PAIRING CORRELATIONS IN STATISTICAL LEVEL DENSITIES WITHIN THE MICRO-MACROSCOPIC APPROACH

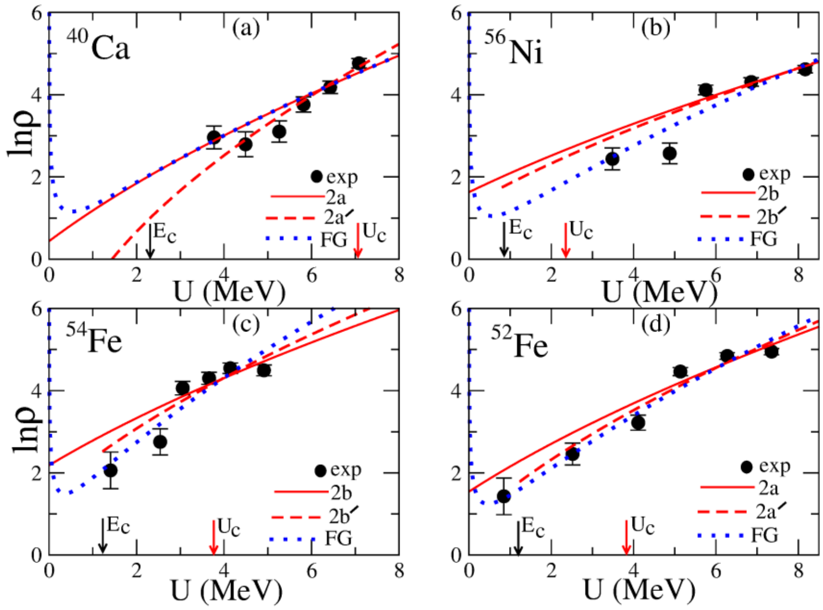
A. G. Magner[1,2], A. I. Sanzhur[1], S. N. Fedotkin[1], A. I. Levon[1], U. V. Grygoriev[1,3], S. Shlomo[2]

[1] *Institute for Nuclear Research, National Academy of Sciences of Ukraine, Kyiv, Ukraine*
[2] *Cyclotron Institute, Texas A&M University, College Station, USA*
[3] *University of Groningen, Groningen, Netherlands*

In this report, we present the statistical level density $\rho(E,N,Z)$ for several magic nuclei as a function of the total energy E, and number of neutrons N and protons Z within the micro-macroscopic approach (MMA) [1], with main focus on pairing correlations. This level density ρ was improved at low excitation energy U [1]. The density ρ was derived as a function of the excitation energy U, $\rho \propto S^{-\nu} I_\nu(S)$, through the system entropy, $S = 2(aU)^{1/2}$, where α is the level density parameter, $I_\nu(S)$ is the modified Bessel function of order v. The orders $v = 2$ and $v = 3$ correspond to the cases of neglecting (MMA1) and dominating (MMA2) shell contributions, respectively. Taking into account the particle number fluctuations beyond the Bardeen - Cooper - Schrieffer (BCS) theory, the pairing gap Δ_0 can be considered as a smooth function of the particle number A. The pairing gap Δ_0 is often approximated by the phenomenological quantity $\Delta_0 = 12/A^{1/2}$ MeV. For the condensation energy E_c and the critical excitation energy U_c for a superfluid-normal phase transition, one can use the well-known approximations, $E_c = 3a\Delta^2/(2\pi^2)$ and $U_c = aT_c^2 + \Delta^2/(4G)$, where $T_c = e^C \Delta_0/\pi$ with the Euler constant C, and G is the mean matrix element of residue interaction. The excitation energy U of the system entropy S is shifted over E_c due to superfluidity, and T_c is the evaluated critical temperature where superfluidity disappears. In this way, we take into account the nuclear shell and pairing effects in terms of the inverse level density parameter $K = A/a$ and the condensation energy shift E_c.

Figure presents a comparison between the MMA approaches for relatively small excitation energies U, below neutron resonances, in four complex nuclei ^{40}Ca (*a*), ^{56}Ni (*b*), ^{54}Fe (*c*), and ^{52}Fe (*d*), and the experimental data obtained from the database http://www.nndc.bnl.gov/ensdf. Close points with errors are obtained by using the energies and spins of excited states (with spin degeneracies) by the macroscopic sample method [1]. The results for MMA2a level density approach (with dominating contributions of shell and pairing corrections from [2]) in magic nucleus ^{40}Ca ($E_c = 2.3$ MeV, $U_c = 7.1$ MeV) with the least mean square fit (LMSF) error $\sigma = 1.3$ agrees well with the experimental data obtained by LMS fitting using one physical parameter – the inverse level density parameter K. Those for the MMA2b approach (also with dominating contributions of these corrections but due to their large derivatives of the shell corrections over the chemical potential) in magic nucleus ^{56}Ni ($E_c = 0.8$ MeV, $U_c = 2.5$ MeV, $\sigma = 2.2$) are less in agreement with the experimental data when using similar LMS fitting. Pairing effects are larger for ^{40}Ca (*a*), see the difference between dashed and solid lines, in contrast to the ^{56}Ni (*b*) case. Condensation energies E_c and superfluid-normal phase transition energies U_c are marked by black and red arrows, respectively. The range between arrows for calcium, ^{40}Ca, overlaps whole excitation energies while for the nickel, ^{56}Ni, there is no such overlap. Therefore, we may predict that the pairing effects are easier to detect in ^{40}Ca than in ^{56}Ni. In contrast to these close-shell results, one has an intermediate situation for semi-magic ^{54}Fe (*c*) and open-shell ^{52}Fe (*d*) nuclei.

The largest pairing effect is clearly seen in ^{40}Ca (*a*) and there is no such effect for ^{56}Ni, though both are closed-shell magic nuclei. In contrast to another opinion, we think that we cannot use these properties (close/open shell arguments) for evaluation of the pairing contributions. Concerning the difference between two symmetric magic ^{56}Ni and open-shell ^{52}Fe nuclei, one can find qualitative agreement with the experimental results obtained in Ref. [3] though our theoretical arguments are somewhat different from those used in Ref. [3]. Note also that the values of the inverse level density parameter $K = 9.6$ (*a*), 27.3 (*b*), 17.9 (*c*), and 17.7 (*d*) MeV, respectively, are found to be essentially different from those deduced from neutron resonances, mainly due to major shell and pairing effects.



Level density (in logarithms) as a function of excitation energy U for low energy states in the magic (close-shell) ^{40}Ca (*a*) and ^{56}Ni (*b*), semi-magic ^{54}Fe (*c*), and non-magic (open-shell) ^{52}Fe (*d*) nuclei. Solid lines show the MMA approach for minimal values of LMS errors σ with pairing condensation being neglected. Dashed lines are the same but taking into account the pairing effect through the found condensation energy E_c. Blue dotted lines present the results of the Fermi gas approach. Experimental close circles are obtained from the ENSDF excitation energy data.

As perspectives, we will continue our study, within the MMA, of the effects of nuclear rotations, pairing, and collective dynamics within statistical level density.

1. A.G. Magner et al. arxiv:2308.07784. Submitted to Eur. J. Phys. A 2023.
2. P. Möller et al. Atomic Data and Nuclear Data Tables 109-110 (2016) 1.
3. B. Le Crom et al. Phys. Lett. B 829 (2022) 137057.