BRUSLIB and NETGEN: the Brussels nuclear reaction rate library and nuclear network generator for astrophysics

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Abstract. Nuclear reaction rates are quantities of fundamental importance in astrophysics. Substantial efforts have been devoted in the last decades to measure or calculate them. The present paper presents for the first time a detailed description of the Brussels nuclear reaction rate library BRUSLIB and of the nuclear network generator NETGEN in a journal and in a format so as to make these nuclear data packages easily accessible to astrophysicists for a large variety of applications. BRUSLIB is made of two parts. The first one contains the 1999 NACRE compilation based on experimental data for 86 reactions with (mainly) stable targets up to Si. BRUSLIB provides an electronic link to the published, as well as to a large body of unpublished, NACRE data containing adopted rates, as well as lower and upper limits to these rates. The second part of BRUSLIB concerns nuclear reaction rate predictions that have to complement the experimentally-based rates for use in a large variety of astrophysics modelings. An electronic access is provided to tables of thousand of rates calculated within a statistical Hauser-Feshbach approximation, which limits the reliability of the rates to reactions producing compound nuclei with a high enough level density. These calculations make use of global and coherent microscopic nuclear models for the quantities entering the rate calculations. The use of such models is utterly important, and makes the BRUSLIB rate library unique. A description of the Nuclear Network Generator NETGEN that complements the BRUSLIB package is also presented. NETGEN is a tool to generate nuclear reaction rates for temperature grids specified by the user. The information it provides can be used for a large variety of applications, including Big Bang nucleosynthesis, the energy generation and nucleosynthesis associated with the non-explosive and explosive hydrogen to silicon burning stages, or the synthesis of the heavy nuclides through the s-, α- and r-, rp- or p-processes.

Key words. Nuclear Reactions – Stellar Evolution – Nucleosynthesis

1. Introduction

Since around the nineteen fifties, astrophysics has advanced at a remarkable pace, and has achieved an impressive record of success. One of the factors contributing to these rapid developments is undoubtedly a series of spectacular breakthroughs in nuclear astrophysics, which embodies the special interplay between nuclear physics and astrophysics.

The close relationship between these two major scientific disciplines comes about because of the clear demonstration that the Universe is pervaded with nuclear physics imprints at all scales. Starting with the Big Bang nucleosynthesis episode, the structure, evolution and composition of a large variety of cosmic objects, including the Solar System and its various constituents (down to meteoritic grains), bear strong imprints of the properties of atomic nuclei, as well as of their interactions. Therefore, careful and dedicated experimental and theoretical studies of a large variety of nuclear processes are indispensable tools for the modeling of the ultra-macroscopic systems astrophysics has to deal with.

Over the years, an impressive body of nuclear data of astrophysics interest have been obtained through laboratory efforts, complemented with theoretical developments. The latter are indispensable as nuclear experiments conducted today or expected to be performed in any foreseeable future can and will cover only a minute fraction of the astrophysics needs. This is because an extremely large variety of highly unstable ‘exotic’ nuclei that, for long, will not be produced and studied in the laboratory are expected to be involved in the modelling of many astrophysics processes and events. Many of the basic properties of these nuclei are to be known for this purpose, and so are their interactions, in particular those with nucleons or α-particles. Even when laboratory-studied nuclei are considered, theory has very often to be called for assistance.
In many respects, laboratory conditions are indeed very different from stellar ones, which are highly versatile and are often characterized by high temperatures and/or densities that are out of reach of laboratory simulations. In addition, nuclear reactions between charged particles inside non-explosing stars take place in an energy regime that is in all but a few exceptional cases out of reach of direct experimental scrutiny. Indirect methods bring some complement of information, but clearly do not cover all the needs. In explosive situations, the energies of astrophysical interest are higher, and the cross sections are correspondingly larger. However, in such events, many reactions involve unstable targets, so that the fraction of those reactions of potential interest for which experimental reaction data are lacking is even larger.

The experimental and theoretical nuclear physics achievement mentioned above in fact let nuclear astrophysics face a new and difficult challenge. The rapidly growing wealth of nuclear data becomes, ironically, less and less easily accessible to the astrophysics community. Mastering this volume of information and making it available in an accurate and usable form for incorporation into astrophysics models become urgent goals of prime necessity. The establishment of the required level in the privileged communication between nuclear physicists and astrophysicists necessarily requires the build-up of well documented and evaluated sets of experimental data or theoretical predictions of astrophysical relevance. Some years ago, the Institut d’Astronomie et d’Astrophysique of the Université Libre de Bruxelles has decided to tackle this challenge. This work has grown into the BRUSsels nuclear LIbrary for astrophysics applications, referred to as BRUSLIB, and into a nuclear NETwork GENerator called NETGEN.

One goal of this paper is to present for the first time a detailed description of BRUSLIB and of NETGEN in a journal and in a format such that these nuclear packages become easily accessible to astrophysicists for a large variety of applications. In particular, the BRUSLIB reaction rates presented in a tabular form that is well suited to astrophysics needs are available electronically at the address [http://www-astro.ulb.ac.be](http://www-astro.ulb.ac.be). BRUSLIB is composed of two main parts. The first one concerns the Nuclear Astrophysics Compilation of REaction rates referred to as NACRE. This compilation provides the rates of 86 thermonuclear reactions of astrophysical relevance based on an in-depth analysis of experimental data. Its description is presented in Sect. 2. The second part describes theoretical evaluations of a collection of about 100000 rates for thermonuclear reactions induced by nucleons or α-particles, as well as photo-induced reactions not included in NACRE, including nuclei with \( 8 \leq Z \leq 110 \) lying between the proton and the neutron drip lines (Sect. 3). The rate calculations are based on the statistical Hauser–Feshbach (hereafter HF) model. They require the knowledge of a substantial amount of data concerning basic properties of the nuclei and of their interactions. The predictions of these properties rely on the use of global and coherent microscopic nuclear models. These utterly important model characteristics make the BRUSLIB rate library unique. A confrontation between selected experimental data and the predictions used in BRUSLIB is provided in Sect. 4.

