A&A 441, 1195–1203 (2005)
DOI: 10.1051/0004-6361:20052944

Astronomy & Astrophysics

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

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Received 28 February 2005 / Accepted 9 June 2005

ABSTRACT

Nuclear reaction rates are quantities of fundamental importance in astrophysics. Substantial efforts have been devoted in the last decades to measuring or calculating them. This paper presents a detailed description of the Brussels nuclear reaction rate library BRUSLIB and of the nuclear network generator NETGEN. 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 BRUSLIB provides an electronic link to the published, as well as to a large body of unpublished, NACRE data containing adopted rates, as well as lower and upper limits. The second part of BRUSLIB concerns nuclear reaction rate predictions to complement the experimentally-based rates. An electronic access is provided to tables 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 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, nucleosynthesis, abundances

1. Introduction

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

The close relationship between these two disciplines comes about because the Universe is pervaded by 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 constituants (down to meteoritic grains), bear strong imprints of the properties of atomic nuclei, as well as of their interactions. Therefore, experimental and theoretical studies of a large variety of nuclear processes are indispensable for the modelling of the ultra-macroscopic astrophysics systems.

Over the years, an impressive body of nuclear data of astrophysics interest have been obtained through laboratory efforts. However, theoretical developments still have to complement them because very many highly unstable "exotic" nuclei that cannot be produced in the laboratory are expected to be involved in the modelling of a large variety of astrophysics processes and events. Many of the basic properties of these nuclei are to be known for this purpose, as 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 varied and are often charaterized by high temperatures and/or densities that are out of reach of laboratory simulations. In addition, nuclear reactions between charged particles inside non-exploding stars take place in an energy regime that is in all but a few exceptional cases out of reach of direct experiment. 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 reactions of potential interest for which experimental reaction data are lacking is even larger.

* Entire database for nuclear reactions is only available in electronic form at the CDS via anonymous ftp to
cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/441/1195

The rapidly growing volume of nuclear data is less and less easily accessible to the astrophysics community. Mastering this volume of information and making it available in an accurate and usable form is needed. One goal of this paper is to present a detailed description of BRUSLIB and of NETGEN.

BRUSLIB provides in an electronic form at the address `http://www-astro.ulb.ac.be` tables of reaction rates that are well suited to astrophysics needs. The library 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 100 000 rates for thermonuclear reactions induced by nucleons or α-particles, as well as photo-induced reactions not analyzed 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 important model characteristics make the BRUSLIB rate library unique. A comparison of 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 based on the nuclear physics input from BRUSLIB and, when necessary, from other sources.

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 NACRE database is a compilation aimed at superseding the work of Fowler and collaborators (see Caughlan & Fowler 1988, hereafter CF88, and references therein). The goal was not just to update the CF88 rates with newly available experimental data, but also to modify different aspects of the format of the CF88 compilation. Slightly more than half of the CF88 rates have been re-compiled on the basis of a careful evaluation of experimental data available up to 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 to date 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 NACRE;
(3) the procedure adopted for extrapolating experimental data when required in order to evaluate 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, including 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 may 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 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 $T_9 = 10$ (T_9 is the temperature in billion K) 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;
(4) 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 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

Table 1. List of the NACRE compiled reactions. References to compilations, new data or evaluations concerning some of these reactions that have appeared after the completion of NACRE are provided. A + sign indicates that only the most recent reference to a given reaction is provided. Reaction rates are given in the corresponding reference (*a*) in tabular form, (*b*) as analytic formulae, or (*c*) as a figure.

