Challenges in Heavy Elements nucleosynthesis

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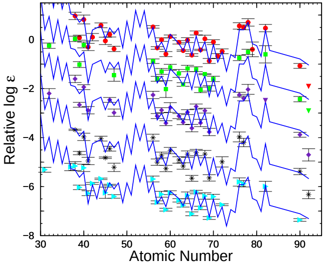
Outline

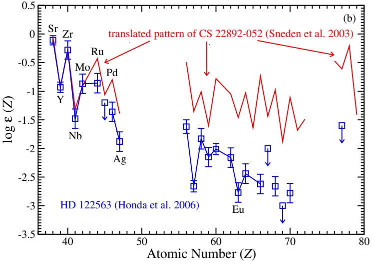
Heavy elements and metal-poor stars

Cowan & Sneden, Nature **440**, 1151 (2006)



- Stars rich in heavy r-process elements ($Z > 52$) and poor in iron (r-II stars, $[\mathrm{Eu/Fe}] > 1.0$).
- Robust abundance patter for $Z > 52$, consistent with solar r-process abundance.
- These abundances seem the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**, 237 (2007)]
- Possible Astrophysical Scenario: Neutron star mergers.

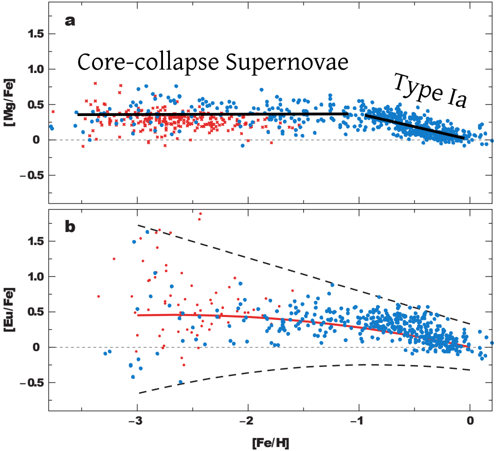
- Stars poor in heavy r-process elements but with large abundances of light r-process elements (Sr, Y, Zr)
- Production of light and heavy r-process elements is decoupled.
- Astrophysical scenario: neutrino-driven winds from core-collapse supernova



Honda *et al*, ApJ **643**, 1180 (2006)

Evolution metalicity

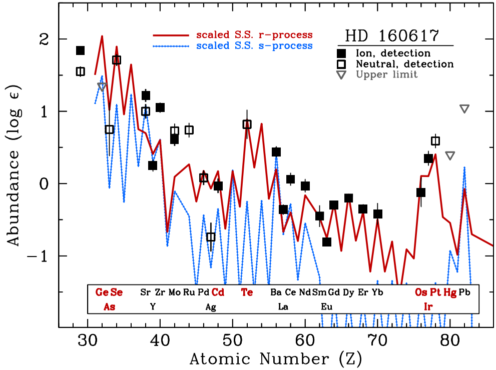
Sneden, Cowan & Gallino 2008



- r-process occurs already at early galactic history
- r-process is related to rare events not correlated with Iron. Large scatter at large low metalicities.

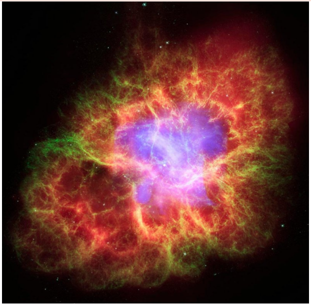
Observation three r-process peaks

Roederer & Lawler, ApJ **750**, 76 (2012)



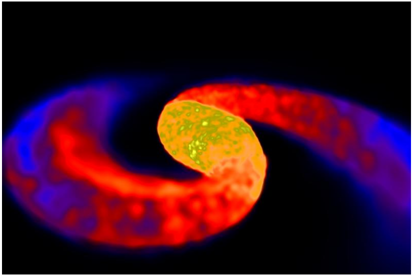
- So far no star observed without Sr (light r-process) or Ba (heavy r-process): Roederer, AJ **145**, 26 (2013)
- Every r-process site has to produce both the light and heavy components.

Astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, ... [Winteler *et al*, ApJ **750**, L22 (2012)]
- Neutrino-induced r-process in He layers [Banerjee *et al.*, PRL **106**, 201104 (2011)]

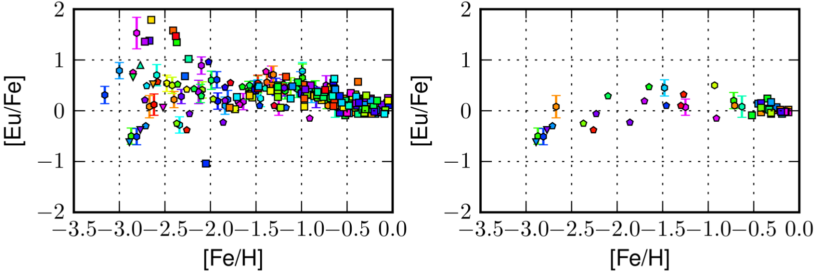


Neutron star mergers

- Dynamically ejected matter from merger (Possible observational consequences)
- Winds from accretion disks around black holes [Wanajo & Janka, ApJ **746**, 180 (2012)]

What are metal-poor stars telling us?

