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Nuclear Physics A 941 (2015) 255–264
NUCLEAR PHYSICS A
www.elsevier.com/locate/nuclphysa

Approximating the spin distributions in capture reactions between spherical nuclei

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Received 10 June 2015; accepted 26 June 2015

Available online 8 July 2015

Abstract

Twenty years ago an approximation for the spin distribution of the dinuclear systems formed in capture reactions with heavy ions was proposed. This approximation is used nowadays. However, since that time the experimental errors of the measured capture cross sections were reduced drastically. We show that the accuracy of the old spin distribution approximation is certainly out of date and propose a new approximation built on the dynamical modeling of the capture process. Results suggest that this new approximation might be useful especially for performing modeling of decay of excited dinuclear systems (compound nuclei) formed during heavy-ion collisions.

Keywords: Spin distribution; Transmission coefficient; Heavy-ion fusion

1. Introduction

Nuclear fission although being for a long time one of the branches of the energy production is still a field of intensive research [1–5]. The dinuclear systems, whose decay is studied, are usually formed in the capture process of two complex nuclei [6]. The dinuclear system possesses a given

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http://dx.doi.org/10.1016/j.nuclphysa.2015.06.019
0375-9474/

excitation energy and rather wide spin distribution. Some observables of the fission process, like fission probability, are very sensitive to the spin distribution.

In the literature for this distribution a Fermi-step ansatz is usually applied [6–8]

$$T_L = \left\{1 + \exp\left[\frac{L - L_c}{\delta L}\right]\right\}^{-1}. \tag{1}$$

The capture cross section is then calculated according to the well-known formula

$$\sigma = \frac{\pi \hbar^2}{2m_R E_{c.m.}} \sum_{L=0}^{\infty} (2L+1) T_L. \tag{2}$$

Here m_R stands for the reduced mass and $E_{c.m.}$ denotes the collision energy in the center-of-mass frame. For the parameters of the Fermi-step 20 years ago an approximation [9] was proposed which reads

$$L_{ca0} = C_R\{d_0 + d_1\sqrt{E_{c.m.} - V_c}\}, \tag{3}$$

$$V_c = 1.18 Z_P Z_T / \left(A_P^{1/3} + A_T^{1/3} + 1.6\right) \text{ MeV} \tag{4}$$

$d_0 = 0.33$, $d_1 = 0.205$ MeV$^{-1/2}$, and

$$C_R = \sqrt{A_P A_T/(A_P + A_T)}\left(A_P^{1/3} + A_T^{1/3}\right), \tag{5}$$

$$\delta L_{a0} = (A_P A_T)^{3/2}\left\{b_0 + b_1(E_{c.m.} - V_c - 10)\right\}, \tag{6}$$

$b_0 = 1.5 \cdot 10^{-5}$, $b_1 = 2.0 \cdot 10^{-7}$ MeV^{-1} at $E_{c.m.} > V_c + 10$ and $b_1 = -4.0 \cdot 10^{-7}$ MeV^{-1} at $E_{c.m.} < V_c + 10$.

Since then this approximation was used in many theoretical works [10–15] modeling the fission process. In [10] it was shown that the typical error resulting from this approximation for the capture cross section σ calculated within the framework of the surface friction model for seven reactions was about 10% (see Fig. 34 in [10]).

During the last 20 years the experimentalists managed to reduce the errors of σ down to 0.5–3% [16,17]. In [18,19] we made dynamical modeling of the capture process reproducing the high precision data on the cross sections with the typical error of 3%.

In Fig. 1 we compare the capture cross sections resulting from Eqs. (1)–(6), σ_{a0}, with the data $\sigma_{\rm exp}$. For convenience, proper information of all the reactions involved in our analysis is collected in Table 1. Note that these reactions involve only spherical nuclei and the collision energies are well above the barrier (see details in [18,19]). In Fig. 1 the ratio $\sigma_{a0}/\sigma_{\rm exp}$ is shown as the function of $E_{c.m.} - B_Z$, where

$$B_Z = Z_P Z_T \left(A_P^{1/3} + A_T^{1/3}\right)^{-1}. \tag{7}$$

In Fig. 1 the rms deviation of the points from unity is equal to 13% and more than in half cases the values of $\sigma_{a0}/\sigma_{\rm exp}$ differ from unity by 10% or more. Another quantitative characteristic of the quality of a theory or an approximation is χ^2_σ:

$$\chi^2_\sigma = \frac{1}{\nu}\sum_{i=1}^{\nu}\left(\frac{\sigma_i - \sigma_{i\,\rm exp}}{\Delta\sigma_{i\,\rm exp}}\right)^2 \tag{8}$$

Here σ_i denotes a theoretical or approximated cross section, $\sigma_{i\,\rm exp}$ and $\Delta\sigma_{i\,\rm exp}$ are the experimental cross section and its error, respectively, summation is performed over all data points (in