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Nuclear structure and r-process modeling

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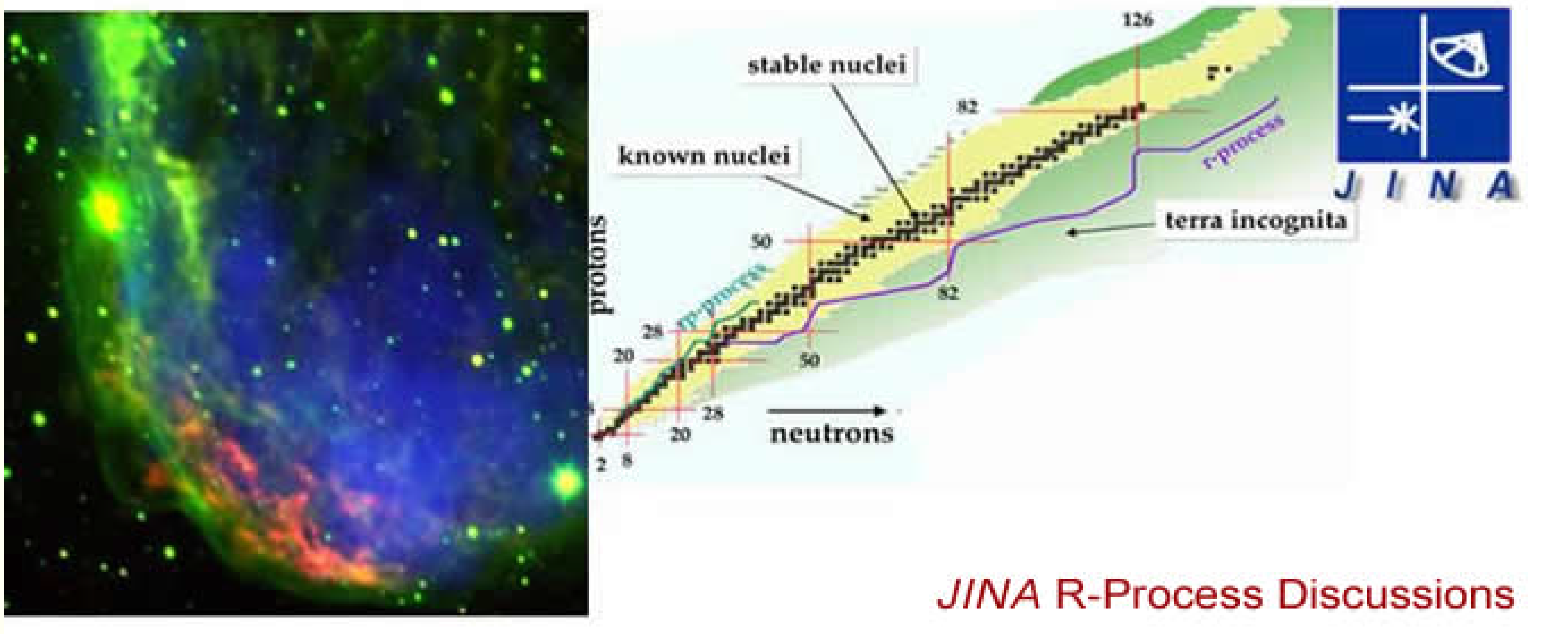
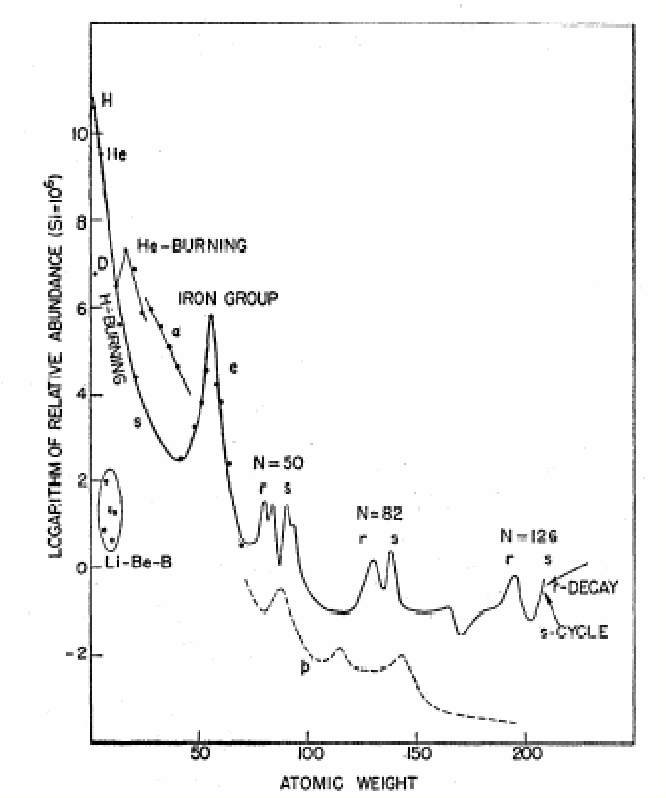


