Capitalizing on Nuclear Data Libraries’ Comprehensiveness to Obtain Solar System $r$-process Abundances

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Abstract. The recent observation of neutron stars merger by the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration and the measurements of the event’s electromagnetic spectrum as a function of time for different wavelengths have altered profoundly our understanding of the $r$-process site as well as considerably energized nuclear astrophysics research efforts. $r$-process abundances are a key element in $r$-process simulations, as a successful calculation must account for these abundances in the final debris of a stellar catastrophic event. In this article, mankind’s complete knowledge of neutron cross sections obtained over the last 80 years, as encapsulated in the latest release of the Evaluated Nuclear Data File (ENDF/B) library, is used to obtain solar system $r$-process abundances in a comprehensive data approach. ENDF/B cross sections have been successfully used for decades in nuclear power and defense applications and are now used to obtain $r$-process abundances in a fully traceable and documented way. This article $r$-process abundances provide complementary insights on the astrophysical events, overall quality of neutron capture data in the astrophysical region of temperatures, and demonstrate issues with the $s$-process contribution subtraction procedure.

Understanding the origin of the elements has been a long intellectual adventure [1]. A scientifically sound theory began to materialize by the late 1950s, thanks to an emerging wealth of nuclear physics, chemistry, and solar system abundance data [2, 3]. In particular, it was understood that most of the heavy elements could only be produced by neutron capture following two possible mechanisms: (1) the slow capture or $s$-process, characterized by low densities and temperatures environments and (2) the rapid capture or $r$-process, where both densities and temperatures are large enough that successive neutron captures could lead in within seconds to the synthesis of Uranium nuclides and possibly beyond. It is currently thought that Asymptotic Giant Branch and red giant stars are the site for the $s$-process; while neutron star mergers, core-collapsed supernovae and magneto-rotational (MHD-jet) magnetars would produce the density and temperature needed for the $r$-process [4, 5]. The recent multi-messenger observation of a binary neutron stars merger (GW170817) and the
indirect clues of $r$-process production of lanthanide elements \[6, 7\] have further refined our understanding of the $r$-process site and exemplified the benefits of synergistic observations. The lanthanides production findings are based on atomic physics models and include additional uncertainties.

Several sets of data needed to understand the $r$-process, including the sun and metal-poor stars $r$-process abundances. The solar system $r$-process abundances are tabulated as a function of atomic mass ($A$) for the stable nuclides produced as residual after subtracting the $s$-process and, in some cases, proton captures from the total solar system abundances. The low-metallicity older stars elemental abundances are based on atomic spectra observations, and they provide a window into early nucleosynthesis \[8, 9, 10\]. The obtention of a set of solar $r$-process abundances is the core of this article and will be extensively discussed in the following paragraphs.

The solar system residuals include 21 stable nuclei solely produced by the $r$-process in the $100 \leq A \leq 208$ range and a large number of nuclei with the $s$-process contributions. Knowledge of the $r$-process-only nuclei is not sufficient to obtain a comprehensive picture of the $r$-process production pattern; one must subtract the $s$-process component from nuclides that can be produced by both processes. For instance, in the well-known $r$-process peak in the $190 \leq A \leq 200$ range caused by the $N=126$ magic number, only two nuclides, $^{192}$Os and $^{198}$Pt, are $r$-process-only nuclides; the peak truly emerges when subtracting the $s$-process contribution. Previously, the Maxwellian-averaged cross sections (MACS) compiled by the Karlsruhe Astrophysical Database of Nucleosynthesis in Stars (KADoNiS) \[11\] were extensively used in $s$- and $r$-process simulations. Many of the KADoNiS MACS were normalized to a $^{197}$Au(\(n,\gamma\)) activation measurement that produced a 30-keV MACS equal to 582\(\pm9\) mb \[12\]. For years, the disagreement between this value and that from the international evaluation of neutron cross-section standards, 620\(\pm11\) mb \[13, 14\], was not understood. However, it was recently resolved by re-analyzing activation measurements. The new KADoNiS gold value is 612\(\pm6\) mb \[15\], which has led to an identification and renormalization effort of 63 KADoNiS cross sections. These relatively small astrophysical data sets deviations represent a serious problem for the stellar pattern analysis where precision up to 1% is needed \[16\].

The current analysis reveals a strong need for a reliable $s$-process model to predict the $s$-process component using the solar system observables and nuclear physics inputs. The model should include high-fidelity neutron cross section data sets over the broad energy range with comprehensive coverage of neutron resonances. Such data sets have been developed for nuclear power and national security applications worldwide. In the USA, the Cross Section Evaluation Working Group (CSEWG) was created in 1966 \[17\] and charged to produce the ENDF/B library. The library was first released in 1968 with its latest release in 2018 \[18\]. This release included efforts from 70 people and 29 organizations worldwide. The ENDF/B library contains recommended values of neutron-induced cross sections, first compiled in the Experimental Nuclear Reaction Data (EXFOR) library \[19\], then critically reviewed and augmented with extensive use of R-matrix and Hauser-Feshbach codes, and finally validated with a vast set of...
integral experiment benchmarks. The recommended cross sections are tabulated in the laboratory system and include comprehensive covariance matrices obtained not only from experimental conditions but also by including nuclear physics model correlations and validated with integral experiments. The ENDF/B library consists of unique reaction data evaluations that are based on all available nuclear physics results evaluated and optimized across the broad $10^{-5}$ eV - 20 MeV energy span. The standalone ENDF/B-VIII.0 $^{197}$Au neutron capture evaluation incorporates the main neutron time of flight measurements \[15, 18\] that are essentially free of systematic errors associated with activation measurements. The ENDF/B library development benefits from CSEWG’s cumulative and collective experience as well as by frequent interactions with other similar national and regional organizations. These include Japanese Evaluated Nuclear Library (JENDL) \[20\], Joint Evaluated Fission and Fusion (JEFF) European nuclear data library \[21\], Chinese Evaluated Nuclear Library (CENDL) \[22\], and the Russian Fund of Evaluated Neutron Data (ROSPOND) \[23\]. These exchanges are facilitated through the coordinating efforts of organizations, such as the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency Data Bank \[24\] and the International Atomic Energy Agency (IAEA) Nuclear Data Section \[25\]. The recently released ENDF/B-VIII.0 library \[18\] includes many new evaluations, such as an s-process seed $^{56}$Fe \[26\], and incorporates data from the sixth edition of the Atlas of Neutron Resonances \[27\]. Neutron resonances dominate the astrophysical range of temperatures in many nuclei, and the comprehensive analysis of resonances is essential in nuclear astrophysics applications.

