

Impact of nuclear masses on r -process nucleosynthesis: Bulk properties versus shell effects

Samuel A. Giuliani ¹, Gabriel Martínez-Pinedo ^{2,3,4}, Andreas Bauswein ^{2,4} and Vimal Vijayan ²

¹*Departamento de Física Teórica and CIAFF, Universidad Autónoma de Madrid, Madrid 28049, Spain*

²*GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*

³*Institut für Kernphysik (Theoriezentrum), Fachbereich Physik, Technische Universität Darmstadt, Schlossgartenstraße 2, D-64289 Darmstadt, Germany*

⁴*Helmholtz Forschungsakademie Hessen für FAIR (HFHF), GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany*



(Received 2 December 2024; revised 9 December 2025; accepted 30 March 2026; published 27 April 2026)

We investigate the impact of the model estimating the masses of exotic nuclei on r -process nucleosynthesis, assessing the dependence of the abundance distribution on the specific properties of nuclear masses. By decomposing theoretical nuclear mass predictions into a liquid-drop parametrization and local shell effects, we show that r -process abundances are virtually insensitive to large variations of the masses, which originate from nuclear bulk properties of the model, such as the symmetry energy. In contrast, the mass component associated with local shell effects is the main driver of r -process abundance variations, despite its relatively minor contribution to the absolute value of neutron separation energies. Our work suggests that experimental and theoretical studies of masses devoted to r -process applications, such as the nucleosynthesis in the ejecta of neutron star mergers, should focus on the physical origin and determination of local changes in mass trends.

DOI: [10.1103/k64z-32sr](https://doi.org/10.1103/k64z-32sr)

I. INTRODUCTION

The cosmic origin of heavy elements is a major challenge in modern science [1]. Roughly half of the elements heavier than iron are produced in a nucleosynthesis process known as rapid neutron-capture process, or r process [2,3]. It occurs in an astrophysical environment with extreme neutron fluxes, where exotic neutron-rich nuclei are produced by subsequent neutron captures and β decays. As such, a fundamental understanding of the r process requires a multidisciplinary effort involving the modeling of astrophysical environments, astronomical observations, as well as the knowledge of nuclear and atomic properties of the synthesized nuclei (see Refs. [4–7] for recent reviews).

When it comes to the modeling of r -process abundances, the two major sources of uncertainty are the astrophysical conditions at which the r process operates and the nuclear properties of the involved nuclei. In recent years, increasing efforts have been made to understand which astrophysical scenarios could provide suitable conditions for the production of heavy elements and identify observational constraints. Numerical simulations suggest three main candidates: compact binary mergers, such as binary neutron star mergers (NSM) [8] and NS-black hole mergers [9]; magnetorotational core-collapse supernova [10]; and accretion disk outflows from collapsars [11]. So far, the only direct evidence of the production of heavy elements has been obtained for NSM,

through the observation of the AT2017gfo kilonova light curve [12,13], the electromagnetic counterpart associated to the gravitational wave event GW170817 [14].

From the nuclear physics side, the main challenge resides in the fact that the nuclei produced during the r process are extremely neutron rich and short lived. As such, measuring the relevant reaction rates in current experimental facilities is often not possible, and one must rely on theoretical modeling that results in large differences in predictions as the neutron drip line is approached. Uncertainties in the nuclear physics input and astrophysical conditions produce degeneracies in the predicted abundances, hindering the identification of the astrophysical conditions and relevant nuclear properties by confronting r -process models and observations. Among the nuclear properties that are required for modeling the r process, nuclear mass is the most basic quantity, as it determines the energy threshold of all reactions and decays. As a consequence, several experimental campaigns in radioactive ion-beam facilities have been devoted to the measurement of masses of neutron-rich nuclei, and more experiments are currently ongoing and envisaged to extend the reach further into the r -process region [4,5,7,15]. At the same time, more refined global nuclear models capable of predicting nuclear masses across the entire nuclear chart have been developed, some of them capable of reproducing experimental data with a root-mean-square (rms) error smaller than 700 keV [16–20]. In recent years, these global calculations of nuclear masses have been supplemented with machine learning techniques, to alleviate the computational burden and/or effectively reduce model discrepancies with experimental data [21–26].

Despite all the progress made, discrepancies among models in the predicted masses tend to increase with neutron excess. Because of the fundamental role that nuclear masses

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

play for the r process, it has always been assumed that absolute differences have *per se* a major impact on r -process abundances. Therefore, experimental efforts have been dedicated to constraining the value of nuclear masses with the highest possible precision [4]. From a theory side, several studies explored the impact of different mass models on predicted r -process abundances [27–35]. However, when comparing different theoretical predictions (among themselves or against experimental data), there has been so far no attempt to determine which features in the evolution of nuclear masses with neutron and proton number, the so-called mass surface, are important and which ones are negligible for the determination of the r -process abundances.

In this work, we show that variations in the predicted masses that are related to differences in their bulk or global properties, e.g., symmetry energy, remarkably, do not affect the r -process abundances. Instead, the nucleosynthesis outcome is highly sensitive to shell effects that induce local changes in neutron separation and neutron shell gap energies. We decompose the predicted masses into two contributions: one that represents the bulk properties and changes smoothly with proton and neutron number, and a second part that accounts for local variations on top of the smooth global behavior. The first part is described using a liquid drop model parametrization obtained from a fit to a specific mass model, while the second represents the difference. We consider two mass models, which have been widely used in r -process nucleosynthesis studies: the finite-range droplet model (FRDM) [36] and the Duflo-Zuker mass formula (DZ31) [16]. We then generate new mass tables by mixing the smooth energy part and shell corrections of the original models. By performing nuclear network calculations for a large set of trajectories corresponding to the dynamical ejecta of a neutron star merger [37], we demonstrate the insensitivity of predicted abundances to large variations of the nuclear masses, provided that they originate from the smooth part of the underlying nuclear mass model. In contrast, we show that local shell effects are the main drivers in shaping the abundances distribution.

The paper is organized as follows. In Sec. II we describe the methodology employed for decomposing nuclear masses into a smooth bulk part and local shell effects. In Sec. III we present the abundances predicted by mass models differing in their bulk properties and/or shell effects. Our findings and conclusions are summarized in Sec. IV.

II. DECOMPOSITION OF NUCLEAR MASSES

We assume that the binding energy of a nucleus can be decomposed into an average contribution, which depends smoothly on the number of protons (Z) and neutrons (N), and a quantum shell correction arising from local changes in single-particle levels [38]. The homogeneous, bulk part of the energy can be efficiently parametrized using a leptodermous expansion such as the liquid drop model (LDM) [39]:

$$\begin{aligned} \frac{E^{\text{LDM}}}{A} = & a_{\text{vol}} + a_{\text{sur}}A^{-1/3} + a_{\text{cur}}A^{-2/3} + a_{\text{sym}}I^2 \\ & + a_{\text{ssym}}A^{-1/3}I^2 + a_{\text{sym}}^{(2)}I^4 + a_{\text{Coul}}Z^2A^{-4/3} + a_{\text{pai}}\delta, \end{aligned} \quad (1)$$

TABLE I. LDM parameters (in MeV) of Eq. (1) corresponding to the mass models employed in this work. The last row corresponds to the LDM parameter obtained from the AME2020 experimental masses [41].