JINA R-Process Discussions

UNIVERSITY OF NOTRE DAME

January, 28 – 29 2005   Notre Dame, IN

Since the end of the 50’s, there exist successful theories of post-Big-Bang nucleosynthesis.



Suess and Urey
„Abundances of the Elements“
(Rev. Mod. Phys. 28 (1956) 53)

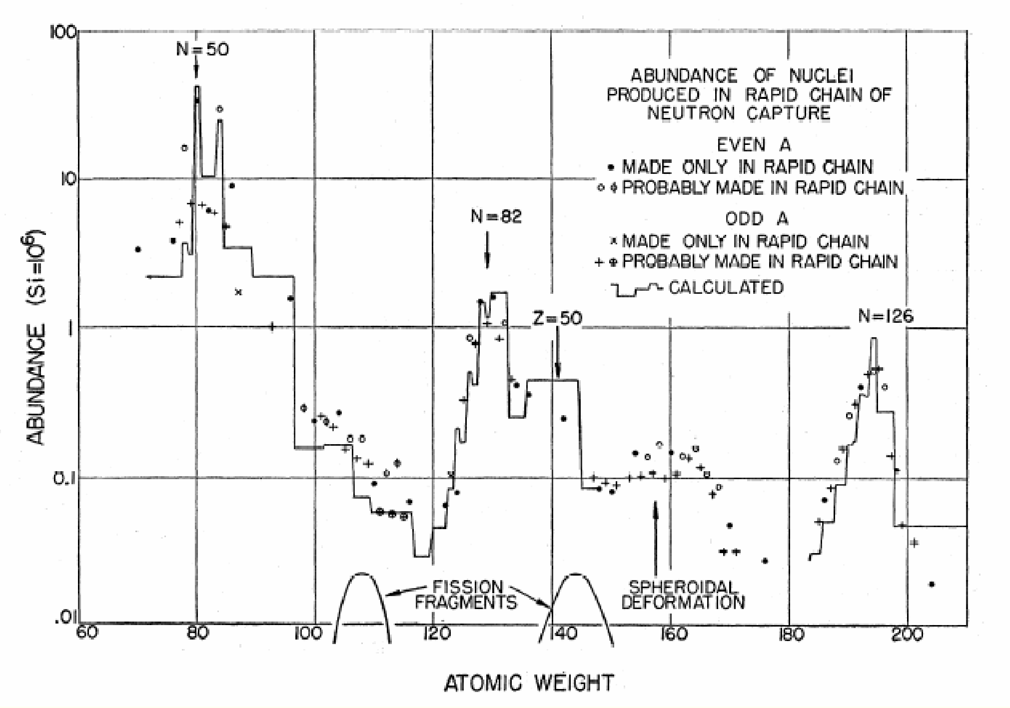


Fig. VII,3 of B^{2}FH: Classical static r-process calculation compared to observed abundances of Suess and Urey.

B^{2}FH concluded back in 1957 that for the r-process a
„*reasonable but not exact agreement with observed abundances is obtained*“.

A fine example of British understatement!
Quite some work had (and still has) to be invested to get better results.