Reaction	Rate	Other refs.	Reaction	Rate	Other refs.
^{1}H(p, νe^{+})^{2}H			^{15}N(p, α)^{12}C		
^{2}H(p, γ)^{3}He	[D]^{a}, [N]^{a}		^{15}N(α, γ)^{19}F		[WI02]+
^{2}H(d, γ)^{4}He		[SA04]	^{16}O(p, γ)^{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		[FI05]+
^{2}H(α, γ)^{6}Li			^{17}O(p, α)^{14}N		[FO04]
^{3}H(d, n)^{4}He	[D]^{a}		^{17}O(α, n)^{20}Ne		
^{3}H(α, γ)^{7}Li	[D]^{a}		^{18}O(p, γ)^{19}F		
^{3}He(^{3}He,2p)^{4}He		[KU04]+	^{18}O(p, α)^{15}N		
^{3}He(α, γ)^{7}Be	[D]^{a}	[NA04]	^{18}O(α, γ)^{22}Ne	[DA03]^{a}	
^{4}He(αn,γ)^{9}Be	[SU02]^{a}+		^{18}O(α, n)^{21}Ne		
^{4}He($\alpha\alpha$, γ)^{12}C	[FY05]^{c}		^{19}F(p, γ)^{20}Ne		
^{6}Li(p, γ)^{7}Be		[PR04]	^{19}F(p, n)^{19}Ne		
^{6}Li(p, α)^{3}He		[TU03]	^{19}F(p, α)^{16}O	[SP00]^{c}	
^{7}Li(p, γ)^{8}Be	[N]^{a}		^{20}Ne(p, γ)^{21}Na	[I]^{a}	
^{7}Li(p, α)^{4}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			^{21}Ne(p, γ)^{22}Na	[I]^{a}	
^{7}Be(p, γ)^{8}B		[CY04]+	^{21}Ne(α, n)^{24}Mg		
^{7}Be(α, γ)^{11}C			^{22}Ne(p, γ)^{23}Na	[HA02]^{a}, [I]^{a}	
^{9}Be(p, γ)^{10}B	[N]^{a}		^{22}Ne(α, γ)^{26}Mg		
^{9}Be(p, n)^{9}B			^{22}Ne(α, n)^{25}Mg	[JA01]^{a}	
^{9}Be(p, d)^{8}Be		[BR98]	^{22}Na(p, γ)^{23}Mg	[JE04]^{c}, [I]^{a}	
^{9}Be(p, α)^{6}Li		[BR98]	^{23}Na(p, γ)^{24}Mg	[HA04]^{a}, [I]^{a}	[RO04]
^{9}Be(α, n)^{12}C			^{23}Na(p, n)^{23}Mg		
^{10}B(p, γ)^{11}C	[TO03]^{b}		^{23}Na(p, α)^{20}Ne	[HA04]^{a}, [I]^{a}	[RO04]
^{10}B(p, α)^{7}Be			^{23}Na(α, n)^{26}Al^{g}		
^{11}B(p, γ)^{12}C	[N]^{a}		^{23}Na(α, n)^{26}Al^{m}		
^{11}B(p, n)^{11}C			^{23}Na(α, n)^{26}Al^{t}		
^{11}B(p, α)^{8}Be		[SP04]	^{24}Mg(p, γ)^{25}Al	[I]^{a}	
^{12}C(p, γ)^{13}N			^{24}Mg(p, α)^{21}Na		
^{12}C(α, γ)^{16}O	[KU02]^{a}	[TI02]	^{25}Mg(p, γ)^{26}Al^{g}	[I]^{a}	
^{13}C(p, γ)^{14}N	[MU03a]^{a}		^{25}Mg(p, γ)^{26}Al^{m}	[I]^{a}	
^{13}C(p, n)^{13}N			^{25}Mg(p, γ)^{26}Al^{t}	[I]^{a}	
^{13}C(α, n)^{16}O	[KU03]^{b}		^{25}Mg(α, n)^{28}Si		
^{13}N(p, γ)^{14}O	[TA04]^{a}		^{26}Mg(p, γ)^{27}Al	[I]^{a}	
^{14}N(p, γ)^{15}O	[MU03b]^{a},[AN01]^{a}	[RU05]+	^{26}Mg(α, n)^{29}Si		
^{14}N(p, n)^{14}O			^{26}Al^{gs}(p, γ)^{27}Si	[I]^{a}	
^{14}N(p, α)^{11}C			^{26}Al^{ms}(p, γ)^{27}Si	[I]^{a}	
^{14}N(α, γ)^{18}F	[GÖ00]^{a}		^{27}Al(p, γ)^{28}Si	[HA00]^{a}, [I]^{a}	
^{14}N(α, n)^{17}F			^{27}Al(p, α)^{24}Mg	[I]^{a}	
^{15}N(p, γ)^{16}O			^{27}Al(α, n)^{30}P		
^{15}N(p, n)^{15}O			^{28}Si(p, γ)^{29}P	[I]^{a}	