Model	a_{vol}	a_{sur}	a_{cur}	a_{sym}	a_{ssym}	$a_{\text{sym}}^{(2)}$	a_{Coul}	a_{pai}
DZ31	−14.96	13.16	7.96	27.91	−27.97	−3.22	0.67	−9.05
DZ31*								
FRDM	−14.56	11.21	10.39	26.16	−23.10	−1.28	0.66	−9.86
FRDM*								
AME20	−15.63	19.17	−4.74	26.48	−20.56	−5.21	0.68	−6.78

being $A = N + Z$, and $I = (N - Z)/A$ the so-called neutron excess. The pairing term δ takes the value $A^{-3/2}$ for even-even nuclei, $-A^{-3/2}$ for odd-odd nuclei, and zero for odd-mass nuclei. A detailed discussion of the physical meaning of the different terms entering in Eq. (1) can be found, for instance, in Refs. [39,40]. Starting from a mass table (either DZ31 or FRDM), we fit the a_i coefficients of Eq. (1) to parametrize the smooth behavior of mass surfaces. The residuals between nuclear masses and the smooth contribution constitute the shell effects of the original mass model. By combining the homogeneous contribution obtained from the DZ31 (FRDM) mass table with the shell effects of FRDM (DZ31), we create a new mass table denoted DZ31*(FRDM*). Table I summarizes the LDM parameters of the mass tables employed in this work.

Evidently, the four mass tables predict rather different nuclear masses, particularly in the region far from stability, where the original models DZ31 and FRDM have not been fitted. This is shown in Fig. 1(a), where nuclear masses along the neodymium isotopic chain are plotted as a function of neutron number N . By subtracting the homogeneous contribution given by the AME2020 LDM parametrization (obtained from the fit of Eq. (1) to the AME2020 experimental masses [41], see last row in Table I), it becomes visible that the model pairs DZ31/FRDM* and FRDM/DZ31* predict different values of nuclear masses, while sharing the same local shell effects. Due to this, despite the large discrepancies in the binding energies, we observe that the neutron separation energies S_{2n} predicted by the different models show a rather similar behavior, as depicted in Fig. 1(b) (for displaying purposes, we plot S_{2n} rather than S_n). The modified mass tables result in a slight change in the S_{2n} slope, mostly due to changes in the symmetry energy term a_{sym} , which governs the evolution of masses with neutron excess. We recall that neutron-capture rates depend exponentially on the neutron separation energy, suggesting that the impact of variations in nuclear masses can be easily overestimated, as local changes in S_{2n} are more relevant for shaping the r -process abundances. Such local changes can be quantified by means of the (two-)neutron shell-gap energies, which are given by the difference between two-neutron separation energies $\Delta_{2n}(N, Z) = S_{2n}(N, Z) - S_{2n}(N + 2, Z)$. This quantity is extremely sensitive to variations in single-particle levels between neighboring nuclei, providing a proxy for local changes in the binding energies due to nucleonic (shell) effects [42–44]. For instance, local maxima in Δ_{2n}

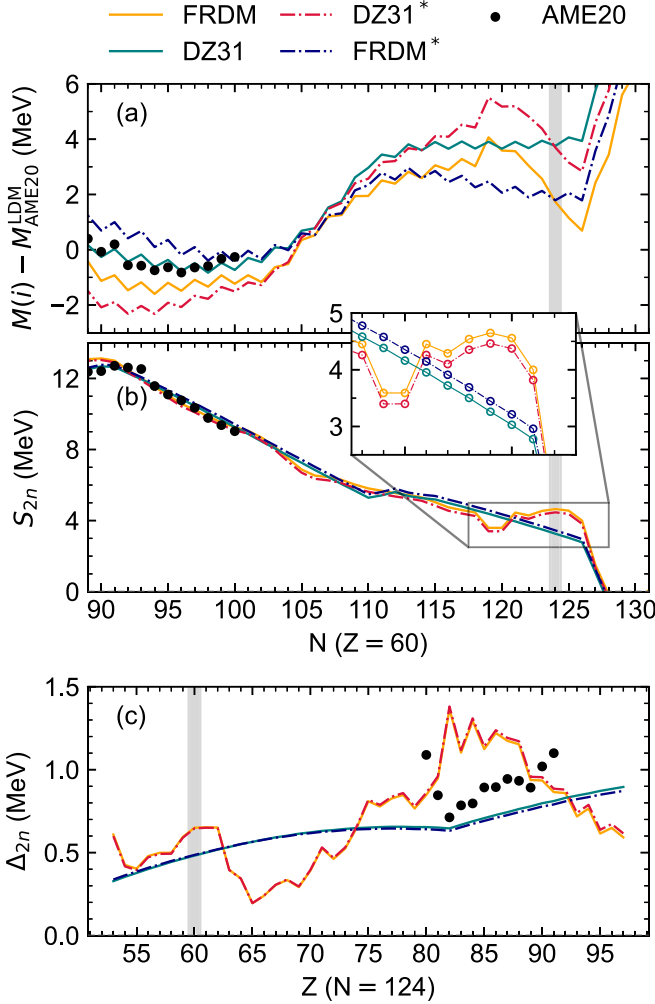


FIG. 1. (a) Comparison of theoretical and experimental masses for neodymium ($Z = 60$) isotopes as a function of neutron number. The bulk LDM AME2020 contribution is subtracted from all the masses. (b) Comparison of two-neutron separation energies. (c) Comparison of two-neutron shell-gap energies as a function of charge number for $N = 124$ isotones. In all the panels, black circles represent AME2020 experimental data.

are associated with the presence of spherical and deformed shell gaps, while negative values usually indicate a nuclear shape transition (see Ref. [45] for a recent detailed discussion on Δ_{2n} and its evolution across the nuclear chart). The Δ_{2n} values along the isotonic chain $N = 124$ predicted by the four models are plotted in Fig. 1(c). As one can see, this quantity is insensitive to changes in the bulk properties of nuclear masses characterized by the LDM parametrization, as its evolution is actually driven by the emergence and disappearance of shell effects with neutron excess.