In this article, the well-understood classical model of s-process nucleosynthesis \[28, 29\] and the ENDF/B-VIII.0 library recommended cross sections \[18\] will be used to quantify the s-process abundance contributions. The classical model is based on a phenomenological and site-independent approach, and it assumes that the seeds for neutron captures are made entirely of $^{56}$Fe. The s-process abundance of an isotope $N(A)$ depends on its precursor $N(A-1)$ quantity as in

$$\frac{dN(A)}{dt} = \lambda_n(A-1)N(A-1) - [\lambda_n(A) + \lambda_\beta(A)]N(A),$$

where $\lambda_n$ is the neutron capture rate, and $\lambda_\beta = \frac{\ln 2}{T_{1/2}}$ is the $\beta$-decay rate for radioactive nuclei. Assuming that the temperature and neutron density are constant, and neglecting s-process branchings, the previous formula simplifies to

$$\frac{dN(A)}{dt} = \sigma_{(A-1)}N(A-1) - \sigma_{(A)}N(A).$$

Equation \[2\] was solved analytically for an exponential average flow of neutron exposure assuming that temperature remains constant over the whole timescale of the s-process \[28, 29\]. The product of MACS and isotopic abundance ($\sigma_{(A)}N_{(A)}$) was written as

$$\sigma_{(A)}N_{(A)} = \frac{f N_{56}}{\tau_0} \prod_{i=56}^{A} \left[1 + \frac{1}{\sigma(i)\tau_0}\right]^{-1},$$
where \( f \) and \( \tau_0 \) are the neutron fluence distribution parameters, and \( N_{56} \) is the initial abundance of \( ^{56}\text{Fe} \) seed.

Center of mass system MACS in Eq. 3 are described as

\[
\sigma^{\text{Maxw}}(kT) = \frac{2}{\sqrt{\pi}} \frac{a^2}{(kT)^2} \int_0^\infty \sigma(E_n^L) E_n^L e^{-E_n^L/kT} dE_n^L,
\]

where \( a = m_2/(m_1 + m_2) \), \( k \) and \( T \) are the Boltzmann constant and temperature of the system, respectively, and \( E \) is the energy of relative motion of the neutron with respect to the target. \( E_n^L \) is the neutron energy in the laboratory system, while \( m_1 \) and \( m_2 \) are the masses of the neutron and the target nucleus, respectively [30, 31]. Equation 4 has been used in the present work to calculate ENDF/B-VIII.0 MACS at \( kT = 30 \) keV. Prior to these calculations, the neutron resonance region evaluated data had been Doppler broadened, assuming a target temperature of \( T = 293.16 \) K with the PREPRO code [32] and the room-temperature cross sections were complemented with the stellar enhancement factors (SEF) of Rauscher [33].

Analysis of pre-solar samples [34, 35] shows that \( s \)-process abundances originate from a superposition of the two major exponential distributions of time-integrated neutron exposure: (1) weak component (responsible for the production of \( 70 \leq A \leq 90 \) nuclei) and (2) the main component (for \( 90 \leq A \leq 204 \) nuclei). Previously, \( s \)-process experimental cross sections have been analyzed and fitted from \( ^{56}\text{Fe} \) to \( ^{210}\text{Po} \) as a sum of the two components that were individually described by Eq. 3 of Ref. [29]. Herein cross sections and solar system abundances were taken from the presently outdated compilations [29, 36] and optimized for \( s \)-process-only target nuclei. In the fit of a weak \( s \)-process component, Käppeler et al. have included \( ^{88}\text{Sr} \), \( ^{89}\text{Y} \), and \( ^{90}\text{Zr} \) to overcome a relatively small number of \( s \)-process-only nuclei in the \( A < 90 \) region. Käppeler et al. have argued that the above-mentioned nuclei solar system abundances have < 20% \( r \)-process contributions, and they could be used in the fitting process. An attempt to reproduce the two-component fitting using the present-day cross sections and abundances was not successful. The present findings are consistent with Arlandini et al. [37], who used the classical model to calculate the \( s \)-process main component and extract \( r \)-process abundances. Arlandini et al. assumed that between Cu and Sr, the contribution of the weak \( s \)-component is described by the single-exposure calculation of Beer et al. [38]. Subsequent analysis of Käppeler et al. [39] shows that the weak component is not firm described by the classical analysis because of a limited number of \( s \)-process-only medium nuclei and lack of equilibrium conditions. The empirical \( \sigma N \) values for heavy nuclei that are not affected by branchings are reproduced with a mean square deviation of only 3%.

