Extraction of level density of 2^+ states in ^{208}Pb and ^{120}Sn nuclei from high energy-resolution (p,p') experiments

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https://www.wits.ac.za/physics/research-areas/nuclear-and-radiation-physics/

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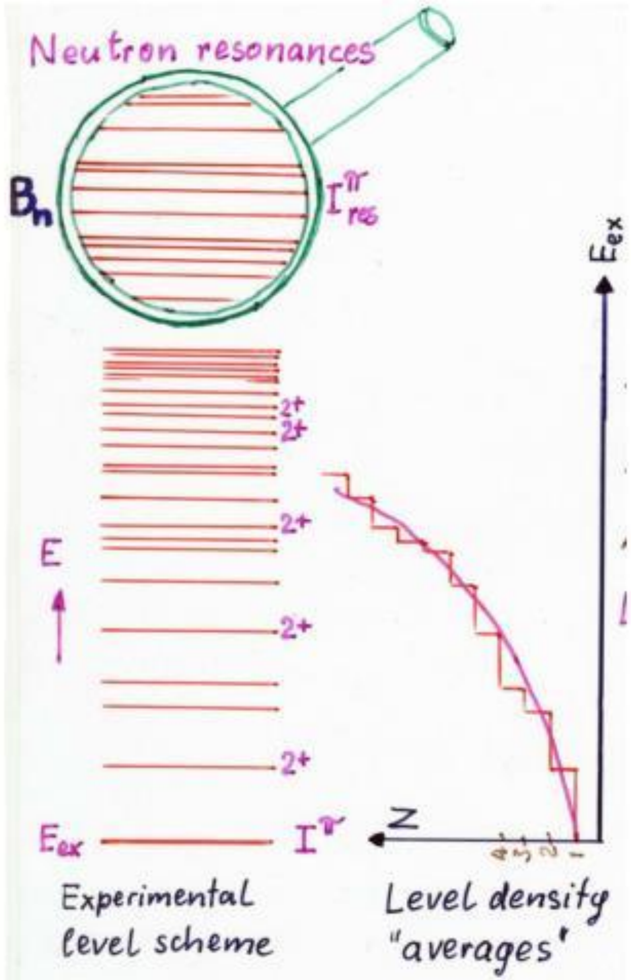
Outline

- Motivation
- Experiments
- Theoretical Models
- Fluctuation Analysis and Autocorrelation functions
- Results
- Conclusion and Outlook

Motivation

Energy Levels of nuclei



Level densities: **averages**

Average level density **ρ(E):**

$$\rho(E) = dN/dE = 1/D(E)$$

Cumulative number **N(E)**

Average level spacing **D**

Level spacing $S_i = E_{i+1} - E_i$

D(E) *determined by fit to individual level spacings* S_i

Level spacing correlation:

Chaotic properties determine fluctuations about the averages and the errors of the LD parameters.

- **High density of unresolved states above S_n**
- **Is there a direct measurement covering both low-lying and giant resonance regions?**

Motivation

PHYSICAL REVIEW C 84, 054322 (2011)

Level density of 2^+ states in ^{40}Ca from high-energy-resolution (p,p') experiments

