UNIVERSITY of the WESTERN CAPE

What If the Nuclear Symmetry Energy is Larger than Expected?

Virtual excitations + correlations, r-process nucleosynthesis, drip line, abundances

Nico Orce

NuSYM23 @ GSI, 20th September 2023

https://nuclear.uwc.ac.za

https://github.com/UWCNuclear

https://www.youtube.com/c/NicoOrce

Cooling down of neutron star mergers

Nurtury of r-process heavy elements from kilonova AT2017gfo: Sr II, Watson et al., Nature (2019)

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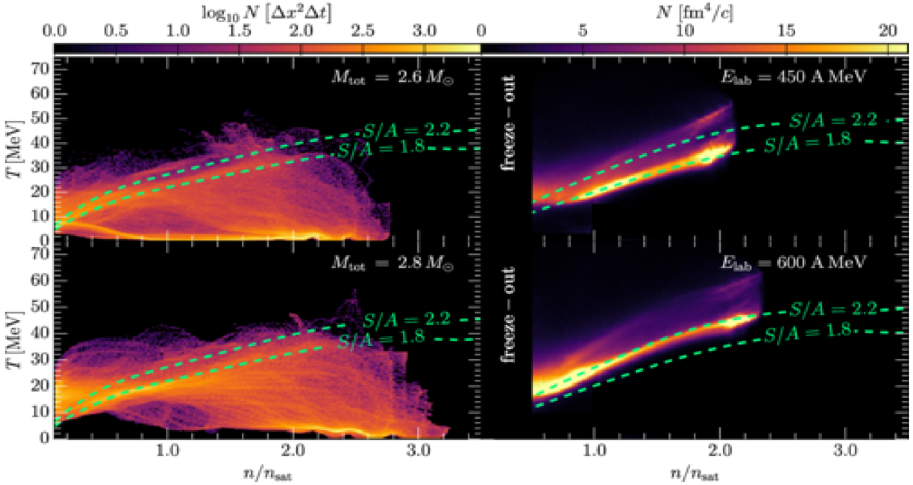


High T ~ 40-50 MeV (≈5×10^{11} K) →
Merger of neutron stars (BNSM vs HIC)
gamma-ray burst, kilonova ejecta:
hadrons, quark-gluon plasma,
protons + neutrons
(HADES talk by Manuel Lorenz)

T ≈ 0.7-1 MeV (0.8-1.2 ×10^{10} K) → Temperatures where seed elements are created before charge reactions freeze out (high neutron/seed ratio).

T ≲ 0.4-0.5 MeV (~5× 10^9 K) → **n-capture occurring** until it also freezes out: time scale for n capture longer than β decay (less neutrons, lower T).

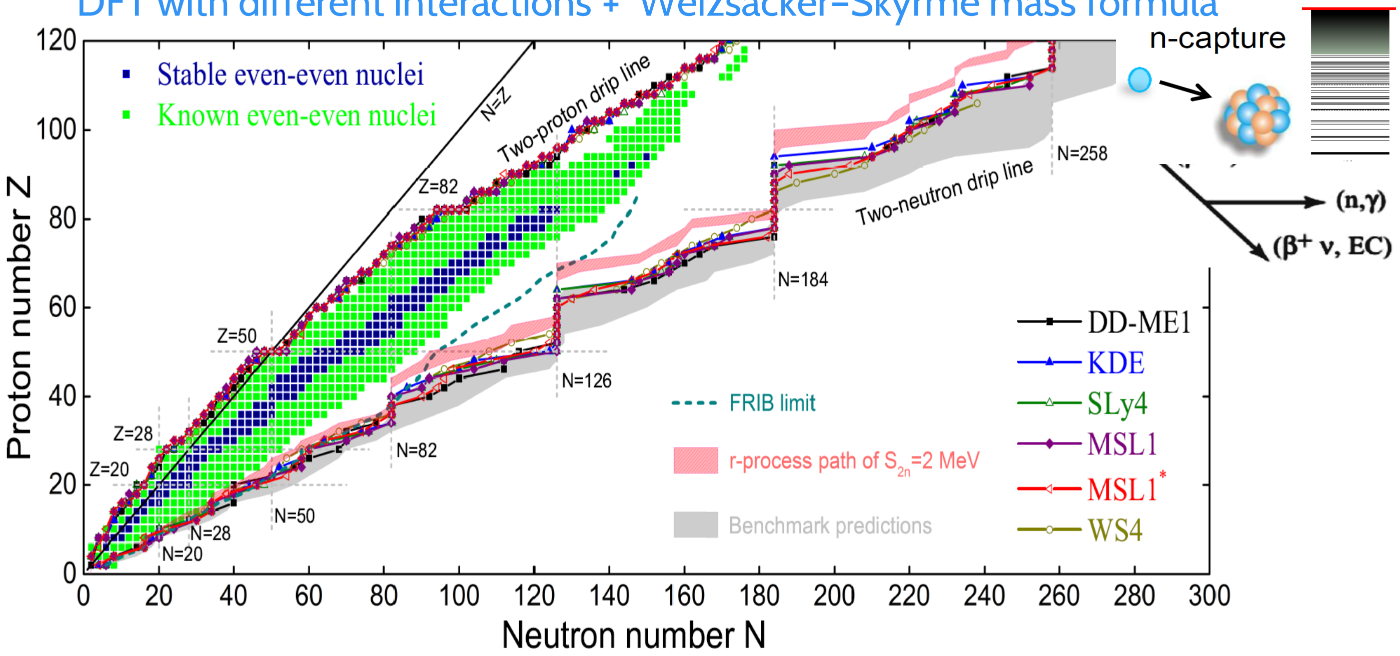
T ≈ 0.03 MeV (A few 10^8 K) → neutrons are finally consumed (T=0 ground state).

Most *et al.,* Phys. Rev. D (2023)
Kilonovae, Metzger, Living Reviews in Relativity (2020)
Probing dense baryon-rich matter with virtual photons. The HADES-Collaboration. Nature Physics (2019)
Neutron Star Mergers & Nucleosynthesis of Heavy Elements, Thielemann, Eichler, Panov & Wehmeyer, ARNPS (2017)

Predictions of neutron drip line & r-process path exhibit a **significant variation** due to wide range of conditions not accurately determined.

Wang & Chen, PRC **92** (2015) 031303(R); Erler *et al.*, Nature **486** (2012) 509

DFT with different interactions + Weizsacker–Skyrme mass formula

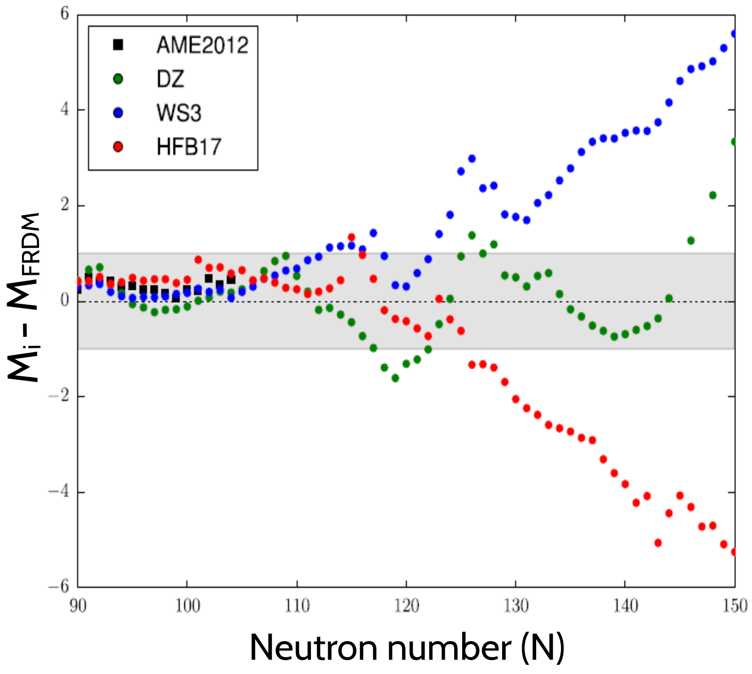


"Studies of nuclear interactions in systems with high or extreme neutron-to-proton ratios are crucial for understanding the neutron drip line (the convergence of a_{sym} for heavy nuclei establishes the frontier of the neutron drip line), the location of which is not well known."

