THE IMPORTANCE OF PARITY-DEPENDENCE OF THE NUCLEAR LEVEL DENSITY IN THE PREDICTION OF ASTROPHYSICAL REACTION RATES

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A simple description for obtaining the parity distribution of nuclear levels in the pf + g9/2 shell as a function of excitation energy was recently derived. We implement this in a global nuclear level density model. In the framework of the statistical model, cross sections and astrophysical reaction rates are calculated in the Fe region and compared to rates obtained with the common assumption of an equal distribution of parities. We find considerable differences, especially for reactions involving particles in the exit channel.

1. Introduction

The nuclear level density is an important ingredient in the prediction of nuclear reaction rates in astrophysics. So far, all 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. We combine a formula for the energy-dependent parity distribution with a microscopic-macroscopic nuclear level density¹. The formula describes well the transition from low excitation energies where a single parity dominates to high excitations where the two densities are equal. It was tested against Monte Carlo shell model calculations. This treatment is further applied in the calculation of astrophysical reaction rates for nuclei
Figure 1. Left: Ratio of odd to even parity partition function $Z_{-}/Z_{+}$ versus inverse temperature $\beta$ for $^{56}\text{Fe}$, $^{60}\text{Ni}$ and $^{68}\text{Zn}$, calculated with the Monte Carlo Method. Right: The parity ratio $\rho_{-}/\rho_{+}$ versus excitation energy $E_{x}$. The solid lines are calculated using Eq. (1), and the solid circles are obtained with the Monte Carlo Method of Nakada et al. in the Fe region.

2. Method

Y. Alhassid et al. have calculated the ratio $Z_{-}/Z_{+}$ for nuclei in the iron region using the complete pf + g9/2 shell. In Fig. 1 the ratio of odd to even parity states as a function of inverse temperature $\beta$ for three nuclei in the iron region is shown. The observed parity dependence can be explained quantitively by a simple model. Single particle levels are divided into two groups, according to their individual parities. The group which has the smaller average occupation number is denoted by $\Pi$. The distribution of the occupancies of the $\Pi$ parity group can be assumed to be Poisson, if the single particle states are occupied independently and randomly:

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

Here $f$ is the average occupancy of orbitals with parity $\Pi$. The probability to have an odd/even parity state is given by:

$$P_{+}(n) = \sum_{n,\text{even}} P(n) = e^{-f} \cosh f$$

$$P_{-}(n) = \sum_{n,\text{odd}} P(n) = e^{-f} \sinh f.$$
and their ratio by

\[
\frac{P_-}{P_+} = \frac{Z_-}{Z_+} = \tanh f.
\]  

(1)

The arguments leading to this equation are easily extended to the case where the protons and neutrons are treated separately — \(f\) has only to be replaced by the sum of individual contributions from neutrons and protons.

The back-shifted Fermi-gas model (BBF) of Rauscher et al.\(^1\) is used to calculate the total partition function \(Z\) at constant excitation energy. Using \(Z_+ + Z_- = Z\) and Eq. (1), we can determine \(Z_{+/−}\) and calculate the thermal energies for even- and odd-parity states. Canonical entropies, heat capacities and the parity projected level densities are calculated from standard thermodynamic relations.

3. Results and Discussion

We have used the parity dependent level density to calculate astrophysical reaction rates in the global Hauser-Feshbach (HF) model NON-SMOKER\(^4\) and compared the results to the standard values\(^5\). We show the parity dependence for three nuclides, \(^{64}\text{Fe},^{66}\text{Ni},^{68}\text{Zn}\) and investigated all reaction channels involving these nuclei. The impact on the rates involving the Ni and Zn nuclei is small and negligible compared to the remaining uncertainties in the global HF model. This is due to the fact that a sufficiently large number of excited states is known experimentally. Up to 20 experimental states are considered in the standard calculation and only above the last known state, the theoretical level density is in effect. However, the case is different for reactions involving \(^{64}\text{Fe}\). No information on experimental states is known here and therefore the full impact of the parity dependence can be seen. In the \((n, γ)\) case 20% difference are found. Much larger differences are seen in the reactions involving \(^{64}\text{Fe}\) in the final particle channel. Because of lack of negative parities at low excitation energies, the particle emission channel becomes strongly enhanced in all such reactions with low or negative \(Q\) values.

4. Outlook

The case for \(^{64}\text{Fe}\) shows that a large effect of the parity dependence can be expected far from stability where no experimental information on excited states is available and that it is extremely important to include such a modified level density. The current approach is valid only for even-even
nuclei in the pf + g9/2 shell. Work is in progress to extend this description to be able to calculate the parity distribution for a large number of nuclei far from stability on the proton-rich as well as neutron-rich side.

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