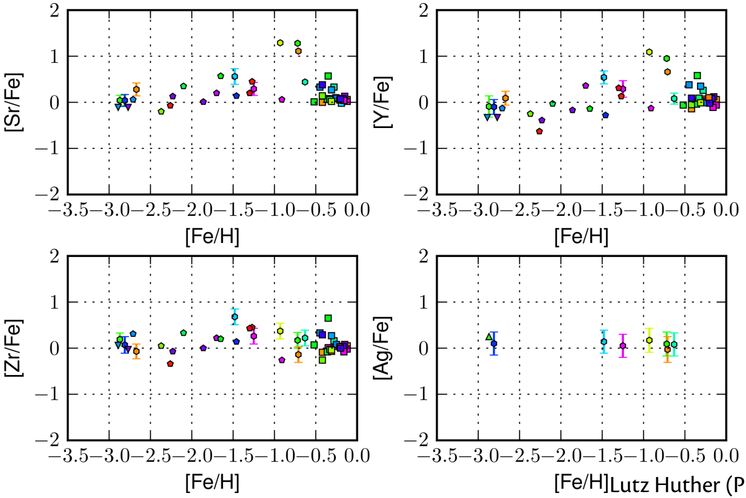
If we select meta-poor stars that are enhanced on light r-process elements (Sr,Y,Zr) compared with Eu. The scatter of Europium is greatly reduced.



Lutz Huther (PhD)

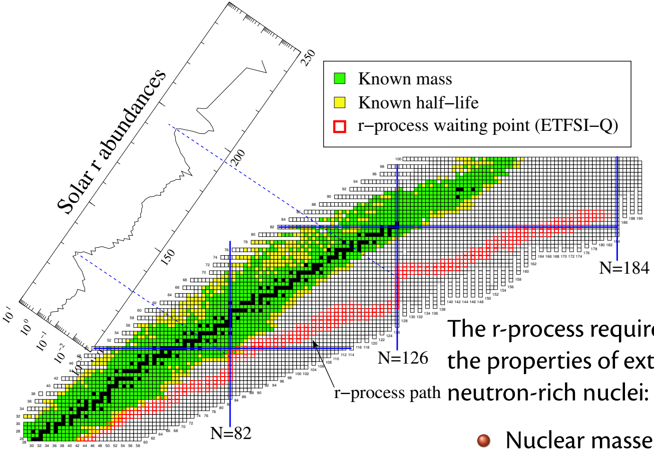
What are metal-poor stars telling us?

A correlation between all elements and Fe seems to emerge (limited by poor statistics)



Lutz Huther (PhD)

Making Gold in Nature: r-process nucleosynthesis

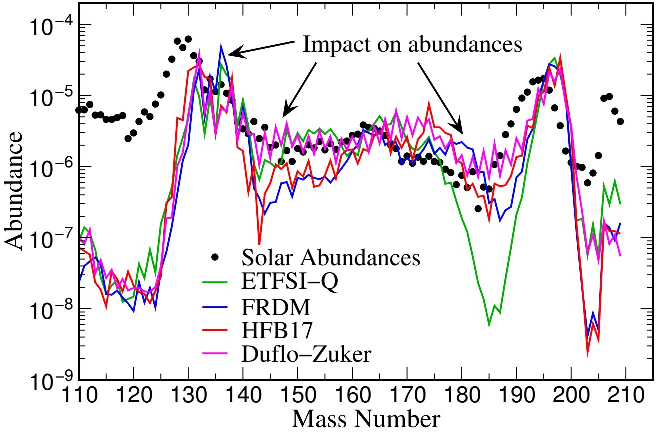


The r-process requires the knowledge of the properties of extremely neutron-rich nuclei:

- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates and yields.