A second goal is to describe NETGEN (Sect. 5), a package for constructing nuclear reaction networks on grounds of the nuclear physics input from BRUSLIB and, when necessary, from other sources.

It has to be noted that no information is provided by the present release of BRUSLIB on the rates of non-statistical (‘direct’) or of non-thermonuclear (‘spallation’) reactions that can develop in low-temperature and low-density astrophysical media, like the interstellar or circumstellar medium.

### 2. The experimentally-based NACRE evaluation and compilation of nuclear reaction rates

The necessity of placing relevant nuclear data of high quality at the disposal of the astrophysics community has been the driving motivation for the construction of a compilation aimed at superseding the work of Fowler and collaborators (see Caughlan & Fowler 1988, hereafter CF88, and references therein to former compilations). The goal was not just to update the CF88 rates with newly available experimental data, but also to modify quite deeply different aspects of the format of the CF88 compilation. At this point, slightly more than half of the CF88 rates have been re-compiled on grounds of a careful evaluation of experimental data available by 15 June 1998, and the results of the work make the so-called NACRE (Nuclear Astrophysics Compilation of REactions) compilation (Angulo et al. 1999). The reactions analyzed up to now are listed in Table 1. They comprise an ensemble of 86 charged particle induced reactions on stable targets up to Si involved in Big Bang nucleosynthesis and in the non-explosive H- and He-burning modes, complemented with a restricted number of reactions of special astrophysical significance on the unstable \(^7\)Be, \(^{22}\)Na and \(^{26}\)Al nuclides. An updated and enlarged version of NACRE is currently in preparation.

NACRE is described in detail by Angulo et al. (1999). It contains in particular

1. the formalism that has been adopted in order to derive the Maxwellian-averaged astrophysical rates of the (exothermic and endothermic) charged particle induced reactions and of their reverse;
2. a general description of the treatment of the data, which has sometimes to be adapted to specific cases, as described in the comments accompanying each of the compiled reactions. If necessary, tables of narrow resonances with their characteristics are provided. A careful analysis of the experimental uncertainties in the quantities involved in the evaluation of the reaction rates is carried out for each reaction. From this, adopted rates are provided, as well as low and high limits. This large-scale estimate of
the uncertainties is considered to be an essential feature of the NACRE compilation;

(3) the procedure adopted for extrapolating experimental data when required in order to estimate the reaction rates. This extrapolation to the very low energies necessary to evaluate the rates down to the lowest considered temperatures raises many difficult problems. A particular one concerns the necessity to correct the laboratory cross sections for electron screening (e.g. Rolfs & Rodney 1988) before their use in the rate calculations. This effect becomes significant for relative energies $E$ of the reaction partners such that $E/U_e \leq 100$, where $U_e$ is the so-called screening potential. An approximate procedure is devised in order to eliminate data that can be 'polluted' by laboratory screening. On the other hand, in stellar conditions, the nuclei are surrounded by a dense electron gas that reduces the Coulomb repulsion and makes the penetration of the Coulomb barrier easier. The cross sections