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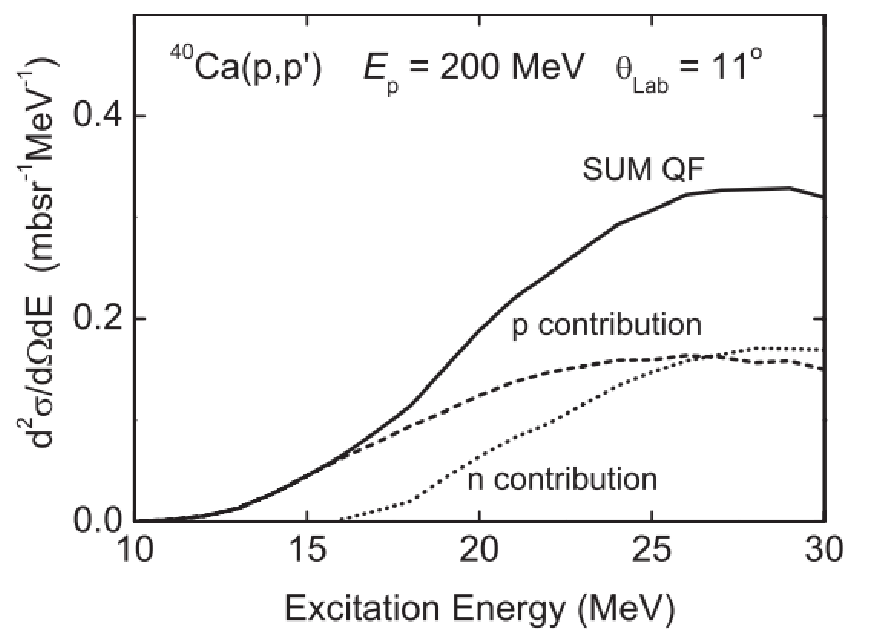
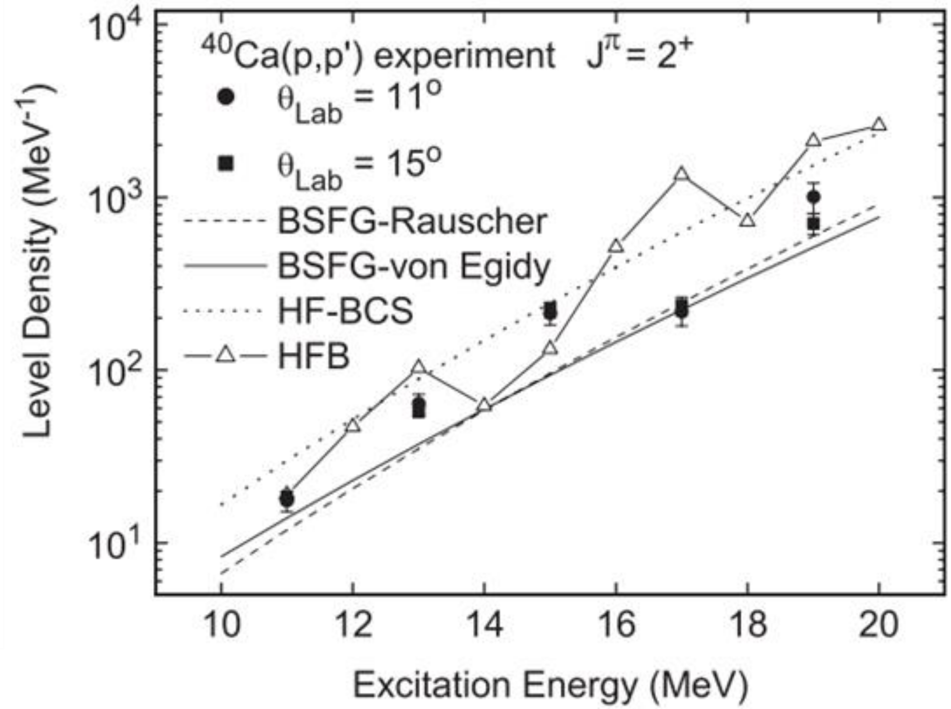
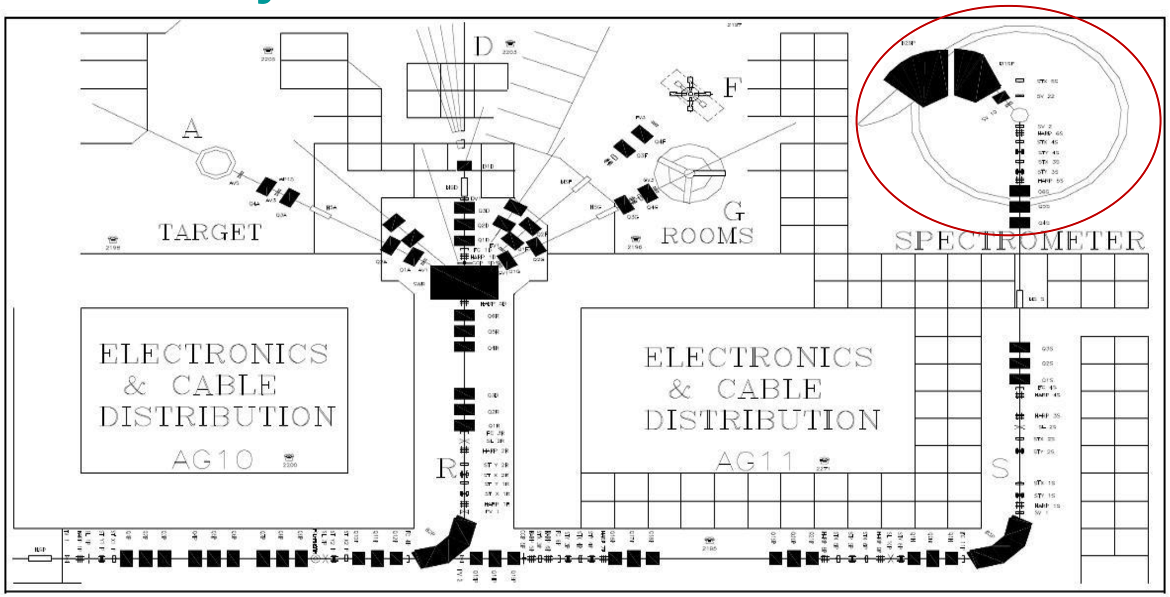


