An Improved Nuclear Level Density Description

T. Rauscher[1], F.-K. Thielemann[2]
[1]Institut für Kernchemie, Universität Mainz, Mainz, Germany
[2]Institut für theoretische Physik, Universität Basel, Basel, Switzerland

The availability of a reliable method for the prediction of nuclear level densities for stable and unstable nuclei is vital for the theoretical treatment of nuclear reaction rates in astrophysical applications. Most of the relevant reaction cross sections are calculated in the statistical model approach (Hauser-Feshbach, HF) [1]. Essential for the quality of the HF calculations is the level density description employed. Up to now, the level density predictions were the weakest point in the present procedures for HF cross section calculations [1]. Another reaction mechanism – direct reactions (DR) – may dominate when the level density of a nucleus becomes too low ($< 10\ \mathrm{MeV}^{-1}$) at the energies considered [2]. Therefore it is also important to have a reliable criterion enabling one to decide which reaction model to apply. We present an improved method for calculating level densities, based on the preliminary work discussed in [3].

The nuclear level density $\rho(U)$ usually is described with the backshifted Fermi gas expression [1,4]. Then $\rho(U)$ is dependent only on two quantities: the level density parameter a and the backshift δ, which determines the energy of the first excited state. In order to get a reasonably good fit to experimental level densities it was previously necessary to divide the nuclei into three classes [1] (nuclei close to magic numbers, other spherical nuclei, and deformed nuclei), thus increasing the number of parameters by a factor of three. The deviations were still up to a factor of 4–5.

We employed a different treatment of the density parameter a which includes thermal damping of shell effects [5]. The parameter a is then given by

$$a(U,Z,N) = a^*(A)[1 + C(Z,N)\frac{f(U-\delta)}{U-\delta}] \quad ,$$

where $a^* = \alpha A + \beta A^{2/3}$, and A, U, and δ denote the mass number, excitation energy, and backshift, respectively. The shell correction is given by C. The shape of the function $f(U)$ was found by approximation of numerical microscopic calculations [5],

$$f(U) = 1 - \exp(-\gamma U) \quad .$$

The open parameters α, β, γ were obtained by a fit to experimental data for 278 nuclei [1,5], including unstable nuclei.

The backshift δ is directly related to the pairing gap Δ [1,4]. We calculated the neutron pairing gap Δ_{n} via the even-odd mass difference $\frac{1}{4}[E^G(Z,N-2)$ $-3E^G(Z,N-1)+3E^G(Z,N)-E^G(Z,N+1)]$, with $E^G(Z,N)$ being the mass for the nucleus (Z,N) [6]. The same procedure can be applied for the proton energy gap Δ_{p}. Thus, better structural effects can be incorporated in a consistent way, regardless of the mass formula used.

The best fit was found using the Möller mass formula [7] with the pairing gaps determined by the mass differences. Compared to previous fits [3], a large part of the improvement was due to clarifying the meaning of the so-called "shell correction" C. Initially, the parameter C was introduced to account for effects which are not considered in the spherical droplet (or liquid drop) model [4], but the term "shell correction" is used with a slightly different meaning in today's macroscopic-microscopic models. Therefore one has to identify the parameter C rather with what is currently called "microscopic correction". By consistently using the Möller microscopic corrections one is able to get a highly improved fit, without the band structure previously seen [3]. With the values $\alpha = 0.136$, $\beta = -0.0804$, and $\gamma = 0.0499$, we obtain a mean deviation of only 1.5 for the 278 nuclei considered.

Summarizing, we were able to improve considerably the prediction of nuclear level densities by employing a different description for the level density parameter and by correctly including microscopic corrections. All nuclei can now be described with a single parameter set consisting of just three parameters. This will also make it worthwile to recalculate the cross sections and thermonuclear rates of the full reaction rate library from Ne to Kr and the proton to neutron drip line for neutron and charged-particle induced reactions, as well as for all nuclei up to Z=100 from stability to the neutron drip line for r-process applications.

Acknowledgement: TR is supported by the Alexander von Humboldt foundation.

References

[1] J.J. Cowan et al.; Phys. Rep. 208, 267 (1991).

[2] H. Oberhummer, G. Staudt; in Graduate Texts in Contemporary Physics, Springer Verlag, p. 29 (1991).

[3] T. Rauscher et al.; Inst. f. Kernchemie, Jahresbericht 1993.

[4] A. Gilbert, A.G.W. Cameron, Can. J. Phys. 43, 43 (1965).

[5] A.S. Iljinov et al.; Nucl. Phys. A543, 517 (1992).

[6] R.-P. Wang et al.; Phys. Lett. B 284, 196 (1992).

[7] P. Möller et al.; At. Dat. Nucl. Data Tabl. (1995), in print.