Impact in r-process abundances

Large differences in the predicted masses in transitional regions have a huge impact in r-process abundances



A. Arcones & GMP, Phys. Rev. C **83**, 045809 (2011)

Reliability Global Mass models

New 2012 Atomic Mass Evaluation (Wang *et al*, 2012)

Root Mean Square (MeV) deviation

Model	AME2003	New 219 Masses	AME2012
FRDM	0.655	0.765	0.666
HFB21	0.576	0.646	0.584
DZ10	0.551	0.880	0.588
DZ31	0.363	0.665	0.400
WS3	0.336	0.424	0.345

FRDM: Möller, *et al*, PRL **108**, 052501 (2012)
HFB21: Goriely *et al*, PRC **82**, 035804 (2010)
DZ31: Duflo & Zuker, PRC **52**, R23 (1995)
WS3: Liu *et al*, PRC **84**, 014333 (2011)

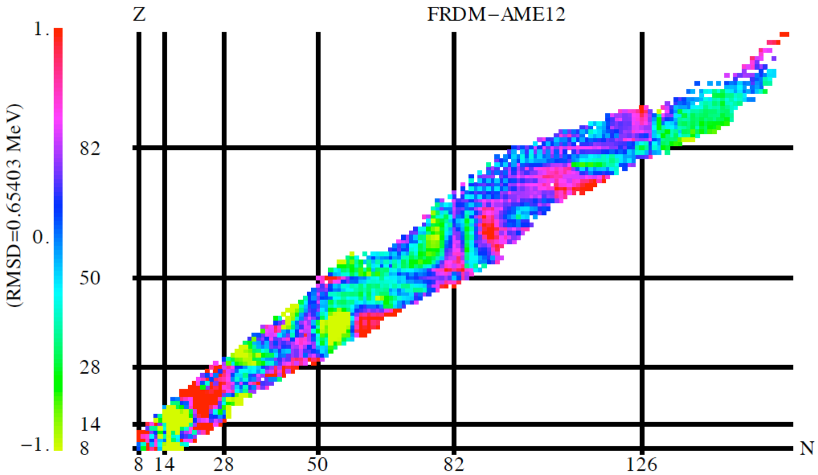
Comparison mass models

Root Mean Square (keV) deviations between different models.

	Audi-Wapstra (03)	DZ10	DZ31	FRDM	HFB17
Audi-Wapstra (03)	–	545	359	656	577
DZ10	545	–	427	721	770
DZ31	359	427	–	662	603
FRDM	656	721	662	–	735
FRDM(DZ10)	618	282	495	663	764
FRDM(DZ31)	578	543	457	491	655
HFB17	577	770	603	735	–
HFB17(DZ10)	590	219	470	689	742
HFB17(DZ31)	471	567	339	657	506

J. Mendoza, GMP, A. P. Zuker

Global Mass models



Similar behaviour for all mass models

Role of nuclei around $N \sim 90$

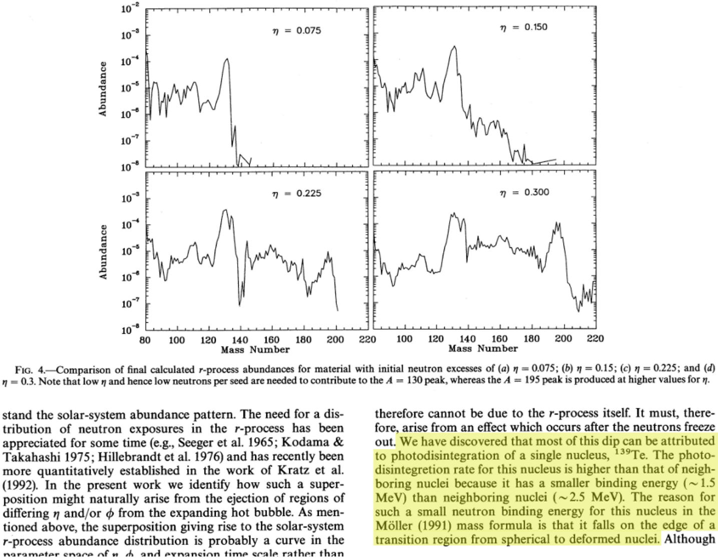


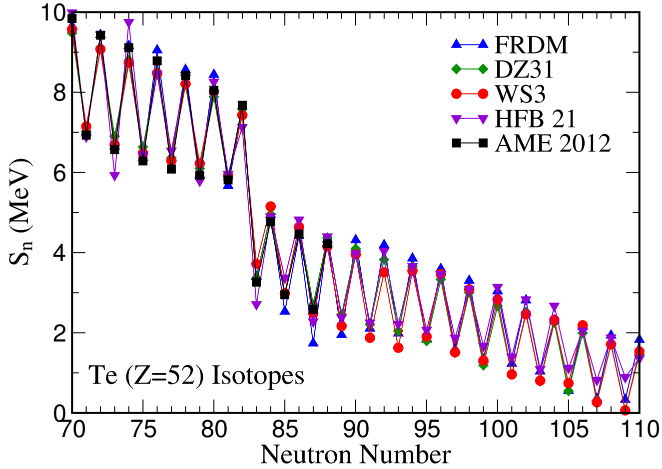
FIG. 4.—Comparison of final calculated *r*-process abundances for material with initial neutron excesses of (*a*) $\eta = 0.075$; (*b*) $\eta = 0.15$; (*c*) $\eta = 0.225$; and (*d*) $\eta = 0.3$. Note that low η and hence low neutrons per seed are needed to contribute to the $A = 130$ peak, whereas the $A = 195$ peak is produced at higher values for η.

