KADoNiS- The Karlsruhe Astrophysical Database of Nucleosynthesis in Stars

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Abstract. The "Karlsruhe Astrophysical Database of Nucleosynthesis in Stars" (KADoNiS) project is an online database for experimental cross sections relevant to the s process and p process. It is available under http://nuclear-astrophysics.fzk.de/kadonis and consists of two parts. Part 1 is an updated sequel to the previous Bao et al. compilations from 1987 and 2000 for (n,γ) cross sections relevant to the big bang and s-process nucleosynthesis. The second part will be an experimental p-process database, which is expected to be launched in winter 2005/06. The KADoNiS project started in April 2005, and a first partial update is online since August 2005. In this paper we present a short overview of the first update of the s-process database, as well as an overview of the status of stellar (n,γ) cross sections of all 32 p isotopes.

Keywords: stellar neutron cross sections, database, compilation, s process, p process
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STELLAR NEUTRON CAPTURE COMPILATIONS

The first collection of stellar neutron capture cross sections was published in 1971 by Allen and co-workers [1]. This paper reviewed the role of neutron capture reactions in the nucleosynthesis of heavy elements and presented also of a list of recommended (experimental or semi-empirical) Maxwellian averaged cross sections at kT= 30 keV (MACS30) for nuclei between carbon and plutonium.

The idea of an experimental and theoretical stellar neutron cross section database was picked up again by Bao and Käppeler [2] for s-process studies. This compilation published in 1987 included cross sections for (n,γ) reactions (between 12C and 209Bi), some (n,p) and (n,α) reactions (for 33Se to 59Ni), and also (n,γ) and (n,f) reactions for long-lived actinides. A follow-up compilation was published by Beer, Voss and Winters in 1992 [3]. In the update of 2000 this compilation [4] was extended to big bang nucleosynthesis. It now included a collection of recommended MACS30 for isotopes between 1H and 209Bi, and – like the original Allen paper – also semi-empirical recommended values for nuclides without experimental cross section information. These estimated values are normalized cross sections derived with the Hauser-Feshbach code NON-SMOKER [5], which account for known systematic deficiencies in the nuclear input of the calculation. Additionally, the database provided stellar enhancement factors and energy-dependent MACS for energies between kT= 5 keV and 100 keV.
The most recent KADoNiS version of this compilation has the aim to provide a clearly arranged and user-friendly online database, which is regularly updated and will be in later stages also extended to \( p \)-process studies.

**PART 1: UPDATED BIG BANG AND S-PROCESS DATABASE**

Included in the present update (status August 2005) were only cross sections, which are already published. Six semi-empirical estimates (see Table 1) were replaced by experimental data, and 20 recommended cross sections were updated by inclusion of new measurements (Table 2). A full list of measurements with references, which were (will be) included in the update(s) can be found on the KADoNiS homepage in the menu section "Logbook".

Future efforts will be focussed on the re-evaluation of semi-empirical cross sections, as well as the inclusion of theoretical results derived with the Hauser-Feshbach code MOST [6]. Another topic will be the re-calculation of cross sections for isotopes, where a recent change in physical properties (e.g. \( t_{1/2} \), \( I_\gamma \)) leads to changes in already measured cross sections.

**TABLE 1.** List of recommended semi-empirical stellar cross sections, which were now replaced by experimental values.

| Isotope | Old recomm. value \([mb]\) | New exp. value \([mb]\) |
|---------|---------------------------|---------------------|
| \(^{128}\)Xe | 248 \(\pm\) 66 | 262.5 \(\pm\) 3.7 |
| \(^{129}\)Xe | 472 \(\pm\) 71 | 617 \(\pm\) 12 |
| \(^{130}\)Xe | 141 \(\pm\) 51 | 132.0 \(\pm\) 2.1 |
| \(^{147}\)Pm | 1290 \(\pm\) 470 | 709 \(\pm\) 100 |
| \(^{151}\)Sm | 2710 \(\pm\) 420 | 3031 \(\pm\) 68 |
| \(^{180}\)Ta | 1640 \(\pm\) 260 | 1465 \(\pm\) 100 |

The KADoNiS homepage provides a datasheet with all necessary informations for each isotope similar to the layout in Ref. [4]. On the top of this page the recommended MACS30 for the total and all partial cross sections are shown. In the "Comment" line one can find the previous recommended values, special comments, and the date of the last review. The field "List of all available values" includes the original values as given in the respective publications, renormalized values, year of publication, type of value (theoretical, semi-empirical or experimental), a short comment about the method (accelerator, neutron and reference source), and the (linked) reference(s).