| Reaction                  | Rate | Other refs. | Reaction                  | Rate | Other refs. |
|---------------------------|------|-------------|---------------------------|------|-------------|
| $^1$H(p,e+)$^2$H          |      |             | $^{15}$N(p,α)$^{12}$C     |      |             |
| $^2$H(p,γ)$^3$He          | [D]a | [N]a        | $^{15}$N(α,γ)$^{19}$F     |      |             |
| $^2$H(d,γ)$^3$He          | [SA04]|            | $^{16}$O(γ,p)$^{17}$F     |      |             |
| $^2$H(d,n)$^3$He          | [D]a |             | $^{16}$O(α,γ)$^{20}$Ne    |      |             |
| $^2$H(d,p)$^3$H           | [D]a |             | $^{17}$O(p,γ)$^{18}$F     |      |             |
| $^2$H(α,γ)$^5$Li          | [D]a |             | $^{17}$O(α,γ)$^{14}$N     |      |             |
| $^3$H(d,n)$^4$He          | [D]a |             | $^{17}$O(α,γ)$^{20}$Ne    |      |             |
| $^3$H(α,γ)$^7$Li          | [D]a |             | $^{18}$O(p,γ)$^{19}$F     |      |             |
| $^3$He(2He,2p)$^4$He      |      |             |                           |      |             |
| $^3$He(α,γ)$^7$Be         | [D]a |             | $^{18}$O(p,α)$^{15}$N     |      | [KU04]+     |
| $^4$He(α,γ)$^9$Be         | [SU02] + |            | $^{18}$O(α,γ)$^{22}$Ne    |      |             |
| $^4$He(α,γ)$^{12}$C     | [FY05] |            | $^{18}$O(α,γ)$^{21}$Ne    |      | [NA04]      |
| $^6$Li(p,γ)$^7$Be        | [PR04]|            | $^{19}$F(p,γ)$^{20}$Ne    |      |             |
| $^6$Li(p,α)$^7$He         | [TU03]|            | $^{19}$F(p,α)$^{19}$Ne    |      |             |
| $^7$Li(p,γ)$^8$Be        | [N]a |             | $^{20}$Ne(p,γ)$^{21}$Na   |      | [I]a        |
| $^7$Li(p,α)$^7$He         | [D]a |             | $^{20}$Ne(p,α)$^{17}$F    |      |             |
| $^7$Li(α,γ)$^{11}$B     | [GY04]|            | $^{20}$Ne(α,γ)$^{24}$Mg   |      |             |
| $^7$Li(α,n)$^{10}$B     | [CY04]+ |          | $^{21}$Ne(p,γ)$^{22}$Na   |      |             |
| $^7$Be(p,γ)$^8$B         | [I]a |             | $^{21}$Ne(α,γ)$^{24}$Mg   |      |             |
| $^7$Be(α,γ)$^{11}$C     | [I]a |             | $^{22}$Ne(p,γ)$^{23}$Na   |      | [HA02]+     |
| $^9$Be(p,γ)$^{10}$B      | [N]a |             | $^{22}$Ne(α,γ)$^{26}$Mg   |      |             |
| $^9$Be(p,α)$^9$B        | [BR98]|            | $^{22}$Ne(α,γ)$^{25}$Mg   |      |             |
| $^9$Be(p,α)$^8$Be        | [BR98]|            | $^{22}$Na(p,γ)$^{23}$Mg   |      | [JE04]+     |
| $^9$Be(p,α)$^6$Li        | [BR98]|            | $^{23}$Na(p,γ)$^{24}$Mg   |      | [HA04]+     |
| $^9$Be(α,γ)$^{13}$C     | [TO03] |            | $^{23}$Na(p,α)$^{20}$Ne   |      |             |
| $^{10}$B(p,γ)$^{11}$C    | [I]a |             | $^{23}$Na(α,γ)$^{26}$Al   |      | [HA04]+     |
| $^{10}$B(p,α)$^{10}$B    | [I]a |             | $^{23}$Na(α,γ)$^{26}$Al   |      |             |
| $^{11}$B(p,γ)$^{12}$C    | [I]a |             | $^{23}$Na(α,γ)$^{26}$Al   |      |             |
| $^{11}$B(p,α)$^{11}$C    | [I]a |             | $^{23}$Na(α,γ)$^{26}$Al   |      |             |
| $^{11}$B(p,α)$^{10}$Be   | [SP04]|            | $^{24}$Mg(p,γ)$^{25}$Al   |      |             |
| $^{12}$C(p,γ)$^{13}$N    | [TI02]|            | $^{24}$Mg(p,α)$^{21}$Na   |      |             |
| $^{12}$C(α,γ)$^{15}$O    | [KU02]+ |          | $^{25}$Mg(p,γ)$^{26}$Al   |      |             |
| $^{13}$C(α,γ)$^{14}$N    | [MU03a]+ |         | $^{25}$Mg(p,γ)$^{26}$Al   |      |             |
| $^{13}$C(p,γ)$^{15}$N    | [I]a |             | $^{25}$Mg(p,γ)$^{26}$Al   |      |             |
| $^{13}$C(α,γ)$^{16}$O    | [KU03]+ |          | $^{25}$Mg(α,γ)$^{28}$Si   |      |             |
| $^{14}$N(α,γ)$^{14}$F    | [GÖ00]+ |          | $^{26}$Mg(γ,α)$^{27}$Si   |      |             |
| $^{14}$N(α,γ)$^{16}$O    | [RO04]+ |         | $^{26}$Mg(γ,α)$^{27}$Si   |      |             |
| $^{15}$N(p,γ)$^{16}$O    | [TA04]+ |         | $^{27}$Al(γ,α)$^{28}$Si   |      | [HA00]+     |
| $^{15}$N(p,α)$^{15}$O    | [RU05]+ |         | $^{27}$Al(γ,α)$^{28}$Si   |      | [I]a        |
| $^{15}$N(p,α)$^{14}$O    | [AN01]+ |         | $^{27}$Al(γ,α)$^{28}$Si   |      | [I]a        |
are therefore enhanced in comparison with those of reactions between bare nuclei. This stellar screening effect can be evaluated by applying, for example, the Debye-Hückel theory (e.g. Cox & Giuli 1968). The NACRE rates exclude these stellar screening factors.

The evaluation of the rates for temperatures as high as $T_9 = 10$ also requires the application of special extrapolation techniques when reliable cross section data are lacking at sufficiently high energies. In those cases, a duly documented HF approach is used (see also Sect. 3.1), which smoothly connects to the experimentally-based rate estimates;

(3) the procedure used to evaluate the contribution of excited states of the target nuclei to the effective stellar reaction rates. In a stellar plasma, the excited levels of a target nucleus are indeed thermally populated, and thus contribute to the reaction mechanism. As a result, the stellar rates may differ from those obtained when the target nuclei are in their ground state. This difference is expressed in terms of a correction factor $r_{tt}$ that has to multiply the target ground state rate in order to obtain the stellar rate. In general, this correction cannot be derived experimentally. The very approximate treatment of this correction by Caughlan & Fowler (1988) is replaced in NACRE by a more quantitative procedure based on the use of the HF model (Sect. 3.1), and on the classical assumption of a Maxwellian population of the nuclear excited states. Note that this assumption may be invalid if the target nucleus has an isomeric state which is not in thermal equilibrium with the ground state in certain astrophysical situations. Such an example of astrophysical interest concerns $^{26}$Al, to which a special treatment is applied.