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

$$G_i(T) = \frac{1}{2J_i^0 + 1} \sum_\mu (2J_i^\mu + 1) \exp\left(-\frac{\epsilon_i^\mu}{kT}\right), \quad (1)$$

where the summation extends over the states μ of target i with excitation energy ϵ_i^μ and spin-parity J_i^μ ($\mu = 0$ for the ground state);
(5) the values of the adopted, low and high Maxwellian-averaged unscreened rates on the ground state target provided in tabular form for a selection of temperatures in the $0.001 \leq T_9 \leq 10$ range. Analytical formulae approximating the tabulated adopted ground state rates or those including the contribution of thermalized excited states are provided as well. Some of these expressions have a form deviating from those classically used in the nuclear astrophysics literature (e.g. Caughlan & Fowler 1988; Rolfs & Rodney 1988; see e.g. Eq. (23) of Angulo et al. 1999). They are considered to provide more secure approximations of 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`. 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 be evaluated 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. However, difficulties related to the conditions prevailing in astrophysical plasmas remain. In particular, charged-particle induced reactions at stellar energies (far below the Coulomb barrier) have extremely small cross sections that are very 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, 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 an 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 α-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 (γ, n), (γ, p) and (γ, α) 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 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. The reliability of the BRUSLIB rates may thus be limited to nuclides with mass numbers $A \gtrsim 40$ close enough to the valley of stability, this mass limit being shifted to higher values as one moves further away from the valley. If these constraints are not met, a non-statistical treatment is more suited (Goriely 1997). Purely theoretical HF rates are provided for some reactions already included in NACRE (Table 1). In these cases, it is advisable 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.

The evaluation of the various nuclear structure ingredients or interaction properties entering the HF BRUSLIB rates is based to the largest possible extent on global and coherent microscopic (or at least semi-microscopic) models. This is not the case for HF calculations made with 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 required because, for many specific applications including nuclear astrophysics, a very large body of reaction rates for which no experimental data exist has 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 inaccurate rate evaluations.

The microscopic models used to calculate the ingredients of the BRUSLIB MOST rates (Sect. 3.1) reach a satisfactory compromise between accuracy and reliability. The level of accuracy of these models is in fact comparable to the one obtained from available parametrized phenomenological approaches, while their reliability is better.

The BRUSLIB reaction rates 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. (4) 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 reviewed in e.g. Arnould & Goriely (2003). Let us just recall that, 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 account of the contributions of the various excited states μ of the target is expressed in classical notation as

$$N_{\rm A}\langle\sigma v\rangle^*_{jk}(T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_{\rm A}}{(kT)^{3/2}\, G(T)} \times \int_0^\infty \sum_\mu \frac{(2J_I^\mu + 1)}{(2J_I^0 + 1)} \sigma^\mu_{jk}(E) E \exp\left(-\frac{E + \varepsilon_I^\mu}{kT}\right) {\rm d}E, \quad (2)$$

where k is the Boltzmann constant, m the reduced mass of the $I^0 + j$ system, $N_{\rm A}$ the Avogadro number, $\sigma^\mu_{jk}(E)$ the cross section at relative energy E of the $I^\mu + j \rightarrow L + k$ reaction, and $G(T)$ is the partition function given by Eq. (1), where J_I^μ and ϵ_I^μ are defined. The BRUSLIB photodisintegration rates are estimated by applying the reciprocity theorem to the radiative capture rates derived from Eq. (2). This procedure leads to

$$\lambda^*_{(\gamma,j)}(T) = \frac{(2J_I + 1)(2J_j + 1)}{(2J_L + 1)} \frac{G_I(T)}{G_L(T)} \left(\frac{A_I A_j}{A_L}\right)^{3/2} \times \left(\frac{kT}{2\pi\hbar^2 N_{\rm A}}\right)^{3/2} N_{\rm A}\langle\sigma v\rangle^*_{(j,\gamma)}\, {\rm e}^{-Q_{j\gamma}/kT}, \quad (3)$$

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 that 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 photon widths T_γ. See Arnould & Goriely (2003) for more details.