Therefore, the main component only findings are shown in the present work and nuclei abundances are taken from Ref. [34]. Neutron fluence parameters for \( s \)-process-only isotopes were derived using Eq. 3 above. Later, the derived parameters were optimized using least squares procedures, and \( f \) and \( \tau_0 \) neutron fluence distribution numerical values were obtained. The resulting fluence parameters are shown in Table 1.
Table 1: S-process main component neutron fluence distribution parameters for ENDF/B-VIII.0 library [18].

| Parameters | ENDF/B-VIII.0 |
|------------|---------------|
| f          | 0.000402±0.000083 |
| \( \tau_0 \) | 0.332365±0.027410 |

Figure 1: Upper panel: ENDF/B-VIII.0 \((n, \gamma)\) MACS at 30 keV times solar system abundances (circles) as function of the atomic mass number for s- and r-process nuclides. The s-process-only nuclei are shown as full circles, and the squares correspond to the classical s-process values derived as described in the text. Lower panel: Ratio of the calculated to the solar system abundances for s-process-only nuclei.

The s-process contribution to solar system abundances can be estimated using neutron fluence parameters and compared with observed values. The ENDF/B-VIII.0 MACS at \( kT = 30 \text{ keV} \) times abundance and expected classical model product values are shown in the upper panel of Fig. 1. The calculated ratios for s-process-only nuclei are shown in the lower panel of Fig. 1.

The data in the figure indicate a surplus production for many nuclei compared with the s-process expectations. This surplus is commonly attributed to the r-process contribution, and it can be obtained by subtracting the expected classical model s-process production from the total values. The classical model r-process abundances derived from ENDF/B-VIII.0 library and Arlandini et al. [37] together with a multi-component model fits of Goriely [40] & Arnould et al. [35] are shown in Fig. 2 and Table 2. The present r-process abundances are based on the s-process main component calculation only. The main component complements the weak s-process component production of medium nuclei, and it is dominant for heavy nuclei. These
complementary values were used in the present work to extract the upper bounds on $r$-process abundances of medium nuclei from Ga to Sr. For comparative purposes, the $s$-process main component values calculated by Arlandini et al. [37] were deduced using the Anders and Grevesse [41] solar system abundances in $Z = 31 - 38$ region.

The analysis of Goriely Table 3 [40] and Arnould et al. Table 1 data [35] shows multiple coincidences, it was assumed that Goriely values were superseded by Arnould et al. The numerical values and comments for the present work, Arlandini et al. [37] and Arnould et al. [35] are given in the Appendix. The present work $r$-process uncertainties are due to least squares fitting of $s$-process-only nuclei $\sigma N$ product and subtraction of the classical model contribution from the total product values. The total product value uncertainties are solely based on ENDF/B cross section uncertainties since the solar system abundances of Lodders, Palme and Gail [34] contain absolute values only, and stellar enhancement factors are calculated from nuclear theory [33]. The Fig. 2 data analysis shows the second and third $r$-process abundance peaks and the broad surge due to production of lanthanides that were tentatively found in neutron stars merger [6, 7]. These peaks provide indisputable evidence that nuclear shell closing (magic numbers) persists outside the valley of stability for $N \sim 82$ and 126. The current $r$-process abundances agree well with the classical analysis of Arlandini et al. [37] and values of Goriely [40] & Arnould et al. [35] deduced from Ref. [42] with an exception to $N=82$ lanthanide nuclei where the current work data are not smooth and show structure. This observation concurs with Kratz et al. [43] who noticed that the subtraction of $s$-process contribution from the total values is accurate for nuclei with little $s$-process contribution.
but results in significant uncertainties when s-process fraction is dominant. The issues with spectra subtraction are not unique to nuclear astrophysics; these phenomena are well documented in nuclear reaction physics \[44\] and discoveries of double-beta decay in $^{76}\text{Ge}$ and $^{100}\text{Mo}$ \[45, 46\].

The present work classical modeling ignores s-process branching nuclei; for calculation of these nuclei additional information on stellar neutron fluxes (exposures) and accurate beta decay rates are needed. The stellar neutron fluxes are astrophysical site dependent while beta decay rates along the valley of stability in the Evaluated Nuclear Structure Data File (ENSDF) \[47\] are often impacted by relatively old and not precise measurements. In light of this disclosure, only the lower bounds for r-process abundances for branching nuclei are deduced in the present work. Further examination of the lanthanide region abundances shown in Fig. 3 demonstrates the high quality of ENDF/B-VIII.0 library r-process abundances with an exception to $^{138}\text{Ba}$ and $^{140}\text{Ce}$ where the expected s-process contributions exceed total product values. The main s-process component overproduction in $^{138}\text{Ba}$ has been previously reported by Palme & Beer \[42\] and interpreted by Arnould et al. \[35\] as r-process abundance of $0.214^{+0.786}_{-0.214}$ (Si=10$^6$). Arlandini et al. \[37\] values for $^{138}\text{Ba}$ and $^{140}\text{Ce}$ are slightly below and above zero, respectively. ENDF barium and cerium neutron capture cross sections are based on the SubGroup 23 (International Library of Fission Product Evaluations) recommendations \[48\] clearly have to be revisited. These ENDF/B-VIII.0 MACS solar system abundance \[18, 34\] product deficiencies highlight mutually beneficial relations between nuclear data and astrophysics efforts, and they will be addressed in the next release of ENDF/B library. The present results demonstrate a large potential of