The calculation of $r_{tt}$ requires in particular the knowledge of the temperature-dependent partition functions of the target nuclei normalized to their ground state

$$G_i(T) = \frac{1}{2J_i^\mu + 1} \sum_\mu (2J_i^\mu + 1) \exp \left( -\frac{\epsilon_i^\mu}{kT} \right),$$

where the summation extends over the states $\mu$ of target $i$ with excitation energy $\epsilon_i^\mu$ and spin-parity $J_i^\mu (\mu = 0$ for the ground state);

(4) The values of the adopted, low and high Maxwellian-averaged unscreened rates on the ground state target are provided in tabular form for a selection of temperatures in the 0.001 $\leq T_9 \leq 10$ range ($T_9$ is the temperature in billion K). As they may be desired by some users, analytical formulae approximating the tabulated adopted ground state rates or those including the contribution of thermalized excited states are provided as well. It has to be noted that some of these expressions have a form deviating from those classically advertised in the nuclear astrophysics literature (e.g. Caughlan & Fowler 1988; Rolls & Rodney 1988; see e.g. Eq. (23) of Angulo et al. 1999). They are considered to provide more secure approximations to the numerically calculated Maxwellian-averaged rates. In addition, NACRE provides analytical formulae for the multiplicative factor that has to be applied to the rate of a given reaction in order to evaluate the rate of the inverse process, as well as for the nuclear partition functions for the targets involved in the compiled reactions (see Eq. 1).

NACRE is accessible electronically through the BRUSLIB library website [http://www-astro.ulb.ac.be](http://www-astro.ulb.ac.be). Much more material is available there than presented above or published by Angulo et al. (1999). In particular, reaction rates are available for far more extended temperature grids. In addition, graphical material (astrophysical S-factors) can be retrieved.

Finally, it is noted that other astrophysics-oriented experimentally-based reaction rate compilations have appeared around the time of the NACRE publication (Adelberger et al. 1998), or later (Iliadis et al. 2001; Descouvemont et al. 2004). The reactions considered in the latter two compilations are identified in Table 1, which also provides references to additional data or evaluations of relevance. This additional information will of course be duly analyzed and integrated into the new version of NACRE currently in preparation.

3. The BRUSLIB theoretical reaction rates

Much effort has been devoted in the last decades to measurements of reaction cross sections for astrophysical purposes. As already stated in Sect. 1 difficulties related to the conditions prevailing in the astrophysical plasmas remain, however. In particular, charged-particle induced reactions at stellar energies (far below the Coulomb barrier) have extremely small cross sections that are highly difficult to measure. Specific difficulties are also raised by the measurements of photoreactions that have to be included in many astrophysics models (e.g. Arnould & Goriely 2003 for a review). In addition, a huge number (thousands) of reactions of relevance involve more or less exotic nuclides. Clearly, many of these reaction rate experiments will remain unfeasible for a long time to come. Theory has thus to supply the necessary data, which represents a major challenge of its own.

BRUSLIB provides astrophysicists with a very extended set of thermonuclear rates in the 0.01 $\leq T_9 \leq 10$ temperature range for all the reactions induced by neutron, proton and $\alpha$-particle captures by all nuclei with $Z, N \geq 8$ and $Z < 110$ located between the neutron and proton drip lines (i.e some 8000 nuclei). The rates of the $(\gamma,n)$, $(\gamma,p)$ and $(\gamma,\alpha)$ photodisintegrations of all these nuclides are also tabulated for the same temperature grid. The calculations rely on the code MOST (Goriely 1998; Arnould & Goriely 2003) based on the HF model (Hauser & Feshbach 1952). This approach is valid if the density of nuclear levels of the compound systems formed as a result of these captures is high enough. This is indeed the case if the targets are heavy enough and if they are located far enough from the proton or neutron drip lines to ensure that the excitation energies of the compound systems are high enough. Roughly speaking, the reliability of the BRUSLIB rates may thus be limited to nuclides with mass numbers $A \geq 40$ close enough to the valley of
stability, this mass limit being of course shifted to higher and higher values as one moves further and further away from the valley. If these constraints are not met, a non-statistical treatment is more suited (Goriely 1997). It has to be noticed that purely theoretical HF rates are provided for some reactions already included in NACRE (Table 1). In these cases, it is advised to adopt the NACRE rates, or those from the Iliadis et al. (2001) or Descouvemont et al. (2004) compilations, as these rely on experimental data.

A few words are in order at this point to clarify the basic philosophy governing the selection of the models necessary for the calculation of the various ingredients entering the HF BRUSLIB rates. Their evaluation is based on global and coherent microscopic (or at least semi-microscopic) models. These features have an importance in the astrophysics modellings that cannot be underestimated, and make the BRUSLIB rate library unique. They are indeed not shared by HF calculations based on other codes, like Talys (Koning et al. 2002), Empire (Herman et al. 2002), or Non-Smoker (Rauscher & Thielemann 2001).

The global character of the underlying models is made highly desirable by the fact that, for many specific applications including nuclear astrophysics, a very large body of reaction rates for which no experimental data exist have to be provided. The microscopic nature of the underlying models is essential as well. For nuclear astrophysics, as well as in other fields, a large amount of data need to be extrapolated far away from experimentally known regions. In these situations, two major features of the nuclear theories have to be considered. The first one is the accuracy of a model. In most nuclear applications, this criterion has been the main, if not the unique, one for selecting a model. The second one is the reliability of the predictions. A physically sound model that is based on first principles and is as close as possible to a microscopic description of the nuclear systems is expected to provide the best possible reliability of extrapolations far away from experimentally known regions. Of course, the accuracy of such microscopic models in reproducing experimental data may be poorer than the one obtained from more phenomenological models in which enough free parameters can guarantee a satisfactory reproduction of the data at the expense of the quality of the input physics, and consequently of the reliability. The coherence (or ‘universality’) of these microscopic models (through e.g. the use of the same basic nuclear inputs, like the effective nuclear forces) is also required as different ingredients have to be predicted in order to evaluate each reaction rate. Failure to meet this requirement could lead to bad ways in the rate evaluations.