stand the solar-system abundance pattern. The need for a distribution of neutron exposures in the *r*-process has been appreciated for some time (e.g., Seeger et al. 1965; Kodama & Takahashi 1975; Hillebrandt et al. 1976) and has recently been more quantitatively established in the work of Kratz et al. (1992). In the present work we identify how such a superposition might naturally arise from the ejection of regions of differing η and/or ϕ from the expanding hot bubble. As mentioned above, the superposition giving rise to the solar-system *r*-process abundance distribution is probably a curve in the parameter space of η, ϕ, and expansion time scale rather than

therefore cannot be due to the *r*-process itself. It must, therefore, arise from an effect which occurs after the neutrons freeze out. We have discovered that most of this dip can be attributed to photodisintegration of a single nucleus, ^{139}Te. The photodisintegretion rate for this nucleus is higher than that of neighboring nuclei because it has a smaller binding energy (~1.5 MeV) than neighboring nuclei (~2.5 MeV). The reason for such a small neutron binding energy for this nucleus in the Möller (1991) mass formula is that it falls on the edge of a transition region from spherical to deformed nuclei. Although

Meyer *et al*, ApJ **399**, 656 (1992)

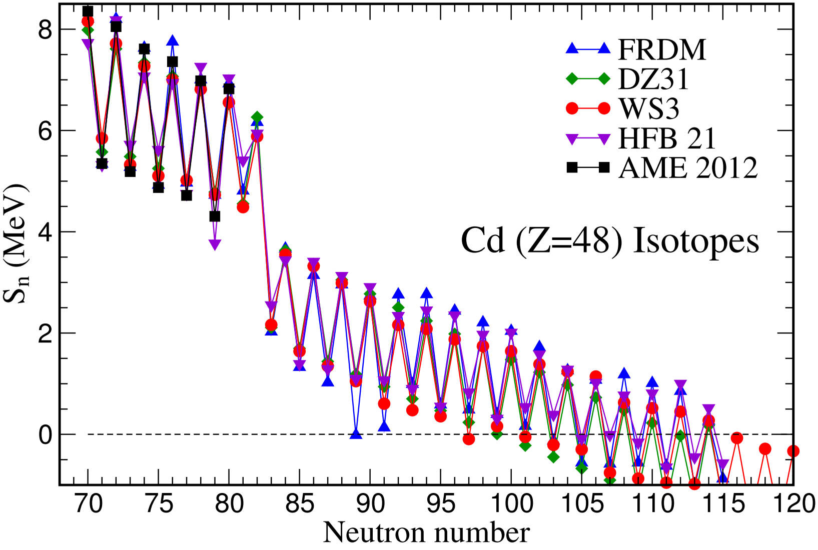
Neutron Separation energies Te isotopes



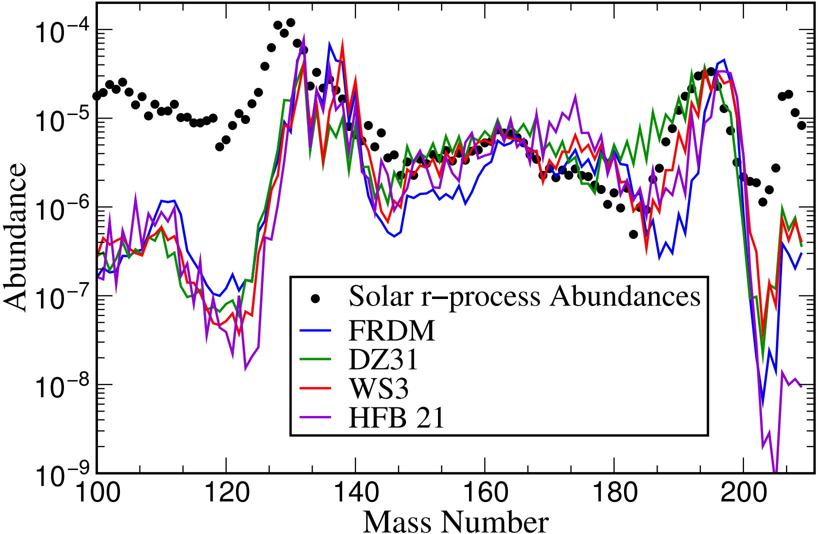
Hakala *et al*, PRL **109**, 032501 (2012)

Van Schelt, *et al*, PRC **85**, 045805 (2012)

