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Nuclear Physics A 788 (2007) 136c–141c
NUCLEAR PHYSICS A

Spin- and Parity-Resolved Level Densities from High-Resolution Hadron and Electron Scattering Studies of Giant Resonances*

Y. Kalmykov[a], K. Langanke[b a], G. Martínez-Pinedo[b], D. Mocelj[c], P. von Neumann-Cosel[a], I. Poltoratska[a], V.Yu. Ponomarev[a †], A. Richter[a], A. Shevchenko[a], J. Wambach[a]

[a]Institute für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany

[b]Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany

[c]Institut für Physik, Universität Basel, 4056 Basel, Switzerland

We present spin- and parity-resolved level densities extracted from high-resolution hadron and electron scattering data by means of a fluctuation analysis. A nearly model-independent method based on discrete wavelet transform is introduced for the determination of a non-resonant background. The data obtained are compared to the predictions of two models widely used in applications for astrophysical network calculations with an emphasis on a possible parity dependence of nuclear level densities.

1. Introduction

Level densities play a crucial role in numerous studies. One of the most prominent examples are astrophysical network calculations. They commonly use two models. One of them is the back-shifted Fermi gas (BSFG) model [1,2], i.e. a semiempirical approach taking into account shell closures and pairing effects. Besides, level densities obtained with a microscopic statistical model [3] are often applied. These calculations are performed using the deformed Hartree-Fock-BCS (HF-BCS) predictions of the ground-state structure properties and include a consistent treatment of the shell effects, pairing correlations, deformation effects and collective excitations. Although these models provide comparable degrees of accuracy there are still discrepancies affecting the results of the network calculations. Thus, one of our goals is to test them by high-resolution studies of giant resonances. Another aspect is a possible parity dependence of level densities in the excitation energy region of giant resonances. So far, astrophysical network calculations neglect it [4]. On the other hand, Monte-Carlo shell model calculations [5,6], although questioned by recent experiments [7], predict a significant parity dependence in the pf-shell mass region which is of prime interest in astrophysics. Our data with a strong sensitivity to modes with a specific spin and parity enable us to check this issue.

*This work was supported by the SFB 634 of the Deutsche Forschungsgemeinschaft.
†Permanent address: Bogoliubov Laboratory for Theoretical Physics, JINR, Dubna, Russia.

0375-9474/$ – see front matter
doi:10.1016/j.nuclphysa.2007.01.059

2. Fluctuation Analysis

Usually the mean level spacing in the region of giant resonances is smaller than the achieved energy resolution. Thus, fluctuations result from the high density of non-resolved states and their incoherent overlap. In this regime level spacings can be determined by means of a fluctuation analysis. Its detailed description and some examples can be found elsewhere [8–11]. For the lack of space we give a short introduction only.

This technique is restricted to the energy range where the mean level width is smaller than the average distance between levels $\langle D \rangle$ and is based on two assumptions. In a highly excited nucleus with strong configuration mixing of levels with the same spin and parity, the spacing between adjacent states is given by the Wigner distribution [12], and the transition strengths obey a Porter–Thomas distribution [13]. The analysis is carried out as follows. The measured spectrum, with the background subtracted, is smoothed by convolution with a Gaussian function whose width is large compared to the experimental resolution σ. To reduce uncertainties arising from the finite statistics the spectrum is also folded with a Gaussian function with a width smaller than σ. Dividing the folded spectra by each other leads to a stationary spectrum $d\,(E_x)$ whose individual points lie around $\langle d\,(E_x) \rangle = 1$. The main idea is to take advantage of the autocorrelation function of $d\,(E_x)$ in order to obtain a measure of the cross-section fluctuations with respect to a stationary mean value. According to [8], this function is connected to $\langle D \rangle$ by

$$C(\epsilon) \; - \; 1 \quad = \quad \frac{\alpha \cdot \langle \mathrm{D} \rangle}{2\sigma\sqrt{\pi}} \; \times f\,(\epsilon, \sigma) \; , \tag{1}$$

where $f\,(\epsilon, \sigma)$ denotes a function depending on properties of the experimental spectrum only. The value α is a sum of the normalized variances of the assumed spacing and transition width distributions. For a spectrum containing states of several spins and parities its exact calculation already requires a knowledge of corresponding level densities. Thus, high selectivity is needed to extract $\langle D \rangle$ in a model-independent way and minimize the systematic error. Another requirement is obvious from Eq. (1). If σ is too large the autocorrelation function is strongly dumped leading to a significant uncertainty in the mean level spacing. Therefore, high resolution is also of great importance for the fluctuation analysis.