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 ϵ^ω 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 desirable 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 $40 \leq A \leq 209$ 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 are needed, 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 α-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 α-nucleus scattering data at energies $E \gtrsim 80$ MeV or, in some cases, to (n, α) 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 of astrophysical interest is more insecure than in the case of nucleons. Several attempts to devise a global α-nucleus OP for the description of the scattering and reaction cross sections at energies $E \lesssim 20$ MeV 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 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 α-particle-nucleus OPs. The BRUSLIB α-capture rates are calculated with the global OP III developed by Demetriou et al. (2002).

3.4. γ-ray strength function

When applied to radiative captures, the total photon transmission coefficient entering the calculation of the $\sigma^{\mu}_{j\gamma}$ cross section of Eq. (2) 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 various shortcomings. 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)

Thus, it is of interest to develop models of the microscopic type to provide 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. Comparison of measured and calculated reaction rates

In order to evaluate the overall quality of the BRUSLIB reaction rate predictions, we compare 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 laboratory conditions.

Figure 1 compares the BRUSLIB predictions of the Maxwellian-averaged (n, γ) rates $\langle\sigma v\rangle$ at $T = 3.5 \times 10^8$ K with experimental data for some 228 nuclei heavier than ^{40}Ca included in the compilation of Bao et al. (2000). It appears that the calculations agree with all data to within a factor of three. Figure 2 compares the experimental cross sections for some low-energy (p, γ) reactions on targets heavier than Fe with the corresponding BRUSLIB rates. The agreement is satisfactory for the majority of the (p, γ) data. However, it is difficult to be more specific, as the quality of this agreement may depend 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 are needed to refine the predictions.

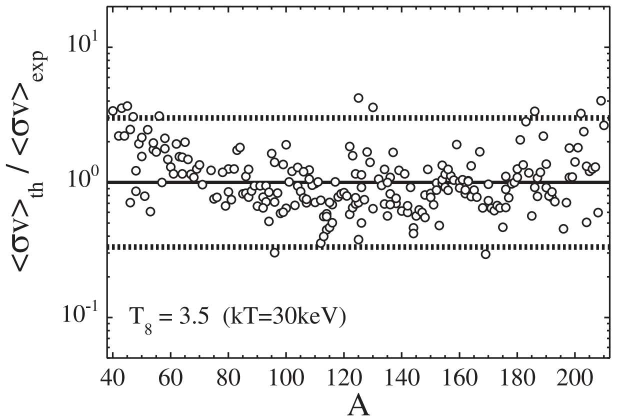

Fig. 1. Comparison of BRUSLIB Maxwellian-averaged (n, γ) rates $\langle\sigma v\rangle_{\rm th}$ with experimental values (Bao et al. 2000) at $T = 3.5 \times 10^8$ K.

