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The ASTRAL database for neutron-capture nucleosynthesis studies

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Abstract. Present nuclear reaction network computations for astrophysical simulations involve many different types of rates, including neutron-capture reactions of interest for the modeling of heavy-element nucleosynthesis. While for many of them we still have to rely on theoretical calculations, an increasing number of experimentally-determined cross sections have now become available. In this contribution, we present "ASTrophysical Rate and rAw data Library" (ASTRAL), a new online database for neutron-capture cross sections based on experimental results, mainly obtained through activation and time-of-flight measurements. For the evaluation process, cross sections were recalculated starting from raw data and by considering recent changes in physical properties of the involved isotopes (e.g., half-life and γ-ray intensities). We show the current status of the database, the techniques adopted to derive the recommended Maxwellian-averaged cross sections, and future developments.

1 Introduction

The understanding of nucleosynthesis in stars has become a forefront field of experimental and theoretical research owing to recent developments in observational techniques, astrophysical models, and laboratory experiments. The vast majority of nuclei heavier than iron are synthesized through the slow process [1] and the rapid process [2]. Experimental determination of the (n, γ) cross sections at stellar thermal energies is of utmost importance in studying these processes. In light of this, it is of paramount importance to have a database of neutron-capture cross sections to perform accurate astrophysical calculations of heavy element nucleosynthesis. To date, there is no recent database of this kind, the last such work being more than 10 years old and no longer maintained [3]. We aim to fill this gap by creating a new, updated, and homogeneous database of Maxwellian-averaged cross sections (MACS) to be used for astrophysical computations, named ASTRAL - "ASTrophysical Rate and rAw data Library".

2 The ASTRAL database

In contrast to previous databases, ASTRAL does contain not only actual cross sections but also experimentally-determined raw data that are directly used to evaluate the MACS from 1 to 500 keV. To cover the whole energy range, energy-differential cross sections are needed

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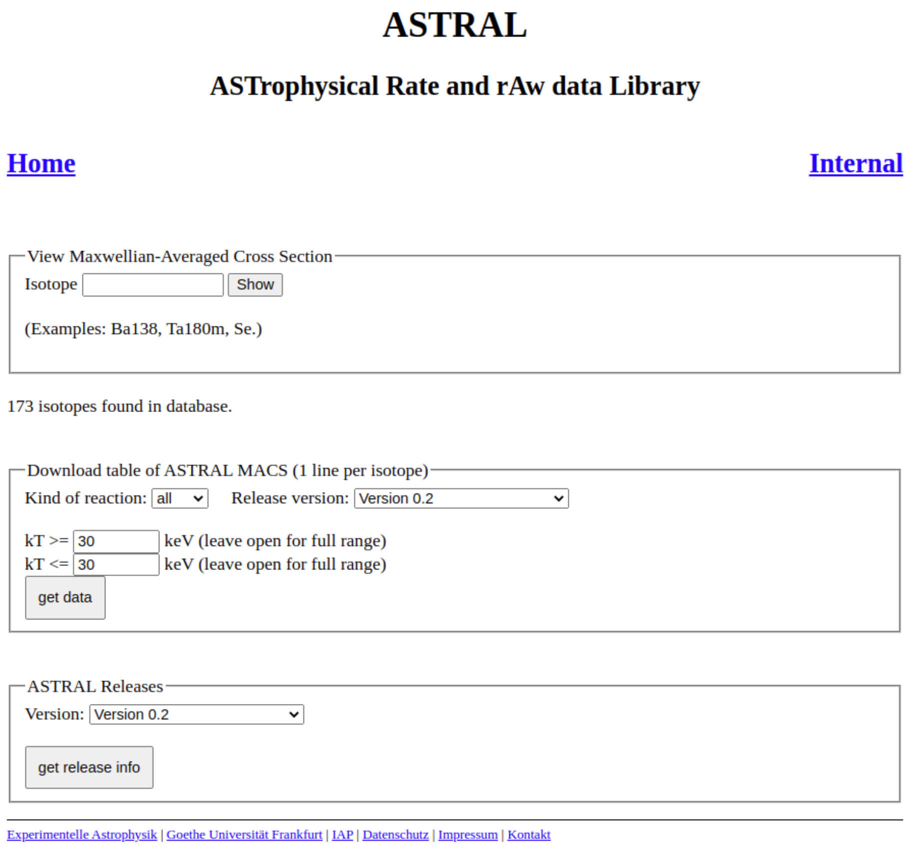

ASTRAL

ASTrophysical Rate and rAw data Library

View Maxwellian-Averaged Cross Section

Isotope

(Examples: Ba138, Ta180m, Se.)