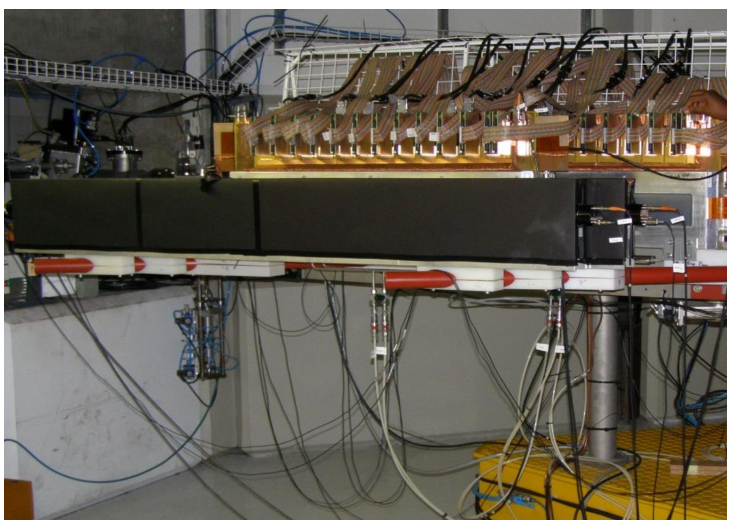


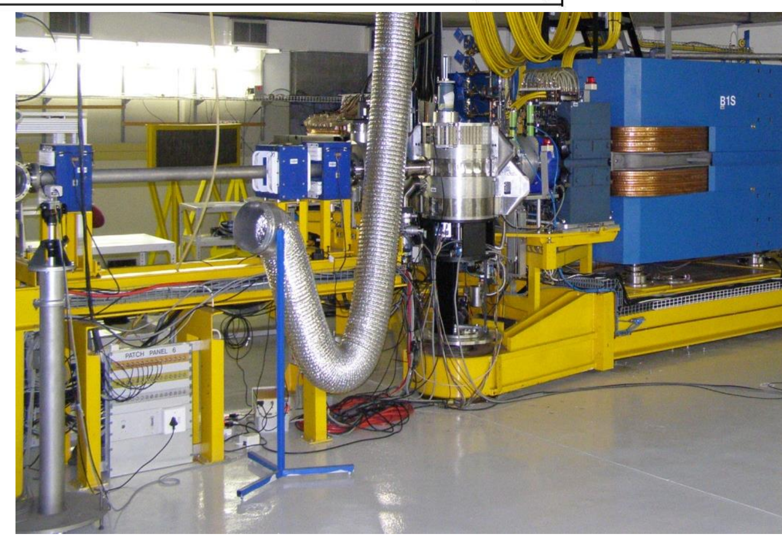
Backgrounds determined using Quasi-free + DWT