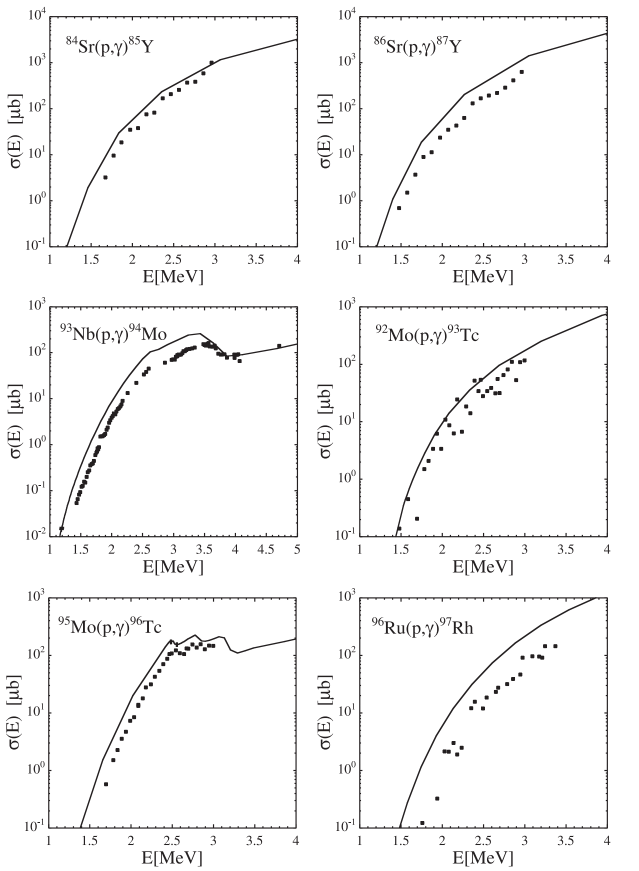

Fig. 2. Comparison between the BRUSLIB predictions and the measured cross sections of some (p, γ) reactions on targets heavier than ^{84}Sr (see Arnould & Goriely 2003 for references to the laboratory work).

The situation is 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 in constructing 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

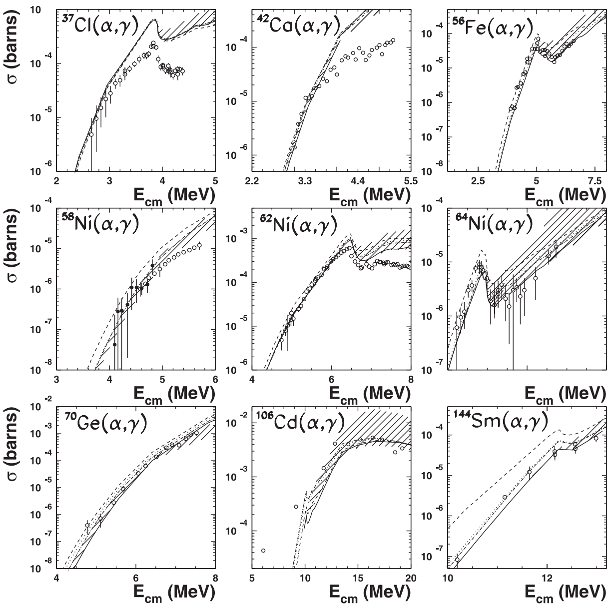

Fig. 3. Cross sections for the (α, γ) reactions on ^{37}Cl, ^{42}Ca, ^{56}Fe, ^{58}Ni, ^{62,64}Ni, ^{70}Ge, ^{106}Cd and ^{144}Sm (see Arnould & Goriely 2003 for references to the laboratory work). Black and open circles represent experimental data. The solid lines give the calculated cross sections used to construct the BRUSLIB rates.

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 ^{144}Sm (α, γ) ^{148}Gd reaction of special 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 `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).

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 available. Note that all rates take into account the contribution from the excited states of the target nuclei, as discussed in previous sections.

Various NETGEN options are currently offered through the web interface, as described in detail on the web site:
(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 for ease of use. They are made available through the web site `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 10^6 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 100 000 thermonuclear rates of nucleon and α-captures on about 8000 ($8 \leq Z < 110$) 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 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 photodisintegrations 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`.

BRUSLIB will be continuously improved and expanded, and new releases will be made every time a substantial enough body of new data becomes available.

Acknowledgements. The authors thank all the collaborators who have made possible the development of the Brussels library of nuclear data, and in particular M. Pearson, P. Demetriou and E. Khan. This work has been supported in part by the Interuniversity Attraction Pole IAP 5/07 of the Belgian Federal Science Policy and by the Konan University - Université Libre de Bruxelles convention "Construction of an Extended Nuclear Database for Astrophysics". S.G. is FNRS Research Associate. A.J. is FNRS Senior Research Associate.

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