3. Experiments

Good selectivity is achieved by proper kinematics. For the present studies we utilize hadron scattering at very forward angles (including zero degrees) and intermediate energies. Another opportunity is provided by 180° electron scattering at low momentum transfers. High energy resolution can be achieved by lateral and angular dispersion matching, most effectively realized by the so-called "faint beam" method [14].

A spectrum of the ^{90}Zr(^{3}He,t)^{90}Nb reaction [15] is shown in Fig. 1(a). At $E_0 = 140$ MeV/u and $\Theta \approx 0°$ the selectivity to Gamow-Teller (GT) transitions is significantly enhanced. Owing to the good resolution $\Delta E = 50$ keV (FWHM) the fine structure of the GT resonance is clearly observed and one can extract level densities of 1^+ states in ^{90}Nb.

Electron scattering at 180° is a versatile tool to study transverse, first of all magnetic, excitations. Selectivity to a certain mode can be increased by varying the momentum

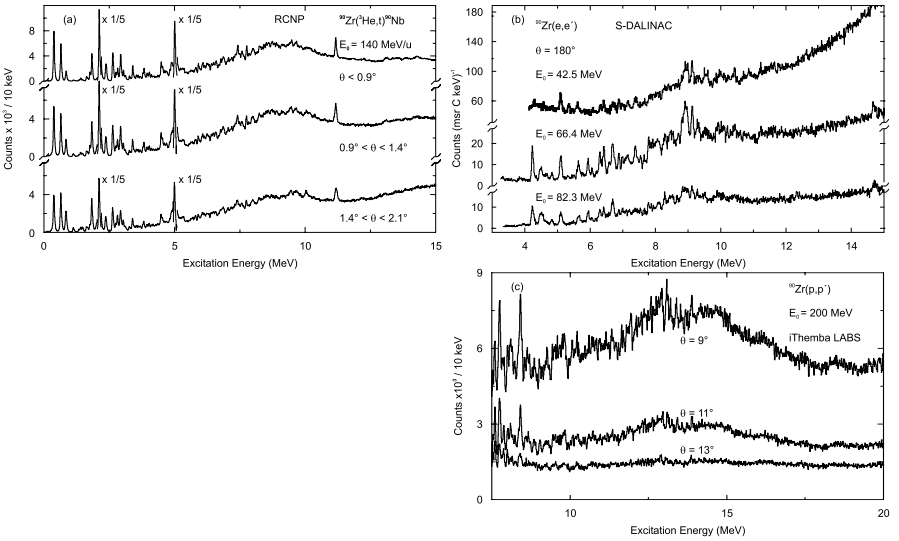

Figure 1. (a) Spectra of the ^{90}Zr(^{3}He,t)^{90}Nb reaction at $E_0 = 140$ MeV/u. (b) Spectra of the ^{90}Zr(e,e′) reaction at $\Theta = 180°$. (c) Spectra of the ^{90}Zr(p,p′) reaction at $E_0 = 200$ MeV.

transfer. Thus, $E_0 \approx 66$ MeV corresponds to the maximum of the M2 form factor in ^{90}Zr and 2^- states prevail in the middle spectrum of Fig. 1(b) taken from [16]. A resolution of $\Delta E \simeq 60$ keV (FWHM) also reveals the fine structure of the resonance and allows for an extraction of their densities.

In order to test the parity dependence, hadron scattering can be used for $J^\pi = 2^+$ states. Figure 1(c) shows spectra of the ^{90}Zr(p,p′) reaction at $E_0$200 MeV[17]. At $\Theta = 9°$ excitation of the isoscalar giant quadrupole resonance is dominant. Pronounced fine structure is visible and level densities of 2^+ states can be unraveled from the data.