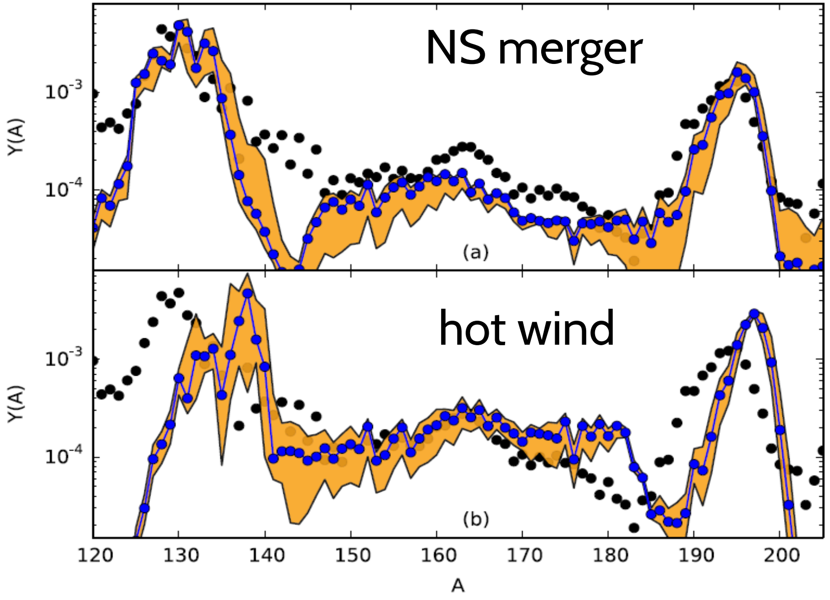
Francesca Sammarruca, Symmetry 2023

Sensitivity studies of r-process network calculations

SEMF, HFB-21, FRDM, WS, DZ and other mass models
present rms deviations of $\gtrsim$ 300 keV with respect to the available mass data



Difference between theoretical mass predictions.
Gray band at ±1 MeV shows the **mass variation size**.

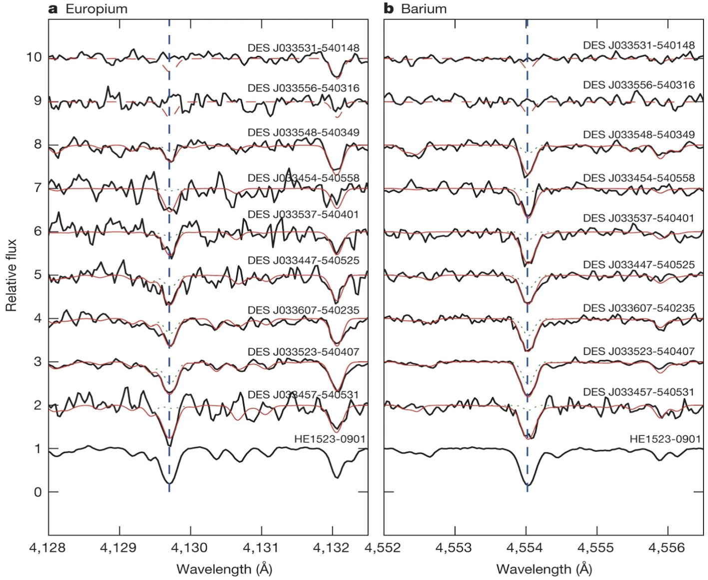


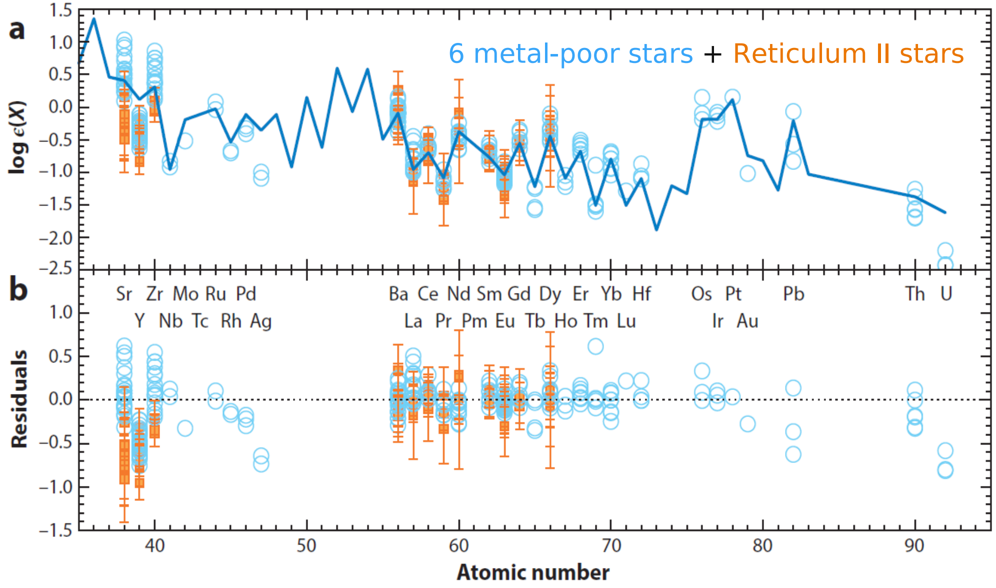
Only a reduction of global rms errors <100 keV may allow for **accurate r-process predictions** and **differentiation between model predictions,** which can range orders of magnitude.

Mumpower, Surman, Aprahamian, JPG & EPJ Web of Conferences 2015

Universality of elemental r-process abundances from Ba to Pb

Normalized r-process-element abundances of six undisturbed (~13-billion-year-old) r-process Galactic halo + Reticulum II (first r-process galaxy) stars overlaid with the scaled solar r-process pattern (blue line)



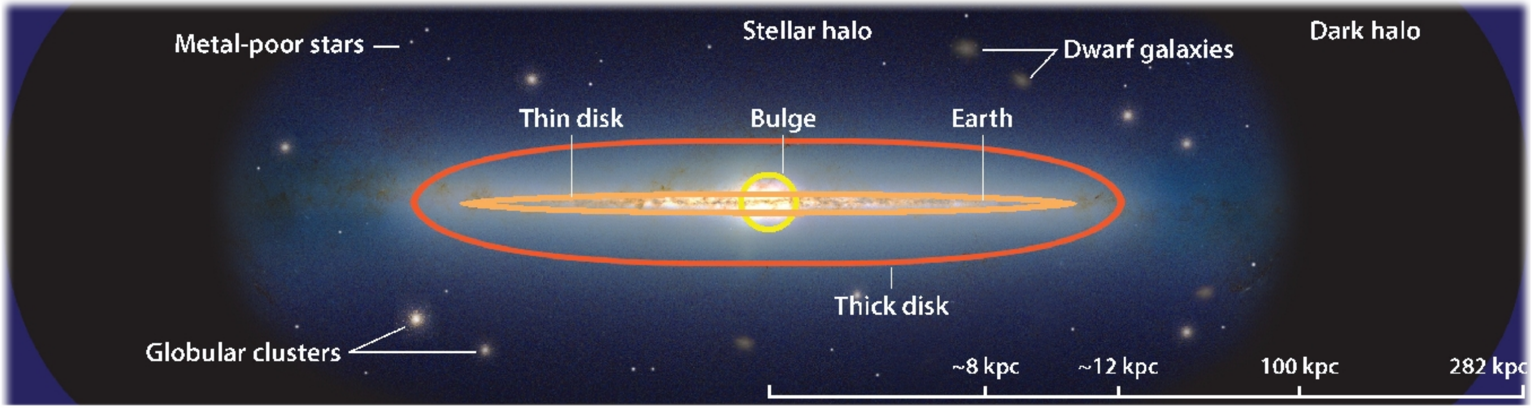


"Given that the Sun (Population I) formed billions of years after these metal-poor stars (Population II), from gas that was enriched by many stellar generations in various ways, the astounding agreement between the patterns suggests that the **r-process is universal**."

