Towards a parity-dependent level density for astrophysics

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Abstract. Astrophysical reaction rates are sensitive to the parity distribution at low excitation energies. We combine a formula for the energy-dependent parity distribution with a microscopic-macroscopic nuclear level density. This approach describes well the transition from low excitation energies where a single parity dominates to high excitations where the two densities are equal.

1. Introduction

The nuclear level density is an important ingredient in the prediction of nuclear reaction rates in astrophysics. So far, most theoretical, global calculations of astrophysical rates assume an equal distribution of the state parities at all energies. It is obvious that this assumption is not valid at low excitation energies of a nucleus. However, a globally applicable recipe was lacking. For nuclei far from stability, where no experimental information on excited states at astrophysical important energies is available, a large effect of the parity dependence on predicted cross sections can be expected.

2. Method

A total level density ρ_{tot} is commonly used in nuclear and astrophysical applications, either calculated or extracted from experiment. We strive to derive an excitation-energy dependent parity-factor which can be easily implemented. To achieve this, single particle levels with different parities are treated separately. We then follow the assumption introduced in [1], namely that the occupancy n of the single particle orbits with smaller average occupation f is Poisson distributed,

$$P(n) = \frac{f^n}{n!} e^{-f}. \tag{1}$$

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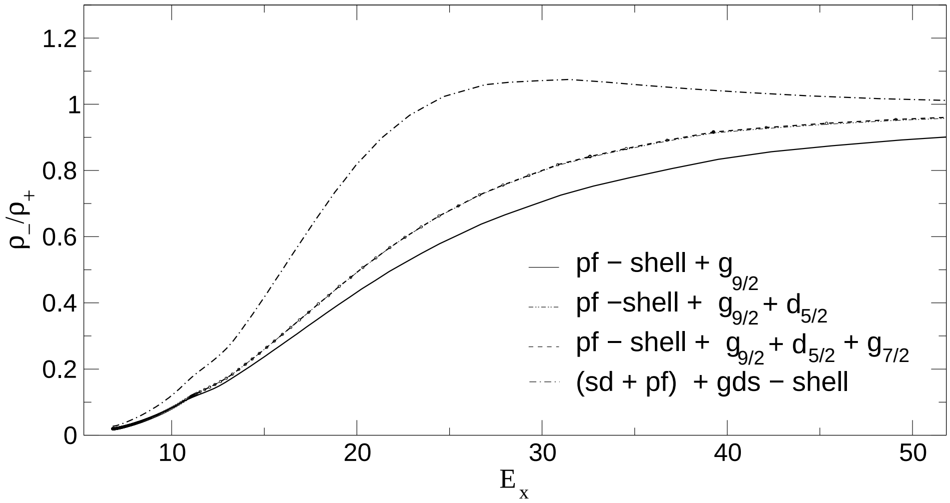

Figure 1. Parity ratio as function of excitation energy (MeV) when including only pf+$g_{9/2}$ (full line), pf+$g_{9/2}$+$d_{5/2}$ (dashed-double dot) pf+$g_{9/2}$+$d_{5/2}$+$g_{7/2}$ (dashed, full overlap with pf+$g_{9/2}$+$d_{5/2}$), (sd+pf) + full gds-shell (dot-dashed) for ^{56}Fe. The inclusion of the $g_{7/2}$-shell does not bring improvement but the consideration of the $d_{5/2}$-shell and sd-shells in addition to pf+$g_{9/2}$ is essential.

For even-even nuclei, the probability ratio of odd and even parities is

$$\frac{P_-}{P_+} = \frac{Z_-}{Z_+} = \tanh f. \tag{2}$$

To calculate the total partition function Z we use the macroscopic-microscopic nuclear level density of [2]. The average occupancy f is computed from BCS occupation numbers based on single particle levels from an axially symmetric deformed Saxon-Woods potential [3] with parameters from [4] which reproduce experimental data well [5, 6]. Using $Z_+ + Z_- = Z$ and equation (2), we can thus determine $Z_\pm$ and calculate the thermal energies for even- and odd- parity states. The parity projected level densities at a given excitation energy, and thus the desired parity factor, are derived from standard thermodynamic relations.

All major shells up to $11\hbar\omega$ were included which allows to extend our calculations way beyond the previously studied $pf + g_{9/2}$ shell. This will certainly be important for heavy nuclei but it is already necessary for the Fe-region presented in this work. As shown in figure (1) considerable contributions arise also from the sd and full gds-shell.

