REACTION RATES AND NUCLEAR PROPERTIES
RELEVANT FOR NUCLEOSYNTHESIS IN MASSIVE STARS
AND FAR FROM STABILITY

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Explosive nuclear burning in astrophysical environments produces unstable nuclei which again can be targets for subsequent reactions. In addition, it involves a large number of stable nuclides which are not fully explored by experiments, yet. Thus, it is necessary to be able to predict reaction cross sections and thermonuclear rates with the aid of theoretical models. Such predictions are also of interest for investigations at radioactive ion beam facilities. An extended library of theoretical cross sections and reaction rates is presented. The problem of α+nucleus potentials is addressed and new parametrizations presented. The problem of properly predicting cross sections at low level densities is illustrated by the $^{62}\text{Ni}(n,\gamma)$ reaction.

1. Introduction

The majority of reactions in astrophysics involving the strong interaction can be described in the statistical model \(^1\). In predictions of cross sections for astrophysical applications, slightly different points are emphasized than in pure nuclear physics investigations. Firstly, one is confined to the very low energy region, from thermal energies up to a few MeV. Secondly, since most of the ingredients for the calculations are experimentally undetermined, one has to develop reliable phenomenological or microscopic models to predict these properties with an acceptable accuracy across the nuclear chart. Therein one has to be satisfied with a more limited accuracy as
compared to usual nuclear physics standards. Considering the substantially larger uncertainties in many astrophysical scenarios, this seems to be adequate.

2. Statistical model calculations

A recently published large-scale reaction rate library includes neutron-, proton-, and α-induced reactions on all target nuclei from Ne up to Bi from proton-dripline to neutron-dripline \(^2\),\(^3\). Due to the fact that many very short-lived nuclides can be produced in astrophysical sites, it is necessary to provide cross sections and rates for about 4600 targets and 32000 reactions. These numbers show that theory will always play a major role in providing cross section, despite the potential of future Rare Isotope Accelerators. The calculations were performed with the Hauser-Feshbach code NON-SMOKER \(^4\) which is especially tuned to such large-scale predictions. Details of the nuclear properties used are given elsewhere \(^2\). This rate set has already be adopted as a standard for nucleosynthesis in stellar evolution and in type II supernovae \(^5\).

Fits to the astrophysical reaction rates – ready for direct astrophysical application – as well as tables of cross sections, reaction rates, and nuclear inputs for all possible reactions with light projectiles can also be downloaded from http://nuastro.org/reaclib.html.

3. Optical α-nucleus potentials

There have only been few attempts to derive global optical potentials for α-projectiles \(^6\) and most of them are only valid at α-energies larger than 30 MeV. Due to the high Coulomb barrier and nuclear structure effects defining the imaginary part of the potential it is difficult to obtain a global potential at astrophysical energies. Elastic α-scattering data can constrain the real part of the potential \(^7\),\(^8\) and detailed analysis can also improve on the imaginary part \(^9\),\(^10\), describing the absorption into other channels than the elastic scattering, i.e. the Hauser-Feshbach channel. Due to the scarcity of data for intermediate and heavy nuclei, attempts to improve on the potential are mostly concentrating on single reactions \(^14\),\(^10\). More global approaches suffer from the lack of data to confine their parameters \(^6\),\(^11\).

We have tried to find a potential for the \(A \equiv 140\) mass region by simultaneously fitting data for \(^{143}\)Nd(n,α)^{140}Ce \(^12\), \(^{147}\)Sm(n,α)^{144}Nd \(^13\), and
Figure 1. Cross sections, reaction rates, and S-factors from a simultaneous χ² fit of the Fermi-type energy-dependent α-nucleus optical potentials of three reactions (see text). The dashed lines are the statistical model calculation. The errors on the ¹⁴⁷Sm(n,α) rates were assumed to be 10%.

¹⁴⁴Sm(α,γ)¹⁴⁸Gd. The optical potential is parametrized as

\[ V(r, E) = -\frac{V_0}{1 + \exp \left( \frac{r-r_0 A^{1/3}}{a_r} \right)} - i \frac{W(E)}{1 + \exp \left( \frac{r-r_0 A^{1/3}}{a_V} \right)} \]  \hspace{1cm} (1)

Different parameters for the potential geometry and the energy dependence of the depth of the imaginary part were explored. We did not find significant differences between using a Brown-Rho shape \(^8\) \( W(E) = W_0((E - E_0)^2/((E - E_0)^2 + \Delta^2) \) or a Fermi-type shape \(^{14}\) \( W(E) = W_0/(1 + \exp((E^* - E)/a^*)) \) of the energy dependence. For the latter we found the parameters \( E^* = 18.74 \text{ MeV}, a^* = 2.1 \text{ MeV}, \) with all other parameters as in the previous paper. The Brown-Rho best fit was obtained with \( E_0 = 6.35 \text{ MeV} \) and \( \Delta = 28.4 \text{ MeV} \), with the same fixed parameters \( V_0 = 162 \text{ MeV}, r_r = 1.27 \text{ fm}, a_r = 0.48 \text{ fm}, W_0 = 19 \text{ MeV}, r_V = 1.57 \text{ fm}, a_V = 0.6 \text{ fm} \). The results from the simultaneous fit of three reactions are shown in Figs. 1 and 2.