III. RESULTS

Nucleosynthesis calculations are performed using a large nuclear reaction network, including all nuclei up to $Z = 110$ from the valley of stability to the neutron dripline. We derived neutron capture rates consistently for each mass model

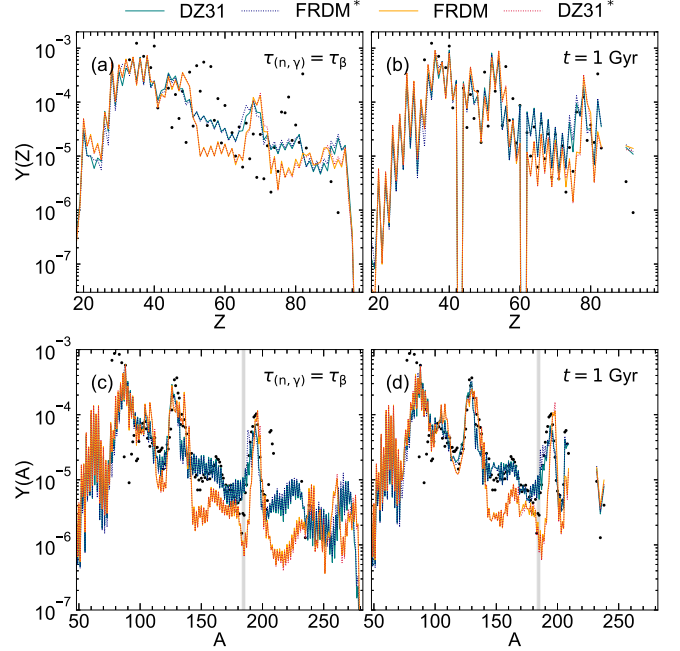


FIG. 2. Mass-integrated abundances as a function of atomic number (top panels) and mass number A (bottom panels) predicted by different mass models at $\tau_{(n,\gamma)} = \tau_\beta$ (left panels) and at 1 Gyr (right panels). Black circles are r -process abundances in the solar system.

by means of the Hauser-Feshbach statistical theory, employing the talys 1.95 nuclear reaction code [46]. Experimental masses are employed whenever available. Photodissociation rates are obtained from neutron-capture rates using detailed balance. We adopted the FRDM β -decay rates, which have been renormalized for each mass table according to their predicted Q values. To isolate the impact of masses on predicted abundances, in all the calculations we employed the neutron-induced fission rates based on the FRDM + TF model [47], and the fission yields derived using the code ABLA [48].

We compute the r -process abundances for a set of 1015 trajectories simulating the dynamical ejecta produced in neutron star mergers [37] (see Ref. [49] for code details). We use this specific r -process scenario because it covers a broad range of astrophysical conditions, in particular regarding the proton-to-nucleon ratio (see Fig. 2 of Ref. [37]). By this, we show that our result is fully general and does not depend on considering a specific trajectory. We also expect our conclusions to be valid for any r -process scenario.

A. Impact of bulk properties on r -process abundances

We start by exploring the sensitivity of r -process abundances on bulk properties of nuclear masses. Figure 2 shows the total integrated elemental and mass abundances predicted from the four mass tables of Table I at two different phases of the evolution: when the average timescale for neutron captures becomes equal to the average timescale for β decay ($\tau_{(n,\gamma)} = \tau_\beta$), and at 1 Gyr. The abundances obtained with the four models at 1 Gyr (when most of the material has decayed to stability) present the main characteristics of a strong r -

process pattern: we observe the presence of the second and third peaks, as well as the production of uranium and thorium. When comparing the different models, we notice that already at the freezeout the abundances predicted by masses with the same shell effects but different bulk properties, are virtually identical: only minor differences in the strength of odd-even staggering are observed in mass abundances, which are subsequently washed out by β -delayed neutron emissions and late neutron captures. We observe no connection between the bulk properties of masses (as determined by LDM parameters) and the abundance distribution. In other words, models with the same LDM coefficients a_i result in very different abundances patterns.

To better understand the fundamental connection between variations in nuclear masses and abundances, we study the case of neodymium isotopes ($Z = 60$) around neutron number $N = 124$, which dominate the abundances at freezeout in the region $A = 184$ (indicated with a gray vertical band in Fig. 2). Figure 2(c) shows that the abundances predicted by FRDM/DZ31* strikingly differ from DZ31/FRDM*. In particular, FRDM and DZ31* show a deeper trough right before the third r -process peak compared to DZ31 and FRDM*. This behavior of abundance distributions cannot be explained by the differences in the predicted masses around the region $Z/N = 60/124$. As one can notice in Fig. 1(a), the DZ31* predictions at $N = 124$ (gray band) are closer to DZ31, while those predicted by FRDM* around this mass number are more in agreement with FRDM predictions. Instead, one has to look at the predicted S_{2n} shown in Fig. 1(b). Despite the absolute difference in predicted masses, which is a consequence of variations in the bulk part of the binding energy, FRDM and DZ31* (as well as DZ31 and FRDM*) show the same S_{2n} trend and, in turn, a strikingly similar r -process path. In particular, FRDM and DZ31* predict a local increase in S_{2n} around $Z/N = 60/124$, resulting in a larger Δ_{2n} . This change in the slope of S_{2n} reduces the probability of neutron captures for nuclei in this region, producing in turn a deeper trough in the abundance distribution around $A \sim 184$ [27]. More generally, this result shows that features of the r -process abundances are not connected to global variations in nuclear masses, but rather the result of local changes in binding energies as a consequence of configuration changes in single-particle levels.

To further assess the impact produced by global changes of mass surfaces, we study the variation of elemental abundances with increasing deviations between nuclear masses. To do so, we introduce a new term in the LDM formula (1):

$$a_{\text{Nsym}}[N - N_{\text{max}}^{\text{exp}}(Z)]H[N - N_{\text{max}}^{\text{exp}}(Z)]I^2, \quad (2)$$

with $H(x)$ being the Heaviside step function and $N_{\text{max}}^{\text{exp}}(Z)$ the maximum N value for each isotopic chain Z with a measured mass in the AME2020 dataset [41]. By varying the a_{Nsym} term, we produce mass tables that diverge at different rates with increasing isospin asymmetry. Figure 3 shows the nuclear masses along the neodymium isotopic chain for five different values of a_{Nsym} applied to the FRDM LDM parametrization. One can notice that the smallest absolute values of a_{Nsym} roughly match the absolute differences between FRDM and DZ31 masses, while $a_{\text{Nsym}} = \pm 0.01$ and 0.05 MeV pro-

