Enhanced symmetry energy bears universality of the r-process

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Abstract
The abundance of about half of the stable nuclei heavier than iron via the rapid neutron capture process or r-process is intimately related to the competition between neutron capture and $\beta$-decay rates, which ultimately depends on the binding energy of neutron-rich nuclei. The well-known Bethe-Weizsäcker semi-empirical mass formula\cite{1, 2} describes the binding energy of ground states – i.e. nuclei with temperatures of $T \approx 0$ MeV – with the symmetry energy parameter converging between 23 – 27 MeV for heavy nuclei. Here we find an unexpected enhancement of the symmetry energy at higher temperatures, $T \approx 0.7 – 1.0$ MeV, from the available data of giant dipole resonances built on excited states. Although these are likely the temperatures where seed elements are created – during the cooling down of the ejecta following neutron-star mergers\cite{3} or collapsars\cite{4} – the fact that the symmetry energy remains constant between $T \approx 0.7 – 1.0$ MeV, suggests a similar trend down to $T \approx 0.5$ MeV, where neutron-capture may start occurring. Calculations using this relatively large symmetry energy yield a reduction of the binding energy per nucleon for heavy neutron-rich nuclei and inhibits radioactive neutron-capture rates. This results in a substantial close-in of the neutron dripline – where nuclei become unbound – which elucidates the long sought universality of heavy-element abundances through the r-process; as inferred from the similar abundances found in extremely metal-poor stars and the Sun.

Keywords: symmetry energy, dipole polarizability, photo-absorption cross sections, r-process, neutron dripline

The binding energy of a nucleus with $Z$ protons and $N$ neutrons can be described by the well-known Bethe-Weizsäcker semi-empirical mass formula (SEMF)\cite{1, 2},

$$B(Z, A) = a_v A - a_s A^{2/3} - a_c Z(Z-1) A^{-1/3} - a_{\text{sym}} (A-2Z)^2 A^{-1/3} + a_p A^{3/4},$$ (1)

where $A = Z + N$ is the mass number and $a_v, a_s, a_c, a_{\text{sym}}$ and $a_p$ are the volume, surface, Coulomb, symmetry energy and pairing coefficients, respectively. The symmetry energy, $a_{\text{sym}}(A)(N-Z)^2/A$, reduces the total binding energy $B(Z, A)$ of a nucleus as the neutron-proton asymmetry becomes larger, i.e. for $N \gg Z$, and yields the typical negative slope of the binding energy curve\cite{5} for $A > 62$. It is divided by $A$ to reduce its importance for heavy nuclei, and it depends on the mass dependency of $a_{\text{sym}}(A)$. Its convergence for heavy nuclei establishes the frontiers of the neutron dripline for particle-unbound nuclei and eventually leads to the disappearance of protons at extreme nuclear densities\cite{6}.

Furthermore, $a_{\text{sym}}(A)$ is relevant to understanding neutron skins\cite{7}, the effect of three-nucleon forces\cite{8} and – through the equation of state (EoS) – supernovae cores, neutron stars and binary mergers\cite{9, 11}. The latter are the first known astrophysical site where heavy elements are created through the rapid neutron-capture or r-process\cite{12, 13}. The identification of heavy elements in neutron star mergers is supported by the short duration gamma-ray bursts via their infrared afterglow\cite{14} – only understood by the opacities of heavy nuclei – as well as blueshifted Sr II absorption lines\cite{15}, following

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the expansion speed of the ejecta gas at $v = 0.1 - 0.3$ c. Mergers are expected to be the only source for the creation of elements above lead and bismuth, as inferred from the very scarce abundance of actinides in the solar system [16].

The universality of the r-process for the heaviest elements with $56 < Z < 90$ is further inferred from the similar abundance patterns observed in both extremely metal-poor stars and the Sun [17, 18]. Other potential sources of heavy elements involve different types of supernova (e.g. collapsars [4] – the supernova-triggering collapse of rapidly rotating massive stars – and type-II supernova [19]), which need to be considered in order to explain all neutron-capture abundances [19, 20].