Neutron Separation energies Cd isotopes

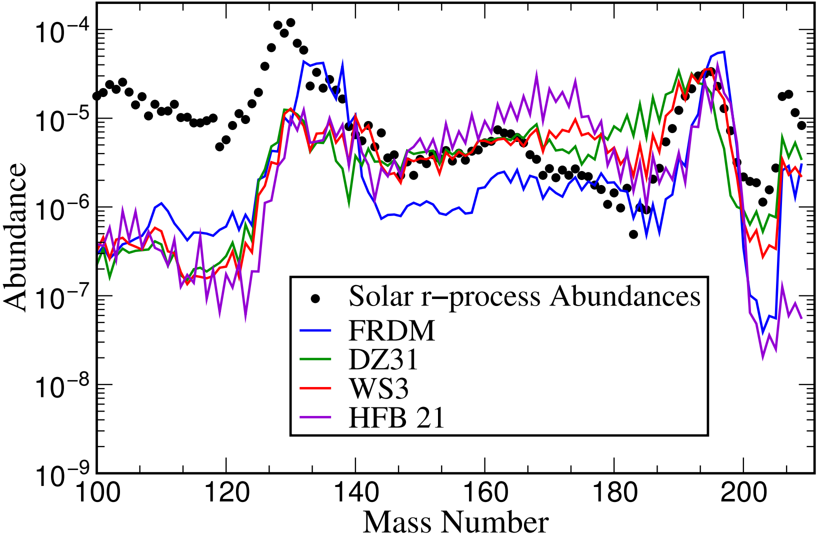


Impact r-process abundances (Hot r-process)



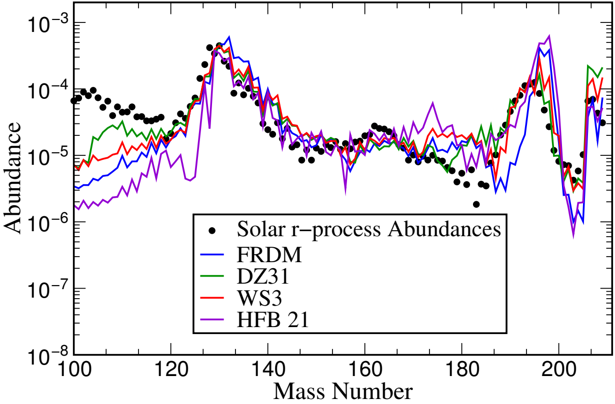
Joel Mendoza-Temis (PhD)

Impact r-process abundances (Cold r-process)



Joel Mendoza-Temis (PhD)

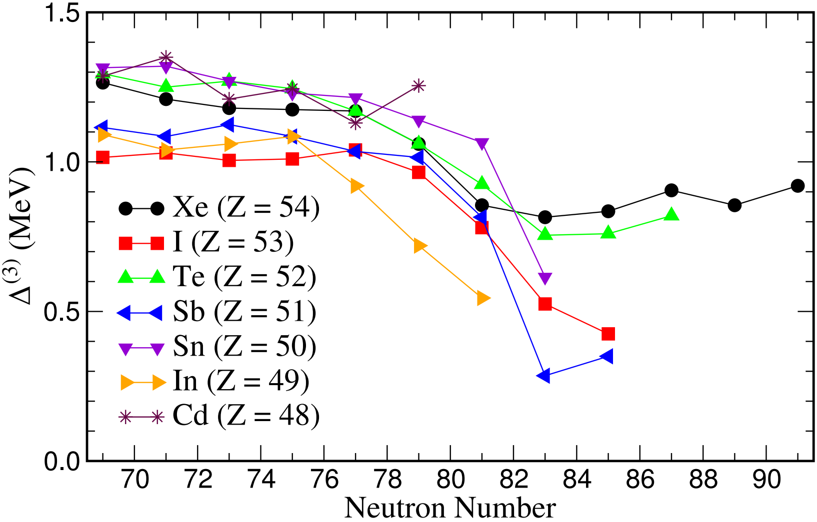
Impact r-process abundances (NS Mergers)



- Masses around $N = 90$ determine the mass flow from second to third r-process peaks.

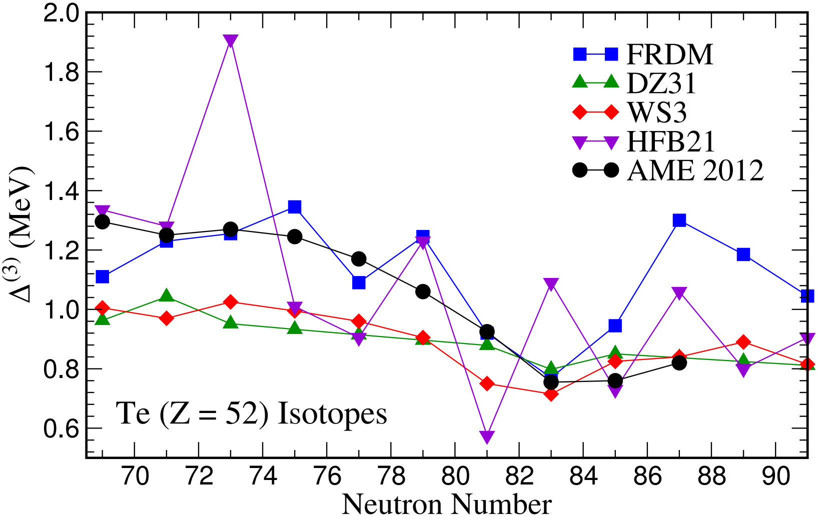
Joel Mendoza-Temis (PhD)