The BRUSLIB MOST rates are based on microscopic (or at least semi-microscopic) models for the necessary nuclear structure ingredients or interaction properties (Sect. 4.1) that have been constructed to be global and coherent to the largest possible extent. In addition, these models have the major advantage of reaching a satisfactory compromise between accuracy and reliability for the relevant nuclear inputs, and consequently for the rates themselves. The level of accuracy of these models is in fact fully comparable to the one obtained from available more or less highly parametrized phenomenological approaches, while their reliability is by far better.

Finally, the BRUSLIB reaction rates duly take into account the necessary astrophysical specificities. The temperature dependence of the rates is predicted from the consideration of the Maxwell-Boltzmann distribution of the relative velocities of the reaction partners and of the target nuclear excited states (par. (3) of Sect. 2). In contrast, the provided rates are not corrected for stellar electron screening effects.

### 3.1. Reaction rate calculations: general framework

Some basics of the HF formalism adopted in the code MOST are briefly recalled in e.g. Arnould & Goriely (2003), and are not repeated here. The limits of its validity are also reminded above. Let us just point out the following:

1. under local thermodynamic equilibrium conditions, the effective stellar rate of \( I + j \rightarrow L + k \) per pair of particles in the entrance channel at temperature \( T \) taking due account of the contributions of the various excited states \( \mu \) of the target is expressed in a classical notation as

\[
N_A(\sigma v)_{jk}^\ast(T) = \left( \frac{8}{\pi mN_A} \right)^{1/2} \left( \frac{kT}{G(T)} \right)^{3/2} \int_0^\infty \sum_{\mu} \frac{(2J_1^\mu + 1)}{(2J_L^\mu + 1)} \sigma_{jk}^\mu(E) E \exp\left(-\frac{E + \epsilon_j^\mu}{kT}\right) dE, \tag{2}
\]

where \( k \) is the Boltzmann constant, \( m \) the reduced mass of the \( I^0 + j, \mu \) system, \( \sigma_{jk}^\mu(E) \) the cross section at relative energy \( E \) of the \( I^0 + j \rightarrow L + k \) reaction, and \( G(T) \) is the partition function given by Eq. 11 where \( J_1^\mu \) and \( \epsilon_j^\mu \) are defined. The BRUSLIB photodisintegration rates are estimated by applying the reciprocity theorem on the radiative capture rates derived from Eq. 2. This procedure leads to

\[
\lambda_{(\gamma,j)}(T) = \frac{(2J_L + 1)(2J_1 + 1)}{(2J_L^0 + 1)} \frac{G_L(T)}{G_1(T)} \left( \frac{A_j A_L}{A_1 A_L} \right)^{3/2} \frac{kT}{2\pi\hbar^2 N_A} \left( \begin{array}{c} \frac{3/2}{N_A(\sigma v)_{(j,\gamma)}^\ast} e^{-Q_j^\gamma/kT} \end{array} \right), \tag{3}
\]

where \( Q_j^\gamma \) is the Q-value of the \( I^0(j,\gamma)L^0 \) capture. Note that, in stellar conditions, the reaction rates for targets in thermal equilibrium obey reciprocity since the forward and reverse channels are symmetrical, in contrast to the situation which would be encountered for targets in their ground states only (Holmes et al. 1976).

The uncertainties involved in any HF prediction are dominated by those involved in the evaluation of the nuclear quantities necessary for the calculation of the cross sections, such as the masses, deformations, matter distributions, single-particle levels, and level densities of target and residual nuclei, as well as the optical potentials. Special problems are also raised by the evaluation of the
3.2. Nuclear masses, level densities, and partition functions

The BRUSLIB MOST predictions rely on the experimental nuclear mass data compiled by Audi et al. (2003). When not measured (a very common situation for various astrophysics applications), use is made of the HFB-9 microscopic mass model (Goriely et al. 2005). This model also provides the necessary information on nuclear deformation, charge and matter distributions, pairing properties and single-particle spectra. The nuclear level densities are extracted from a microscopic model developed by Goriely (1996) (see also e.g. Demetriou & Goriely 2001).

The nuclear partition functions \( G_i(T) \) entering the evaluation of the astrophysical reaction rates (Sects. 2 and 3) are calculated from (i) a summation over experimentally known levels (Eq. 1) up to an excitation energy \( \epsilon \omega \) above which the knowledge of the energy spectrum is considered to be incomplete, and (ii) a generalization of Eq. 1 involving an integration over a level density evaluated as described above.

3.3. Optical potentials

Phenomenological optical potentials (OPs) (generally of the Woods-Saxon type) may not be well suited for certain applications, particularly those involving exotic nuclei. It is considered profitable to use more microscopically-based potentials, whenever possible. A semi-microscopic OP, usually referred to as the JLM potential (Jeukenne et al. 1977), is available for the description of the nucleon-nucleus case. This OP has been revised recently for nucleons incident on spherical or quasi-spherical nuclei with masses 40 \( \leq A \leq 200 \) at energies ranging from 1 keV to 200 MeV (Bauge et al. 2001). The resulting new version gives a global satisfactory agreement with experimental data, even if some improvements would be most welcome, especially in the low-energy domain and in the treatment of deformed or exotic nuclei. It is adopted for the BRUSLIB rate evaluations.