It is the motivation of this work to understanding the limits of the neutron dripline and heavy-element production by investigating $a_{\text{sym}}(A)$ at different temperatures $T$ using available data of potential interest to the r-process; namely, data from photoabsorption cross sections, binding energies and giant dipole resonances.

Generally, $a_{\text{sym}}(A)$ is parametrized using the leptodermous approximation of Myers and Swiatecki, where $A^{-1/3} \ll 1$ [21],

$$a_{\text{sym}}(A) = S_v \left(1 - \frac{S_s}{S_v} A^{-1/3}\right),$$

which considers the modification of the volume symmetry energy, $S_v$, by the surface symmetry energy $S_s$. This particular leptodermous parametrization was chosen on the account of its better fit to the masses of isobaric nuclei [22]. Constraints on these parameters have been investigated using experimental and theoretical information concerning properties of ground states, i.e. at $T = 0$ MeV [23, 24].

The giant dipole resonance (GDR) represents the main contribution to the absorption and emission of electromagnetic radiation (photons) in nuclei [25]. The dynamics of this quantum collective excitation is characterized by the inter-penetrating motion of proton and neutron fluids out of phase [26], which results from the density-dependent symmetry energy, $a_{\text{sym}}(A)(\rho_n - \rho_p)^2/\rho$, acting as a restoring force [25], where $\rho_n$, $\rho_p$, and $\rho = \rho_n + \rho_p$ are the neutron, proton and total density, respectively, which spread uniformly throughout the nucleus.

The ratio of the induced dipole moment to an applied constant electric field yields the static nuclear polarizability, $\alpha$. Using the hydrodynamic model and assuming inter-penetrating proton and neutron fluids with a well-defined nuclear surface of radius $R = r_n A^{1/3}$ fm and $\rho_s$ as the potential energy of the liquid drop, Migdal [26] obtains the following relation between the static nuclear polarizability, $\alpha$, and $a_{\text{sym}}$,

$$\alpha = \frac{e^2 R^2 A}{40 a_{\text{sym}}} = 2.25 \times 10^{-3} A^{5/3} \text{fm}^{3},$$

where $r_n = 1.2$ fm, $e^2 = 1.44$ MeV fm in the c.g.s. system, and a constant value of $a_{\text{sym}} = 23$ MeV was utilized.

Alternatively, $\alpha$ can be calculated for the ground states of nuclei using second-order perturbation theory [27] following the sum rule,

$$\alpha = 2 e^2 \sum_n \left(\frac{\langle n \parallel E_1 \parallel i \rangle}{E_1}\right) f_n,$$

$$\sigma = \frac{e^2}{2\pi^2} \sum_n \frac{f_n}{E_n^2} = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma_{\text{total}}(E_\gamma)}{E_\gamma^2} dE_\gamma,$$

where $E_\gamma$ is the $\gamma$-ray energy corresponding to a transition connecting the ground state $|i\rangle$ and an excited state $|n\rangle$, $M$ the nucleon mass, $f_n$ the dimensionless oscillator strength for E1 transitions [27] and $\sigma_2$, the second moment of the total electric-dipole photo-absorption cross section,

$$\sigma_2 = \int_0^\infty \frac{\sigma_{\text{total}}(E_\gamma)}{E_\gamma^2} dE_\gamma,$$

where $\sigma_{\text{total}}(E_\gamma)$ is the total photo-absorption cross section, which generally includes $(\gamma, n)$, $(\gamma, p n)$, $(\gamma, 2n)$, $(\gamma, 3n)$, photo-neutron and available photoproton and photofission cross sections [28], in competition in the GDR region [29, 30]. By comparing Eqs. 5 and 6, a mass-dependent symmetry energy, $a_{\text{sym}}(A)$, is extracted in units of MeV,

$$a_{\text{sym}}(A) = \frac{e^2 R^2 \pi^2 A}{20 \hbar c \sigma_2} \approx 5.2 \times 10^{-3} A^{5/3} \sigma_2^{-1} [31].$$

Empirical evaluations reveal that $\sigma_2$ can also be approximated by $\sigma_2 = 2.4 \kappa A^{5/3}$, where the dipole polarizability parameter $\kappa$ measures the ratio of the GDR strength for $E1$ transitions [27] and $\sigma_2$, the second moment of the total electric-dipole photo-absorption cross section. 

