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2^+ level densities in ^{40}Ca extracted from high energy-resolution (p,p′) experiments

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Abstract. Level densities of 2^+ states in ^{40}Ca have been extracted from the high energy-resolution (p,p′) experimental data by means of a fluctuation analysis. Two different methods of background determination have been considered, namely, Quasi-free calculations and Discrete Wavelet Transform (DWT) technique. The results are then compared to theoretical models based on phenomenological and microscopic approaches.

Level density is one of the classical and fundamental quantities in the description of many-body systems. This is particularly so for reaction cross-sections [1] needed for many practical applications in astrophysics for determining thermonuclear rates for nucleosynthesis and in fission and fusion reactor design [2] as well as in structure models. The purpose of this work is to extract for ^{40}Ca specific spin- and parity-dependent level densities from the high energy-resolution isoscalar giant quadrupole resonance (ISGQR) data in the excitation energy region between 10 and 20 MeV. The method involves the use of fluctuation analysis, incorporating the autocorrelation function. This type of analysis has been successfully applied recently to giant resonance data [3, 4] whereby spin- and parity-resolved level densities were extracted in the region of the Gamow-Teller (GT) and magnetic quadrupole resonances, respectively.

High energy-resolution experiments on the ISGQR have been performed [5] for the low-mass region $12 \leq A \leq 40$ using a 200 MeV proton beam produced by the Separated Sector Cyclotron (SSC) of the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), South Africa. The proton beams were dispersion-matched to the K600 magnetic spectrometer and inelastically scattered on a ^{40}Ca target with areal density of 3.0 mg/cm^2. Dispersion matching techniques were used in order to exploit the high energy-resolution capability of the spectrometer. Energy resolutions of ΔE $\simeq$ 40 keV (FWHM) were achieved which revealed pronounced fine structure of the ISGQR. The scattering angle was selected to be at the maximum of the cross section for $\Delta L = 2$ transitions into the ISGQR. In particular, the resulting measured spectra allowed for the extraction of 2^+ level densities for ^{40}Ca in the region of the ISGQR.

In this study, the level densities of 2^+ states in ^{40}Ca were extracted by means of a self-consistent procedure based on a fluctuation analysis [6] in the excitation energy interval between 10 and 20 MeV on a background-subtracted spectrum. This method employs the autocorrelation function [7] in order to obtain a measure of the cross-section fluctuations with respect to a stationary mean value. The background contributions due to the experimental instrumentation, multipole admixtures and quasi-free scattering were treated explicitly in the excitation energy region of interest. Quasi-free scattering can contribute significantly to the background in the excitation energy region just above the particle thresholds at forward scattering angles where the ISGQR is measured. Here, the excitation energies of ^{40}Ca(p,p$'$) in the region of the ISGQR are a few MeV above the proton and neutron thresholds. As such, the contributions from (p,2p) and (p,pn) reactions to the measured ^{40}Ca(p,p$'$) data were calculated within the Distorted Wave Impulse Approximation (DWIA) [8]. In addition, the shape of the non-resonant background was also determined in a nearly model independent way [3, 4, 9] using Discrete Wavelet Transform (DWT) [10] analysis techniques employing a Biorthogonal wavelet of higher vanishing moment. The fluctuation analysis provides a method to determine the level densities of excited nuclei in the region of overlapping levels. This method is applicable to the energy range where $\langle\Gamma\rangle/\langle D\rangle \ll 1$ with $\langle D\rangle < \Delta E$, with $\langle\Gamma\rangle$ representing the mean level width, $\langle D\rangle$ is the mean level spacing and ΔE is the experimental energy resolution. Wigner and Porter-Thomas distributions have been applied in the estimation of mean widths and resonance spacings as explained in the calculation of nuclear reaction data [1]. The resulting spectrum is shown in Fig. 1a, b and c. The stationary spectrum (Fig. 1c) is a direct measure of the local intensity fluctuations. The experimental autocorrelation function can be approximated by an analytical expression [6] which depends only on the experimental energy resolution ΔE and can be simplified as