Experiments

Nuclear Physics Beamlines at iThemba LABS



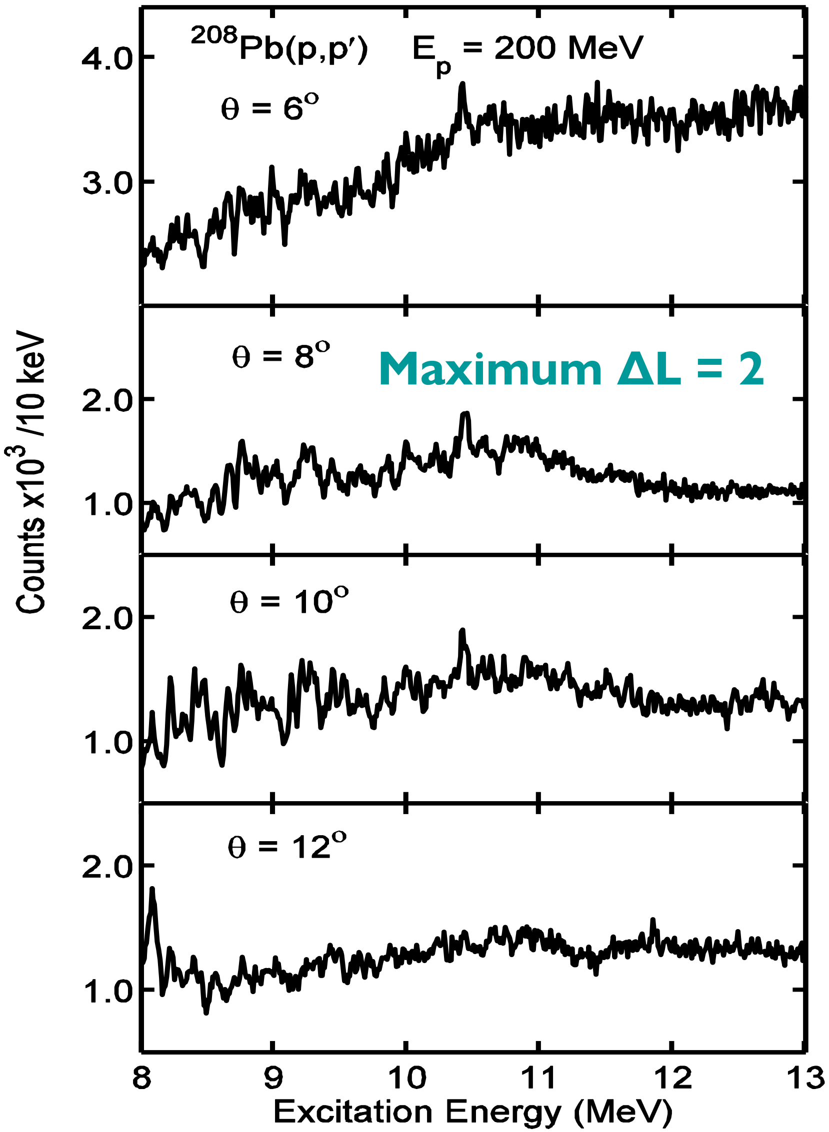


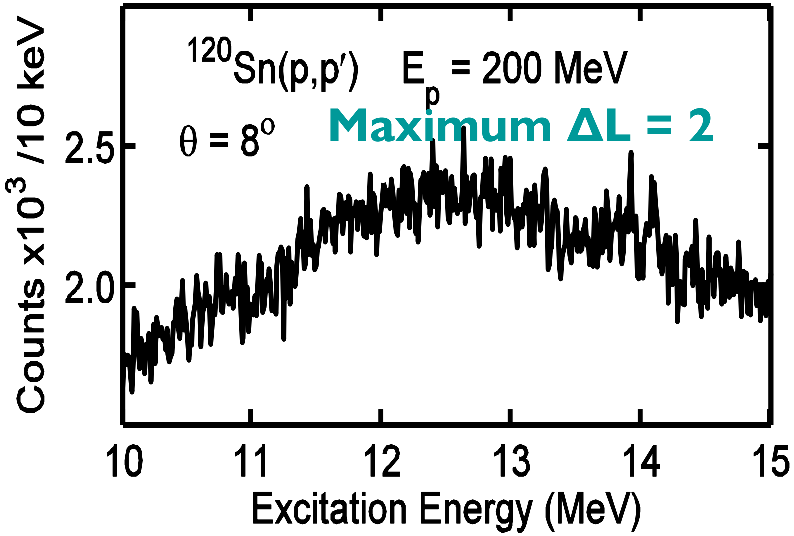


✓High energy-resolution ⟶ 25 – 45 keV @ E_p = 200 MeV

✓Dispersion matching technique

Energy Spectra: ^{208}Pb, ^{120}Sn





A. Shevchenko, *et.al.*, Phys. Rev. C 77, (2008) 024302.
A. Shevchenko *et al.*, Phys. Rev. Lett. 93, (2004) 122501.

Theoretical Models

1) Back-Shifted Fermi Gas (BSFG)

Phenomenological Approach

T. Rauscher, F. K. Thielemann, and K.-L. Kratz, Phys. Rev. C 56, (1997) 1613.
T. von Egidy and D. Bucurescu, Phys. Rev. C 80, (2009) 054310.

$$\rho\left(E_x, J\right) = \frac{2J+1}{2\sigma^2} \frac{\exp\left(2\sqrt{a\left(E_x-\delta\right)} - J\left(J+\tfrac{1}{2}\right)^2 / 2\sigma^2\right)}{12\sqrt{2\sigma}\, a^{1/4}\left(E_x-\delta\right)^{5/4}}$$

with

$$\delta = \Delta\left(Z, N\right)$$

$\boldsymbol{\rho(Ex)}$ = Level density at energy E_x
$\boldsymbol{\sigma}$ = Spin-cutoff parameter
$\boldsymbol{a}$ = *L*evel density parameter
$\boldsymbol{\delta}$ = Backshift energy
Δ = Pairing energy

Theoretical Model Parameters

	^{208}Pb	^{120}Sn
mass number A	208	120
number of protons Z	82	50
number of neutrons N	126	70
spin of states	2	2
parity of states	+	+
back shift in MeV	1.9089	1.9620
microscopic energy correction in MeV	-12.84	0.19
mass of the (Z,N) nucleus in MeV	193729	111688
mass of the (Z+1,N+1) nucleus in MeV;	195598	113553
mass of the (Z-1,N-1) nucleus in MeV	191865	109829
pairing energy in MeV	-3.22602	-3.3248
Proton separation energy in MeV	8.00376	10.6895
Neutron separation energy in MeV	7.36786	9.10802
Alpha separation energy in MeV	-0.51687	4.81059
local level density parameter BSFG in MeV^{-1}	10.01	13.14
local energy shift BSFG in MeV	1.17	0.85

2) Hartree-Fock-Bogoliubov (HFB) and HF-BCS

Microscopic Single-Particle Levels Approach

P. Demetriou and S. Goriely, Nucl. Phys. A 695, (2001) 95.
S. Goriely, S. Hilaire, and A. J. Koning, Phys. Rev. C 78, (2008) 064307.