Figure 3: Zoomed view of Fig. 2 that allows a better inspection of solar r-process abundances for the lanthanide nuclides (A=139-176).
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To evaluate the possible impact of different data sets, the KADoNiS 0.3 library [11] cross sections were processed in the current work, and the corresponding $r$-process abundances were extracted. Figure 4 shows the KADoNiS 0.3 to ENDF/B-VIII.0 ratio of $r$-process abundances. The calculated abundances ratios include several outliers near the neutron magic numbers $N=50, 82, 126$ and smaller deviations along the $s$-process path. Large discrepancies could be explained by the KADoNiS 0.3 library over reliance on a single measurement or cross section calculation. The smaller deviations may suggest an additional $\sim 20-30\%$ systematic error for present day nuclear astrophysics calculations. Some of these smaller deviations could be explained by the impact of an erroneous $^{197}$Au Karlsruhe cross section [12] on the KADoNiS library while others are due to the lack of experimental data. Further analysis of the KaDONis 0.3 library cross sections along the $s$-process path shows that $\sim 54\%$ targets are affected by Ratynski and Käppeler neutron flux monitor value [12], $\sim 10\%$ are based on other Karlsruhe measurements, $\sim 7\%$ are purely theoretical, and $\sim 29\%$ reflect experimental findings of other authors. The approximately 50/50 mix between gold monitored and other cross sections effectively randomizes the impact of overestimated neutron flux at Karlsruhe on $r$-process abundances. Due to space and time constraints, the detailed analysis of nuclear data for more than 150 $s$-process nuclei is not given in the current work. It will be addressed in subsequent publications.

In conclusion, the indirect observations of $r$-process elements in the neutron stars...
merger renewed interest in stellar nucleosynthesis calculations and the corresponding nuclear data. Recent re-analysis of KADoNiS library [15] reveals multiple issues with the Karlsruhe data and a strong need for complementary data sets. The release of the ENDF/B-VIII.0 library creates a unique opportunity for nuclear science and technology developments and further exploration in nuclear astrophysics. The Maxwellian-averaged (n,γ) cross sections for 553 ENDF/B-VIII.0 library target nuclides have been produced. These data were combined with the solar system abundances and fitted. Astrophysical r-process abundances have been extracted in the present work, compared with available values, and an agreement was deduced.

The next stage of the current project will involve incorporation of the evaluated nuclear data libraries into astrophysical model codes. Work on ENDF/B-VIII.0 library reaction rates data transfer for (n,γ), (n,α), (n,p) and (n,fission) channels within 0.01-10 GK neutron temperatures into Reaction rate Library (REACLIB) format [50, 51, 52] is currently underway. The new data sets will provide a more extensive coverage of neutron resonances and will make REACLIB fits more reliable across the whole s-process temperature range of 8-90 keV [39].

*Note added in proof:* The corrected values of Karlsruhe group cross sections are available in Ref. [53].

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Appendix

The present work of ENDF/B-VIII.0, Arlandini et al. \[37\] and Arnould et al. \[35\] r-process abundances are shown in Table 2.

Table 2: \( R \)-process abundances (in the Si = 10\(^6\) scale) obtained from ENDF/B-VIII.0 library \[18\], the previous values of Arlandini et al. \[37\] and Arnould et al. \[35\]. \( R \)-process-only abundances for ENDF/B library are adopted from 4.56 Gy ago values of Ref. \[34\]; alpha and beta decay \( T_{1/2} \) are taken from the Evaluated Nuclear Structure Data File \[47\]. The upper bounds on \( r \)-process abundances in the \( Z=31\)–38 region are marked with a * character, while the lower bound for \( s \)-process branching nuclei are identified with a † character.

| Target | ENDF Abundances | Arlandini et al. \[37\] | Arnould et al. \[35\] | Comments |
|--------|-----------------|-------------------------|-----------------------|----------|
| 31-Ga-69 | 1.898E+1 1.533E-1 † | 1.985E+1±2.203E+0* | 6.180E+0 3.190E+0 6.180E+0 | \( s \)-process only |
| 32-Ge-70 | 2.155E+1 1.562E-1 † | 2.003E±2±2.43E+0* | s-process only |
| 30-Zn-70 | 8.000E+0 1.700E-1 † | 7.793E±2±3.91E+0 | s-process only |
| 31-Ga-71 | 1.266E+1 2.188E-1 † | 1.085E±2±9.76E+0* | s-process only |
| 32-Ge-72 | 7.756E+0 1.575E-1 † | 2.632E±2±7.81E+0* | s-process only |
| 32-Ge-73 | 3.645E+1 3.469E-1 † | 3.729E±2±5.48E+0* | s-process only |
| 33-As-75 | 5.650E+0 3.160E-2 † | 5.976E+0±7.53E-1* | s-process only |
| 34-Se-76 | 4.221E+0 3.43E-2 † | 3.390E±2±2.71E-1* | s-process only |
| 32-Ge-76 | 8.500E+0 3.602E-2 † | 9.277E±2±1.16E+0* | s-process only |
| 34-Se-77 | 4.712E+0 2.042E-2 † | 3.973E±2±1.20E+0 | s-process only |
| 34-Se-78 | 1.390E+1 3.469E-1 † | 1.126E±2±2.36E+0* | s-process only |
| 34-Se-79 | -4.520E-1 5.257E-2 † | 5.022E±2±9.74E-1* | s-process only |
| 35-Br-79 | 2.875E+1 7.59E-1 † | 2.741E±2±2.57E+0* | s-process only |
| 34-Se-81 | 4.524E+0 3.99E-2 † | 5.256E+0±1.02E+0* | s-process only |
| 35-Br-81 | -4.520E-1 5.257E-2 † | 4.507E+0±8.0E-1 | s-process only |
| 36-Kr-82 | 4.850E+0 2.69E-1 † | 1.770E+0±3.46E-1* | s-process only |
| 34-Se-82 | 5.890E+0 2.96E-2 † | 5.698E+0±2.82E+0 | s-process only |
| 36-Kr-83 | 5.829E+0 7.10E-2 † | 4.040E+0±7.16E-1* | s-process only |
| 36-Kr-84 | 2.557E+1 7.38E-1 † | 1.749E+1±3.76E+0* | s-process only |
| 36-Kr-85 | 4.599E+0 6.31E-2 † | 2.980E+0±2.26E-1* | s-process only |
| 37-Rb-85 | -6.72E-1 3.63E-1 † | 7.40E+1±4.52E-2* | s-process only |
| 38-Sr-86 | -1.226E-1 2.62E-1 † | 3.900E+1±3.47E-2* | s-process only |
| 38-Sr-88 | -5.70E+0 3.77E+0 † | 1.200E+0±9.72E-2* | s-process only |
| 40-Zr-90 | 1.530E+0 3.64E-1 † | 1.860E+0±2.36E-1 | s-process only |
| 40-Zr-91 | 2.304E-1 1.34E-1 † | -6.400E+3±9.47E-2 | s-process only |
| 40-Zr-92 | 3.536E-1 2.93E-1 † | -1.627E±2.22E-2 | s-process only |
### Table 2: \( R \)-process abundances ... (continued).