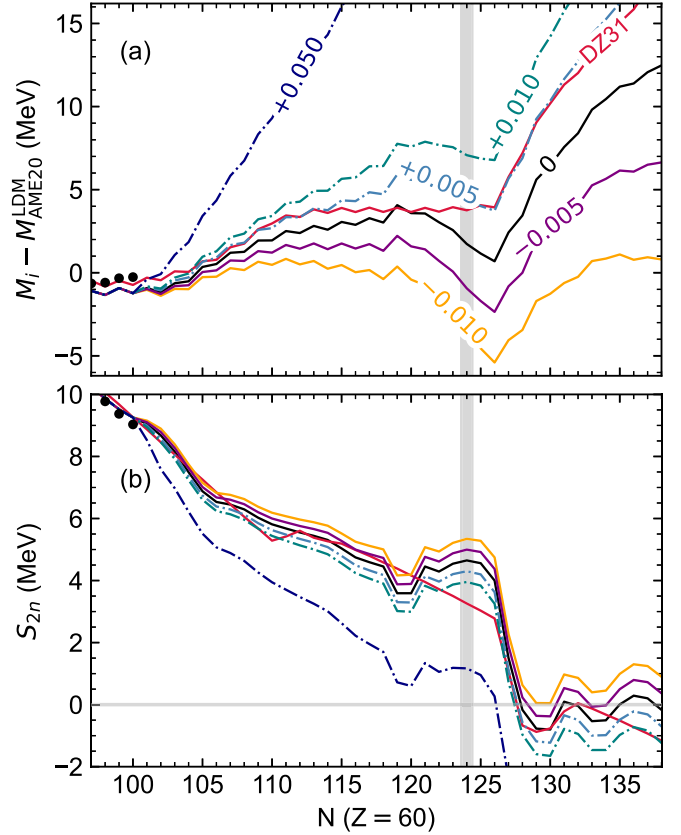


FIG. 3. (a) FRDM masses and (b) two-neutron separation energies in MeV for different values of a_{Nsym} along the neodymium isotopic chain as a function of neutron number. The red solid line represents the DZ31 predictions. Black circles represent the AME2020 experimental data. In (a), the bulk LDM AME2020 contribution is subtracted from all the masses.

duce mass tables that largely differ from the original FRDM predictions.

The integrated r -process abundances obtained with these modified FRDM mass tables are shown in Fig. 4 at three different times: at the neutron capture freezeout (defined as the time when the neutron-to-seed ratio $n/s = 1$), when $\tau_{(n,\gamma)} = \tau_\beta$, and at 1 Gyr. At early times ($n/s = 1$), we observe that variations in the bulk properties of mass surfaces produce a shift in the abundance distribution, while the overall shape resulting from local peaks and troughs remains mostly unaltered. As the evolution proceeds and the r -process path moves closer to stability, the differences are washed out, producing virtually identical abundance distributions at $\tau_{(n,\gamma)} = \tau_\beta$ and 1 Gyr. Actually, noticeable differences in the final abundances only appear for $a_{\text{Nsym}} = 0.05$ MeV in the $Z = 77-81$ region. These differences are produced by the strong decrease of the two-neutron separation energies around the $N = 126$ shell closure, with S_{2n} dropping below zero for nuclei with $Z \lesssim 68$, which shifts the third peak towards heavier atomic numbers. The impact of variations in masses is also visible in the final-integrated abundances as a function of mass number A , with a shift in the position of troughs and peaks for $a_{\text{Nsym}} = 0.05$ MeV. However,

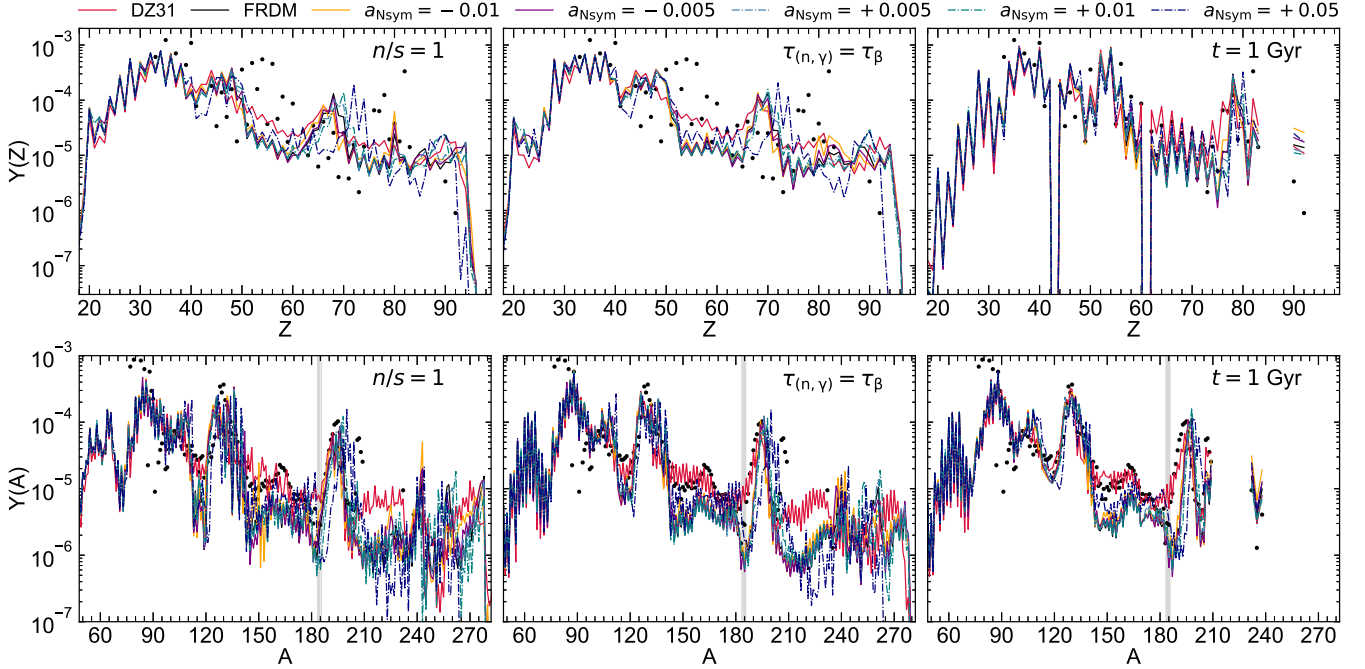


FIG. 4. Integrated abundances as a function of atomic number Z (top row) and mass number A (bottom row) predicted by FRDM mass models with different values of a_{Nsym} and DZ31 at three different times: neutron capture freezeout (left column), when $\tau_{(n,\gamma)} = \tau_\beta$ (middle column), and at 1 Gyr (right column). Black circles are r -process abundances in the solar system.

it is important to notice that variations in the abundances between the FRDM models are generally smaller than the variations observed between DZ31 and any FRDM-based model, regardless of the level of agreement between the absolute masses predicted by the different models. This result provides further evidence that the main drivers of r -process abundances are the local changes in S_{2n} , rather than the global changes of mass surfaces, suggesting that sensitivity studies focused on individual masses could overemphasize their impact on r -process abundances.

B. Impact of local shell effects on r -process abundances

In the previous section, we showed that variations in the bulk properties of nuclear masses have little impact on r -process abundances, suggesting that variations in shell effects drive the changes in the abundances. The goal of this section is to demonstrate this connection explicitly. To do so, we construct four mass tables with the same LDM parametrization (derived from the FRDM model), and different shell effects obtained by mixing the shell effects from DZ31 and FRDM in different proportions ($\delta(\text{DZ31})/\delta(\text{FRDM}) = 25/75, 50/50, 75/25$, and $100/0$, with $\delta(i) = M(i) - \text{LDM}[M(i)]$ being the shell effects of the mass model i). The advantage of this method compared to, for example, a general scaling of the shell effects is that neutron shell closures are preserved, while allowing for a smooth transition between the two mass models. The resulting masses and two-neutron separation energies along the neodymium isotopic chain are depicted in Fig. 5, together with the two-neutron shell gaps along the $N = 124$ and 94 isotonic chains. The two-neutron separation energies [Fig. 5(b)] and the two-neutron shell gaps [Fig. 5(c) and

Fig. 5(d)] show that, indeed, the local trends of the mixed mass tables gradually transition from one model to the other.

