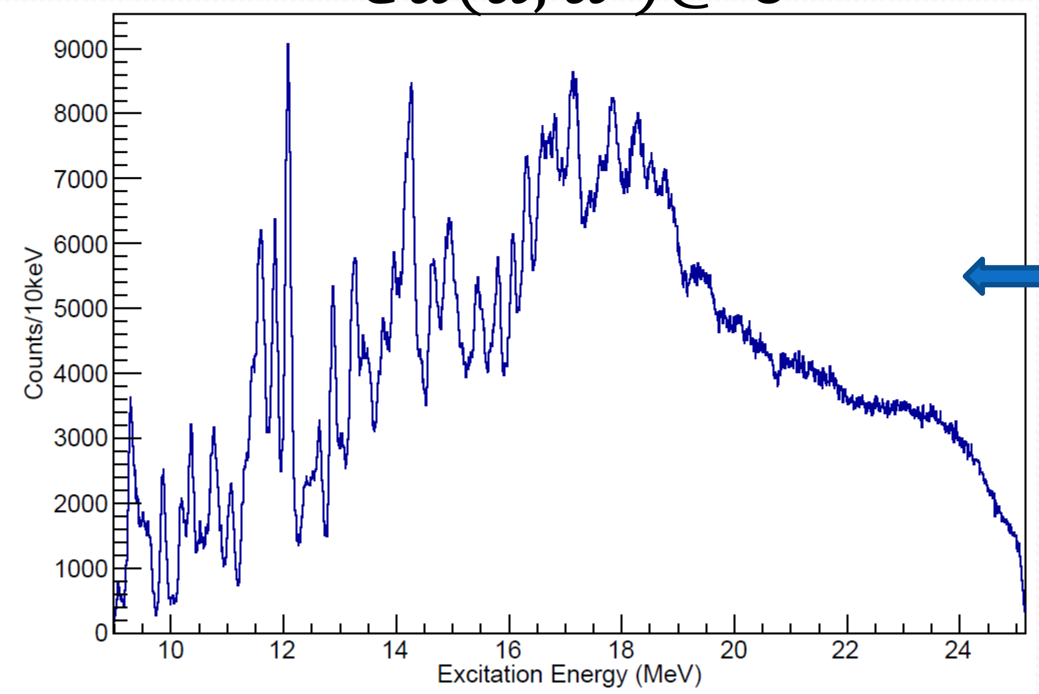


M. Jingo, PhD Thesis (2014)
University of the Witwatersrand

Experimental (filled symbol)
BSFG-Rauscher (red);
BSFG-von Egidy (Green);
HF-BCS (Blue);
HFB (Orange);

Ongoing work:
Fine structure of the ISGMR in ^{40}Ca

$^{40}Ca(\alpha,\alpha')@\,0^o$



Preliminary data analysis !!!

Level density of $J^{\pi} = 0^{+}$ states to be extracted !!!

Summary

- The Fine structure conforms to the global character of phenomenon in ISGQR and IVGDR
- Theoretical calculations: RPA, SRPA, R-QRPA and R-QTBA reveal good agreements with the experimental energy scales
- Spin-parity dependent level densities extraction as important ingredients used as input for calculations in nuclear astrophysics

UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG

DFG Deutsche Forschungsgemeinschaft

NRF National Research Foundation

iThemba LABS Laboratory for Accelerator Based Sciences

Thank you