- Calculations using basic nuclear structure properties:
  Single-particle energies ε_i^k
  Pairing strength Δ_i^k
  Quadrupole deformation parameter β_2
  Deformation energy E_{def}
- For spherical nuclei:

$$\rho_{sph}\left(E,J,\pi\right)=\rho_i\left(E,M=J,\pi\right)-\rho_i\left(E,M=J+1,\pi\right)$$

- For deformed nuclei:

$$\rho_{def}\left(E,J,\pi\right)=\frac{1}{2}\left[\sum_{k=-J,k\neq 0}^{J}\rho_i\left(E-E_{rot}^{J,k},K,\pi\right)\right]+\delta_{(Jeven)}\delta_{(\pi=+)}\rho_i\left(E-E_{rot}^{J,0},0,\pi\right)$$
$$+\delta_{(Jodd)}\delta_{(\pi=-)}\rho_i\left(E-E_{rot}^{J,0},0,\pi\right)$$

Fluctuation Analysis

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

$\langle \Gamma \rangle$ Mean level width

$\langle D \rangle$ Mean level spacing

ΔE Energy resolution

α Sum of normalised variances

Assumptions:

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

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

Procedure:

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

Autocorrelation Function

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

  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* + ***ε***

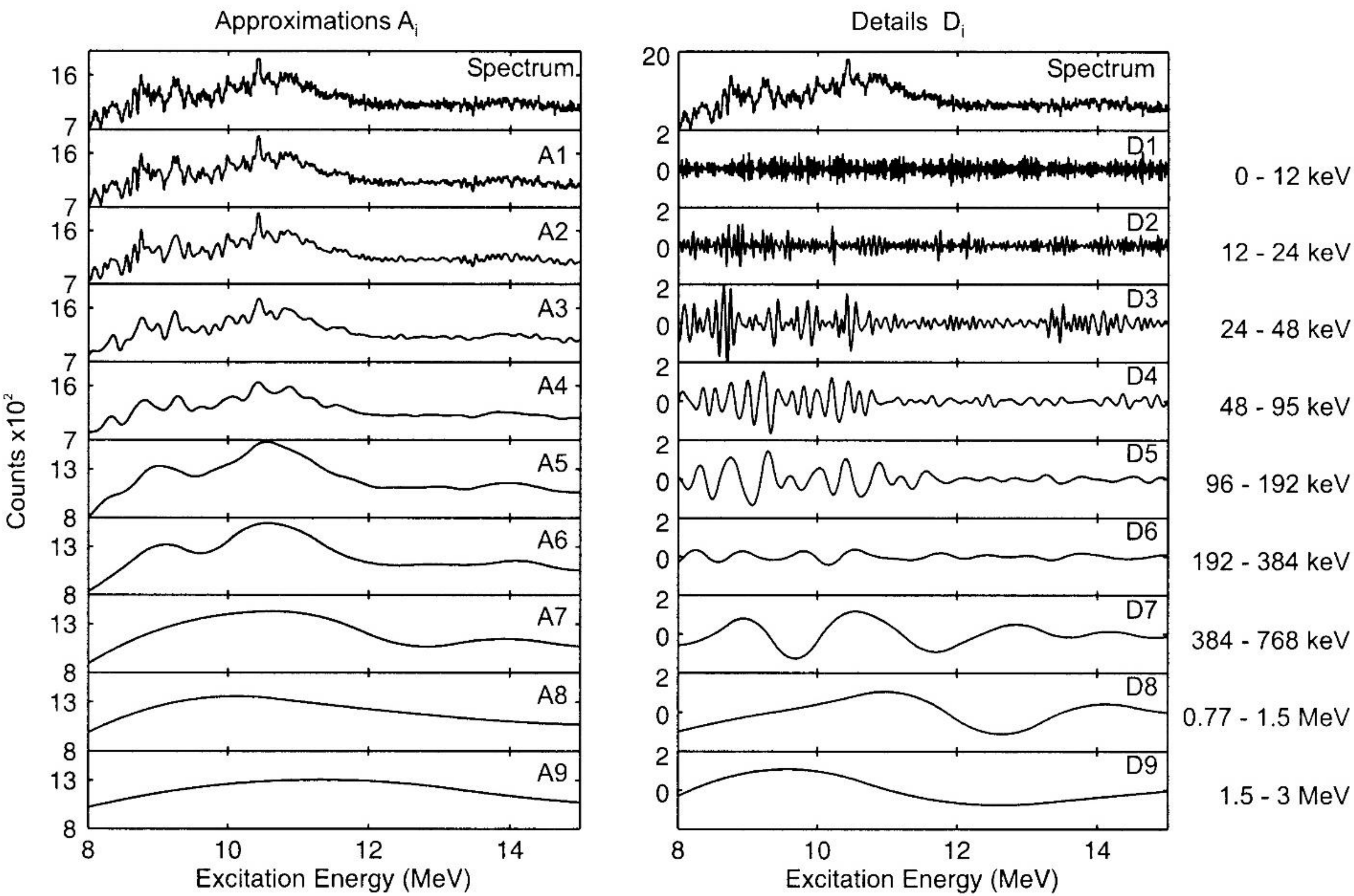
$$C(\varepsilon) = \frac{\langle d(E_x) d(E_x + \varepsilon) \rangle}{\langle d(E_x) \rangle \langle d(E_x + \varepsilon) \rangle}$$