Frebel, Annu. Rev. Nucl. Part. Sci. (2018)

Ji, Frebel, Chiti *et al*. R-process enrichment from a single event in an ancient dwarf galaxy. Nature 531, 610 (2016)

Origin for such universality of r-process abundances remains unknown



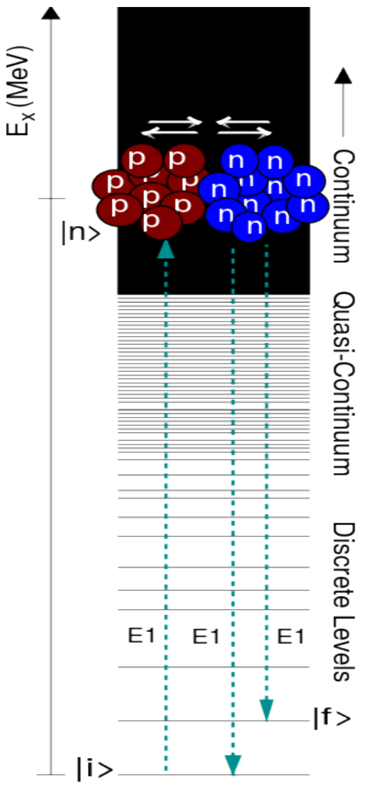
Frebel, Annu. Rev. Nucl. Part. Sci. (2018)

"These observational facts suggest a rather well-defined origin of heavy elements beyond iron. We do not know if this may be only an **artifact of nuclear properties** such as binding energies and β-decay rates, or it may point to **a single cosmic site with astrophysical conditions that are generated uniformly throughout cosmic time**."

Kajino *et al*. Current status of r-process nucleosynthesis, Progress in Particle and Nuclear Physics (2019)

Symmetry energy in Giant Dipole Resonances (GDR)

"In a sense, the nuclear symmetry energy a_{sym}(A) can be considered to be the fundamental parameter of the giant dipole resonance." Herman & Fultz, Rev. Mod. Phys. (1975)



Virtual excitations alike van der Waals force

Hydrodynamic Model (liquid drop)

$$\alpha = \frac{e^2 R^2 A}{40 a_{sym}}$$

$$a_{sym}(\rho_n - \rho_p)^2/\rho$$

Inverse energy weighted sum rule

$$\alpha = 2e^2 \sum_n \frac{\langle i \| \hat{E1} \| n \rangle \langle n \| \hat{E1} \| i \rangle}{E_\gamma}$$

$$= \frac{e^2 \hbar^2}{M} \sum_n \frac{f_{in}}{E_\gamma^2} = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma_{total}(E_\gamma)}{E_\gamma^2} dE_\gamma$$

$$= \frac{\hbar c}{2\pi^2} \sigma_{-2},$$

$$\sigma_{-2} = 2.25 \; A^{5/3} \; \mu b/MeV$$

Migdal, JETP (1945)

$$R = r_0 A^{1/3} \text{ fm}$$

$$a_{sym} = 23 \text{ MeV}$$

$$a_{sym}(A) = \frac{e^2 R^2 \pi^2 A}{20 \; \hbar c \; \sigma_{-2}} \approx 5.2 \times 10^{-3} \frac{A^{5/3}}{\sigma_{-2}}$$

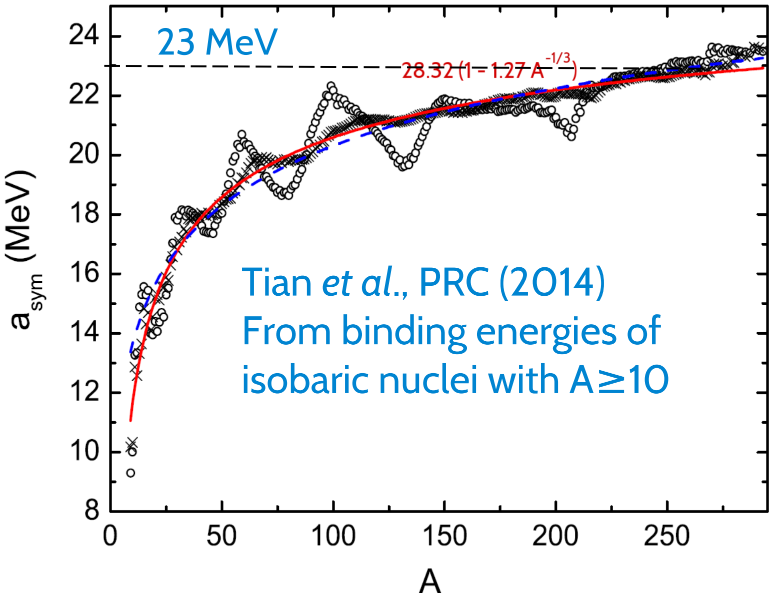
Increase of σ_{-2} values for loosely-bound and diffuse nuclei