Evolution odd-even effects (Data)



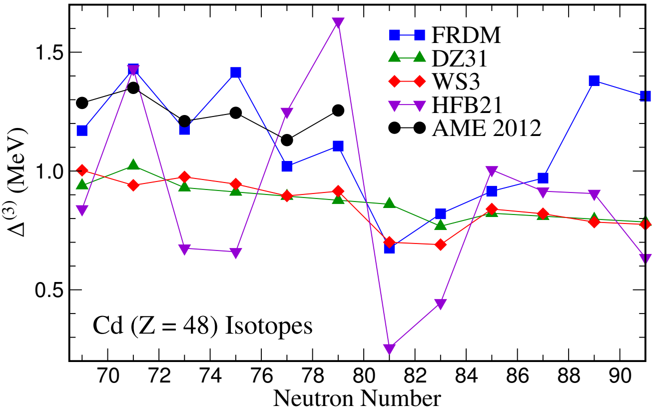
$$\Delta^{(3)} = (-1)^N \left[B_e(Z, N+1) - 2B_e(Z, N) + B_e(Z, N-1)\right]/2$$

Theory vs Data (Te)



$$\Delta^{(3)} = (-1)^N \left[B_e(Z, N+1) - 2B_e(Z, N) + B_e(Z, N-1)\right]/2$$

Theory vs Data (Cd)

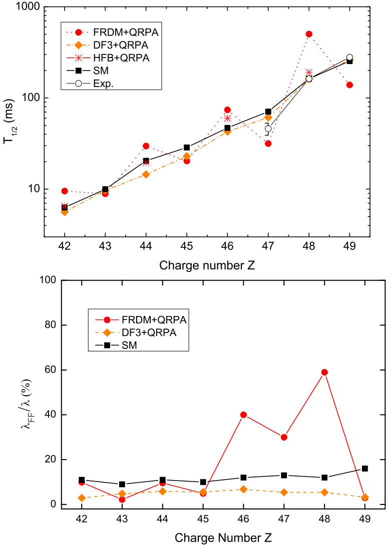


$$\Delta^{(3)} = (-1)^N \left[B_e(Z,N+1) - 2B_e(Z,N) + B_e(Z,N-1)\right]/2$$

All mass models fail to reproduce the evolution odd-even effects.

Beta decays and r-process (N=82)

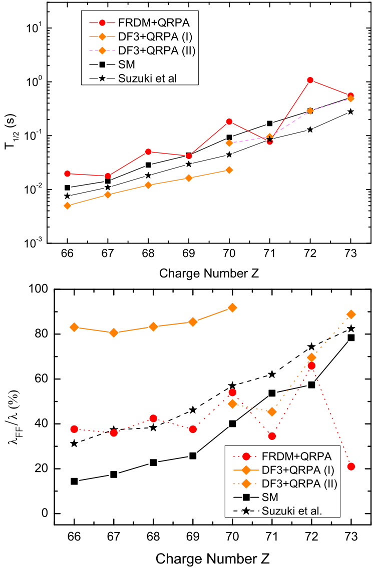
Zhi, Caurier, Cuenca, Langanke, GMP, Sieja, PRC **87**, 025803 (2013)



- Half-lives determine the matter flow from light to heavy nuclei.
- In the astrophysical environment competition between nuclear time scales (beta decays) and hydrodynamical time scales (expansion).
- Experimental data for $N = 82$ isotopes has helped to constrain theoretical models.
- Role of First-Forbidden transitions?

N=126 Isotones Half-lives

Zhi, Caurier, Cuenca, Langanke, GMP, Sieja, PRC **87**, 025803 (2013)

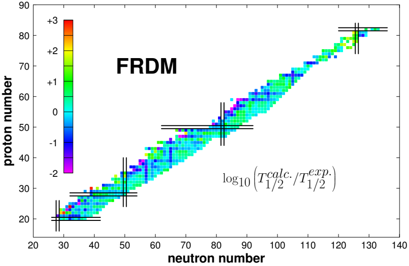


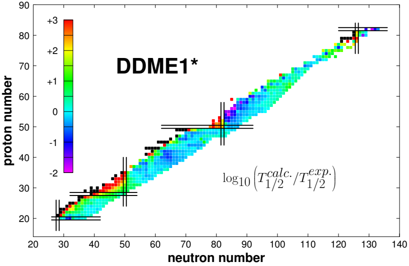
- Recent shell-model calculations including first-forbidden transitions [Suzuki et al, PRC **85**, 015802)]
- Extension to larger model spaces
- Large contributions of first-forbidden transitions.
- Half-lives are shorter than predicted by global models.