Figure 1 shows the distribution of $a_{\text{sym}}(A)$ for the ground state of stable isotopes, along the nuclear landscape, determined from empirical $\sigma_2$ values. Data include all available emission channels. The contribution of $(\gamma, p)$ cross sections are evident in light nuclei, which significantly reduces the symmetry energy. For heavy nuclei, $(\gamma, n)$ cross sections are dominant because of the higher Coulomb barrier. A fit
to the data using Eq. (2) (solid line) yields $a_{\text{sym}}(A) = 31.2(12)(1-1.12(A^{-1/3}) \text{ MeV}$, with an RMS deviation of 22% \cite{34}. Unfortunately, $(\gamma, p)$ cross-section data are very scarce, which directly affects the $a_{\text{sym}}(A)$ trend for $A \lesssim 70$ in Fig. 1.

In addition, Tian and co-workers determined $a_{\text{sym}}(A) = 28.32(1-1.27A^{-1/3}) \text{ MeV}$ from a global fit to the binding energies of isobaric nuclei with mass number $A \geq 10$ \cite{22} – extracted from the 2012 atomic mass evaluation \cite{35} – with $S_v \approx 28.32 \text{ MeV}$ being the bulk symmetry energy coefficient and $S_s \approx 1.27$ the surface-to-volume ratio. Similar coefficients are calculated in Refs. \cite{9, 36}. Within this approach, the extraction of $a_{\text{sym}}(A)$ only depends on the Coulomb energy term in the SEMF and shell effects \cite{37} – which are both included \cite{22} – and $a_{\text{sym}}(A)$ presents a maximum energy around 23 MeV. This description of $a_{\text{sym}}(A)$ has been used to explain the enhanced $\sigma_{\gamma}^{-2}$ values observed for low-mass nuclei \cite{34}.

The symmetry energy $a_{\text{sym}}(A)$ is the fundamental parameter that characterizes the energy of the GDR, $E_{\text{GDR}}$, within the Steinwedel-Jensen (SJ) model of proton and neutron compressible fluids moving within the rigid surface of the nucleus \cite{33}. Danos improved the SJ model by including the GDR width, $\Gamma_{\text{GDR}}$ \cite{25, 39}, in the second-sound hydrodynamic model \cite{25, 39}, where $E_{\text{GDR}}$ and $\Gamma_{\text{GDR}}$ are related to $a_{\text{sym}}(A)$ as \cite{30},

$$a_{\text{sym}}(A) = \frac{M A^2}{8h^2K^2N^2Z} \frac{E^2_{\text{GDR}}}{1 - \left( \frac{\Gamma_{\text{GDR}}}{E_{\text{GDR}}} \right)^2} \approx 1 \times 10^{-3} \left( \frac{A^{8/3}N^2Z}{E_{\text{GDR}}^2} \right) \frac{E^2_{\text{GDR}}}{1 - \left( \frac{\Gamma_{\text{GDR}}}{2E_{\text{GDR}}} \right)^2} \quad (9)$$

where $K$ is the real eigenvalue of $\nabla \rho Z + K \rho Z = 0$, with the boundary condition $(\nabla \rho Z)_{\text{surf}} = 0$, and has a value of $KR = 2.082$ for a spherical nucleus \cite{40}. For quadrupole deformed nuclei with an eccentricity of $a^2 - b^2 = \epsilon R^2$, where $a$ and $b$ are the half axes and $\epsilon$ the deformation parameter, the GDR lineshape splits into two peaks with similar values of $Ka$ and $Kb \approx 2.08$ \cite{39}. For deformed nuclei, we estimate a similar equation to Eq. (9) but using the average centroid energy and the FWHM of the total Lorentzian (see e.g. \cite{41}). Uncertainties in the quoted values arise from the error propagation of Eq. (9).