Sensitive measures of long-range correlations of the nuclear force

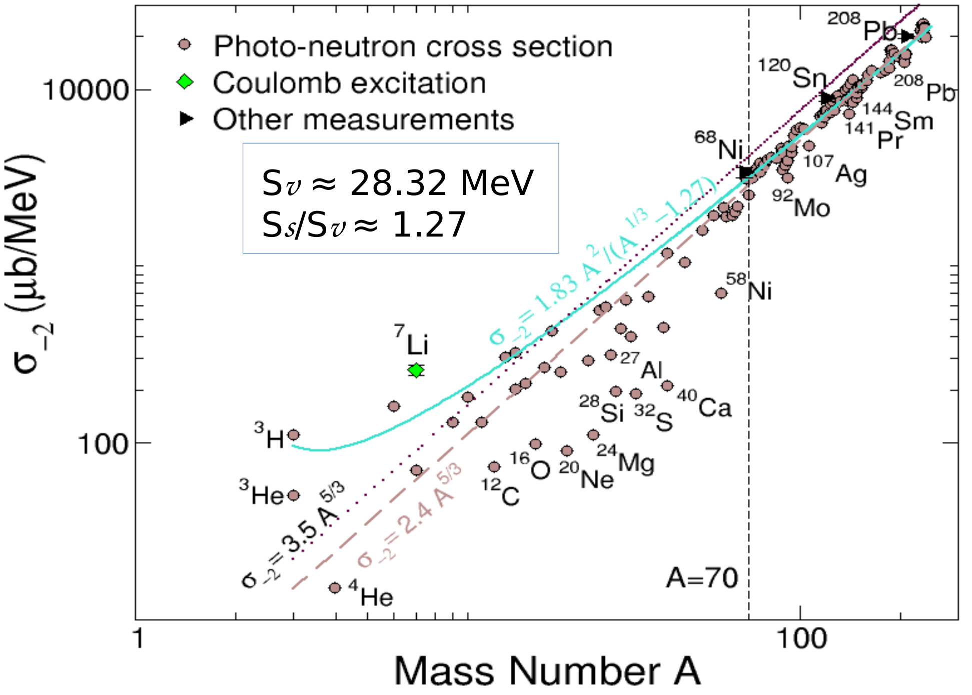
Leptodermus approximation

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

Myers & Swiatecki, 81 (1966) 1



$$\sigma_{-2} = \frac{51.8 A^2}{S_v (A^{1/3} - S_s/S_v)} \mu\text{b/MeV}$$

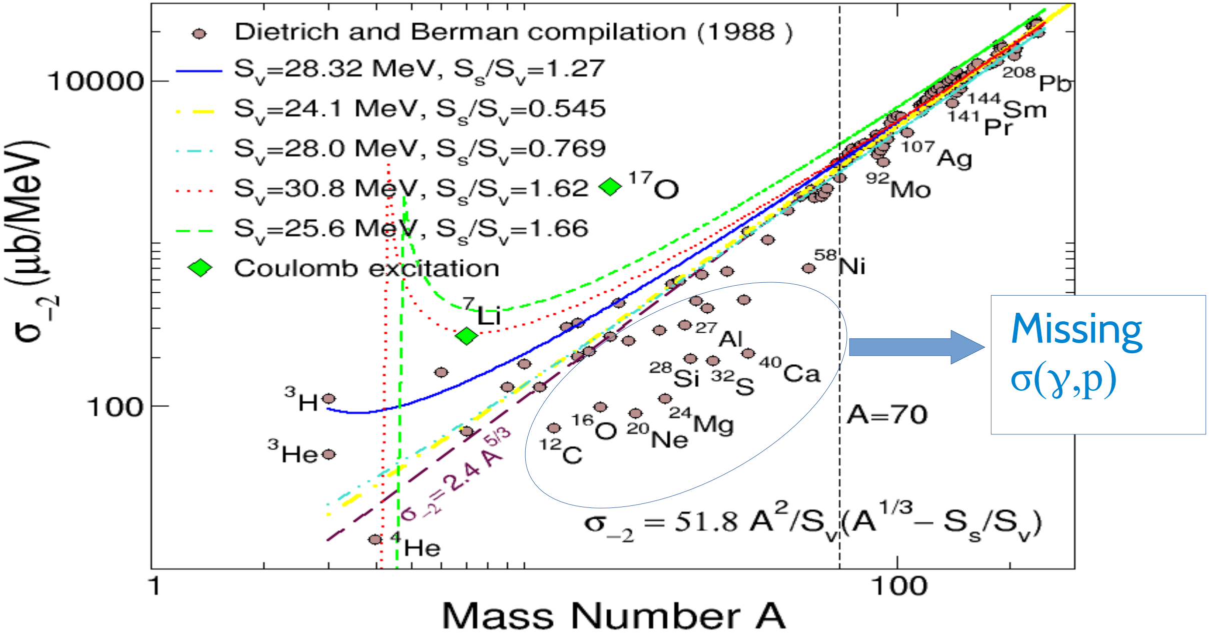


Orce, Phys. Rev. C (2015); Orce, Phys. Rev. C (2016)

Constraining the symmetry energy $a_{sym}(A)$

Theory and experiment provide a wide range of possibilities

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

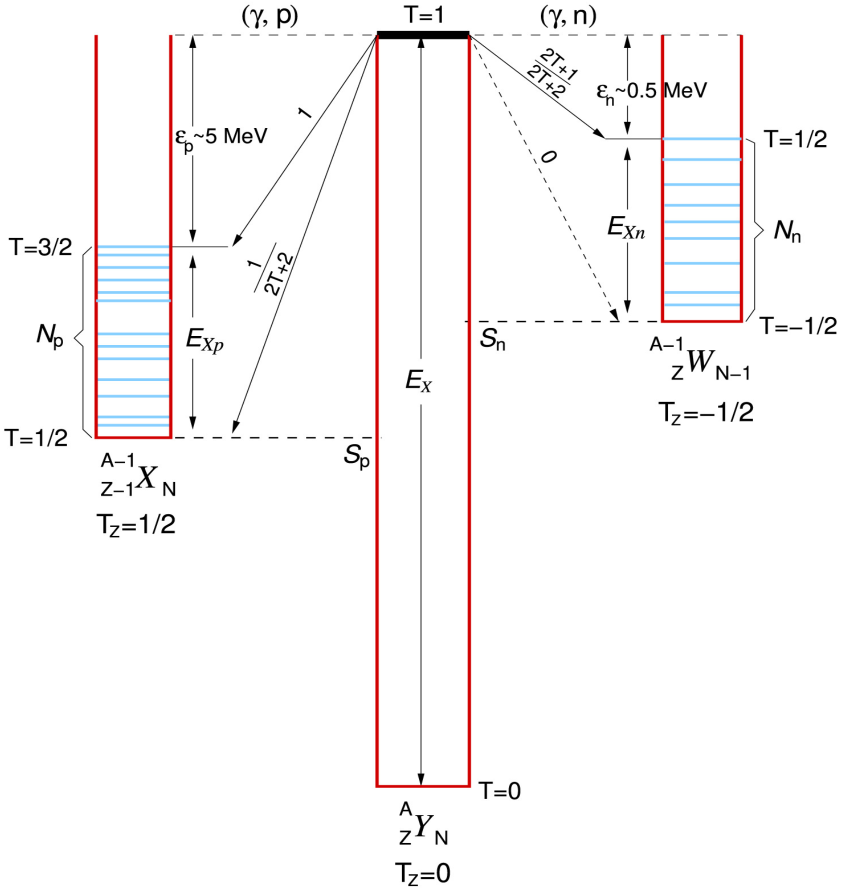


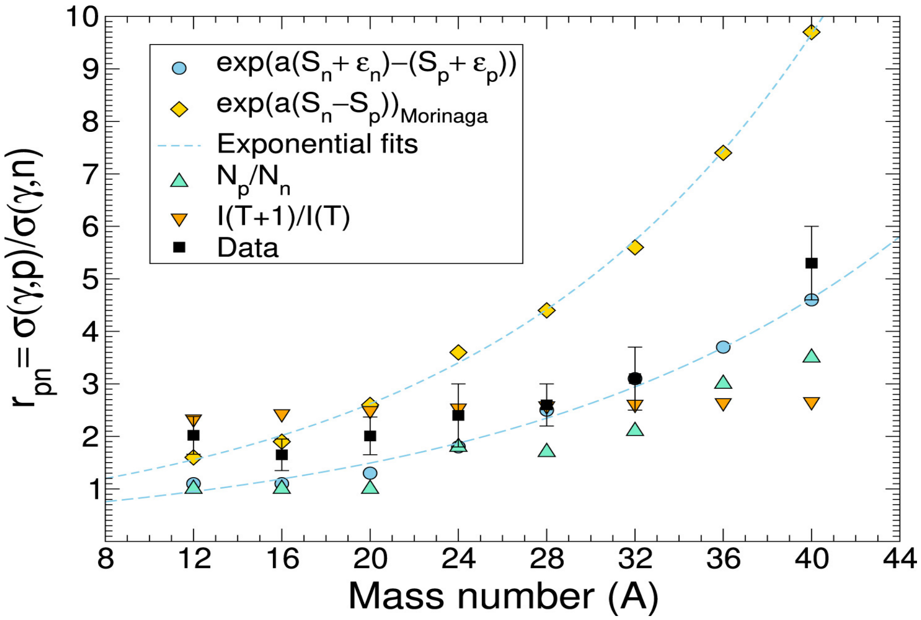
Polarizability of light nuclei through Coulomb excitation @ iThemba LABS, CERN, GSI (*ala* Banu *et al*)

Orce, in Proceedings of the 4th South Africa - JINR Symposium (Dubna) (2015)
Orce, Polarizability effects in atomic nuclei, IJMP E (2020)

σ_{-2} values as a function of a_{sym}(A)

Missing $\sigma(\gamma,p)$ contributions in self-conjugate nuclei





The trend and magnitude of disintegration yields for self-conjugate nuclei are in agreement with the evaporation model of Blatt & Weisskopf.

Orce, Competition between (γ,p) and (γ,n) photo-disintegration yields, Atomic Data & Nuclear Data Tables (2022)

APS | Journals | Physics Magazine | Help/Feedback | Journal, vol, page, DOI, etc.