Global approaches to half-lives

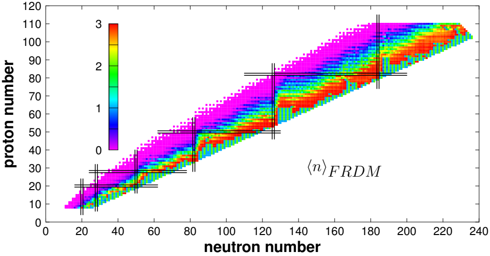
- All r-process calculations are based on Möller *et al* half-lives
- Inconsistent treatment of first-forbidden transitions (based on Gross theory)
- Tendency to overestimate half-lives. Strong odd-even effects not present in data.
- New Global calculations of beta-decay half-lives based on Covariant Density Functional Theory (Tomislav Marketin). Include consistently both Gamow-Teller and Forbidden transition.
- All nuclei treated as spherical, spherical QRPA.

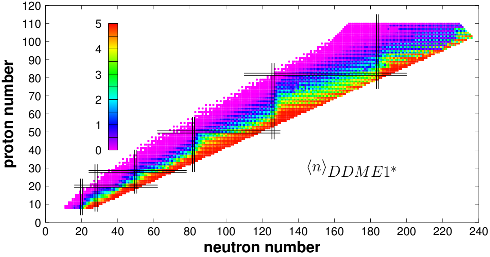
Comparison with data



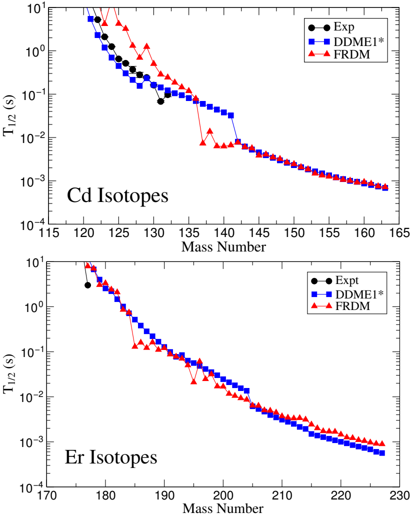


Evolution Neutron emission





Comparison for Er and Cd isotopes



Quantifying the agreement with data

$$r_i = \log \frac{T_{1/2}^{\mathrm{calc}}}{T_{1/2}^{\mathrm{exp}}}$$

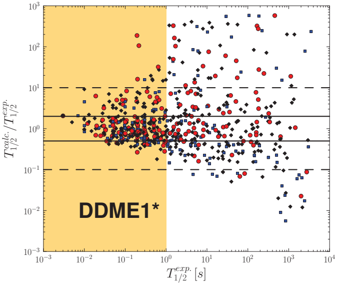
$$\bar{r} = \frac{1}{N} \sum_{i=1}^{N} r_i$$

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (r_i - \bar{r})^2$$

Quantifying the agreement with data

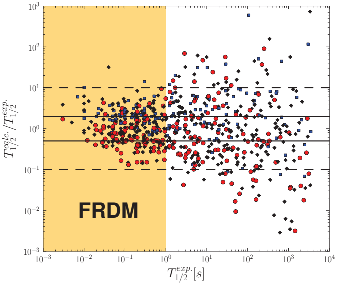
DDME1*

$$\bar{r}_{even} = 0.0315, \quad \sigma = 0.3446$$
$$\bar{r}_{odd\ Z} = 0.1499, \quad \sigma = 0.4035$$
$$\bar{r}_{odd\ N} = 0.0442, \quad \sigma = 0.4041$$
$$\bar{r}_{odd} = 0.1604, \quad \sigma = 0.5127$$
$$\bar{r}_{total} = 0.1009, \quad \sigma = 0.4292$$



FRDM

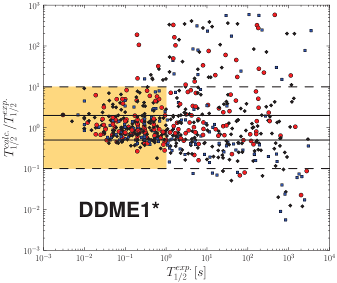
$$\bar{r}_{even} = 0.3466, \quad \sigma = 0.2427$$
$$\bar{r}_{odd\ Z} = -0.0437, \quad \sigma = 0.3434$$
$$\bar{r}_{odd\ N} = 0.1739, \quad \sigma = 0.4068$$
$$\bar{r}_{odd} = -0.1228, \quad \sigma = 0.3842$$
$$\bar{r}_{total} = 0.0728, \quad \sigma = 0.3973$$