173 isotopes found in database.

Download table of ASTRAL MACS (1 line per isotope)

Kind of reaction: all Release version: Version 0.2

kT >= 30 keV (leave open for full range)
kT <= 30 keV (leave open for full range)

ASTRAL Releases

Version: Version 0.2

Figure 1. Web appearance of the ASTRAL database [4].

for neutron energy up to a few MeV. When experimental data in this range is missing, evaluated cross sections from latest data libraries (ENDF, JEFF, JENDL, TENDL) are taken into account. The measured data can be cross section ratios between the isotope under study and the reference cross section or resonance parameters, to be used for computing the differential cross section. The MACS are evaluated upon various experimental measurements of (n,γ) cross sections, based on activation and time-of-flight (TOF) techniques. ASTRAL is an online database [4] (see Fig. 1). The first release (v0.1) of ASTRAL occurred in 2018, in which about 70 isotope MACS, based on TOF measurements, were re-evaluated by taking into account the new recommended value for gold differential cross section [5]. In 2022, the ASTRAL v0.2 has been released [6]. It contains an updated version of the 70 isotopes already evaluated and, in addition, about 50 new isotopes whose experimental cross section data were based on activation measurements.

3 ASTRAL status: activations

The current version of the ASTRAL database (v0.2) includes raw data for around 200 activation measurements, for isotopes from ^{9}Be to ^{209}Bi. For each of them, the needed information to determine the MACS are stored, in particular, the measured ratio (with errors) of

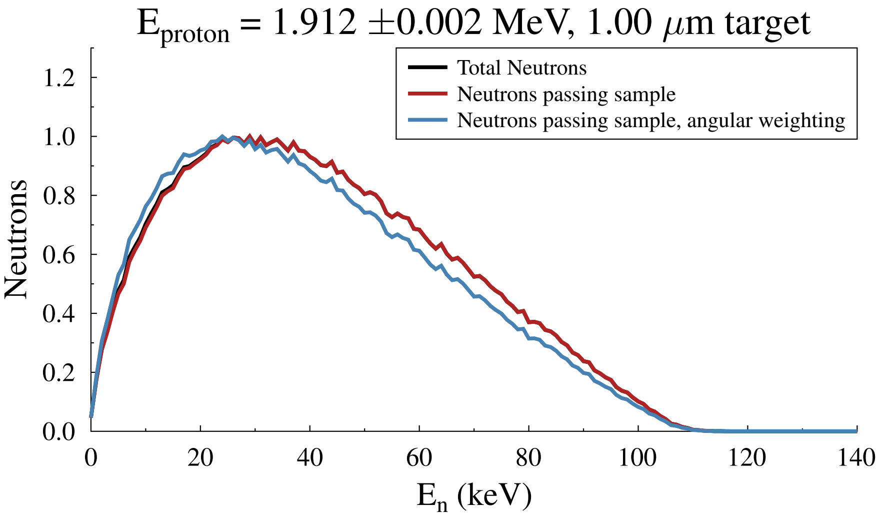

Figure 2. Comparison of the number of angle-integrated neutrons per linear energy bin for a simulation that contain weighting and no weighting for a sample with a radius of 3 mm. The radius of the Li-spot is 3 mm. The simulated spectrum is normalized to a common maximum of 1.

the neutron-capture cross sections relative to gold. In addition, the beam proton-energy distribution, the properties of the neutron sources and target samples, and the geometry of the activation setup are collected as well. These quantities are required to properly simulate the experimental neutron spectrum with a Monte Carlo approach. For this purpose, we make use of the PINO code [7]. An example of the reconstructed neutron spectrum with PINO can be found in Fig. 2. Moreover, cross sections are corrected by considering new values for the adopted gamma-ray intensities of the activation products from the NuDat database[1]. These corrections have to be taken into account since they affect the cross-section value by more than 1%. For some unstable targets, a further corrective factor is applied as well to account for the effect of improved half-life (e.g., ^{60}Fe).

The MACS evaluation is performed in a new manner. In activation measurements, neutron energies are unknown and only spectrum-averaged cross sections (SACS) can be determined. The SACS represent an average over the respective neutron spectrum, i.e.

$$\text{SACS} = \frac{\displaystyle\int \sigma\,(E_n)\Phi\,(E_n)\,dE_n}{\displaystyle\int \Phi\,(E_n)\,dE_n}, \tag{1}$$

where the integral runs from the lower to the upper limit of the experimental neutron spectrum $\Phi(E_n)$. Should $\Phi(E_n)$ be a perfect Maxwellian distribution, the SACS would equal the MACS up to a factor $2/\sqrt{\pi}$. However, due to energy cutoffs in the neutron spectra and variations between experimental and Maxwell-Boltzmann distribution, corrections have to be considered to compute MACS at different thermal energies. This can be accomplished by the use of the experimentally-determined SACS to normalize the energy-dependent cross sections from the evaluated data libraries by means of a suited normalization factor (NF).