There are two essential inputs to our calculations: the total level density $\rho_{\rm tot}$ which is used to calculate the total partition function utilized in equation (2) and the single particle levels from the deformed Saxon-Woods potential needed to compute the average occupancy f. Both inputs are prone to possible uncertainties. In [7] we explored the sensitivity to these uncertainties by simulating the combined effects of uncertainties in both inputs by variation of only the total level density $\rho_{\rm tot}$ and keeping the Saxon-Woods parameters unchanged. We have shown the need for improved consistency within the inputs, especially at shell closures. Therefore the projected level densities are calculated

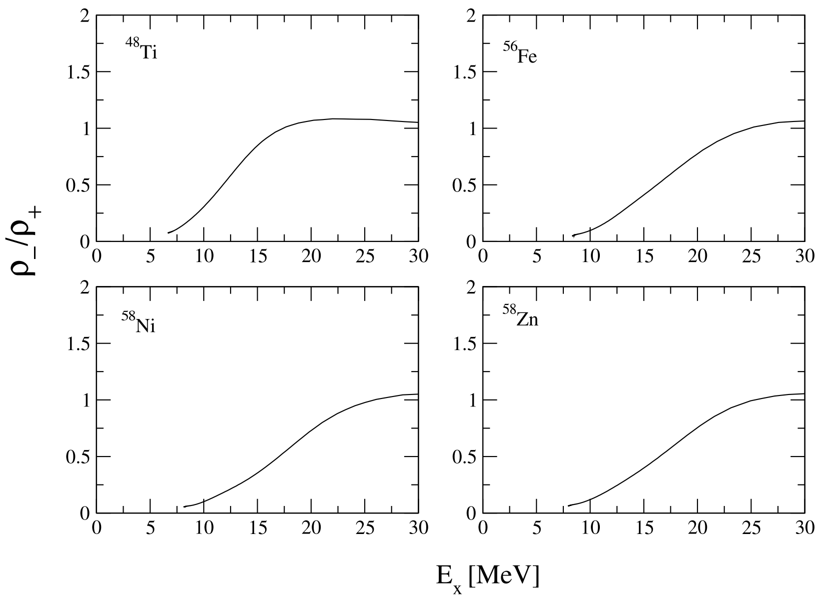

Figure 2. Odd- to even parity ratio calculated for ^{48}Ti, ^{56}Fe, ^{58}Ni and ^{58}Zn

in a self-consistent approach to minimize the combined uncertainties in $\rho_{\rm tot}$ *and* the single particle levels. Starting with the input level density from [2], an iteration scheme is carried out until convergence between the input level density and the extracted level density from the projected quantities is achieved.

3. Results and Discussion

Typical results for nuclei in the Fe-region are shown in figure (2). On can see that the assumption of equally distributed state parities is not fulfilled. Even at excitation energies of 10 - 15 MeV, the parity ratio is not yet equilibrated.

The evolution of the parity ratios within an isotopic chain is shown in figure (3). Starting with ^{54}Zn, where the pf-shell is filled in neutrons only to 20 %, and stopping with ^{74}Zn, where the next major shell has started to be populated, one can see that the ratio approaches unity for lower values of the excitation energy as one approaches the $N = 40$ shell closure. As the parity can only be changed by excitations from the pf to the *sdg* shell, the ratio will equilibrate faster with increasing neutron number as the gap between the last occupied orbit in the pf-shell and the *sdg*-shell will decrease. For ^{70}Zn, where the pf-shell is completely filled, a pronounced peak around 6 MeV shows up, which might be understood as follows: As the pf-shell is completely filled, the parity of the system will be changed by any neutron excitation, resulting in a dominance of negative parity states at the energies for which the peak appears.

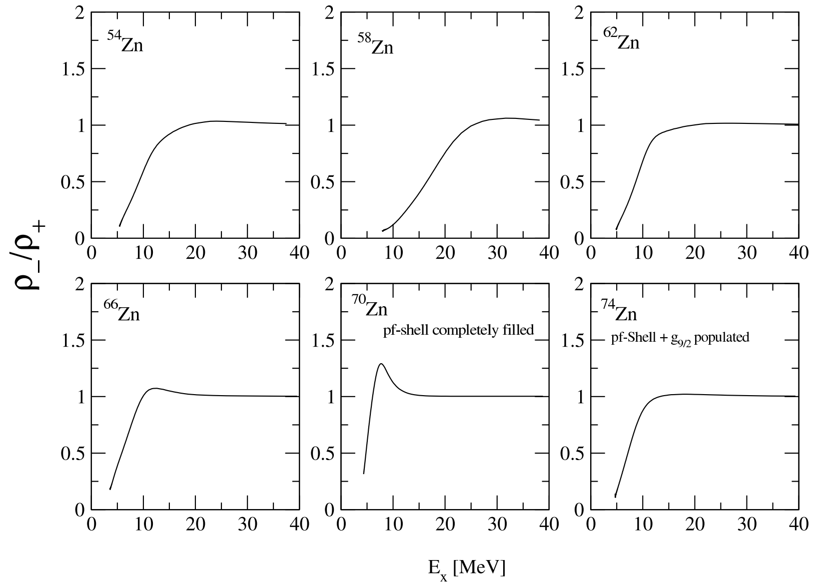

Figure 3. Evolution of the odd- to even-parity ratio within the Zn-Chain.

4. Conclusion and Outlook

We have shown that the assumption of equally distributed state parities is only justified for high excitation energies. For lower energies, even still at particle separation energies which are in the order of several MeV, this assumption is clearly not fulfilled. Work is in progress to calculate the parity distribution for a large number of nuclei far from stability on the proton as well as neutron rich side. Influences on nucleosynthesis calculations will be studied in the future.

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