Quantifying the agreement with data

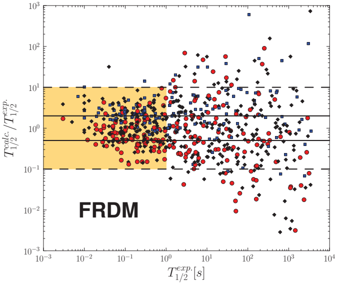
DDME1*

$$\bar{r}_{even} = 0.0129, \quad \sigma = 0.3141$$
$$\bar{r}_{odd\ Z} = 0.1024, \quad \sigma = 0.3345$$
$$\bar{r}_{odd\ N} = -0.0064, \quad \sigma = 0.3314$$
$$\bar{r}_{odd} = 0.0765, \quad \sigma = 0.3559$$
$$\bar{r}_{total} = 0.0488, \quad \sigma = 0.3382$$

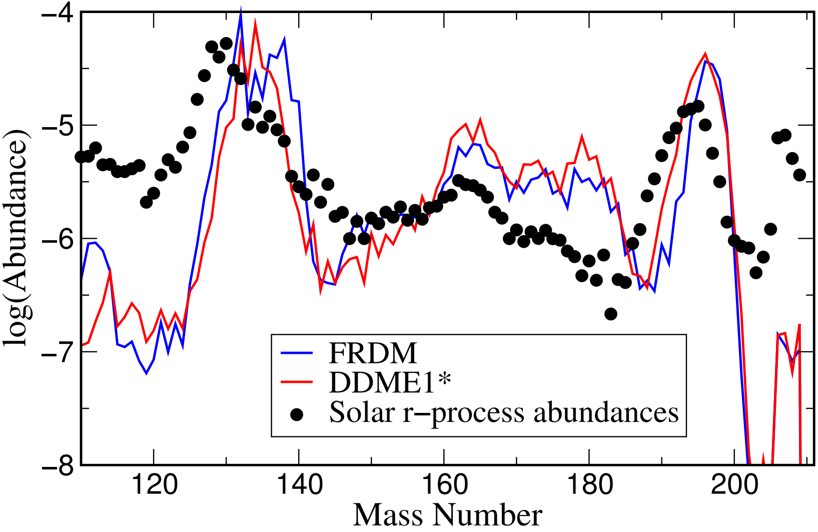


FRDM

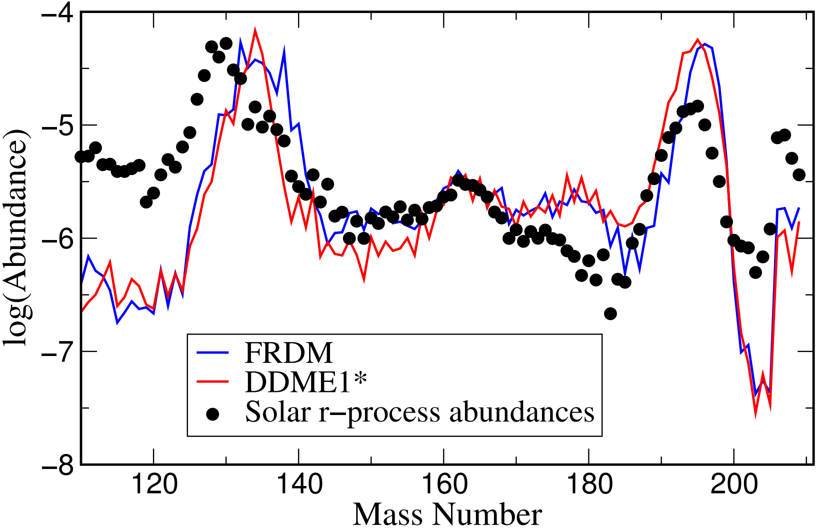
$$\bar{r}_{even} = 0.3230, \quad \sigma = 0.2068$$
$$\bar{r}_{odd\ Z} = -0.0437, \quad \sigma = 0.3434$$
$$\bar{r}_{odd\ N} = 0.1549, \quad \sigma = 0.3772$$
$$\bar{r}_{odd} = -0.1228, \quad \sigma = 0.3842$$
$$\bar{r}_{total} = 0.0609, \quad \sigma = 0.3811$$



Impact on r-process abundances (Hot)



Impact on r-process abundances (Cold)



Summary

- We need at least two different astrophysical sites to explain the production of “r-process” elements.
- Neutrino-winds from core collapse supernova are expected to contribute to the production of elements lighter than $A \sim 120$.
- r-process elements heavier than $A \sim 120$ can be produced in neutron star mergers.
- Masses for nuclei with $Z \lesssim 50$ and $N \sim 90$ have a strong impact in r-process abundances. The regulate the flow of material from second to third peak.
- A new set of global calculations of beta-decay half-lives that includes Gamow-Teller and first forbidden transitions is available.

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