This section is followed by the tabulated MACS, reaction rates and stellar enhancement factors for energies between \( kT = 5 \) and 100 keV. A "click" on the field "Show/hide mass chain" gives a graphical plot of all available recommended total MACS30 for the isotopic mass chain of the respective element. The bottom part of each datasheet shows a chart of nuclides, which can be zoomed by selecting different sizes (S, M, L, or XL). By clicking on an isotope in this chart, one can easily jump to the respective datasheet.
TABLE 2. List of previous and new recommended stellar cross sections, which were updated by inclusion of new experimental values.

| Isotope | Old recomm. value $[mb]$ | New recomm. value $[mb]$ |
|---------|---------------------------|--------------------------|
| $^{22}$Ne | 0.059 ± 0.006 | 0.058 ± 0.004 |
| $^{40}$Ar | 2.6 ± 0.2 | 2.6 ± 0.2 |
| $^{96}$Ru | 238 ± 60 | 207 ± 8 |
| $^{102}$Ru | 186 ± 11 | 151 ± 7 |
| $^{104}$Ru | 161 ± 10 | 156 ± 5 |
| $^{110}$Cd | 246 ± 10 | 237 ± 2 |
| $^{111}$Cd | 1063 ± 125 | 754 ± 12 |
| $^{112}$Cd | 235 ± 30 | 187.9 ± 1.7 |
| $^{113}$Cd | 728 ± 80 | 667 ± 11 |
| $^{114}$Cd | 127 ± 5 | 129.2 ± 1.3 |
| $^{116}$Cd | 59 ± 2 | 74.8 ± 0.9 |
| $^{135}$Cs | 198 ± 17 | 160 ± 10 |
| $^{139}$La | 38.4 ± 2.7 | 31.6 ± 0.8 |
| $^{173}$Lu | 1146 ± 44 | 1219 ± 10 |
| $^{176}$Lu | 1532 ± 69 | 1639 ± 14 |
| $^{176}$Hf | 455 ± 20 | 626 ± 11 |
| $^{176}$Hf | 1500 ± 100 | 1544 ± 12 |
| $^{178}$Hf | 314 ± 10 | 319 ± 3 |
| $^{179}$Hf | 956 ± 50 | 922 ± 8 |
| $^{180}$Hf | 179 ± 5 | 157 ± 2 |

PART 2: EXPERIMENTAL P-PROCESS DATABASE

The second part of KADoNiS will be an experimental p-process database and is expected to be launched in winter 2005/06. It will be a collection of the available experimental reaction rates relevant for p-process studies, e.g. $(\gamma,n)$, $(\gamma,\alpha)$, $(\gamma,p)$, $(n,p)$, $(n,\alpha)$, $(p,\alpha)$, and their inverse rates.

The role of $(n,\gamma)$ reactions in the p process was early recognized by Rayet et al. [7]. The $(n,\gamma)\leftrightarrow(\gamma,n)$ competition hinders the photodisintegration flux towards lighter nuclei. Additionally the decrease in temperature at later stages of the p process leads to a freeze-out ($T_9 \simeq 0.3$, corresponding to $kT=25$ keV) via neutron captures and mainly $\beta^+$ decays, resulting in the typical p-process abundance pattern with maxima at $^{92}$Mo ($N=50$) and $^{144}$Sm ($N=82$). The influence of a variation of reaction rates on the final p abundances has been demonstrated repeatedly [8, 9].

Thus, it is necessary for p-process studies to know the neutron capture rates for both, at freeze-out energies ($kT=25$ keV) and at the p-process energies ($kT=170-260$ keV). Table 3 gives an overview of the status of neutron capture cross sections of all 32 p nuclei at $kT=30$ keV. The Bao et al. compilation from 2000 [4] provided measured cross sections for 20 isotopes, but 9 of them ($^{92,94}$Mo, $^{96}$Ru, $^{124,126}$Xe, $^{130}$Ba, $^{156}$Dy, $^{180}$W, and $^{190}$Pt) with uncertainties $\geq 9\%$. For the remaining 12 p isotopes ($^{74}$Se, $^{84}$Sr, $^{98}$Ru, $^{102}$Pd, $^{120}$Te, $^{132}$Ba, $^{138}$La, $^{158}$Dy, $^{168}$Yb, $^{174}$Hf, $^{184}$Os, and $^{196}$Hg) only theoretical
predictions were available.

The (preliminary) results of our extended measuring program of stellar neutron capture cross sections for $p$ nuclei are shown in Table 3. All of our measurements were carried out on natural samples at the Karlsruhe 3.7 MV Van de Graaff accelerator using the activation technique [10, 11]. Neutrons were produced via the $^7\text{Li}(p,n)^7\text{Be}$ reaction by bombarding 30 $\mu$m thick layers of metallic lithium on a water-cooled copper backing with protons of $E_p = 1912$ keV. The resulting quasi-stellar neutron spectrum approximates a Maxwellian distribution for $kT = 25.0 \pm 0.5$ keV [12]. In all eight cases ($^{74}\text{Se}$, $^{84}\text{Sr}$, $^{96}\text{Ru}$, $^{102}\text{Pd}$, $^{120}\text{Te}$, $^{130,132}\text{Ba}$, and $^{174}\text{Hf}$) we are able to reproduce the previous recommended total cross sections from [4] within 20%. Thus, only 6 $p$ isotopes ($^{98}\text{Ru}$, $^{138}\text{La}$, $^{158}\text{Dy}$, $^{168}\text{Yb}$, $^{184}\text{Os}$, and $^{196}\text{Hg}$) remain without any experimental stellar neutron cross section. With exception of $^{98}\text{Ru}$ and $^{138}\text{La}$, all isotopes can be measured with the activation technique.