To quantify the impact in nuclear masses induced by variations in the shell effects, we computed the rms error (σ) between the mixed mass models and the original FRDM. The results are summarized in Table II. Obviously, the rms errors are proportional to the percentage of DZ31 shell effects employed in the mixed mass models: increasing the contribution of DZ31 shell effects by 25% produces an increase of 0.57, 0.24, and 0.27 MeV in the rms error of binding energies, two-neutron separation energies, and two-neutron shell gaps, respectively. We point out that the rms error in Δ_{2n} between DZ31 and FRDM is the same as between 100% DZ31 and

TABLE II. Deviations between mixed models and FRDM. First three rows: rms error (in MeV) for nuclear masses M , two-neutron separation energies S_{2n} , and two-neutron shell gaps Δ_{2n} . Fourth and fifth rows: average deviation of elemental and mass abundance percent difference with respect to FRDM [$\Delta Y = (Y - Y_{\text{FRDM}})/Y_{\text{FRDM}} \times 100$] depicted in Fig. 6. As a reference, the last row shows the rms errors (in MeV) for nuclear masses between the mixed mass models and AME20, while the last column summarizes the results for DZ31.

	25/75	50/50	75/25	100/0	DZ31
$\sigma_{\text{FRDM}}(M)$	0.57	1.13	1.70	2.26	3.30
$\sigma_{\text{FRDM}}(S_{2n})$	0.24	0.48	0.71	0.95	0.98
$\sigma_{\text{FRDM}}(\Delta_{2n})$	0.27	0.54	0.82	1.09	1.09
$\langle \Delta Y(Z) \rangle$	30.2%	58.0%	82.4%	105.0%	105.2%
$\langle \Delta Y(A) \rangle$	34.6%	68.1%	101.9%	134.41%	135.44%
$\sigma_{\text{AME20}}(M)$	0.84	0.69	0.69	0.83	0.43

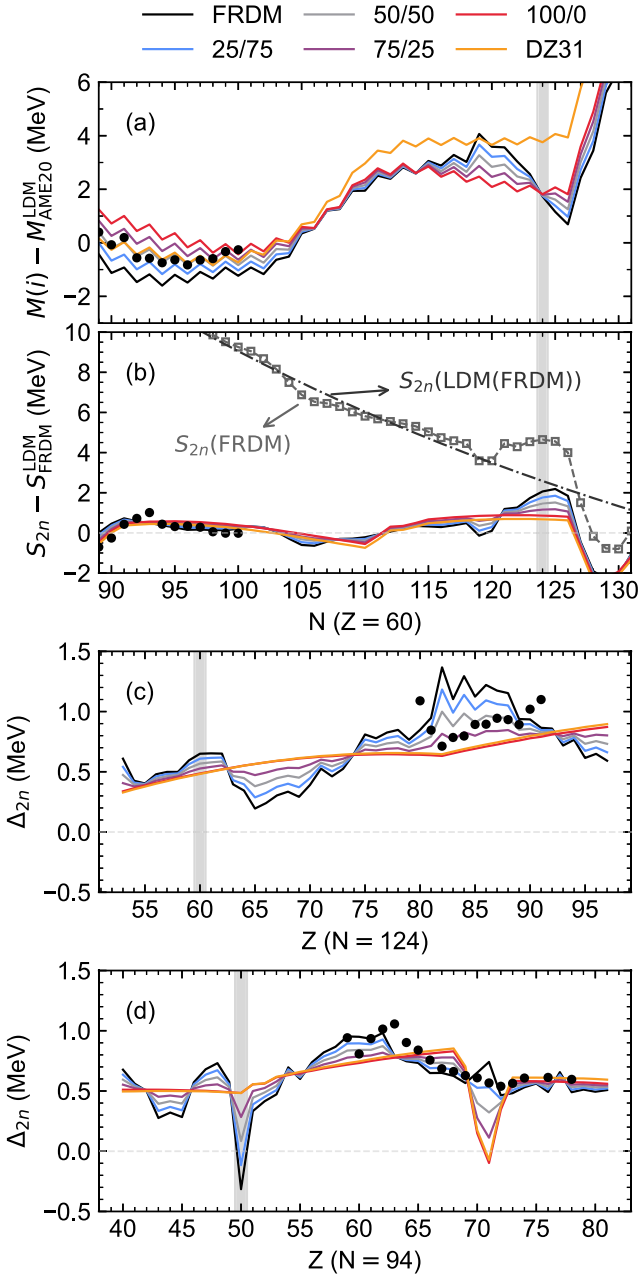


FIG. 5. (a) and (b) Nuclear masses and two-neutron separation energies (in MeV) for different mixtures of DZ31 and FRDM shell effects (DZ31/FRDM) along the neodymium isotopic chain as a function of neutron number. The bulk LDM contribution extracted from AME2020 experimental data is subtracted from all the masses. The bulk LDM extracted from the FRDM model is subtracted from all the S_{2n} . (c) and (d) Two-neutron shell-gap energies for the same models as in the top panels along the $N = 124$ and $N = 94$ isotonic chains as a function of proton number. Black circles represent the AME2020 experimental data.

FRDM, indicating that this quantity is mostly sensitive to local shell effects, as shown in Fig. 5(c). As a reference, Table II indicates the rms error between the mixed mass models and the AME2020 experimental data. As one can see, the mixed models

have a performance between FRDM ($\sigma_{\text{AME20}} = 1.07$ MeV) and DZ31 ($\sigma_{\text{AME20}} = 0.43$ MeV).

Figure 6 shows the integrated elemental and mass abundances predicted by the different mixed mass models from Table II at three different times ($n/s = 1$, $\tau_{(n,Y)} = \tau_\beta$, and 1 Gyr). For each time, we also plot the percent difference of the abundances with respect to the FRDM results [$\Delta Y = 100 \times (Y_i - Y_{\text{FRDM}})/Y_{\text{FRDM}}$, with i being one of the mixed mass models]. The smooth transition in the local shell effects in the mixed mass models introduced above translates into a gradual change in the abundance distributions. In particular, the shift in the location of peaks and the progressive filling of the troughs are clearly visible at all times. For example, the gradual disappearance of the S_{2n} saddle point around $Z/N = 60/124$ (Fig. 5) occurring between FRDM and DZ31 translates into a progressive filling of the through at $A \approx 184$. Similarly, the erosion of the FRDM S_{2n} saddle point around $Z/N = 50/94$, corresponding to a smoothening in Δ_{2n} shown in Fig. 5(d), produces the increase of the abundances at $A = 144$.