| Target       | ENDF Abundances | Arlandini et al. | Arnould et al. | Comments |
|--------------|-----------------|------------------|----------------|----------|
| 40-Zr-93     | N\(_{\odot}\)-N\(_{\text{main}}\) | N\(_{\odot}\)-N\(_{\text{main}}\) | [37] | [35] |
| 40-Zr-94     | -5.724E-1, 7.214E-2 | 1.396E-2±3.350E-4 | 9.870E-2, 1.714E-1 | s-process branching; \( \beta^- \), \( T_{1/2}=1.61\times10^6 \) y |
| 40-Zr-95/41-Nb-93 | -2.766E-1, 1.779E-2 | 3.168E-1±2.313E-2 | 0.000E+0, 6.020E-2 | s-process branching |
| 40-Zr-95/41-Nb-95 | 2.695E-1, 1.865E-2 | 1.820E-1±1.256E-2 | 1.400E-1, 2.420E-2 | \( \beta^- \), \( T_{1/2}=64.032 \) d; \( \beta^- \), \( T_{1/2}=34.991 \) d |
| 40-Mo-95     | -5.911E-3, 6.393E-2 | 6.800E-2±4.828E-3 | s-process only |
| 40-Mo-96     | 3.020E-1, 6.718E-2 | 1.570E-1±1.146E-2 | r-process only |
| 40-Mo-97     | 1.197E-1, 1.746E-2 | 7.700E-2±5.313E-3 | 8.080E-2, 3.120E-2 |
| 40-Mo-98     | 1.134E-1, 6.678E-2 | 6.300E-2±4.725E-3 | 7.390E-2, 7.910E-2 |
| 40-Mo-99     | -4.381E-3, 5.723E-3 | 1.666E-1±8.380E-2 | 1.730E-1, 2.700E-2 |
| 43-Tc-99     | -5.911E-3, 6.393E-2 | 6.800E-2±4.828E-3 | s-process only |
| 44-Ru-100    | -5.533E-2, 2.997E-2 | -2.574E-2±1.236E-3 | s-process only |
| 44-Ru-101    | 2.500E-1 | 2.460E-1±5.240E-2 | 2.260E-1, 2.400E-2 |
| 44-Ru-102    | 2.566E-1, 6.173E-3 | 2.622E-1±1.757E-2 | 2.670E-1, 3.800E-2 |
| 44-Ru-103    | 3.208E-1, 3.140E-3 | 3.060E-1±2.448E-2 | 3.150E-1, 7.110E-2 |
| 45-Rh-103    | 3.136E-1, 7.431E-3 | 2.790E-1±2.288E-2 | 2.970E-1, 8.800E-2 |
| 46-Pd-104    | -9.022E-3, 2.255E-2 | -2.170E-2±2.604E-3 | s-process only |
| 46-Pd-105    | 3.320E-1 | 3.443E-1±2.832E-2 | 3.370E-1, 4.600E-2 |
| 46-Pd-106    | 2.656E-1, 4.874E-3 | 2.669E-1±2.215E-2 | 2.660E-1, 3.700E-2 |
| 46-Pd-107/47-Ag-107 | -3.386E-3, 4.777E-3 | 2.140E-1±8.988E-3 | 2.110E-1, 3.300E-2 |
| 47-Ag-107    | 1.495E-1, 2.707E-2 | 1.220E-1±1.452E-2 | 1.190E-1, 7.400E-2 |
| 48-Cd-110    | 1.399E-2, 6.358E-3 | 1.000E-3±1.380E-4 | 1.720E-1, 4.100E-2 |
| 48-Pd-110    | 1.590E-1 | 1.627E-1±2.474E-2 | 1.560E-1, 1.800E-2 |
| 49-In-115    | 1.550E-1, 5.968E-3 | 1.599E-1±2.143E-2 | 1.520E-1, 2.700E-2 |
| 50-Sn-116    | 1.508E-1 | 1.830E-1±2.635E-2 | 1.760E-1, 7.400E-2 |
| 52-Te-122    | 1.495E-1, 1.619E-2 | 1.530E-1±1.451E-2 | 1.500E-1, 4.300E-2 |
| 50-Sn-117    | 2.755E-1, 8.550E-2 | 2.390E-1±2.247E-2 | 2.440E-1, 9.300E-2 |
| 50-Sn-118    | 1.431E-1, 2.387E-2 | 9.700E-2±2.056E-2 | 1.830E-1, 6.000E-2 |
| 50-Sn-119    | 2.015E-1, 1.402E-1 | 1.800E-1±1.710E-2 | 2.140E-1, 1.980E-1 |
| 51-Sb-121    | 1.121E-1, 9.715E-3 | 1.048E-1±1.907E-2 | 8.360E-2, 9.240E-2 |
| 52-Te-122    | -2.259E-2, 1.784E-2 | -6.324E-4±6.324E-5 | s-process only |
| 50-Sn-122    | 1.670E-1, 1.616E-1 | 1.616E-1±4.315E-2 | 1.520E-1, 2.800E-2 |
| 52-Te-122    | 1.411E-3, 6.056E-3 | -1.241E-3±1.241E-4 | s-process only |
Table 2: $R$-process abundances ... (continued).