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[1] https://www.nndc.bnl.gov/nudat3

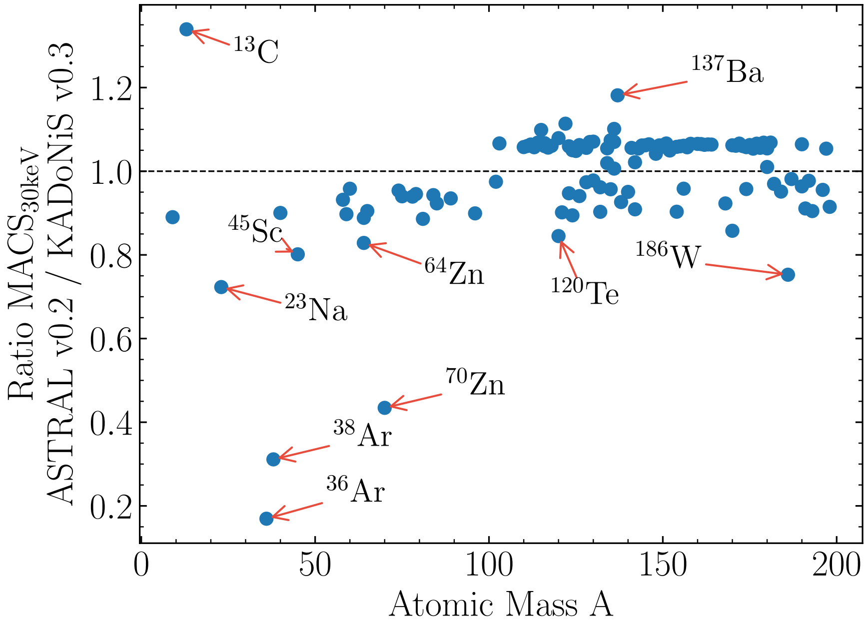

Figure 3. Comparison of MACS at kT=30 keV from the present ASTRAL v0.2 and the KADoNiS v0.3 compilation [3].

In general, the normalization factor should be temperature-dependent and if several activation measurements with spectra corresponding to different thermal energies are available, they have to be properly considered. For this reason, in ASTRAL, activation measurements at different energy regimes have been accounted for by computing proper weighting factors, based on the overlap between the experimental neutron spectra, simulated with a Monte Carlo approach with the PINO code, and the Maxwellian energy distribution. As a result, the relative weights of each activation vary depending on the temperature. This method assures that the experimental spectrum with the highest weight is the one closest to the stellar energy distribution. The normalization factor was calculated based on the weights to scale the evaluated cross sections [6]. The corresponding MACS for each thermal energy kT was then determined using this energy-dependent evaluated cross section as

$$\mathrm{MACS} = \frac{2}{\sqrt{\pi}} \frac{NF}{(kT)^2} \int_0^\infty \sigma_{\mathrm{lib}}(E_n)\, E_n \exp\left(-\frac{E_n}{kT}\right) dE_n. \tag{2}$$

In this way, about 50 isotopes, whose SACS are determined by activation measurements, were evaluated [6].

4 ASTRAL status: TOF

In ASTRAL v0.2, we made use of the latest evaluated data to recompute MACS of around 70 isotopes already present in ASTRAL v0.1. For them, TOF data are available across a narrow neutron energy range, while MACS computation requires data virtually ranging from zero to infinity. Therefore, the use of cross sections from evaluated data library, properly normalized to the measured data from TOF experiments, is needed in the energy region not covered by experimental data [5]. While ASTRAL v0.1 was largely based on ENDF-B/VII.1 [8], in version 0.2 we mostly adopted ENDF-B/VIII [9] and, in some cases, JENDL-4.0 [10] or JEFF-3.3 [11].

5 Conclusions and perspectives

Figure 3 gives an overview of the changes between the present version of ASTRAL (v0.2) and the KADoNiS v0.3 compilation [3]. The isotopes with the largest changes are labeled. Whereas most of these changes are due to the revised reference gold cross section [5], some of these nuclei were measured for the first time and thus replace theoretical estimates (e.g., ^{36}Ar and ^{38}Ar). Other important variations are also due to the adoption of new data libraries (e.g., ^{70}Zn) or revised gamma-intensities (e.g., ^{186}W). Another database version is foreseen to be released by the end of 2022, containing more MACS based on activation and TOF measurements.

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