The same data set exists for $A = 58$. For 1^+ states ^{58}Ni(^{3}He,t)^{58}Cu spectra are available [18]. High-resolution electron and proton scattering experiments [17,19,20] also studied M2 and isoscalar giant quadrupole resonances in ^{58}Ni, respectively.

4. Discrete Wavelet Transform and Background Determination

For background determination a wavelet analysis is used. This technique permits a separation of generic and nongeneric features of the spectrum and the extraction of information in the presence of noise [21]. By folding the original spectrum $\sigma(E)$ with a wavelet function Ψ, wavelet coefficients

$$C(E_x, \delta E) = \frac{1}{\sqrt{\delta E}} \int \sigma(E) \Psi(\frac{E_x - E}{\delta E}) dE \qquad (2)$$

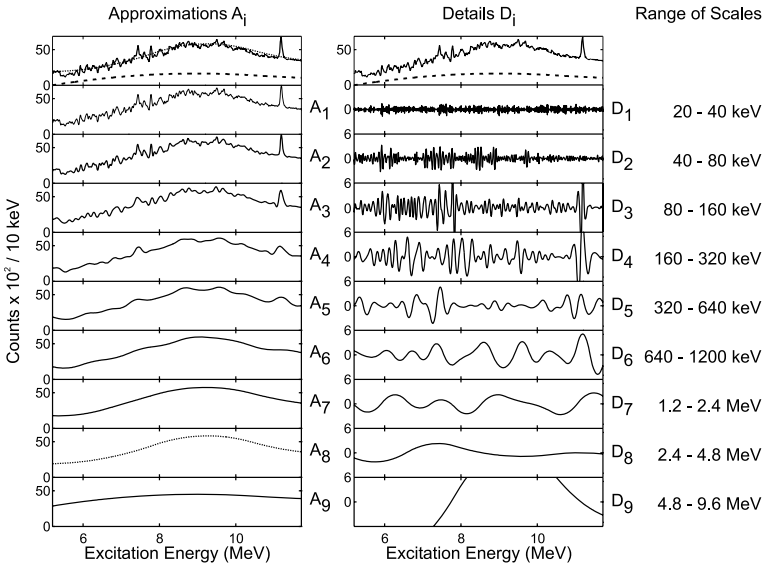

Figure 2. Discrete wavelet transform decomposition of the ^{90}Zr(^{3}He,t)^{90}Nb spectrum of Fig. 1(a). The dotted line (A_8) shows the largest physical scale in the spectrum. The dashed line in the total spectrum represents the deduced background.

are obtained. The parameters (excitation energy E_x and scale δE) can be varied continuously or in discrete steps $\delta E = 2^j$, $E_x = k\delta E$, j, $k = 1, 2, 3...$, corresponding to continuous or discrete (DWT) wavelet transform, respectively. The latter offers the possibility to reassemble the original signal from the wavelet coefficients. Another useful feature is linked to the number of vanishing moments. If the condition

$$\int E^n \Psi(E)\, dE = 0, \quad n = 0, 1...m \tag{3}$$

is satisfied, the function Ψ is said to have $m + 1$ vanishing moments. Therefore, any non-resonant background in the spectrum does not contribute to the wavelet coefficients if it can be approximated by a polynomial function of the mth order.

A nearly model-independent background definition is based on a scheme known as two-channel subband codding in signal processing. It can be interpreted as the application of lowpass (large δE) and highpass (small δE) filters on the spectrum separating it into a so-called approximation (A) and detail (D). Starting at the smallest scale one gets $\sigma(E) = A_1 + D_1$. Since D_1 is obtained from the wavelet coefficients, non-resonant background is found in the approximation. In the second step A_1 is decomposed into A_2 and D_2 and so forth. An example of such a decomposition is given in Fig. 2. The largest physical scale, viz. the total width of the GTR in ^{90}Nb, is reproduced by A_8. Thus, A_9 matches the shape of the background present in the spectrum. The analysis is repeated independently for various angle bins. Since the background shows a different angular dependence than