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

where the function $f(\epsilon, \Delta E)$ is normalised such that $f(\epsilon = 0) = 1$ and ϵ is the energy increment at excitation energy E_{x}. The value $C(\epsilon = 0) - 1$ is known as the variance. From Eq. (1), the value of the variance of the stationary spectrum is proportional to the mean level spacing $\langle D\rangle$. Thus, $\langle D\rangle$ can be extracted directly once the value of the normalised variance α is known. Figure 1d shows results of autocorrelation functions for both the theoretical model and the experimental data. Finally, the level density in each excitation energy interval of 2 MeV can be calculated as the reciprocal of the mean level spacing.

Basic research on nuclear level densities has been concerned with various phenomenological and microscopic models, their validation by comparison with measurements and the extraction of level density parameters from experimental data. For example, the Back-Shifted Fermi Gas (BSFG) model [11] provides a fit on stable nuclei across the nuclear chart by including parameters for an improvement of the description in local mass areas. The BSFG model of Ref. [12] performed a global fit with parameters dependent on experimental masses only. Hartree-Fock Bogoliubov (HFB) plus combinatorial [14] is an example of a microscopic model which includes rotational and vibrational degrees-of-freedom together with a combinatorial model for the occupation of single-particle states. There exists also the Hartree-Fock-Bardeen-Cooper-Schriffer (HFBCS) [15] Model. As can be seen in Fig. 2, the phenomenological models of BSFG give a good estimate of the extracted 2^+ level densities in the region of ISGQR while the microscopic calculations HFB and HF-BCS over estimates the observed level densities by a factor of two. The uncertainties of the extracted level densities were obtained by varying the input parameters of the autocorrelation function and the fluctuation analysis as well as the background subtraction method and repeating the analysis. These lead to about 17% error in the extracted level densities. In conclusion, both microscopic and phenomenological approaches are good for the level density calculations in the considered excitation energy region.

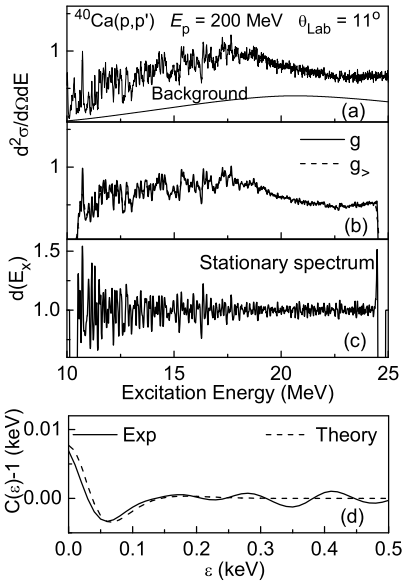

Figure 1. From top to bottom: experimental ^{40}Ca(p,p′) spectrum including background, smoothed spectra $g(E_x)$ and $g_>(E_x)$, stationary spectrum d(E_x) obtained by dividing the two smoothed spectra, autocorrelation functions from experiment (full line) and theoretical (dashed line) model.

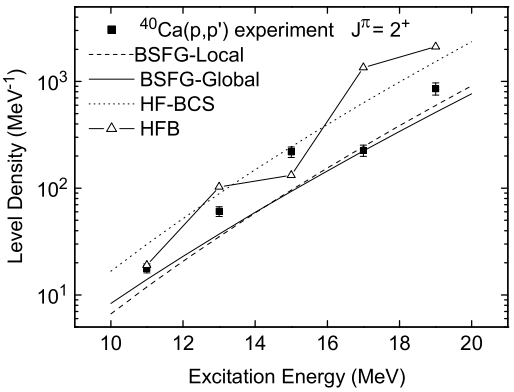

Figure 2. Extracted level density of 2^+ states in ^{40}Ca(p,p′) (Filled square) compared to local BSFG [11] (dashed line), global BSFG [12] (full line), HF-BCS [15] (dotted line) and HFB [14] (open triangle) theoretical model calculations.

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