GLOBAL TRANSMISSION COEFFICIENTS IN
HAUSER–FESHBACH CALCULATIONS FOR
ASTROPHYSICS

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Abstract

The current status of optical potentials employed in the prediction of
thermonuclear reaction rates for astrophysics in the Hauser–Feshbach
formalism is discussed. Special emphasis is put on $\alpha+$nucleus potentials.
Further experimental efforts are motivated.

1 Introduction

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. Cross sections and astrophysical reaction rates for a
large number of nuclei are required to perform complete network calculations
which take into account all possible reaction links and do not postulate a priori
simplifications.

The majority of reactions can be described in the framework of the statisti-
cal model (compound nucleus mechanism, Hauser–Feshbach approach, HF) [1],
provided that the level density of the compound nucleus is sufficiently large
in the contributing energy window [2]. In astrophysical applications usually
different aspects are emphasized than in pure nuclear physics investigations.
Many of the latter in this long and well established field were focused on
specific reactions, where all or most "ingredients", like optical potentials for
particle transmission coefficients, level densities, resonance energies and widths
of giant resonances to be implemented in predicting E1 and M1 $\gamma$–transitions,
were deduced from experiments. As long as the statistical model prerequisites
are met, this will produce highly accurate cross sections. For the majority
of nuclei in astrophysical applications such information is not available. The
real challenge is thus not the well–established statistical model, but rather to

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provide all these necessary ingredients in as reliable a way as possible, also for
nuclei where none of such information is available.

2 Transmission Coefficients

The final quantities entering the expression for the cross section in the statis-
tical model [1] are the averaged transmission coefficients. They do not reflect
a resonance behavior but rather describe absorption via an imaginary part in
the (optical) nucleon–nucleus potential [3]. In astrophysics, usually reactions
induced by light projectiles (neutrons, protons, α particles) are most impor-
tant. Global optical potentials are quite well defined for neutrons and protons.
It was shown [4, 5] that the best fit of s–wave neutron strength functions is
obtained with the optical potential by [3], based on microscopic infinite nuclear
matter calculations for a given density, applied with a local density approxima-
tion. It includes corrections of the imaginary part [7, 8]. A similar description
is used for protons. Deformed nuclei are treated by an effective spherical poten-
tial of equal volume [5]. For a detailed description of the formalism used
to calculate E1 and M1 γ–transmission coefficients and how to include width
fluctuation corrections, see [2, 5] and references therein.

2.1 α+Nucleus Potentials

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, 10]. The
high Coloumb barrier makes a direct experimental approach very difficult at
low energies. More recently, there were attempts to extend those parametriza-
tions to energies below 70 MeV [11].

Early astrophysical statistical model calculations [12, 13] made use of sim-
plicated equivalent square well potentials and the black nucleus approxima-
tion. Improved calculations [14] employed a phenomenological Saxon–Woods po-
tential [13], based on extensive data [16]. This potential is an energy– and
mass–independent mean potential. However, especially at low energies the
imaginary part of the potential should be highly energy–dependent.

Most recent experimental investigations [17, 18] found a systematic mass–
and energy–dependence and were very successful in describing experimental
scattering data, as well as bound and quasi–bound states and B(E2) values,
with folding potentials [14]. Motivated by that description (a global para-
metrization is not given in [18]), the following global α+nucleus potential is
proposed. The real part \( V = \lambda V_f \) of the optical potential is calculated by a double-folding procedure:

\[
V_f(r) = \int \int \rho_P(r_P) \rho_T(r_T) v_{\text{eff}}(E, \rho_N = \rho_P + \rho_T, s = |\vec{r} + \vec{r}_P - \vec{r}_T|) d^3r_P d^3r_T ,
\]

where \( \rho_P, \rho_T \) are the nuclear densities of projectile and target, respectively, and \( v_{\text{eff}} \) is the effective nucleon-nucleon interaction taken in the well-established DDM3Y parametrization [20]. The remaining strength parameter \( \lambda \) can be determined from the systematics [17] of the volume integral per interacting particle pair

\[
J_R = \frac{1}{A_PA_T} \int V(r) d^3r .
\]

Introducing a mass-dependence in addition to the energy-dependence, one can reproduce the behavior derived from the imaginary part by applying the dispersion relation [18], by the relation

\[
J_R = \left\{ \begin{array}{ll}
0 & \text{for } E_{\text{c.m.}} \leq E_0 \\
J_0 \cdot \frac{(E_{\text{c.m.}} - E_0)^2}{(E_{\text{c.m.}} - E_0)^2 + \Delta^2} & \text{for } E_{\text{c.m.}} > E_0
\end{array} \right.
\]

where \( E_0 \) is the threshold energy for inelastic channels, \( J_0 \) is a saturation parameter and \( \Delta \) the rise parameter.

As can be seen [18], the resulting volume integrals are quite diverse for different nuclei and a straight-forward mass-dependent parametrization is not possible. In Ref. [18], \( J_0 \) and \( \Delta \) were fitted to experimental data. For a global parametrization, one has to include nuclear structure and deformation information into the fit. Having chosen the (probably energy-dependent) geometry parameters [14] (and appropriately modified them for deformed nuclei), the depth \( W \) of an imaginary Saxon-Woods potential can be determined with Eq. [4]. At energies \( E_{\text{c.m.}} > 100 \text{ MeV} \), the value of \( W \) should reach the saturation value [10]. This determines the parameter \( J_0 \). The threshold \( E_0 = E_0(\rho) \)
is given by the energy of the first excited state. The increase in the number of inelastic (competing) channels is described by $\Delta$. As a first estimate, this can be related to the increase in the total number $n = n(\rho)$ of levels:

$$\Delta = f \left( \frac{dn}{dE} \right) = \alpha E_0 + \beta A^{2/3} + \gamma \ln \left( \frac{dn}{dE} \right).$$

The functional dependence is found by comparison with experimental values for $\Delta$ [18]. Thus, microscopic and deformation effects are implicitly included via the level density $\rho = \rho(E)$.

With nuclear level densities $\rho(E)$ taken from [2], a good fit is obtained to the values given in [18], as well as for various $(\alpha,\gamma)$ and $(n,\alpha)$ data [22]. However, it has to be emphasized that the aim is to obtain a reasonable global potential, i.e. with a low average deviation from experiment. For specific reactions, such a potential might be improved by fine-tuning to a particular nucleus (e.g. [23, 24]) but will lose predictive power by that.

3 Conclusion

With the recent improvements of the level density treatment [2] and the $\alpha$+nucleus potential, the two major remaining uncertainties in the existing global astrophysical reaction rate calculations have been attacked. The new descriptions will provide more reliable predictions of the low–energy cross sections of unstable nuclei.

Nevertheless, to check and further improve current parametrizations, not only of $\alpha$+nucleus potentials but of all involved quantities, experimental data is needed. Especially investigations over a large mass range would prove useful to fill in gaps in the knowledge of the nuclear structure of many isotopes and to construct more powerful parameter systematics. Such investigations should include neutron– and proton–strength functions, as well as radiative widths, and charged particle scattering and reaction cross sections for stable and unstable isotopes. This information can be used to make future large–scale statistical model calculations even more accurate.

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