- $\langle D \rangle$ can be extracted from

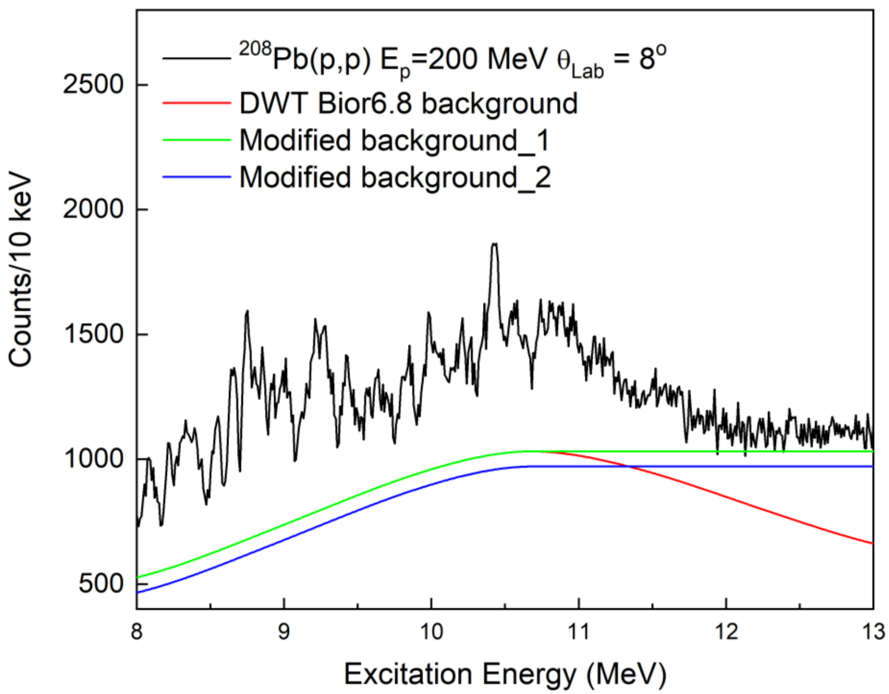
$$C(\varepsilon) - 1 = \frac{\alpha \langle D \rangle}{2\Delta E \sqrt{\pi}} f(\varepsilon, \Delta E)$$

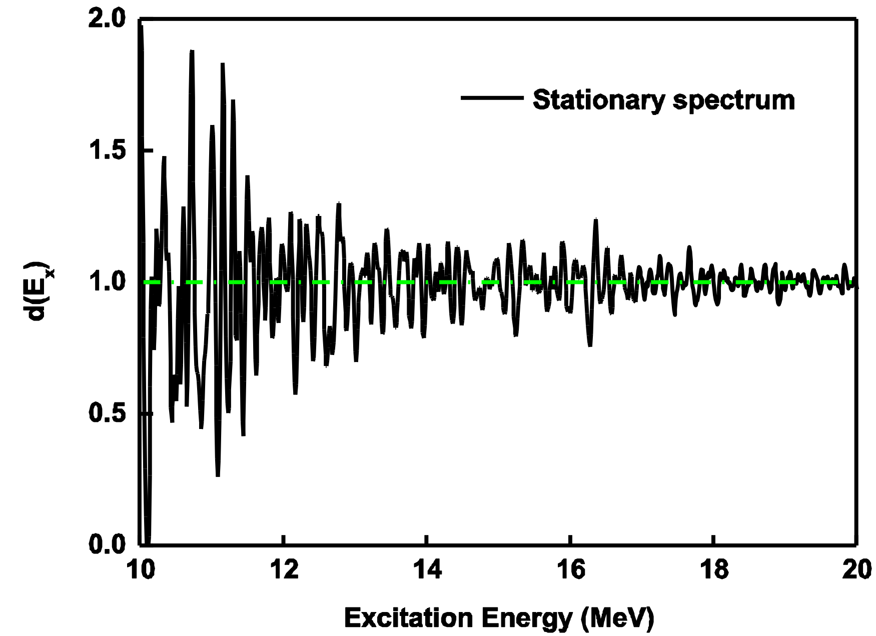
ε *= energy increment;* ***C***(***ε***) *= Autocorrelation function*