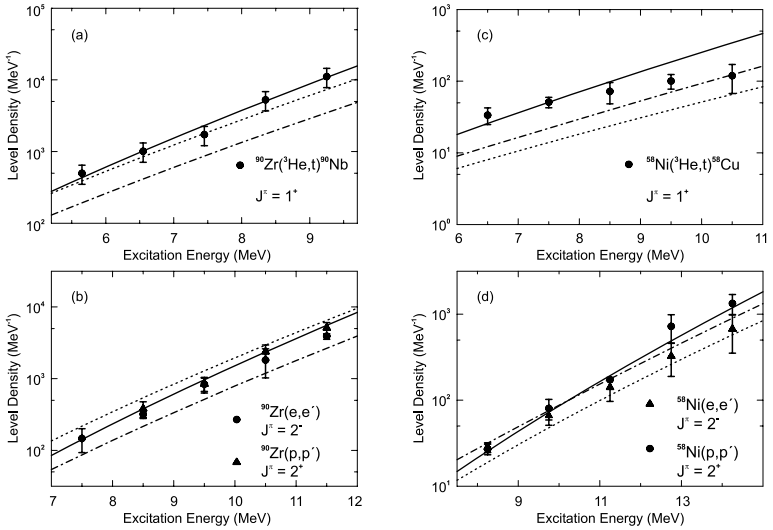

Figure 3. (a) Level density for 1^+ states in ^{90}Nb obtained from the ^{90}Zr(^{3}He,t)^{90}Nb measurement. (b) Level density for $J = 2$ states in ^{90}Zr obtained from the ^{90}Zr(e,e′) and ^{90}Zr(p,p′) measurements. (c) Same as (a) but for 1^+ states in ^{58}Cu obtained from the ^{58}Ni(^{3}He,t)^{58}Cu measurement. (d) Same as (b) but for $J = 2$ states in ^{58}Ni obtained from the ^{58}Ni(e,e′) and ^{58}Ni(p,p′) measurements. Solid lines: BSFG parametrization [1]. Dashed lines: BSFG parametrization [2]. Dashed-dotted lines: HF-BCS calculations [3].

the GT strength, the requirement of a constant level density in all spectra confirms the validity of the chosen background shape.

5. Results and Test of the Models

Figure 3(a) shows level densities for 1^+ states in ^{90}Nb along with the model predictions. Assuming no parity dependence, one half of the theoretical $J = 1$ value is taken to compare to the experimental results. While HF-BCS calculations yield a correct energy dependence but are about a factor of two too low, the BSFG parametrizations reveal good agreement with the data. Thus, there is no signature for a parity dependence. Figure 3(b) provides a direct test of this issue using the data on $J = 2$ states in ^{90}Zr. The experimental data points obviously exclude any parity dependence. Similar to the $J = 1$ case in ^{90}Nb, the HF-BCS model underestimates the observed level densities by a factor of two, reproducing, however, their energy dependence, while back-shifted Fermi gas curves are in accordance with them.

Level densities for 1^+ states in ^{58}Cu are plotted in Fig. 3(c). Strong deviations from the model predictions, both in absolute values, and in the slope, could be a signature for a parity dependence. Indeed, recent calculations for *pf*-shell nuclei [4,6] show that the investigated energy range corresponds to the transition from low excitation energies

where a single parity dominates to the region where the two densities are equal. On the other hand, these calculations deal with total level densities while spin-projected ones may have different behaviors due to alternating gaps between the last occupied and empty orbits. A direct test of a parity dependence for $A = 58$ is presented in Fig. 3(d) and does not disclose any differences for 2^+ and 2^- states. Also, analogously to the case of ^{90}Zr, measurements reveal a reasonable agreement between theory and experiment. Thus, even for $A = 58$ a parity dependence of nuclear level densities is still questionable.

6. Summary

In summary, the sensitivity of the studied reactions along with the excellent energy resolution enables an extraction of level densities of 1^+, 2^+ and 2^- states in $A = 90$ and $A = 58$ nuclei by means of a fluctuation analysis. An essential extension of the method is presented by a DWT analysis which provides a nearly model-independent method for the background determination. The data obtained give no signature for a possible parity dependence in $A = 90$. For $A = 58$ this question is still open. Application of the fluctuation analysis to other nuclei and modes is in progress.

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