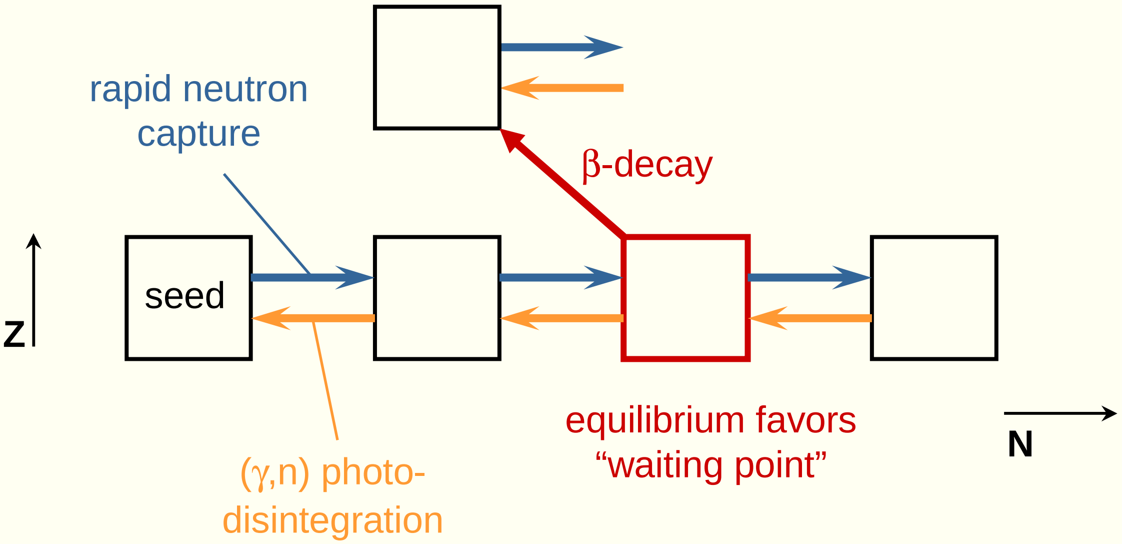
classical approach of the r process

waiting point approximation

assume

- <u>(n,γ) ↔ (γ,n) equilibrium</u> within isotopic chain, and
- <u>β-flow equilibrium</u>

  β-decay of nuclei from each Z-chain to (Z+1) is equal to the flow from (Z+1) to (Z+2)


rapid neutron capture

β-decay

seed

Z

N

equilibrium favors "waiting point"

(γ,n) photo-disintegration

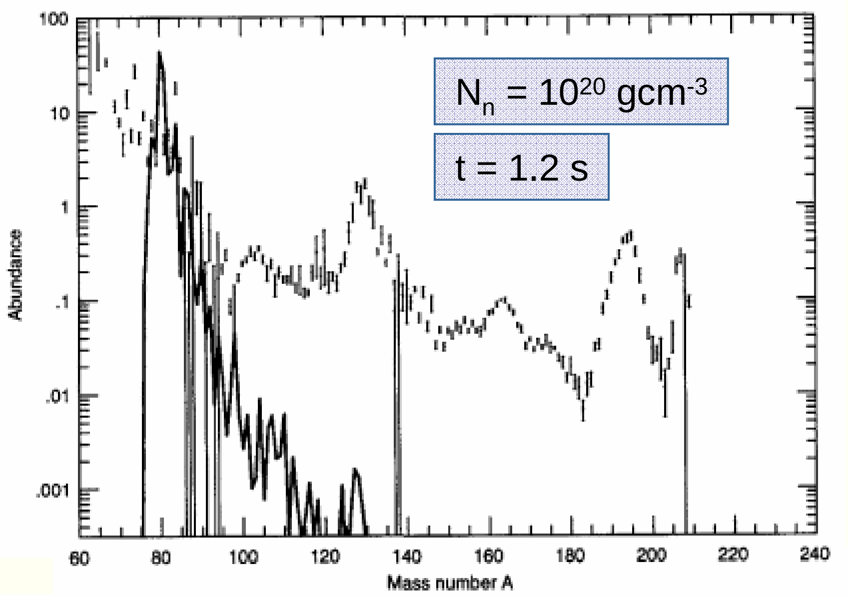
the nucleus with maximum abundance in each isotopic chain must wait for the longer β-decay time scales

good approximation for parameter studies, BUT steady-flow approximation is not always valid