Despite the fact that the considered targets are in the same mass re-
Figure 2. Cross sections, reaction rates, and S-factors from a simultaneous $\chi^2$ fit of the Brown-Rho energy-dependent $\alpha$+nucleus optical potentials of three reactions (see text). The dashed lines are the statistical model calculation. The errors on the $^{147}\text{Sm}(n,\alpha)$ rates were assumed to be 10%.

...the derived parameters also describe acceptably well the reaction $^{96}\text{Ru}(\alpha,\gamma)^{100}\text{Pd}$. However, it is remarkable that even better overall agreement with all four reactions can be obtained when using a mass- and energy-independent potential of Saxon-Woods form for the real and imaginary parts (see Fig. 3). The real parameters are given by $V_0 = 162.3$ MeV, $r_r = 1.27$ fm, $a_r = 0.48$ fm, the imaginary ones by $W_0(E) = W_V = 25$ MeV, $r_V = 1.4$ fm, $a_V = 0.52$ fm. Thus, the real part is identical to the potential by Somorjai et al. but without energy dependence, whereas the imaginary part is similar to the one used in McFadden & Satchler. Since the McFadden & Satchler parameters were derived from extensive elastic scattering data it seems reasonable that they are applicable to a wider range of targets. The Somorjai et al. parameters were derived for one reaction only but seem to work also for the nuclides investigated here. Certainly, at very low $\alpha$-energies an additional energy-dependence has to be introduced. Here, we do not show our results from fitting each reaction separately. Obviously, potentials fitted to single reactions can describe those – but only...
Figure 3. Results for four different reactions using the energy-independent potential (see text). The dashed lines are the statistical model calculation. Note that the $^{147}\text{Sm}(n,\alpha)$ result is renormalized by a factor 1/1.4.

4. The $^{62}\text{Ni}(n,\gamma)$ case

For neutron-induced reactions at low energies, close to magic numbers, and far off stability where low separation energies are encountered, another problem emerges. In such targets, the level density is too low to allow the application of the statistical model. Also for other nuclides it is not straightforward to bridge the region of thermal energies to the region of overlapping resonances where the Hauser-Feshbach formalism can be used. Single resonances and direct reactions become important. This is also an issue for neutron-rich nuclei in the $r$-process path with low neutron-separation energies.

As an example for the difficulties in extrapolating thermal data to $s$-process energies of up to a few hundred keV, the reaction $^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$ is discussed here. Two compilations give disagreeing 30 keV cross sections, based on the same thermal data. Both extrapolations assume $s$-wave behavior of a direct capture component. The more recent one in-
Figure 4. Direct neutron capture Maxwellian averaged cross section of $^{62}$Ni. The final value is given by adding the resonant contribution to the “total” direct term. Upper and lower limits on the direct components are from experimental errors on the input, i.e. in the thermal scattering length and the spectroscopic factors.

We have calculated the direct capture component using DWBA and found a considerable p-wave contribution which enhances the cross section at 30 keV $^{19}$. Thus, even when including the subthreshold resonance, the 30 keV value is coincidentally similar to the value in the older compilation (Fig. 4). However, also the general energy dependence of the cross section is altered. Resonances were also included but they only contribute less than 15%. The enhanced cross section has an important impact on s-processing in massive stars. A previously seen overproduction of $^{62}$Ni in stellar models can be cured when using our enhanced rate because of increased destruction of this nucleus with the larger neutron capture rate $^{5,19}$.

5. Conclusions

Despite considerable successes in the prediction of cross sections and reaction rates close to and far off stability, the description of certain nuclear inputs, such as optical $\alpha$-potentials, still needs to be improved. It is also
still unclear whether nuclear properties far off stability can be predicted with sufficiently high accuracy. Although future advances in microscopic theories may alleviate that problem, experimental data is clearly needed. Rare Isotope Accelerators will make it possible to study highly unstable nuclides but also “classical” nuclear physics experiments with stable or long-lived nuclei are indispensable. They can provide the systematics for global descriptions and shed light on the interaction of different reaction mechanisms.

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