It is worth noticing that the contribution from the shell effects to the two-neutron separation energies is usually subdominant compared to the bulk LDM part, as shown in Fig. 5(b). Despite this, the shaping of the r -process abundances is mostly driven by these relatively small local changes, which impact the trend of neutron separation energies and the magnitude of neutron shell gaps.

By combining Fig. 6 with Table II, we conclude that changes in nuclear masses related to shell effects of the order of 570 keV translate to changes in the final abundance distribution up to a factor of two. However, it is important to note that the impact on the abundances is not necessarily proportional to the magnitude of the variations in the shell effects. The reason is that variations in shell effects become more relevant when they induce structural changes in the behavior of neutron separation energies, such as the appearance or disappearance of local saddle points [27]. As a consequence, the impact of changes in the shell effects strongly depends on the trends of the underlying mass surface. To better quantify the impact of changes in local shell effects in r -process abundances, we compute the ΔY average at 1 Gyr for the different mixed models. The results are summarized in Table II for nuclei with $Z > 20$, $A > 50$, $Y(Z)$, $Y(A) > 10^{-7}$. We find that, indeed, changes in local shell effects are quantitatively linked to changes in the abundances distribution: changing the shell effects by 0.57 keV (i.e., the S_{2n} by 0.24 MeV and Δ_{2n} by 0.27 MeV) changes the mass abundances by approximately 35% in a rather consistent fashion. The impact on the elemental abundances is not as constant, but still in a relatively narrow range between 22–30%. It is important to note that the σ_{FRDM} values presented in Table II account only for changes in local shell effects. In most cases, we expect the σ between mass models to be larger due to the additional change in the bulk term, as shown by the comparison between the 100/0 and DZ31 models. Also, the results obtained for these two models provide additional evidence that the rms error of nuclear masses can be a misleading indicator for the precision required in r -process studies. Despite the large difference in rms errors between 100/0 and DZ31, both mass

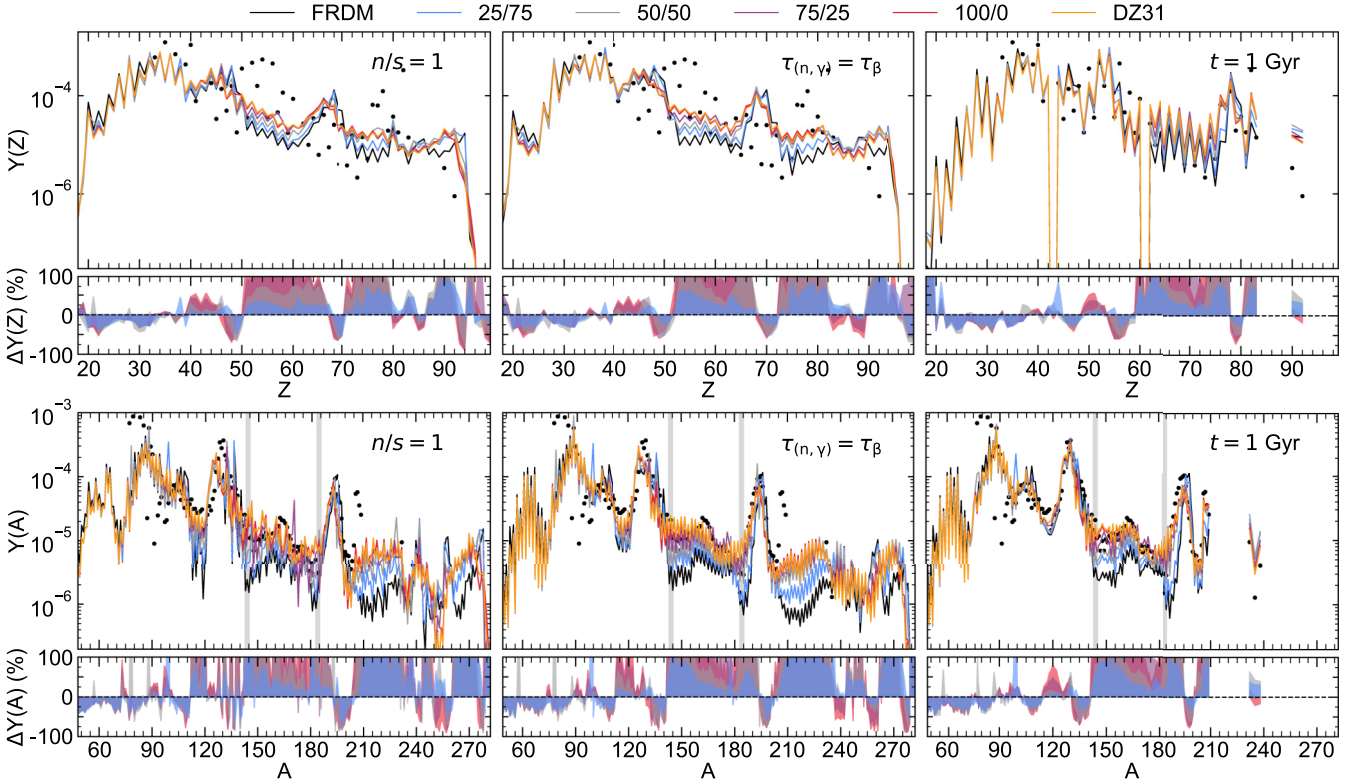


FIG. 6. Integrated abundances predicted by mass models with mixed shell effects DZ31/FRDM (Table II) at three different times: when $n/s = 1$ (left column), when $\tau_{(n,\gamma)} = \tau_\beta$ (center column) and at 1 Gyr (right column). First row: integrated elemental abundances as a function of atomic number Z . Second row: percent difference of integrated elemental abundances to FRDM ($\Delta Y = (Y - Y_{\text{FRDM}})/Y_{\text{FRDM}} \times 100$). Third row: integrated mass abundances as a function of mass number A . Fourth row: percent difference of integrated mass abundances with respect to FRDM. Black circles are the solar r -process abundances.

models predict very similar abundance distribution. Finally, we point out that the $\langle Y \rangle$ values presented in Table II could be affected by the impact of shell effects in nuclear processes such as β decays and fission, which can introduce nonlocal effects through, e.g., β -delayed emission of neutrons and fission fragments.

IV. CONCLUSIONS

We have shown that variations in predicted nuclear masses do not necessarily correlate with changes in the r -process abundance distributions. We employ the LDM to decompose the mass surface into a smooth contribution and local shell effects for the two mass models considered: FRDM and DZ31. By performing detailed nuclear network calculations simulating the occurrence of r process in neutron star mergers, we find that large changes in the bulk properties that result in very different theoretical nuclear masses, have little impact on the predicted elemental and mass abundances. The abundance distribution is instead driven by local changes in the (two-)neutron separation energies arising from nucleon shell effects, which can be identified by means of neutron shell-gap energies. We assess the sensitivity of r -process abundances to such local variations by mixing the shell effects of FRDM and DZ31. The resulting mass tables gradually transition from one model to the other, while keeping the same bulk properties. The r -process abundances predicted by the mixed

mass tables show a correlated smooth transition, providing evidence that local changes in mass surfaces are the main drivers of r -process abundances, despite accounting for only a minor fraction of the overall S_{2n} values. While the impact of variations in shell effects on the abundance distribution is not always proportional to the magnitude of the mass changes, and depends on the local S_{2n} and Δ_{2n} trends of the underlying mass model, we find that variations in nuclear masses related to shell effects of the order of 570 keV translate to an average change in the final mass abundance distribution of 35%.