PHYSICAL REVIEW C
covering nuclear physics

Tradition cannot be inherited, and if you want it you must obtain it by great labor.
– T. S. Eliot, "Tradition and the Individual Talent"
Introduction in R. Machleidt's Advances of Nuclear Physics 19 (1989)

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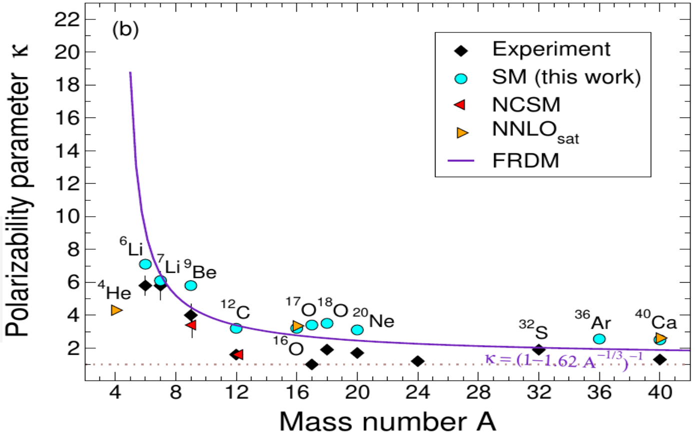
Accepted Paper

Global trends of the electric dipole polarizability from shell-model calculations

Phys. Rev. C

José Nicolás Orce, Cebo Ngwetsheni, and B. Alex Brown

Accepted 13 September 2023



ABSTRACT https://arxiv.org/pdf/2309.08810.pdf

ABSTRACT

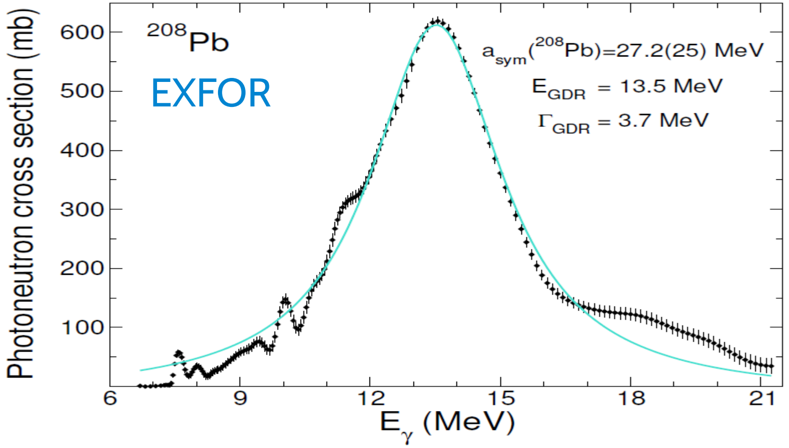
Shell-model calculations of the electric dipole ($E1$) polarizability have been performed for the ground state of selected {} and {}shell nuclei, substantially advancing previous knowledge. Our results are slightly larger compared with the somewhat more scattered photo-absorption cross-section data, albeit agreeing with calculations at shell closures and presenting a smooth trend that follows the leptodermus approximation provided by the finite-range droplet model ({FRDM}). The total $E1$ strengths also show an increasing trend proportional to the mass number which follows from the classical oscillator strength ({TRK}) sum rule for the $E1$ operator. The enhancement of the energy-weighted sum over $E1$ excitations with respect to the {TRK} sum rule arises from the use of experimental single-particle energies and the residual particle-hole interaction.

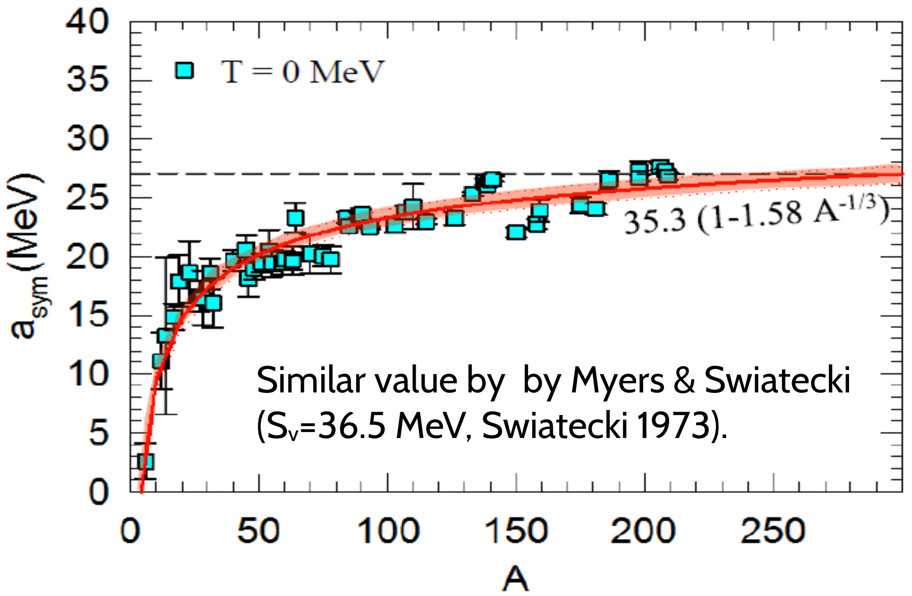
Symmetry energy extracted @ T=0 MeV from ground state GDRs

a_{sym} saturates @ 27 MeV

Spherical nuclei (modified SJ model)

$$a_{sym}(A) = \frac{MA^2}{8\hbar^2 K^2 NZ} \frac{E_{GDR}^2}{1-\left(\frac{\Gamma_{GDR}}{2E_{GDR}}\right)^2} \approx 1\times10^{-3}\left(\frac{A^{8/3}}{NZ}\right)\frac{E_{GDR}^2}{1-\left(\frac{\Gamma_{GDR}}{2E_{GDR}}\right)^2}$$





Similar value by by Myers & Swiatecki (S_v=36.5 MeV, Swiatecki 1973).

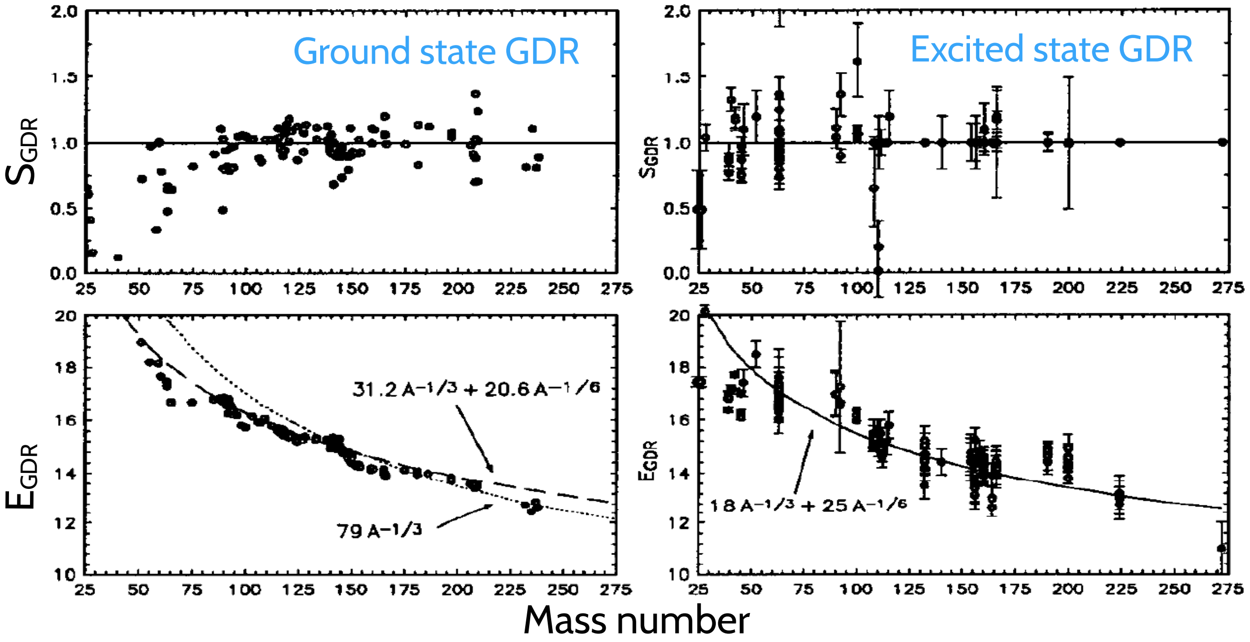
Similar equation for deformed nuclei, but using the average centroid energy and the FWHM of the total Lorentzian

Danos, On the long-range correlation model of the photonuclear effect, Nucl. Phys. (1958)

Orce, Dey, Ngwetsheni, Bhattacharya, Pandit, Lesch, Zulu, MNRAS (2023)