The situation for the \( \alpha \)-particle-nucleus OPs is much less satisfactory, and one still has to rely on phenomenological potentials. Most of the proposed OPs are derived from fits to elastic \( \alpha \)-nucleus scattering data at energies \( E \geq 80 \) MeV or, in some cases, to \( (n,\alpha) \) cross sections at lower energies. However, the OP, and in particular its imaginary component, is known to depend strongly on energy below the Coulomb barrier. As a consequence, its extrapolation to sub-Coulomb energies that is necessitated by astrophysics applications is more insecure than in the case of nucleons. Several attempts to device a global \( \alpha \)-nucleus OP for the description of the scattering and reaction cross sections at energies \( E \leq 20 \) MeV of better relevance to astrophysics have been conducted (e.g. Arnould & Goriely 2003 for more details and references). The scarcity of experimental data, particularly in the \( A > 100 \) mass range, limits dramatically the predictive power of any of the constructed global OPs. This has the immediate consequence of reducing the reliability of the rate predictions as they depend sensitively on the \( \alpha \)-particle-nucleus OPs. The BRUSLIB \( \alpha \)-capture rates are calculated with the global OP III developed by Demetriou et al. (2002).

3.4. \( \gamma \)-ray strength function

When applied to radiative captures, the total photon transmission coefficient entering the calculation of the \( \sigma_\gamma^\mu \gamma \) cross section of Eq. 4 is dominated by the \( E1 \) transitions. The calculation of the \( E1 \)-strength function necessitates the knowledge of the low-energy tail of the Giant Dipole Resonance (GDR) of the compound system formed in the reaction process. The photon transmission coefficient is most frequently described in the framework of the phenomenological generalized Lorentzian model (e.g. Goriely 1998). The Lorentzian GDR approach suffers, however, from shortcomings of various sorts. On the one hand, it is unable to predict the enhancement of the \( E1 \) strength at energies below the neutron separation energy demonstrated by nuclear resonance fluorescence experiments. This departure from a Lorentzian profile may manifest itself more clearly for neutron-rich nuclei, and especially in the form of a so-called pygmy \( E1 \) resonance (Govaert et al. 1998, Zilges et al. 2002). On the other hand, even if a Lorentzian function provides a suitable representation of the \( E1 \) strength, the location of its maximum and its width remain to be predicted from some underlying model for each nucleus. For astrophysical applications, these properties have often been obtained from a droplet-type of model (Myers et al. 1977), which clearly lacks reliability when dealing with exotic nuclei. This introduces large uncertainties in certain rate estimates (e.g. Goriely & Khan 2002, Goriely et al. 2004).

In view of this situation, it is clearly of substantial interest to develop models of the microscopic type which are hoped to provide a reasonable reliability and predictive power for the \( E1 \)-strength function. Various attempts of this sort have been conducted (e.g. Arnould & Goriely 2003, and references therein). The BRUSLIB MOST rate calculations are based on the semi-microscopic QRPA \( E1 \) model developed by Goriely et al. (2004).

4. A confrontation between measured and calculated reaction rates

In order to evaluate the overall quality of the BRUSLIB reaction rate predictions, this section presents a confrontation between selected experimental data and calculations in which only the ground state contribution (\( \mu = 0 \)) is taken into account in Eqs. 2 and 3, the consideration of target excited states being irrelevant in the laboratory conditions.
Figure 1 compares the BRUSLIB predictions of the Maxwellian-averaged (n,γ) rates ⟨σv⟩th with experimental values (Bao et al. 2000) at T = 3.5 × 10^8 K. It appears that the calculations agree with all data to within a factor of three. Figure 2 displays a comparison between some low-energy (p,γ) reactions on targets heavier than Fe with the corresponding BRUSLIB rates. Again, and broadly speaking, the agreement is very satisfactory for the vast majority of the (p,γ) data. It is difficult, however, to be much more specific, as the quality of this agreement may depend more or less drastically on temperature, in contrast to the situation encountered in the neutron capture case. In addition, the comparison is limited to targets up to Sn. Experiments with heavier nuclei would be most welcome, as they might help refining the predictions.

The situation is by far less clear for the (α,γ) reactions. This results from the lack of a large enough body of experimental data for sub-Coulomb cross sections combined with the difficulties to construct global and reliable α-nucleus OPs (Sect. 3.3). These theoretical problems are magnified by the fact that, at the sub-Coulomb energies of astrophysical relevance, the reaction rate predictions are highly sensitive to these potentials through the corresponding α-particle transmission coefficients. Figure 3 displays a comparison between some low-energy measurements of (α,γ) cross sections and MOST predictions used for evaluating the BRUSLIB rates. The quality of the agreement appears to vary from case to case, and is also highly sensitive to temperature. Uncertainties in the calculated values originate mainly from those in the nuclear level densities and α-nucleus OPs (see Arnould & Goriely 2003 for details, and in particular for a discussion of the 144Sm (α,γ)148Gd reaction of special astrophysics interest).

5. The nuclear network generator NETGEN

The Nuclear Network Generator NETGEN is an interactive Web-based tool to generate Maxwellian-averaged nuclear reaction rates for networks and temperature grids specified by the user. It is fully documented at the web address [http://www-astro.ulb.ac.be/Netgen](http://www-astro.ulb.ac.be/Netgen)

NETGEN relies mainly on the BRUSLIB/NACRE library. It also makes use of (1) the post-NACRE compilations by Iliadis et al. (2001) and Descouvemont et al. (2004) (see Table 1); (2) experimentally-based published rates for about 70 charged-particle induced reactions not included in NACRE. Specific references are provided for each of these reactions; (2) more than 200 experimentally-based radiative neutron capture rates. Most of these are adopted from Bao et al. (2000). Specific references are given in each case; (3) β-decay and electron-capture rates, including (i) laboratory measurements compiled by Horiguchi et al. (1996), (ii) theoretical estimates based on the evaluation of individual transitions (Takahashi & Yokoi 1987), on the gross theory (Tachibana et al. 1990), or on the more microscopic ETFSI + cQRPA model (Borzov & Goriely 2000).
Cross sections for the (α,γ) reactions on 37Cl, 42Ca, 56Fe, 58Ni, 62,64Ni, 70Ge, 106Cd and 144Sm (see Arnould & Goriely 2003 for references to the laboratory work). Black and open circles represent experimental data. The solid lines give the calculated cross sections used to construct the BRUSLIB rates.