Our results suggest that theoretical approaches should aim to determine how robust the local mass trends are against variations of the nuclear interaction/functional and improvements in the many-body approach (such as inclusion of beyond mean-field effects). In this context, *ab initio* calculations, that currently do not provide accurate values of the masses but that may capture the local trends [50], may still provide valuable information for r -process studies. Similarly, experimental measurements devoted to nuclear masses for r -process nucleosynthesis should aim to determine mass trends across extended regions, rather than measure isolated individual nuclei. Furthermore, fitting protocols of nuclear interactions and training processes of machine-learning algorithms devoted to large-scale calculations of neutron-rich nuclei should include experimental information of (two-)neutron separation and shell gap energies. While a proper reproduction of nuclear masses is a crucial challenge for nuclear theory, this

work demonstrates that the rms error between theoretical and experimental masses may not necessarily determine which nuclear mass models are the best suited for *r*-process studies. A similar conclusion was reached in Ref. [51] comparing the predictive power of different mass models to masses which were not experimentally known at the time of the model calibration. Finally, we make explicit that the method employed in this work is one possible means of producing variations in nuclear masses that do not affect the abundance distribution. The identification of additional means of variations, and their connection to the properties of the underlying nuclear interaction, will open a new avenue to better understand the physics shaping the *r*-process abundance pattern.

ACKNOWLEDGMENTS

We thank M.-R. Wu, F.-K. Thielemann, W. Nazarewicz, and K. Langanke for helpful discussion and comments. S.G. acknowledges support by the Spanish Agencia Estatal de Investigación (AEI) of the Ministry of Science and Innovation (MCIN) under Grant Agreements No.

PID2021-127890NB-I00 and No. RYC2021-031880-I funded by MCIN/AEI/10.13039/501100011033 and the “European Union NextGenerationEU/PRTR”. This work benefited from support by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award No. DE-SC0023128 (CeNAM). G.M.P. acknowledges support by the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (ERC Advanced Grant KILONOVA No. 885281). G.M.P. and A.B. acknowledge support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) through Project - ID 279384907 - SFB 1245 (subprojects B01, B06, B07), and the State of Hesse within the Cluster Project ELEMENTS. A.B. and V.V. acknowledge support by the European Union (ERC, HEAVYMETAL, 101071865).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

-
- [1] National Research Council, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century* (The National Academies Press, Washington, DC, 2003).
 - [2] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle, Synthesis of the elements in stars, *Rev. Mod. Phys.* **29**, 547 (1957).
 - [3] A. G. W. Cameron, Nuclear reactions in stars and nucleogenesis, *Publ. Astron. Soc. Pacific* **69**, 201 (1957).
 - [4] C. J. Horowitz *et al.*, *r*-process nucleosynthesis: connecting rare-isotope beam facilities with the cosmos, *J. Phys. G: Nucl. Part. Phys.* **46**, 083001 (2019).
 - [5] T. Kajino, W. Aoki, A. Balantekin, R. Diehl, M. Famiano, and G. Mathews, Current status of *r*-process nucleosynthesis, *Prog. Part. Nucl. Phys.* **107**, 109 (2019).
 - [6] M. Arnould and S. Goriely, Astronuclear Physics: A tale of the atomic nuclei in the skies, *Prog. Part. Nucl. Phys.* **112**, 103766 (2020).
 - [7] J. J. Cowan, C. Sneden, J. E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martínez-Pinedo, and F.-K. Thielemann, Origin of the heaviest elements: The rapid neutron-capture process, *Rev. Mod. Phys.* **93**, 015002 (2021).
 - [8] E. Symbalisty and D. N. Schramm, Neutron star collisions and the *r*-process, *Astrophys. Lett.* **22**, 143 (1982).
 - [9] J. M. Lattimer and D. N. Schramm, Black-hole-neutron-star collisions, *Astrophys. J.* **192**, L145 (1974).
 - [10] E. M. D. Symbalisty, D. N. Schramm, and J. R. Wilson, An expanding vortex site for the *r*-process in rotating stellar collapse, *Astrophys. J.* **291**, L11 (1985).
 - [11] A. I. MacFadyen and S. E. Woosley, Collapsars: Gamma-ray bursts and explosions in “failed supernovae”, *Astrophys. J.* **524**, 262 (1999).
 - [12] B. P. Abbott *et al.*, Multi-messenger observations of a binary neutron star merger, *Astrophys. J.* **848**, L12 (2017).
 - [13] V. A. Villar *et al.*, The combined ultraviolet, optical, and near-infrared light curves of the kilonova associated with the binary neutron star merger GW170817: Unified data set, analytic models, and physical implications, *Astrophys. J.* **851**, L21 (2017).
 - [14] B. P. Abbott *et al.*, GW170817: Observation of gravitational waves from a binary neutron star inspiral, *Phys. Rev. Lett.* **119**, 161101 (2017).
 - [15] B. A. Brown *et al.*, Motivations for early high-profile FRIB experiments, *J. Phys. G: Nucl. Part. Phys.* **52**, 050501 (2025).
 - [16] J. Duflo and A. P. Zuker, Microscopic mass formulas, *Phys. Rev. C* **52**, R23 (1995).
 - [17] S. Goriely, N. Chamel, and J. M. Pearson, Further explorations of Skyrme-Hartree-Fock-Bogoliubov mass formulas. XII. Stiffness and stability of neutron-star matter, *Phys. Rev. C* **82**, 035804 (2010).
 - [18] M. Liu, N. Wang, Y. Deng, and X. Wu, Further improvements on a global nuclear mass model, *Phys. Rev. C* **84**, 014333 (2011).
 - [19] P. Möller, A. J. Sierk, T. Ichikawa, and H. Sagawa, Nuclear ground-state masses and deformations: FRDM(2012), *At. Data Nucl. Data Tables* **109-110**, 1 (2016).
 - [20] G. Grams, N. N. Shchepochin, A. Sánchez-Fernández, W. Ryssens, N. Chamel, and S. Goriely, Skyrme-Hartree-Fock-Bogoliubov mass models on a 3D mesh: IV. Improved description of the isospin dependence of pairing, *Eur. Phys. J. A* **61**, 35 (2025).
 - [21] R. Utama and J. Piekarewicz, Refining mass formulas for astrophysical applications: A Bayesian neural network approach, *Phys. Rev. C* **96**, 044308 (2017).
 - [22] Z. Niu and H. Liang, Nuclear mass predictions based on Bayesian neural network approach with pairing and shell effects, *Phys. Lett. B* **778**, 48 (2018).
 - [23] L. Neufcourt, Y. Cao, S. A. Giuliani, W. Nazarewicz, E. Olsen, and O. B. Tarasov, Quantified limits of the nuclear landscape, *Phys. Rev. C* **101**, 044307 (2020).
 - [24] R.-D. Lasserri, D. Regnier, J.-P. Ebran, and A. Penon, Taming nuclear complexity with a committee of multilayer neural networks, *Phys. Rev. Lett.* **124**, 162502 (2020).
 - [25] M. Mumpower, M. Li, T. M. Sprouse, B. S. Meyer, A. E. Lovell, and A. T. Mohan, Bayesian averaging for ground state masses