Need to know what happens @ T > 0 MeV → Brink-Axel hypothesis to the rescue

The photoabsorption cross section is independent of the excitation energy of a nuclear system.
Insensitive to the details of the initial state. A GDR can be built on every state of the nucleus

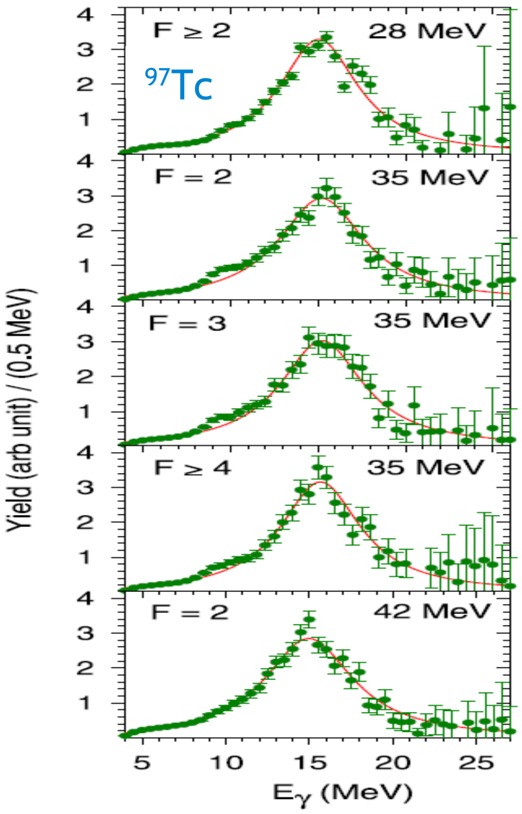


Excited-state GDRs present at moderate $T \lessapprox 1$ MeV and spin $J \lessapprox 0.6\ A^{5/6}$,
similar centroid energies and resonance strengths relative to the TRK dipole sum rule
as those found for the ground-state counterparts → Common physical origin for all GDRs

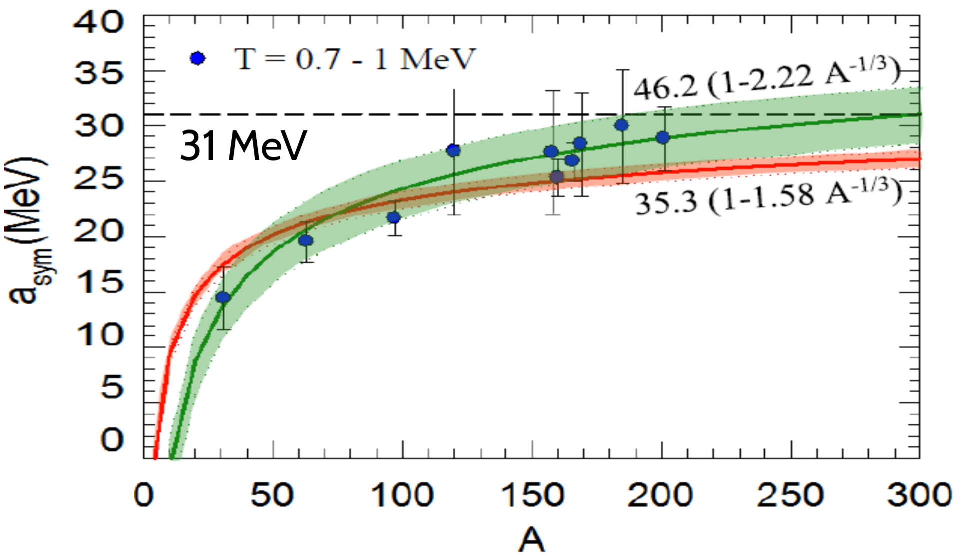
Snover, Annual Review of Nuclear and Particle Science (1986)
Gaardhoje, Annual Review of Nuclear and Particle Science (1992)

Symmetry energy extracted @ T~0.7-1 MeV (GDRs built on excited sates)

The angular momentum distribution is extracted from the fold distribution F (number of multiplicity detectors fired) in coincidence with the high energy gamma rays (Pandit, NIM A 2010)



Increase of ~5% in the centroid energy for T~0.7-1 MeV



Effective mass of the nucleon decreases as T increases (dynamic mean field), and yields an increase in the symmetry energy of ~8% at T~1 MeV for medium and heavy mass nuclei (Donati *et al.* PRL (1994))

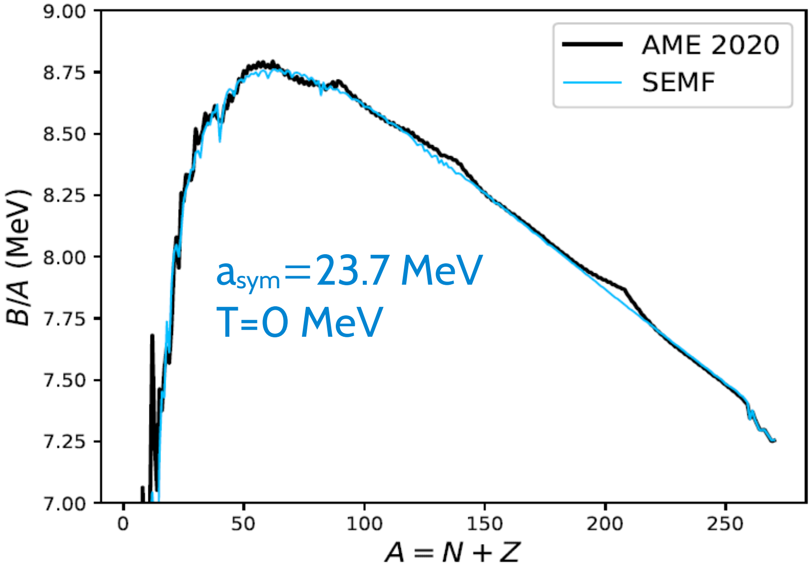
Dey *et al.*, PLB (2014), D. Mondal *et al.*, PLB (2018)
Heckman *et al.*, PLB (2003), D. Pandit *et al.*, PLB (2012)
Kicinska-Habior *et al.*, PRC (1987)

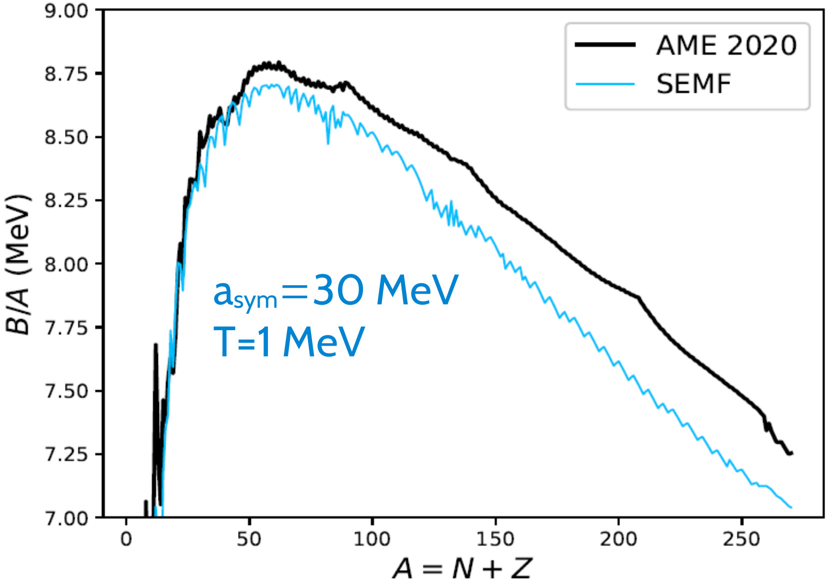
Reduction in the binding energy per nucleon as a_{sym} increases

Reduction of the neutron-capture cross section by ≈100 in the A=200 mass region (TALYS and EMPIRE)

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{asym} \frac{(A-2Z)^2}{A} \pm \frac{a_p}{A^{3/4}}$$

Rohlf, "Modern Physics from alpha to Z0", Wiley (1994)





More sophisticated mass models: modified SEMF, HFB-21, FRDM, WS, DZ...