| Target    | ENDF Abundances | Arlandini et al. | Arnould et al. | Comments                  |
|-----------|-----------------|------------------|----------------|---------------------------|
|           | $N_\odot-N_{\text{main}}$ | $N_\odot-N_{\text{main}}$ |               |                           |
| 51-Sb-123 | 1.340E-1        | 1.298E-1±2.363E-2 | 1.130E-1      | 1.800E-2, r-process only  |
| 52-Te-124 | -2.131E-2       | -7.099E-3±7.170E-4 | 2.050E-2      | s-process only            |
| 50-Sn-124 | 2.090E-1        |                  | 2.200E-1      | 2.200E-2, r-process only  |
| 52-Te-125 | 2.567E-1        | 2.579E-1±2.579E-2 | 2.560E-1      | r-process only            |
| 52-Te-126 | 4.812E-1        | 4.800E-1±4.848E-2 | 4.920E-1      | s-process only            |
| 53-I-127  | 8.351E-3        | 8.450E-1±1.817E-1 | 8.480E-1      | s-process only            |
| 54-Xe-128 | 1.348E-2        | 4.500E-3±1.697E-3 | 1.470E+0      | s-process only            |
| 52-Te-128 | 1.486E+0        | 1.526E+0±1.587E-1 | 1.470E+0      | r-process only            |
| 54-Xe-129 | 8.969E-3        | 1.234E+0±2.691E-1 | 1.080E+0      | r-process only            |
| 54-Xe-130 | 3.733E-2        | 2.400E-2±1.962E-2 | 1.470E+0      | r-process only            |
| 52-Te-130 | 1.585E+0        | 1.580E+0±1.690E-1 | 1.470E+0      | r-process only            |
| 54-Xe-131 | 1.193E-2        | 9.461E-1±2.536E-1 | 8.220E-1      | r-process only            |
| 54-Xe-132 | 8.091E-1        | 7.480E-1±1.616E-1 | 6.530E-1      | s-process only            |
| 55-Cs-133 | 1.089E-1        | 3.089E-1±2.162E-2 | 3.090E-1      | s-process only            |
| 56-Ba-134 | 1.819E-2        | -6.322E-2±4.498E-3| 3.850E-1      | s-process only            |
| 54-Xe-134 | 5.270E-1        | 4.507E-1±9.781E-2 | 3.850E-1      | s-process only            |
| 56-Ba-135 | 2.384E-1        | 2.155E-1±1.530E-2 | 2.480E-1      | s-process only            |
| 56-Ba-136 | -3.803E-2       | -1.306E-1±9.404E-3| 3.300E-1      | s-process only            |
| 54-Xe-136 | 4.290E-1        | 3.454E-3±1.443E-3 | 2.700E-2      | s-process only            |
| 56-Ba-137 | 5.703E-2        | 1.370E-1±1.000E-2 | 1.700E-1      | r-process only            |
| 56-Ba-138 | 3.439E-1        | -5.796E-1±3.767E-2| 2.140E-1      | s-process only            |
| 57-La-139 | 7.730E-2        | 7.700E-2±5.621E-3 | 1.570E-1      | s-process only            |
| 58-Ce-140 | -5.995E-1       | 3.200E-2±1.280E-3 | 1.610E-1      | s-process only            |
| 59-Pr-141 | 8.002E-2        | 7.370E-2±1.990E-3 | 1.100E-1      | s-process only            |
| 60-Nd-142 | -3.542E-2       | -2.700E-2±6.480E-4| 6.600E-2      | s-process only            |
| 58-Ce-142 | 1.310E-1        | 1.143E-1±4.458E-3 | 6.600E-2      | s-process only            |
| 60-Nd-143 | 6.871E-2        | 6.250E-2±1.883E-3 | 7.060E-2      | s-process only            |
| 60-Nd-144 | 9.517E-2        | 8.900E-2±1.958E-3 | 9.980E-2      | s-process only            |
| 60-Nd-145 | 5.633E-2        | 4.670E-2±7.939E-4 | 5.400E-2      | s-process only            |
| 60-Nd-146 | 6.853E-2        | 5.080E-2±8.636E-4 | 5.300E-2      | s-process only            |
| 60-Nd-147 | 7.109E-2        | 6.300E-2±1.280E-3 | 1.300E-2      | s-process only            |
| 61-Pm-147 | 3.327E-2        | 3.340E-2±5.268E-4 | 1.780E-2      | s-process only            |
| 62-Sm-147 | -2.474E-4       | -2.700E-2±8.410E-6| 2.050E-2      | s-process only            |
| 62-Sm-148 | 4.900E-2        | 4.393E-2±7.907E-4 | 4.210E-2      | s-process only            |
| 62-Sm-149 | 3.287E-2        | 3.111E-2±4.978E-4 | 3.230E-2      | s-process only            |
| 62-Sm-150 | 2.621E-3        | 0.000E+0±0.000E+0 | 3.230E-2      | s-process only            |
| 60-Nd-150 | 4.800E-2        | 4.900E-2±2.500E-3 | 3.100E-2      | s-process only            |
| 62-Sm-151 | -2.538E-2       | 4.221E-2±1.815E-3 | 4.520E-2      | s-process only            |
| 63-Eu-151 | -2.538E-2       | 9.300E-4±1.674E-5 | 1.260E-2      | s-process only            |
| 62-Sm-152 | 5.511E-2        | 5.340E-2±8.544E-4 | 5.710E-2      | s-process only            |
| 63-Eu-153 | 4.868E-2        | 4.776E-2±4.824E-3 | 4.950E-2      | s-process only            |
| 64-Gd-154 | 1.980E-4        | 9.300E-4±1.674E-5 | 1.260E-2      | s-process only            |