For the sake of completeness, the references of Table 1 that are not contained in the NACRE, Iliadis et al. (2001) or Descouvemont et al. (2004) compilations are also included in NETGEN.

For each reaction or β-decay rate, NETGEN selects by default the data source that is considered to be the most reliable. We select in order of preference the latest available compilation (NACRE, Iliadis et al. 2001, or Descouvemont et al. 2004), experimental data, detailed microscopic calculations, and BRUSLIB rates derived from global calculations. The user may nevertheless adopt another choice for selected cases by specifying 'bibliographic indexes' for each reaction, the table of rates being accompanied by a 'log file' listing the selected data source among all those available in the library. A FORTRAN program handling the rates is also made available. Note that all rates duly take into account the contribution from the excited states of the target nuclei, as discussed in the previous sections.

Various NETGEN options are currently offered through the web interface, as described in detail at http://www-astro.ulb.ac.be/Netgen.

1. Generate a table of reaction rates on a temperature grid for a network that has been
   - typed in reaction by reaction (offering the possibility to select non-default rates, as mentioned above), or
   - generated automatically between interactively-selected boundaries on the proton and mass numbers, and involving various possible sets of reactions (p-, n-, α-captures, β-decays and/or photodisintegrations), or
   - uploaded on the server.

2. Plot individual reaction rates, and provide .gif or .ps files.

6. Conclusions

This is the first release in an astronomy and astrophysics journal of the BRUSLIB nuclear reaction rate library and of the nuclear network generator NETGEN. The format of the packages is chosen in order to make them easily accessible to astrophysicists and to be well suited for a large variety of astrophysics needs. They are made available through the web sites http://www-astro.ulb.ac.be

The BRUSLIB NACRE package contains a detailed experimentally-based evaluation and compilation of the rates of 86 proton or α-capture reactions on (mainly) stable targets up to Si for temperatures ranging from 10^8 to 10^10 K. The electronic files contain much more information than published by Angulo et al. (1999).

The NACRE data are complemented with about 100000 thermonuclear rates of nucleon and α-captures on about 8000 8 ≤ Z ≤ 110 nuclei located between the proton and neutron drip lines. The calculations are based on a statistical Hauser-Feshbach model featuring a microscopic (or at least very close to microscopic) evaluation of the basic ingredients of the model. These predictions are seen to compare favourably with the limited set of experimental reaction cross section data on intermediate-mass and heavy nuclei at energies close to those of astrophysics relevance. The rates of photodisintegration of the whole set of nuclei are also provided. They are derived from the application of the reciprocity theorem.

NETGEN is an interactive web-based tool allowing the construction on a user-friendly basis of nuclear reaction networks specified by the user on a temperature grid of his/her choice. A full documentation of its use can be found at the web address http://www-astro.ulb.ac.be/Netgen.

It is hoped that the easy availability of a very large set of nuclear reaction rate evaluations and predictions, as well as of a nuclear network generator will be helpful to many researchers for a large variety of applications. Quite clearly, this enterprise is of a highly dynamical and long-term nature. BRUSLIB will be continuously improved and expanded, and new releases will be made accessible to the community every time a substantial enough body of new data becomes available.