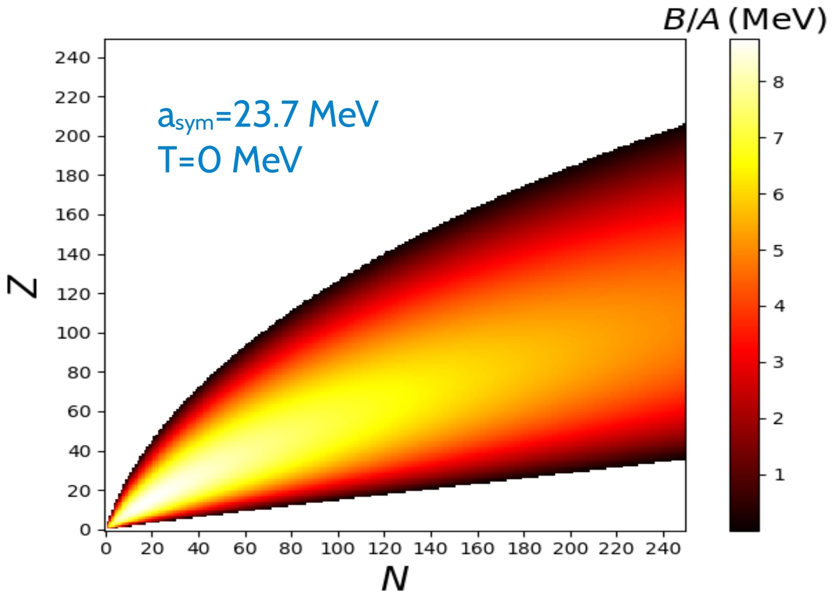
$$a_{sym}(A) = \frac{J}{1 + \frac{9J}{4Q} A^{-1/3}}$$

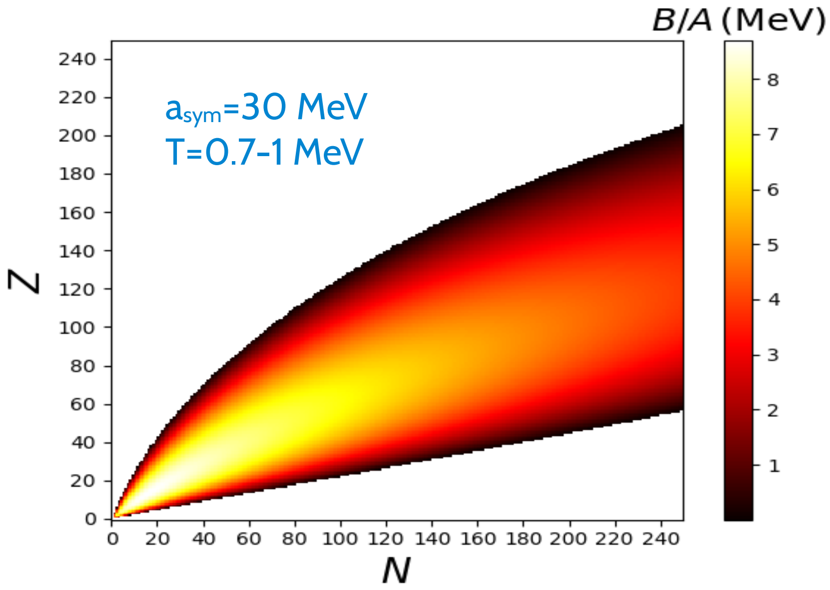
Myers & Swiatecki, Ann. Phys. (1969)

Nuclear chart given by the semi-empirical mass formula

Close-in neutron drip line for heavy elements

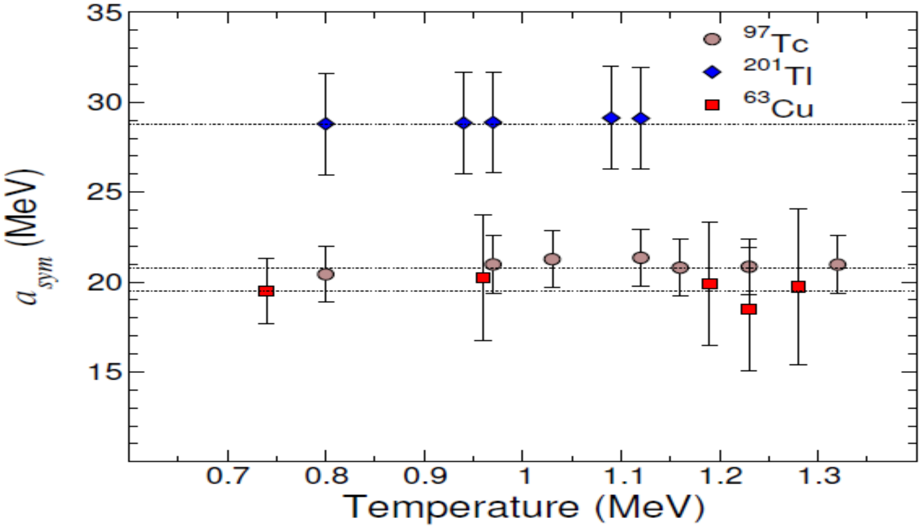
$$B(Z,A) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{asym} \frac{(A-2Z)^2}{A} \pm \frac{a_p}{A^{3/4}}$$





The convergence of a_{sym} for heavy nuclei establishes the frontier of the neutron drip line

Constant a_{sym} between T~0.7-1.3 MeV,
but neutron capture may occur @ T≲0.5 MeV



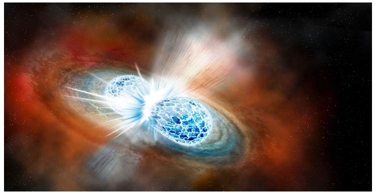
T

High T (40-50 MeV) → kilonova, gamma-ray burst, quarks + gluons, protons + neutrons

T ≈ 0.7-1 MeV → likely the temperatures where seed elements are created before charge reactions freeze out.

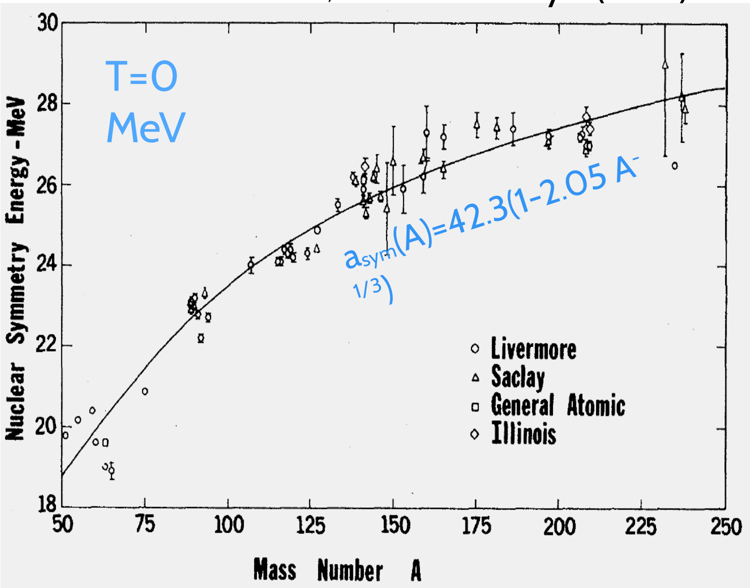
T ≲ 0.5 MeV → neutron-capture may start occurring.

A few 10^8 K → neutrons are finally consumed.

