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Nuclear Physics A718 (2003) 691c–693c

NUCLEAR PHYSICS A

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Microscopic Nuclear Level Densities by the Shell Model Monte Carlo Method

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We have developed *ab initio* methods to calculate nuclear level densities within the shell model Monte Carlo approach. We have applied these methods to nuclei in the mass region $50 \lesssim A \lesssim 70$, and found remarkably good agreement with experimental data. Using projection methods in the Monte Carlo approach, we have also studied the parity- and isospin-dependence of level densities.

1. INTRODUCTION

Accurate nuclear level densities are needed for theoretical estimates of astrophysical nuclear reaction rates, *e.g.*, neutron capture rates in the s and r processes in nucleosynthesis [1]. Experimental level densities are well-described by the backshifted Bethe formula if its parameters are fitted for each nucleus [2]. While the global systematics of these parameters have been studied, their actual values can have significant deviations, and consequently it is difficult to predict accurately level densities of specific nuclei.

The interacting shell model has been successful in describing properties of nuclei, in particular for the low-lying states. It is also a desirable framework to study microscopically thermal properties of nuclei, including level densities. However, such studies have not been possible in medium to heavy nuclei, as the dimensionality of the Hamiltonian matrix is too large for conventional diagonalization methods. The recent development of the shell model Monte Carlo (SMMC) method [3] allows us to overcome this difficulty.

2. SMMC APPROACH TO NUCLEAR LEVEL DENSITIES

We have recently developed *ab initio* methods to calculate level densities [4] using the SMMC approach. The so-called sign problem, which often limits the applicability of Monte Carlo calculations, was circumvented by constructing a good-sign interaction that correctly includes the dominating collective components of realistic effective interactions [5]. Applying these methods to $50 \lesssim A \lesssim 70$ nuclei in the complete $(pf+0g_{9/2})$-shell, we found remarkably good agreement with the experimental data without any adjustable parameters. A few examples are shown in Fig. 1. We have studied the systematics of the level density parameters that we extract from our calculations [7,8], and found that they often follow the data more closely than empirical formulas. The level densities of odd-even

doi:10.1016/S0375-9474(03)00890-X

and odd-odd nuclei were also calculated successfully despite a sign problem introduced by the projection on an odd number of particles [8].

Using a parity-projection method, we have also studied the parity (π) dependence of level densities [4,7,9]. For some nuclei we find significant parity dependence that has not been taken into account in nucleosynthesis calculations.

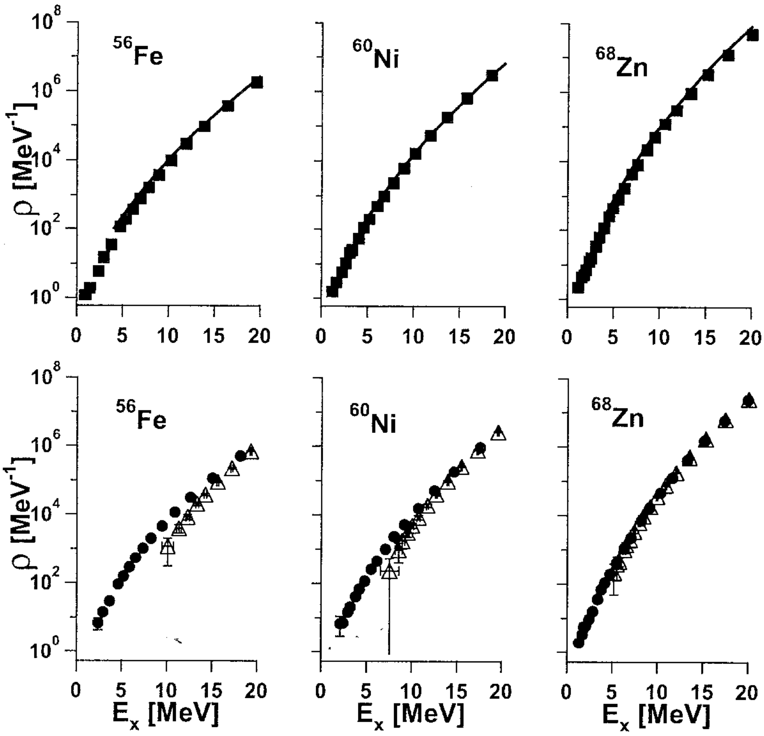

Figure 1. Total and parity-projected level densities of ^{56}Fe, ^{60}Ni and ^{68}Zn. Upper panel: SMMC (squares) and experimental (solid lines) [6,2] total level densities. Lower panel: even- (circles) and odd-parity (open triangles) SMMC level densities.

3. ISOSPIN-PROJECTED LEVEL DENSITIES

The isospin quantum number T is conserved in nuclei to a good approximation. Reliable treatment of the isospin dependence of level densities could be important in $Z \sim N$ nuclei, because the $T = |T_0|$ ($T_0 = (N - Z)/2$) and the $T = |T_0| + 1$ levels are close in energy. However, the relative energy shifts of levels with different T are not well described by the interaction we use [10,11]. To overcome this problem, we have introduced an exact and efficient T projection method in the SMMC approach, and applied it to level density calculations [12]. The T-projected densities of ^{58}Cu are presented in Fig. 2. We also find in this nucleus a significant correction to the total level density when using the T projection method to account for the proper isospin dependence of the energy levels.

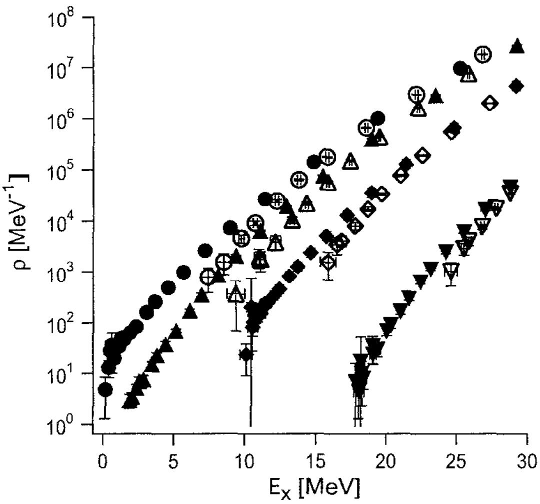

Figure 2. Isospin- and parity-projected SMMC level densities in ^{58}Cu. Circles, triangles, diamonds and inverted triangles describe the level densities for $T = 0, 1, 2$ and 3, respectively, and for $\pi = +$ (solid symbols) and $\pi = -$ (open symbols).

Computations of T projection were performed on the PC cluster Helios and IBM SP3 in JAERI, and on CP-PACS in Center for Computational Physics, University of Tsukuba.

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