- of atomic nuclei in a Machine Learning approach, *Front. Phys.* **11**, 1198572 (2023).
- [26] Y. Saito, I. Dillmann, R. Krücken, M. R. Mumpower, and R. Surman, Uncertainty quantification of mass models using ensemble Bayesian model averaging, *Phys. Rev. C* **109**, 054301 (2024).
- [27] A. Arcones and G. Martínez-Pinedo, Dynamical r -process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input, *Phys. Rev. C* **83**, 045809 (2011).
- [28] A. Arcones and G. F. Bertsch, Nuclear Correlations and the r Process, *Phys. Rev. Lett.* **108**, 151101 (2012).
- [29] J. D. J. Mendoza-Temis, M.-R. Wu, K. Langanke, G. Martínez-Pinedo, A. Bauswein, and H.-T. Janka, Nuclear robustness of the r process in neutron-star mergers, *Phys. Rev. C* **92**, 055805 (2015).
- [30] M. R. Mumpower, R. Surman, D.-L. Fang, M. Beard, P. Möller, T. Kawano, and A. Aprahamian, Impact of individual nuclear masses on r -process abundances, *Phys. Rev. C* **92**, 035807 (2015).
- [31] D. Martin, A. Arcones, W. Nazarewicz, and E. Olsen, Impact of nuclear mass uncertainties on the r -process, *Phys. Rev. Lett.* **116**, 121101 (2016).
- [32] T. M. Sprouse, R. Navarro Perez, R. Surman, M. R. Mumpower, G. C. McLaughlin, and N. Schunck, Propagation of statistical uncertainties of Skyrme mass models to simulations of r -process nucleosynthesis, *Phys. Rev. C* **101**, 055803 (2020).
- [33] N. Vassh, G. C. McLaughlin, M. R. Mumpower, and R. Surman, Markov Chain Monte Carlo predictions of neutron-rich lanthanide properties as a probe of r -process dynamics, *Astrophys. J.* **907**, 98 (2021).
- [34] Y.-L. Zhu, K. A. Lund, J. Barnes, T. M. Sprouse, N. Vassh, G. C. McLaughlin, M. R. Mumpower, and R. Surman, Modeling kilonova light curves: Dependence on nuclear inputs, *Astrophys. J.* **906**, 94 (2021).
- [35] I. K. B. Kullmann, S. Goriely, O. Just, A. Bauswein, and H.-T. Janka, Impact of systematic nuclear uncertainties on composition and decay heat of dynamical and disc ejecta in compact binary mergers, *Mon. Not. R. Astron. Soc.* **523**, 2551 (2023).
- [36] P. Moller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, Nuclear ground-state masses and deformations, *At. Data Nucl. Data Tables* **59**, 185 (1995).
- [37] C. E. Collins, A. Bauswein, S. A. Sim, V. Vijayan, G. Martínez-Pinedo, O. Just, L. J. Shingles, and M. Kromer, 3D radiative transfer kilonova modelling for binary neutron star merger simulations, *Mon. Not. Roy. Astron. Soc.* **521**, 1858 (2023).
- [38] V. M. Strutinsky, Shell effects in nuclear masses and deformation energies, *Nucl. Phys. A* **95**, 420 (1967).
- [39] W. D. Myers and W. J. Swiatecki, The macroscopic approach to nuclear masses and deformations, *Annu. Rev. Nucl. Part. Sci.* **32**, 309 (1982).
- [40] P.-G. Reinhard, M. Bender, W. Nazarewicz, and T. Vertse, From finite nuclei to the nuclear liquid drop: Leptodermous expansion based on self-consistent mean-field theory, *Phys. Rev. C* **73**, 014309 (2006).
- [41] M. Wang, W. J. Huang, F. Kondev, G. Audi, and S. Naimi, The AME 2020 atomic mass evaluation (II). Tables, graphs and references, *Chin. Phys. C* **45**, 030003 (2021).
- [42] W. Satuła, J. Dobaczewski, and W. Nazarewicz, Odd-even staggering of nuclear masses: Pairing or shape effect? *Phys. Rev. Lett.* **81**, 3599 (1998).
- [43] J. Dobaczewski, P. Magierski, W. Nazarewicz, W. Satuła, and Z. Szymański, Odd-even staggering of binding energies as a consequence of pairing and mean-field effects, *Phys. Rev. C* **63**, 024308 (2001).
- [44] R. Bengtsson, J.-y. Zhang, J.-y. Zhang, and S. Åberg, On the analogy between backbending in gauge space and in ordinary space, *Phys. Lett. B* **105**, 5 (1981).
- [45] L. Buskirk, K. Godbey, W. Nazarewicz, and W. Satuła, Nucleonic shells and nuclear masses, *Phys. Rev. C* **109**, 044311 (2024).
- [46] A. J. Koning, S. Hilaire, and M. C. Duijvestijn, TALYS-1.0, in *Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France*, edited by O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray (EDP Sciences, Les Ulis, 2008), pp. 211–214.
- [47] I. V. Panov, I. Y. Korneev, T. Rauscher, G. Martínez-Pinedo, A. Kelić-Heil, N. T. Zinner, and F.-K. Thielemann, Neutron-induced astrophysical reaction rates for translead nuclei, *Astron. Astrophys.* **513**, A61 (2010).
- [48] A. Kelic, M. Valentina Ricciardi, and K.-H. Schmidt, ABLA07 - towards a complete description of the decay channels of a nuclear system from spontaneous fission to multifragmentation, [arXiv:0906.4193](https://arxiv.org/abs/0906.4193).
- [49] R. Ardevol-Pulpillo, H. T. Janka, O. Just, and A. Bauswein, Improved leakage-equilibration-absorption scheme (ILEAS) for neutrino physics in compact object mergers, *Mon. Not. Roy. Astron. Soc.* **485**, 4754 (2019).
- [50] H. Hergert, A guided tour of *ab initio* nuclear many-body theory, *Front. Phys.* **8**, 379 (2020).
- [51] A. Sobczewski and Y. A. Litvinov, Predictive power of nuclear-mass models, *Phys. Rev. C* **90**, 017302 (2014).