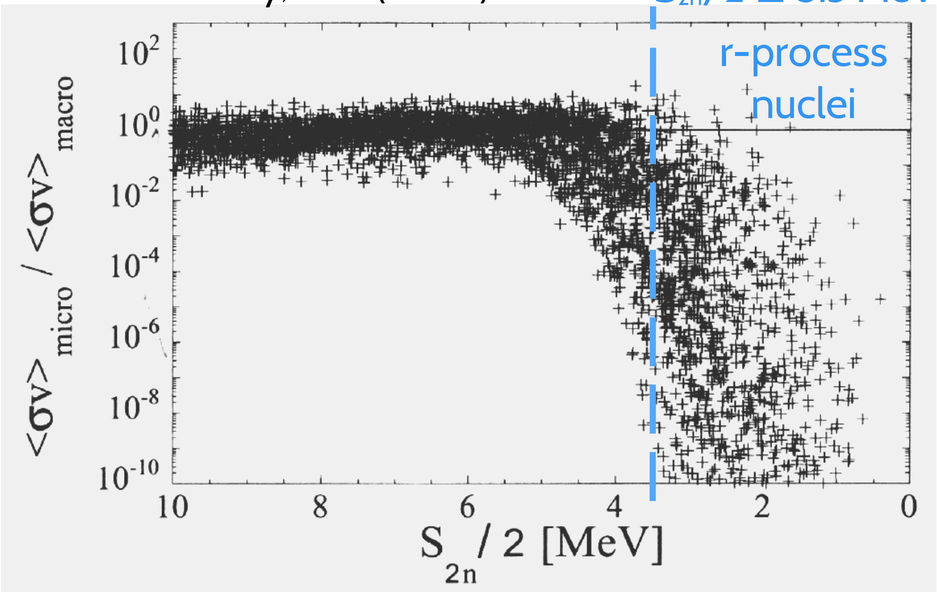


A close-in neutron drip line for heavy elements:
Not first time being suggested

Herman & Fultz, Rev. Mod. Phys. (1975)



Goriely, NPA (2003)



"This large value for this ratio favors a close-in neutron drip line for heavy elements, and hence argues against the production of superheavy elements by the r process in supernovae."

"The "universality" of the r-process abundances could possibly be explained by the rapid drop of microscopic neutron capture rates at increasing neutron excesses (which constrains the r-process flow to remain in the narrow region of the nuclear chart characterized by low β half-lives and large neutron capture rates)."

Conclusions

A larger symmetry energy @ T~0.7-1 MeV results in a close-in neutron drip line which constrains the r-process flow and narrows down the nucleosynthesis path → universal pattern of r-process abundances observed in galactic halo nuclei and our Sun.

Caution: Assumptions which may not be valid for exotic nuclei.
Semi-empirical mass formula (other mass models predict similar rms)
Brink-Axel hypothesis,
Similar temperature dependence below T~0.7 MeV.

Structural effects
Ngwetsheni & Orce, Phys. Lett. B (2019)
Ngwetsheni & Orce, Hyp. Int. (2019)
Ngwetsheni & Orce, EPJ Web (2019)

Future work:

- Polarizability of light nuclei through Coulex @ iThemba LABS, CERN, GSI,...
- What happens far from stability? (FAIR, FRIB, HIE-ISOLDE, etc)
- Real *ab initio* calculations of the nuclear polarizability/symmetry energy using chiral effective field theory (F. Sammarruca's talk)
- SALT: HRS/Infrared high-resolution spectroscopy of metal-poor stars (PI: Nico Orce)

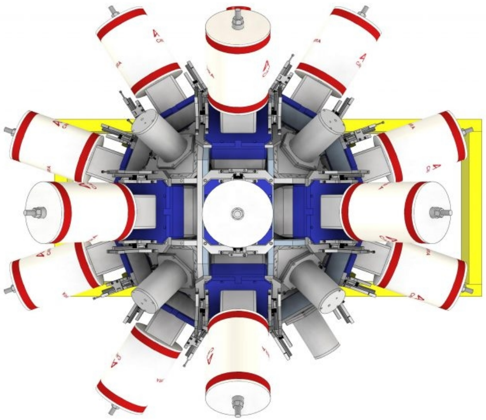
My question/challenge:

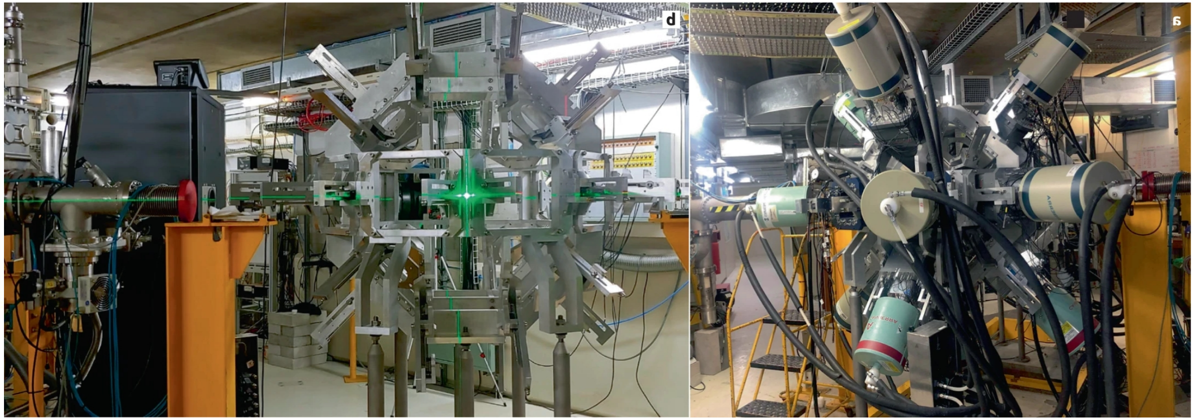
What happens @ T≈0.5 MeV where rapid neutron captures occur?

GAMKA – the Lion

UWC-led (PI: Nico Orce) consortium of four Universities (Stellenbosch, Zululand, Wits and UWC) and iThemba LABS has been awarded ≈€200k by the National Research Foundation (NRF) for a new nuclear spectrometer (up to 30 detectors, configurations of clovers and large $LaBr_3$).

The Gamma Ray Spectrometer for Knowledge in Africa, dubbed GAMKA – the Khoisan word for 'lion' – will be housed at iThemba LABS and will be used to study a wide range of nuclear physics and nuclear astrophysics phenomena such as nuclear shapes, GDRs built on excited states, collective properties, short nuclear lifetimes and gamma-ray strength functions.





GAMKA array @ iThemba LABS commissioned in May 2021

https://www.youtube.com/watch?v=wxLRLOtXwmM&ab_channel=NicoOrce

Acknowledments

Monthly Notices of the Royal Astronomical Society

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JOURNAL ARTICLE ACCEPTED MANUSCRIPT

Enhanced symmetry energy may bear universality of r-process abundances

José Nicolás Orce, Balaram Dey, Cebo Ngwetsheni, Srijit Bhattacharya, Deepak Pandit, Brenden Lesch, Andile Zulu

Monthly Notices of the Royal Astronomical Society, stad2539, https://doi.org/10.1093/mnras/stad2539

Published: 04 September 2023

Abstract

The abundances of about half of the elements heavier than iron are subtly attuned by the rapid neutron capture process or *r*-process, which is intimately related to the competition between neutron capture, photo-disintegration and β-decay rates, and ultimately depends on the binding energy of neutron-rich nuclei. The well-known Bethe-Weizsäcker semi-empirical mass formula describes the binding energy of ground states – i.e., nuclei with temperatures of $T = 0$ MeV – with the symmetry energy parameter converging between 23 – 27 MeV for heavy nuclei. We find an unexpected enhancement of the symmetry energy well above the ground state – at higher temperatures of $T \approx 0.7$ - 1.0 MeV – from the available data of giant dipole resonances built on excited states. Although these are likely the temperatures where seed nuclei are created – during the cooling down of the ejecta following neutron-star mergers or collapsars – the fact that the symmetry energy remains constant between $T \approx 0.7$ - 1.0 MeV, may suggest an enhanced symmetry energy at lower temperatures, where neutron-capture may start occurring. Calculations using this relatively larger symmetry energy yield a reduction of the binding energy per nucleon for heavy neutron-rich nuclei and inhibits radiative neutron-capture rates. This results in a substantial close in of the neutron drip line which may elucidate 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. Sensitivity studies of *r*-process network calculations have been performed using more sophisticated mass models.