Note: $\beta^+$, $T_{1/2}=10.98$ d; $\beta^-$, $T_{1/2}=2.623$ yr; $\alpha$, $T_{1/2}=1.060\times10^{11}$ y; s-process only.
## Table 2: R-process abundances ... (continued).

| Target  | ENDF Abundances | Arlandini et al. | Arnould et al. | Comments |
|---------|-----------------|------------------|----------------|----------|
|         | \(N_\odot-N_{\text{main}}\) | \(N_\odot-N_{\text{main}}\) |                |          |
| 62-Sm-154 | 6.000E-2         | 5.828E-2±3.847E-3 | 5.950E-2±4.400E-3 | \(r\)-process only |
| 64-Gd-155 | 5.054E-2         | 4.530E-2±8.154E-4 | 4.680E-2±3.200E-3 | \(r\)-process only |
| 64-Gd-156 | 6.157E-2         | 5.480E-2±8.786E-4 | 5.790E-2±5.500E-3 | \(r\)-process only |
| 64-Gd-157 | 5.116E-2         | 4.584E-2±8.251E-4 | 4.710E-2±4.200E-3 | \(r\)-process only |
| 64-Gd-158 | 6.610E-2         | 5.800E-2±9.280E-4 | 6.140E-2±1.170E-3 | \(s\)-process only |
| 65-Tb-159 | 5.998E-2         | 5.525E-2±3.315E-3 | 6.010E-2±7.100E-3 | \(s\)-process only |
| 66-Dy-160 | 8.963E-4         | 8.800E-4±1.672E-5 | 9.500E-4±2.000E-3 | \(s\)-process only |
| 66-Gd-160 | 7.870E-2         | 7.208E-2±6.992E-3 | 7.410E-2±4.600E-3 | \(s\)-process only |
| 66-Dy-161 | 7.258E-2         | 7.062E-2±1.201E-3 | 7.410E-2±5.700E-3 | \(s\)-process only |
| 66-Dy-162 | 8.729E-2         | 8.440E-2±1.350E-3 | 9.000E-2±1.050E-2 | \(s\)-process only |
| 66-Dy-163 | 9.404E-2         | 9.335E-2±1.867E-3 | 9.720E-2±1.000E-3 | \(s\)-process only |
| 66-Dy-164 | 8.187E-2         | 9.530E-2±1.811E-3 | 1.030E-1±2.000E-2 | \(s\)-process only |
| 67-Ho-165 | 8.580E-2         | 8.308E-2±4.652E-3 | 8.390E-2±1.110E-2 | \(s\)-process only |
| 68-Er-166 | 7.812E-2         | 7.090E-2±7.161E-3 | 7.530E-2±6.200E-3 | \(s\)-process only |
| 68-Er-167 | 5.558E-2         | 5.237E-2±5.289E-3 | 5.460E-2±5.100E-3 | \(s\)-process only |
| 68-Er-168 | 4.833E-2         | 4.550E-2±5.506E-3 | 5.060E-2±6.300E-3 | \(s\)-process only |
| 69-Tm-169 | 3.430E-2         | 3.102E-2±1.706E-3 | 3.400E-2±5.100E-3 | \(s\)-process only |
| 70-Yb-170 | 7.148E-3         | 1.000E-3±4.200E-5 | 3.690E-3±3.800E-3 | \(s\)-process only |
| 70-Yb-171 | 3.900E-2         | 3.521E-2±5.246E-3 | 3.690E-2±3.800E-3 | \(s\)-process only |
| 70-Yb-172 | 3.072E-2         | 2.933E-2±1.144E-3 | 2.970E-2±4.600E-3 | \(s\)-process only |
| 70-Yb-173 | 3.657E-2         | 3.660E-2±3.074E-3 | 3.810E-2±5.300E-3 | \(s\)-process only |
| 70-Yb-174 | 3.264E-2         | 3.108E-2±2.642E-3 | 3.160E-2±3.700E-3 | \(s\)-process only |
| 71-Lu-175 | 4.004E-2         | 3.610E-2±3.321E-3 | 3.910E-2±1.620E-2 | \(s\)-process only |
| 71-Lu-176/177 | 3.201E-2 | 2.979E-2±1.192E-3 | 3.050E-2±1.490E-2 | \(s\)-process only |
| 72-Hf-176 | 3.330E-2         | 3.040E-2±3.040E-3 | 2.920E-2±4.200E-3 | \(r\)-process only |
| 72-Hf-177 | 2.451E-2         | 2.356E-2±2.154E-3 | 2.380E-2±2.500E-3 | \(r\)-process only |
| 72-Hf-178 | 2.102E-2         | 2.010E-2±7.437E-4 | 1.920E-2±4.400E-3 | \(r\)-process only |
| 72-Hf-179 | 1.446E-2         | 1.420E-2±5.112E-3 | 1.380E-2±2.200E-3 | \(r\)-process only |
| 75-Sc-180 | 2.411E-2         | 1.700E-2±5.780E-4 | 1.450E-2±4.500E-3 | \(s\)-process only |
| 75-Sc-181 | 2.318E-2         | 2.127E-2±3.286E-4 | 1.920E-2±1.060E-3 | \(s\)-process only |
| 75-Sc-182 | 2.149E-2         | 2.150E-2±1.548E-3 | 1.360E-2±3.500E-3 | \(s\)-process only |
| 75-Sc-183 | 8.727E-3         | 6.600E-3±4.752E-4 | 6.500E-3±3.600E-3 | \(s\)-process only |
| 75-Sc-184 | 1.723E-2         | 1.260E-2±9.198E-4 | 1.060E-2±7.300E-3 | \(s\)-process only |
| 75-Sc-185 | 1.537E-2         | 1.339E-2±1.366E-3 | 1.510E-2±2.500E-3 | \(s\)-process only |
| 76-Np-186 | 3.681E-2         | 1.000E-4±7.400E-6 | 9.200E-3±4.300E-3 | \(r\)-process only |
| 76-Np-187 | 3.900E-2         | 2.959E-2±2.071E-3 | 2.450E-2±1.720E-2 | \(s\)-process only |
| 76-Np-188 | 3.447E-3         | 3.080E-3±2.187E-4 | 3.180E-2±4.800E-3 | \(s\)-process only |
| 76-Np-189 | 3.681E-2         | 2.959E-2±2.071E-3 | 2.450E-2±1.720E-2 | \(s\)-process only |
| 76-Np-190 | 3.900E-2         | 2.959E-2±2.071E-3 | 2.450E-2±1.720E-2 | \(s\)-process only |

