Prediction of nuclear reaction rates for astrophysics

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The investigation of explosive nuclear burning in astrophysical environments is a challenge for both theoretical and experimental nuclear physicists. Highly unstable nuclei are produced in such processes which again can be targets for subsequent reactions. The majority of reactions can be described in the framework of the statistical model (compound nucleus mechanism, Hauser–Feshbach approach), provided that the level density of the compound nucleus is sufficiently large in the contributing energy window [1]. Among the nuclear properties needed in this treatment are masses, optical potentials, level densities, resonance energies and widths of the GDR. All these necessary ingredients have to be provided in as reliable a way as possible, also for nuclei where no such information is available experimentally.

A recent experiment [2] has underlined that the low-energy extrapolation of the widely used optical α+nucleus potentials may still have to be improved. Currently, there are only few global parametrizations for optical α+nucleus potentials at astrophysical energies. Most global potentials are of the Saxon–Woods form, parametrized at energies above about 70 MeV, e.g. [3]. The high Coloumb barrier makes a direct experimental approach very difficult at low energies. More recently, there were attempts to extend those parametrizations to energies below 70 MeV [4]. Early astrophysical statistical model calculations [5, 6] made use of simplified equivalent square well potentials and the black nucleus approximation. Improved calculations [7] employed a phenomenological Woods–Saxon potential [8], based on extensive data [9]. However, it was not clear how well all these potentials would work for heavy targets with $A > 60$ or in the thermonuclear energy range.

Most recent experimental investigations [10, 11] found a systematic mass– and energy–dependence of the optical potentials and were very successful in describing experimental scattering data, as well as bound and quasi–bound states and B(E2) values, with folding potentials. Based on that work, a global parametrization of the volume integrals can be found [12]. In this description, the real part of the nuclear potential is given by a folding potential $V_f(r,E)$. The imaginary part $W(r,E)$ is of Woods–Saxon shape with a strongly energy–dependent depth. Nuclear structure and deformation information determines the shape of the energy–dependence by including level density dependent terms [12].

It is easy to show that the final transmission coefficients are not only sensitive to the strength of the potential but also to its geometry. Experimental data seemed to indicate that the geometry may also be energy–dependent [4, 13]. At low energies, the diffuseness of the standard volume Woods–Saxon potential had to be set to smaller values, while the radius parameter was increased, in order to be able to describe experimental scattering data. This can be understood in terms of the semi–classical theory of elastic scattering [14] which shows that the relative importance of contributions from different radial parts of the potential depends on the energy. It was shown [15] that the predicted enhanced surface absorption at low energies can be described by an increased surface Woods–Saxon term. Thus, the artificial change in geometry in the description of scattering data results from the use of a volume term only. Consequently, the optical potential proposed here contains an imaginary part which is given by the sum of a volume Woods–Saxon term and a surface term:

$$V(r,E) = V_C(r) + V_f(r,E) + i\left(W_v(E) f(r,R,a) - W_s(E)\frac{d}{dr} f(r,R,a)\right) \tag{1}$$

with

$$f(r,R,a) = \left[1 + e^{\frac{r-R}{a}}\right]^{-1}, \quad W_v(E) = C - \alpha e^{-\beta E}, \quad W_s(E) = D + \gamma e^{-\delta E} \quad . \tag{2}$$

The depths of the potentials are exponentially dependent on the energy, with the volume depth W_v increasing and the surface depth W_s decreasing when going to higher energies. An increasingly dominant surface term at low energies leads to similar effects as reducing the diffuseness of a pure volume Woods–Saxon potential. The coefficients are related to the height of the Coulomb barrier and the microscopic and deformation corrections as used in Ref. [12]. The total volume integral is still given by the relation derived in Ref. [12]. The energy–dependence of the ^{144}Sm$(\alpha,\gamma)^{148}$Gd excitation curve [2] at low energies can be reproduced by such a description. Nevertheless, more experimental data is needed which should be consistently analyzed at different energies with optical potential parametrizations similar to the one used in Ref. [15].

Based on the well–known code SMOKER [7], the improved code NON–SMOKER for the prediction of astrophysical cross sections and reaction rates in the statistical model has been developed [16]. Among other changes, it includes an improved level density description [1], updated data sets of experimental level information, as well as the new α+nucleus potential. It also allows to treat isospin effects which are especially important in α capture reactions on self–conjugate target nuclei and in proton capture reactions above the neutron separation energy. For a more detailed presentation of the code and possible isospin effects, see [16].

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