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References

Adelberger, E.G., Austin, S.M., Bahcall, J.N., et al. 1998, Rev. Mod. Phys., 70, 1265
Angulo, C., & Descouvemont, P. 2001, Nucl. Phys., A690, 755 [AN01]
Angulo, C., Arnould, M., Rayet, M., et al. 1999, Nucl. Phys., A656, 3
Arnould, M., & Goriely, G. 2003, Phys. Rep. 384, 1
Audi, G., Wapstra, A.H., & Thibault, C. 2003, Nucl. Phys., A729, 337
Bao Z.Y., Beer H., K¨ appeler F., et al. 2000, At. Data Nucl. Data Tables, 75, 1
Bauge, E., Delaroche, J.P., & Girod, M. 2001, Phys. Rev., C63, 024607
Borzov, I., & Goriely, S. 2000, Phys. Rev., C62, 035501
Brune, C.R., Geist, W.H., Karwowski, H.J., et al. 1998, Phys. Rev., C57, 3437 [BR98]
Caughlan, G.R., & Fowler, W.A. 1988, At. Data Nucl. Data Tables, 40, 283
Cox, J.P., & Giuli, R.T. 1968, Principles of Stellar Structure (New York: Gordon and Breach)
Cyburt, R.H., Davids, B., & Jennings, B.K. 2004, Phys. Rev., C70, 045801 [CY04]
Dababneh, S., Heil, M., K¨ appeler, F., et al. 2003, Phys. Rev., C68, 055801 [DA03]
Demetriou, P., & Goriely, S. 2001, Nucl. Phys. A695, 95
Demetriou, P., Graña, C., & Goriely, S. 2002, Nucl. Phys. A707, 253
Descouvemont, P., Adahchour, A., Angulo, C., et al. 2004, At. Data Nucl. Data Tables, 88, 203 [D]
Fitzgerald, R., Abbotoy, E., Bardayan, D.W., et al. 2005, Nucl. Phys., A748, 351 [FI05]
Fox., C., Iliadis, C., Champagne, A.E., et al. 2004, Phys. Rev. Lett., 93, 081102 [FO04]
Goriely, S. 1996, Nucl. Phys. A605, 28
Goriely, S. 1997, A&A 325, 414
Goriely, S. 1998, Phys. Let, B436, 10
Goriely, S., & Khan, E. 2002, Nucl. Phys., A706, 217
Goriely, S., Khan, E., & Samyn, M. 2004, Nucl. Phys., A739, 331
Goriely, S., Samyn, M., Pearson, J.M., & Onsi M. 2005, Nucl. Phys., A750, 425
Gorres, J., Arlandini, C., Giesen, U., et al. 2000, Phys. Rev., C62, 055801 [GO00]
Govaert, K., Bausens, F., Bryssinck, J., et al. 1998, Phys. Rev., C57, 2229
Gy¨ urky, Gy., F¨ ul¨ op, Zs., Somorjai, E., et al. 2004, Eur. Phys. J., A21, 355 [GY04]
Hale, S.E., Champagne, A.E., Iliadis, C., et al. 2002, Phys. Rev., C65, 015801 [HA02]
Hale, S.E., Champagne, A.E., Iliadis, C., et al. 2004, Phys. Rev., C70, 045802 [HA04]
Harissopulos, S., Chronidou, C., Spyrou, K., et al. 2000 Eur. Phys. J., A9, 479 [HA00]
Hauser, W., & Feshbach, H. 1952, Phys. Rev., 87, 366
Herman, M., Capote-Noy, R., Oblizovsky, P., Trkov, A., & Zerkin, V. 2002, in Proc. of Nuclear Data for Science and Technology, J. Nucl. Science and Technology, Suppl. 2, vol. 1, ed. K. Shibata, 116
Holmes, J.A., Woosley, S.E., Fowler, W.A., & Zimmerman, B.A 1976, Atomic Data Nucl. Data Tables, 18, 306
Horiguchi, T., Tachibana, T., & Kataoka, J. 1996, Chart of the Nuclides, Japanese Nuclear Data Committee and Nuclear Data Center
Iliadis, C., D’Auria, J.M., Starrfield, S., et al. 2001, ApJS, 134, 151 [I]
Jaeger, M., Kunz, R., Mayer, A., et al. 2001, Phys. Rev. Lett., 87, 202501 [JA01]
Jenkins, D.G., Lister, C.J., Janssens, R.V.F., et al. 2004, Phys. Rev. Lett., 92, 031101 [JE04]
Jeukenne, J.P., Lejeune, A., & Mahaux, C. 1977, Phys. Rev., C16, 80
Koning, A., Beijers, H., Benlliure J., et al., 2002, in Proc. of Nuclear Data for Science and Technology, J. Nucl. Science and Technology, Suppl. 2, vol. 2, ed. K. Shibata (Atomic Energy Society of Japan) 1161
Kubono, S., Abe, K., Kato, S., et al. 2003, Phys. Rev. Lett., 90, 062501 [KU03]
Kudomi, N., Komori, M., Takahisa, K., et al. 2004, Phys. Rev., C69, 015802 [KU04]
Kunz, R., Fey, M., Jaeger, M., et al. 2002, ApJ, 567, 643 [KU02]
Mukhamedzhanov, A.M., Azhari, A., Burjan, V., et al. 2003, Nucl. Phys., A725, 279 [MU03a]
Mukhamedzhanov, A.M., Bém, P., Brown, B.A., et al. 2003 Phys. Rev., C67, 065804 [MU03b]
Myers, W.D., Swiatecki, W.J., Kodama, T., et al. 1977, Phys. Rev., C15, 2032
Nara Singh, B.S., Hass, M., Nir-El, Y., et al. 2004, Phys. Rev. Lett., 93, 262503 [NA04]
Nelson, S.O., Wulf, E.A., Kelley, J.H., et al. 2000, Nucl. Phys., A679, 199 [N]
Prior, R.M., Spraker, M.C., Anthor, A.M., et al. 2004, Phys. Rev., C70, 055801 [PR04]
Rauscher, T., & Thielemann, F.-K. 2001, At. Data Nucl. Data Tables, 79, 47
Rols, C.E., & Rodney, W.S. 1988, Cauldrons in the Cosmos (Chicago: Chicago Univ. Press)
Rowland, C., Iliadis, C., Champagne, A.E., et al. 2004, ApJ, 615, L37 [RO04]
Runkle, R.C., Champagne, A.E., Angulo, C., et al. 2005, Phys. Rev. Lett., 94, 082503 [RU05]
Sabourou, K., Ahmed, M.W., Canon, S.R., et al. 2004, Phys. Rev., C70, 064601 [SA04]
Spitaleri, C., Lamia, L., Tumino, A., et al. 2004, Phys. Rev., C69, 055806 [SP04]
Spyrou, K., Chronidou, C., Harissopulos, S., et al. Eur. Phys. J., A7, 79 [SP00]
Sumiyoshi, K., Utsumoniya, H., Goko, S., et al. 2002, Nucl. Phys., A709, 467 [SU02]
Takahashi, T., Yamada, M., & Yoshida, N. 1990, Prog. Theor. Phys., 84, 641
Takahashi, K., & Yokoi, K. 1987, Atomic Data Nucl. Data Tables, 36, 375
Tang, X., Azhari, A., Fu, C., et al. 2004, Phys. Rev., C69, 055807 [TA04]
Tischhauser, P., Azuma, R.E., Buchmann, L., et al. 2002, Phys. Rev. Lett., 88, 072501 [TI02]
Tonchev, A.P., Nelson, S.O., Sabourou, K., et al. 2003, Phys. Rev., C68, 045803 [TO03]
Wilmes, S., Wilmes, V., Staudt, G., et al. 2002, Phys. Rev., C66, 065802 [W02]
Zilges, A., Volz, S., Babilon, M., et al. 2002, Phys. Let., B542, 43