Discrete Wavelet Transform (DWT) of $^{208}Pb(p,p')$ data



Background subtraction, Fluctuation Analysis, and Autocorrelation function

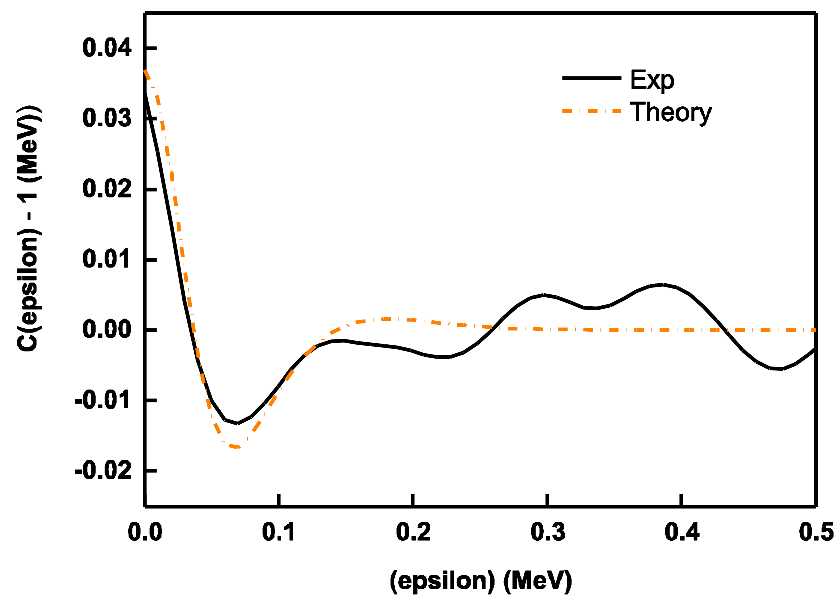




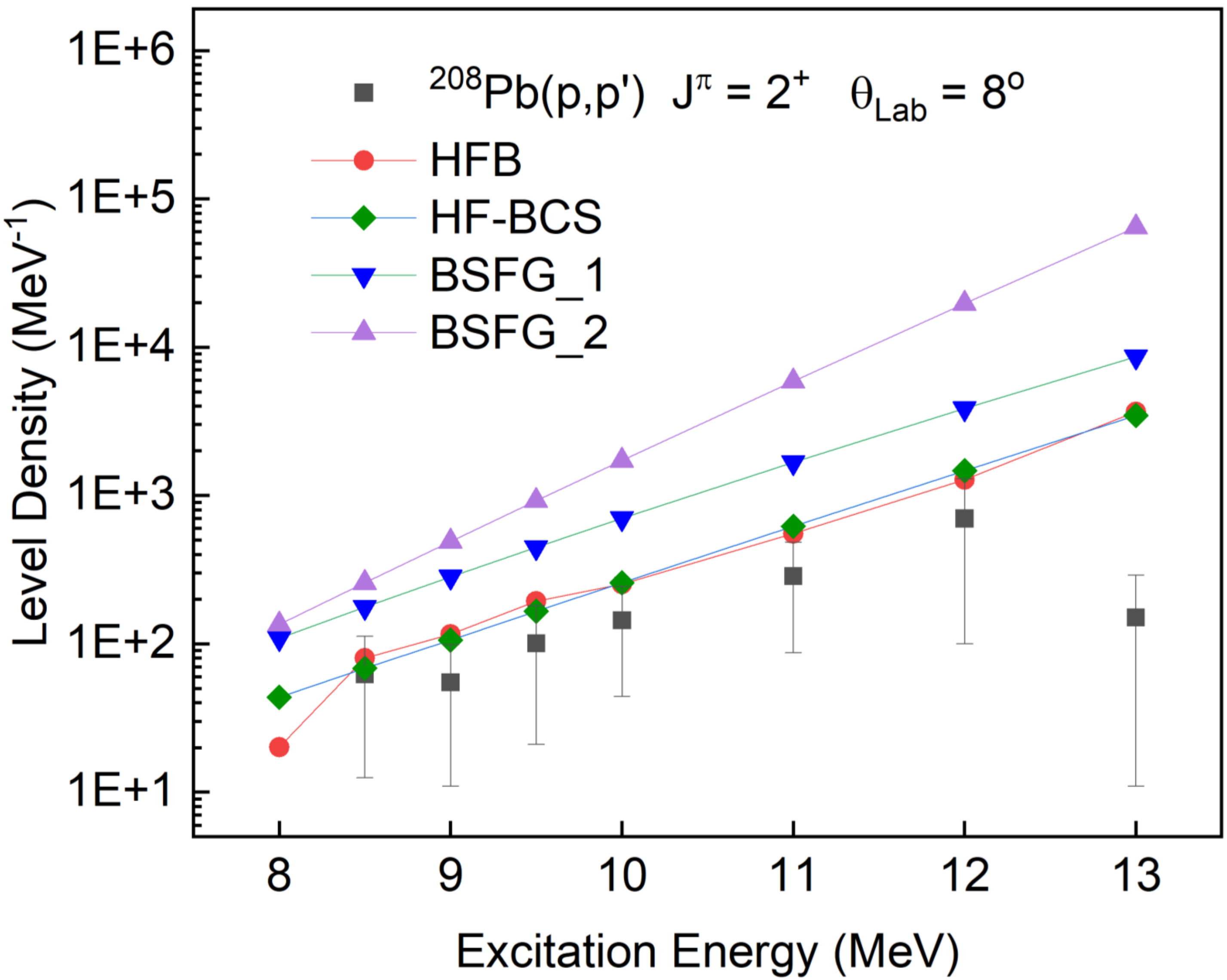
Top Left: Data plus background

Top Right: Stationary Spectrum averaged around 1

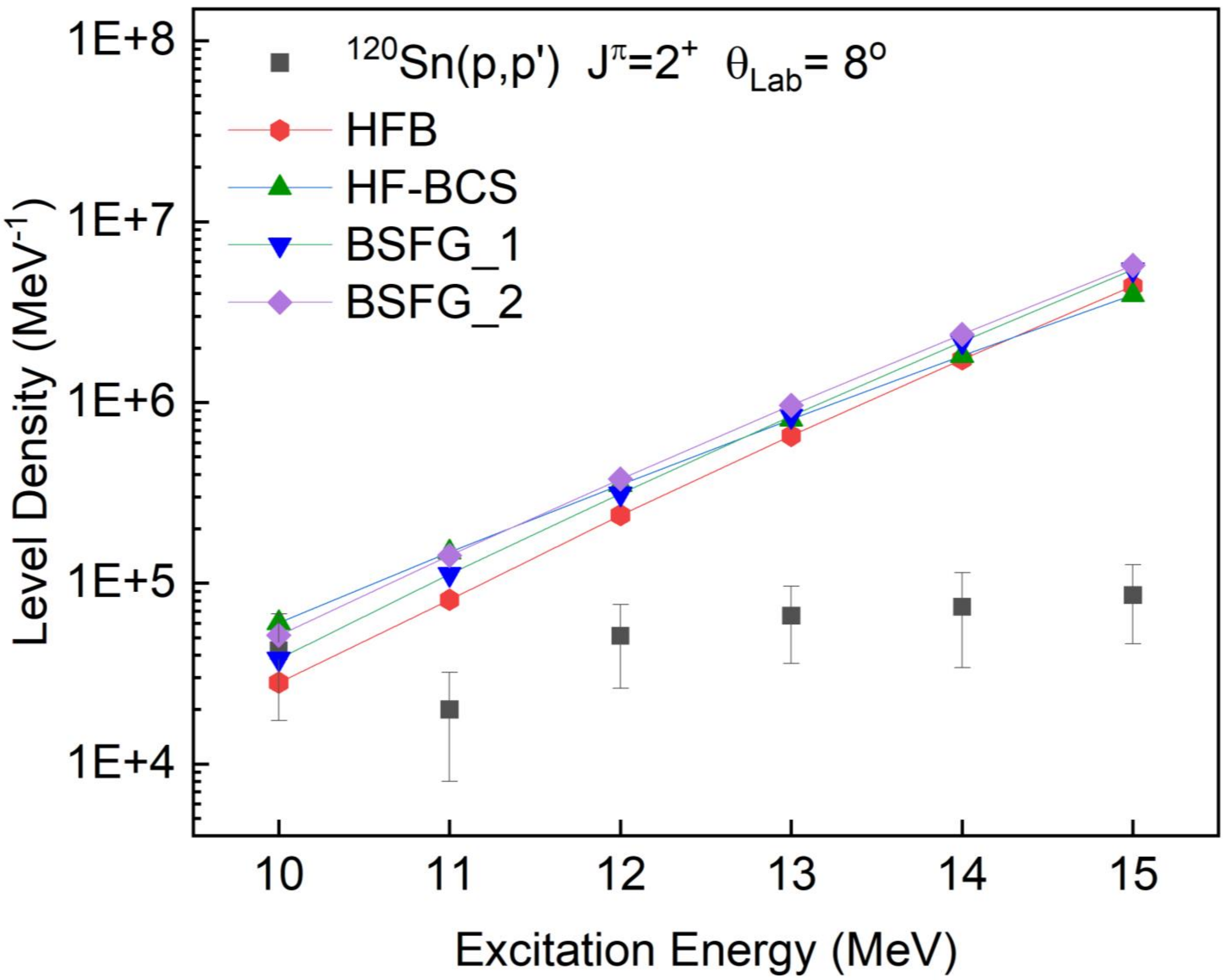
Bottom Right: Autocorrelation function



Experimental and Theoretical Level Density: ^{208}Pb



Experimental and Theoretical Level Density: ^{120}Sn



Summary

- Experimental level density in ^{208}Pb and ^{120}Sn using Autocorrelation function analysis provides fair agreements compared to all models.

- The selectivity of the ISGQR and high energy-resolution data obtained at iThemba LABS makes it an ideal choice for level density extraction above neutron threshold

- Parity dependence results was found to be important.

Conclusions *and* Outlook

- Extracted level densities in the giant resonance region of heavy magic nuclei (^{208}Pb and ^{120}Sn) are considered very low.
- ISGQR data in heavy nuclei is prone to very low peak to background ratio.
- Uncertainties can be due to the assumed background which might not include background due to quasi-free continuum.

- Calculations on ^{90}Zr and ^{58}Ni in progress.
- Comparison with $M2(2^-)$ data from electron spectrometer to be investigated.

Collaborators

I.T. Usman[1], J. Carter[1], E. Sideras-Haddad[1], R. Neveling[2], F. D. Smit[2], R. W. Fearick[3], H. Fujita[4], Y. Fujita[4], P. von Neumann-Cosel[5], A. Richter[5] and A. Shevchenko[5]

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