The GDR cross-section data for each nucleus were obtained from the EXFOR and ENDF databases \cite{32, 33} and fitted with one or two Lorentzian curves to extract $E_{\text{GDR}}$ and $\Gamma_{\text{GDR}}$, as shown e.g. in Fig. 2 for $^{208}\text{Pb}$. The data set for each nucleus was selected based on the number of data points, experimental method and energy range. In this work, the maximum integrated $\gamma$-ray energy, $E_{\gamma}^{\text{max}}$, was in the range 20–50 MeV, therefore excluding contributions resulting from high energy effects such as pion exchange and other meson resonances. The resulting distribution of $a_{\text{sym}}(A)$ is shown in the left panel of Fig. 3 which converges at approximately 27 MeV for heavy nuclei. It is reassuring that the two methods based on photoabsorption cross-section data —
namely $a_{\text{sym}}(A)$ extracted from $\sigma_2$ values and parameters of GDRs built on ground states – present similar trends.

Data obtained from GDR parameters at $T = 0$ can also be fitted to Eq. 2 which yields $a_{\text{sym}}(A) = 35.3(7) \left(1 - 1.58(5)A^{-1/3}\right)$ MeV (red solid band in Fig. 3), with an RMS deviation of 15%. Larger values of $S_v = 42.8$ and $S_s = 89.9$ were determined by Berman using Eq. 9 for 29 nuclei ranging from $A = 75$ to $209$ [42]. Furthermore, Berman argued that assuming a surface binding energy coefficient of $a_s = 20$ MeV in the SEMF, the large symmetry to surface energy ratio, $S_s/a_s = 4.5$, favors – as a result of a steeper slope of the binding energy curve for heavy nuclei – a close-in neutron dripline for heavy elements; hence, constraining the reaction network that produces heavy elements by the r-process in neutron mergers and supernovae. Using our value of $S_v = 44.4, S_s = 97.32$ and $S_s/a_s = 4.87$ (again for $a_s = 20$ MeV). Two bands showing the loci limits of the two fitting curves at $T = 0$ and $T \approx 0.7 – 1$ MeV are shown for comparison. Such a distinct behaviour could clearly affect nucleosynthesis of heavy elements via the r-process during the cooling down of the ejecta.

Lighter or heavier seed nuclei are generally produced depending on the density and temperature of the ejecta gas. Assuming nuclear-statistical equilibrium – when forward and reverse reactions are balanced – abundances follow a Maxwell-Boltzmann distribution where lighter seed nuclei are favoured at very high temperatures ($\propto kT^{3/2}(A^{-1})$) and heavier nuclei are favoured at very high densities ($\propto \rho A^{-1}$), as those found in the ejecta of neutron-star mergers [3]. At temperatures below $T = 1$ MeV (or $1.2 \times 10^{10}$ K), seed nuclei are produced before charge reactions freeze out – impeded by
out – as neutrons are finally consumed – at a few 10
sequent neutron capture until neutron reactions freeze
K). Thereafter, heavy nuclei are produced through sub-

\[ T \approx 0.7 \text{ MeV} \] \[ 0 < T < 1 \text{ MeV} \] \[ 5 \times 10^8 \text{ K} \]

Our work may not be sensitive to the lower temper-
atures occurring during neutron capture in neutron-star
mergers, which likely range from \[ T \approx 0.5 \times 10^8 \text{ K} \] to \[ T \approx 5 \times 10^9 \text{ K} \] (i.e. in the range from \[ T \approx 0.04 \] to 0.43 MeV, respectively). Nevertheless, Fig. 4 shows that the symmetry energy does not change with temperature in the \([0.74,1.3]\) MeV range, which suggests that this relation may still hold at lower temperatures.