However, for an inclusion into the planned $p$-process database, those MACS30 have to be theoretically extrapolated to $p$-process temperatures. Another step is then the calculation of inverse reaction rates by detailed balance.

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| Isotope | Hauser-Feshbach predictions | Recommended MACS30 | Comments/Refs. |
|---------|-----------------------------|------------------|----------------|
|         | MOST [6]                    | NON-SMOKER [13]  | previous [4]   | new            | [mb] | [mb] | [mb] | [mb] |                        |
| ⁷⁴Se    | 247                         | 207              | 267 ± 25       | 276 ± 15       | [11] |
| ⁷⁸Kr    | 388                         | 351              | 312 ± 26       |                |      |
| ⁷⁸Kr→⁺  | -                           | -                | 92.3 ± 6.2     |                |      |
| ⁸⁴Sr    | 246                         | 393              | 368 ± 125      | 302 ± 17       | [11] |
| ⁸⁴Sr→⁺  | -                           | -                | -              | 190 ± 10       | [11] |
| ⁹²Mo    | 46                          | 128              | 70 ± 10        |                |      |
| ⁹⁴Mo    | 85                          | 151              | 102 ± 20       |                |      |
| ⁹⁵Ru    | 338                         | 281              | 238 ± 60       | 207 ± 8        | [10] |
| ⁹⁸Ru    | 358                         | 262              | 173 ± 36       |                |      |
| ¹⁰²Pd   | 670                         | 374              | 373 ± 118      | 379 ± 16       | preliminary |
| ¹⁰⁶Cd   | 365                         | 451              | 302 ± 24       |                |      |
| ¹⁰⁸Cd   | 206                         | 373              | 202 ± 9        |                |      |
| ¹¹³In   | 316                         | 1202             | 787 ± 70       |                |      |
| ¹¹³In→⁺ | -                           | -                | 480 ± 160      |                |      |
| ¹¹²Sn   | 154                         | 381              | 210 ± 12       |                |      |
| ¹¹⁴Sn   | 74                          | 270              | 134.4 ± 1.8    |                |      |
| ¹¹⁵Sn   | 247                         | 528              | 342.4 ± 8.7    |                |      |
| ¹₂⁰Te   | 309                         | 551              | 420 ± 103      | 451 ± 18       | [14] prelim. |
| ¹₂⁰Te→⁺ | -                           | -                | -              | 61 ± 2         | [14] prelim. |
| ¹²⁴Xe   | 503                         | 799              | 644 ± 83       |                |      |
| ¹²⁴Xe→⁺ | -                           | -                | 131 ± 17       |                |      |
| ¹²⁶Xe   | 335                         | 534              | 359 ± 51       |                |      |
| ¹²⁶Xe→⁺ | -                           | -                | -              | 40 ± 6         |      |
| ¹³⁰Ba   | 493                         | 730              | 760 ± 110      | 694 ± 20       | [14] prelim. |
| ¹³²Ba   | 228                         | 467              | 379 ± 137      | 368 ± 25       | [14] prelim. |
| ¹³²Ba→⁺ | -                           | -                | -              | 33.6 ± 1.7     | [14] prelim. |
| ¹³⁶Ce   | 208                         | 495              | 328 ± 21       |                |      |
| ¹³⁶Ce→⁺ | -                           | -                | -              | 28.2 ± 1.6     |      |
| ¹³⁸Ce   | 61                          | 290              | 179 ± 5        |                |      |
| ¹³⁸La   | 337                         | 767              | -              | -              |      |
| ¹⁴⁴Sm   | 39                          | 209              | 92 ± 6         |                |      |
| ¹⁵⁶Dy   | 2138                        | 1190             | 1567 ± 145     |                |      |
| ¹⁵⁸Dy   | 1334                        | 949              | 1060 ± 400*    |                |      |
| ¹⁶²Er   | 1620                        | 1042             | 1624 ± 124     |                |      |
| ¹⁶⁸Yb   | 875                         | 886              | 1160 ± 400*    |                |      |
| ¹⁷⁴Hf   | 763                         | 786              | 956 ± 283      | 1056 ± 53      | preliminary |
| ¹⁸⁰W    | 751                         | 707              | 536 ± 60       |                |      |
| ¹⁸⁴Os   | 709                         | 789              | 657 ± 202*     |                |      |
| ¹⁹⁰Pt   | 634                         | 760              | 677 ± 82       |                |      |
| ¹⁹⁶Hg   | 469                         | 372              | 650 ± 82*      |                |      |

* Semi-empirical estimate.
† No recommended value available, since ¹³⁸La is of pure p-process origin.