...continued on next page...

#### Notes:
- \(N_\odot-N_{\text{main}}\) represents the difference in abundance levels between the solar composition and the main components of the ENDF library.
- Arlandini et al. and Arnould et al. provide additional data sets for comparison.
- Comments indicate specific processes contributing to the abundances, such as \(r\)-process or \(s\)-process.
- Contributions from isotopes like \(^{197}\text{Re}\) are noted with associated comments and uncertainties.

...continued on next page...
Table 2: $R$-process abundances ... (continued).

| Target      | ENDF Abundances | Arlandini et al. | Arnould et al. | Comments                  |
|-------------|-----------------|------------------|----------------|---------------------------|
|             | $N_{\odot}/N_{\text{main}}$ | $N_{\odot}/N_{\text{main}}$ |                |                           |
| 77-Ir-191   | 2.453E-1 4.530E-4 | 2.424E-1±1.915E-2 | 2.290E-1 8.000E-3 | s-process only            |
| 78-Pt-192   | -4.724E-3 1.415E-3 | -5.355E-3±2.704E-3 | 1.051E-2 1.000E-2 | r-process only            |
| 76-Os-192   | 2.780E-1 | 2.760E-1±4.360E-2 | 2.730E-1 1.000E-2 | s-process branching; EC,T$_{1/2}$=50 y |
| 78-Pt-193/  | 4.137E-1 6.970E-4 | 4.079E-1±3.222E-2 | 3.880E-1 1.400E-2 |                           |
| 77-Ir-193   |                |                  |                |                           |
| 78-Pt-194   | 4.014E-1 1.782E-3 | 4.223E-1±2.133E-1 | 4.210E-1 4.900E-2 |                           |
| 78-Pt-195   | 4.327E-1 3.135E-3 | 4.474E-1±2.259E-1 | 4.450E-1 4.800E-2 |                           |
| 78-Pt-196   | 2.929E-1 2.784E-3 | 3.085E-1±4.257E-2 | 3.020E-1 4.500E-2 |                           |
| 79-Au-197   | 1.857E-1 | 8.884E-4 1.574E-3 | 1.773E-1 1.200E-2 |                           |
| 80-Hg-198   | 1.051E-2 3.896E-3 | 2.700E-3±3.996E-4 | 1.972E-3 3.300E-3 |                           |
| 78-Pt-198   | 9.100E-2 | 9.624E-2±2.165E-2 | 9.500E-2 1.000E-2 |                           |
| 80-Hg-199   | 6.263E-2 | 2.425E-3 6.007E-3 | 5.070E-2 1.500E-2 | r-process only            |
| 80-Hg-200   | 2.532E-2 3.135E-3 | 3.350E-2±5.327E-3 | 3.400E-2 3.060E-2 |                           |
| 80-Hg-201   | 3.868E-2 | 2.917E-3 7.407E-3 | 2.550E-2±3.341E-3 |                           |
| 80-Hg-202   | 7.395E-2 | 2.513E-3 3.623E-3 | 3.700E-2±5.452E-3 |                           |
| 81-Tl-203   | 2.352E-2 | 2.860E-3 1.072E-3 | 1.730E-2 1.200E-2 |                           |
| 82-Pb-204   | 4.481E-3 6.593E-3 | 1.280E-2±1.267E-2 | 6.000E-2 4.000E-2 |                           |
| 80-Hg-204   | 3.100E-2 | 2.295E-2±3.511E-3 | 2.660E-2 4.600E-3 |                           |
| 82-Pb-205/  | -2.318E-2 2.153E-3 | 5.390E-2±6.468E-3 | 4.970E-2 4.970E-2 |                           |
| 81-Tl-205   |                 |                  |                |                           |
| 82-Pb-206   | 2.588E-2 | 6.093E-2 3.291E-2 | 4.090E-1±4.335E-2 |                           |
| 82-Pb-207   | 2.014E-1 | 4.298E-2 4.912E-2 | 4.540E-1±4.268E-2 |                           |
| 82-Pb-208   | -2.477E+0 | 7.844E-1 3.794E+1 | 1.649E+0±1.385E-1 |                           |
| 83-Bi-209   | -1.671E-2 | 2.891E-2 1.160E-2 | 1.391E-1±1.822E-2 |                           |

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