Such an increase in the symmetry energy results from
the change in the effective mass of the nucleon, which
decreases as \( T \) increases in the temperature interval
\( 0 < T < 1 \text{ MeV} \). The temperature dependence of
the symmetry energy has been studied within the liquid-
drop and Fermi gas models \[ 53 \], where an effective nu-
cleon mass – the so-called ‘w’ mass – is introduced to
account for the non-locality of the Hartree-Fock poten-
tial. This leads to an increase in the centroid energy of
the GDR and, hence, the symmetry energy of medium
and heavy mass nuclei also increases by approximately
8% at \( T \approx 1 \text{ MeV} \). In the current work, we notice a slight increase of 3-5\% in the centroid energy at \( T \approx 0.7-1 \text{ MeV} \) as compared with the ground-state values for nearly-spherical \[ ^{120}\text{Sn} \] \[ 57 \], \[ ^{208}\text{Pb} \] \[ 58 \] and \[ ^{201}\text{Tl} \] \[ 50 \] nuclei as well as for the deformed nuclei in the \( A = 160-180 \) mass region \[ 41, 51, 52 \]. Although such an increase is within the experimental errors, it leads to a distinct systematic behaviour, as shown in the right panel of Fig. 3.

Finally, the effects from the larger symmetry energy
at \( T \approx 0.7-1 \text{ MeV} \) are illustrated in Fig. 5 which shows the corresponding nuclear charts (top) and binding energy curves (bottom) using \( a_{\text{sym}} = 23.7 \text{ MeV} \) \[ 60 \] (left) and 30 MeV (right), respectively. The nuclear chart de-
termined using \( a_{\text{sym}} = 30 \text{ MeV} \) illustrates a substantial
close-in of the neutron dripline, as a result of the de-
creasing binding energy per nucleon in neutron-rich nu-
clei. For instance, the dripline closes in from \[ ^{254}\text{Pt} \] to
\[ ^{220}\text{Pt} \] for \( a_{\text{sym}} = 23.7 \) and 30 MeV, respectively. Figure
6 shows the respective neutron driplines and clearly il-
lustrates the dramatic effect of an enhanced symmetry energy in the production of heavy elements, which con-
strains exotic r-process paths and plausibly explains the
universality of r-process abundances inferred from the
observation of extremely metal-poor stars and our Sun.

Consequently, such an increase in the symmetry en-
ergy leads to the reduction of radiative neutron capture
rates as neutron-rich nuclei become less bound. The
corresponding change in the capture cross section has
been calculated using TALYS \[ 61 \] and EMPIRE \[ 62 \]
codes by changing only the mass excess with standard input parameters. Both codes yield similar results with a
reduction of the neutron-capture cross section by a fac-
tor of the order of 10\(^2\) in the \( A \approx 200 \) mass region
relevant to the r-process. More detailed calculations will
be presented in a separate manuscript. These findings
support the rapid drop of the neutron capture rates at
increasing neutron excesses inferred from Goriely’s mi-
icroscopic calculations at \( T = 1.5 \times 10^9 \text{ K} \) \[ 12 \].

More experimental data regarding GDRs built on ex-
cited states below \( T \approx 0.7 \text{ MeV} \) are crucially needed in
order to elucidate the nature of the symmetry energy as
a function of temperature. Modern high-efficient spec-
trometers such as GAMiKa in South Africa \[ 63 \] – with
up to 30 HPGe clover and LaBr\(_3\) detectors – may pro-
vide such data.

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Figure 5: Nuclear charts (top panels) and binding energy curves (bottom panels) showing average binding energies per nucleon using the Bethe-Weizsäcker SEMF for $a_{sym} = 23.7 \text{ MeV}$ (left) and $a_{sym} = 30 \text{ MeV}$ (right). Atomic masses in the bottom panels are extracted from the 2020 atomic mass evaluation (AME 2020) [59].

Figure 6: Neutron driplines predicted at symmetry energy coefficients of $a_{sym} = 23.7 \text{ MeV}$ (squares) and $30 \text{ MeV}$ (circles). Dotted lines indicate the proton and neutron magic numbers.

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