Courtesy Marialuisa Aliotta, Edinburgh

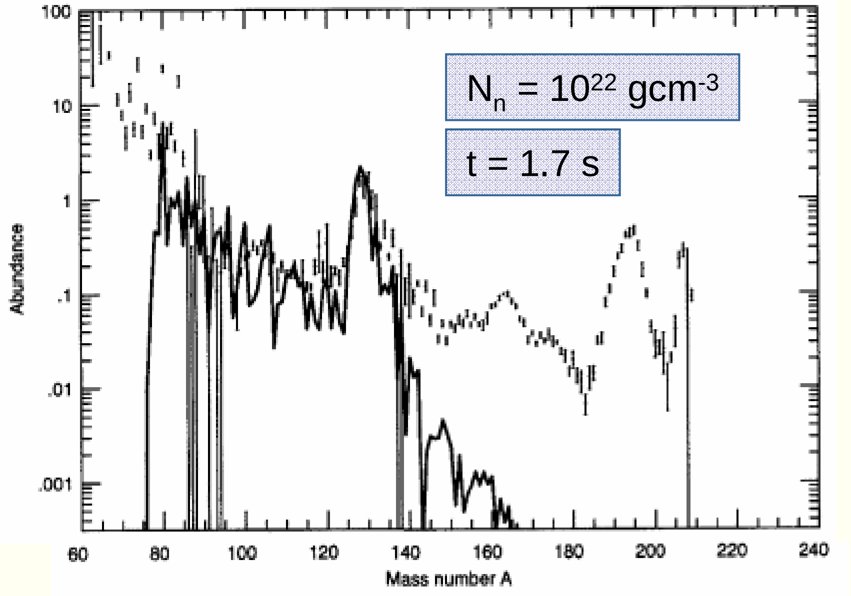
Post - B^{2}FH calculations

T = 1.35x10^9 K



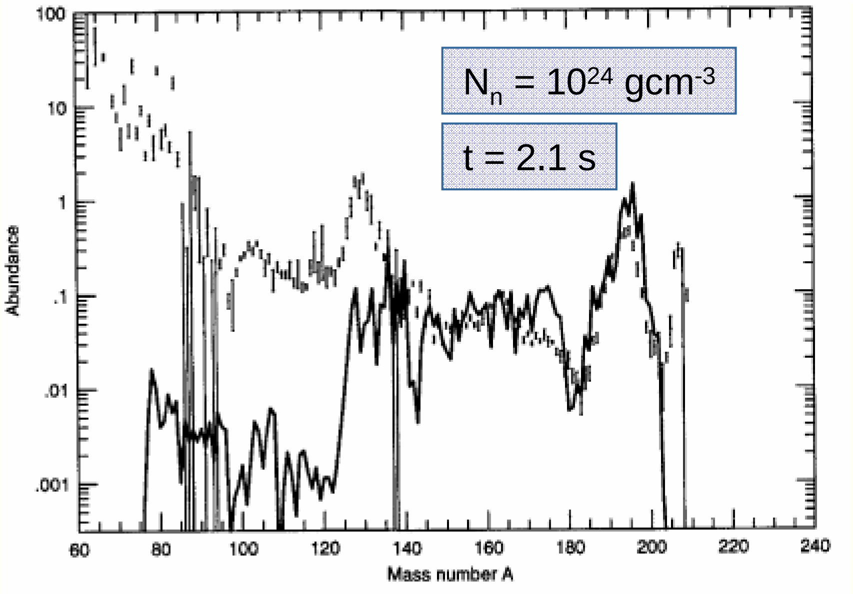
$N_n = 10^{20}$ gcm^{-3}

t = 1.2 s



$N_n = 10^{22}$ gcm^{-3}

t = 1.7 s



$N_n = 10^{24}$ gcm^{-3}

t = 2.1 s

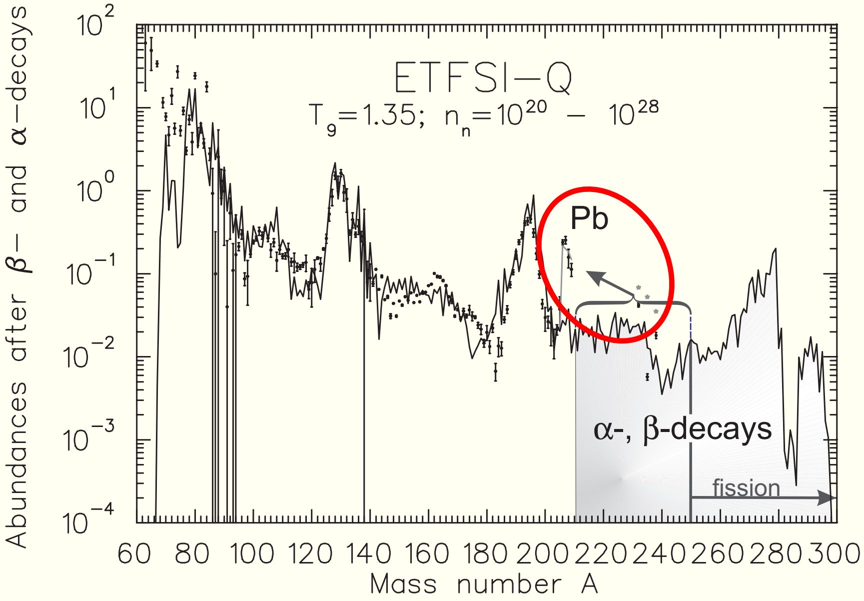
a full fit to the solar r-process abundances requires a superposition of different stellar conditions (not necessarily different sites)

Pfeiffer et al.: Nucl. Phys. A 693 (2001) 282 – 324

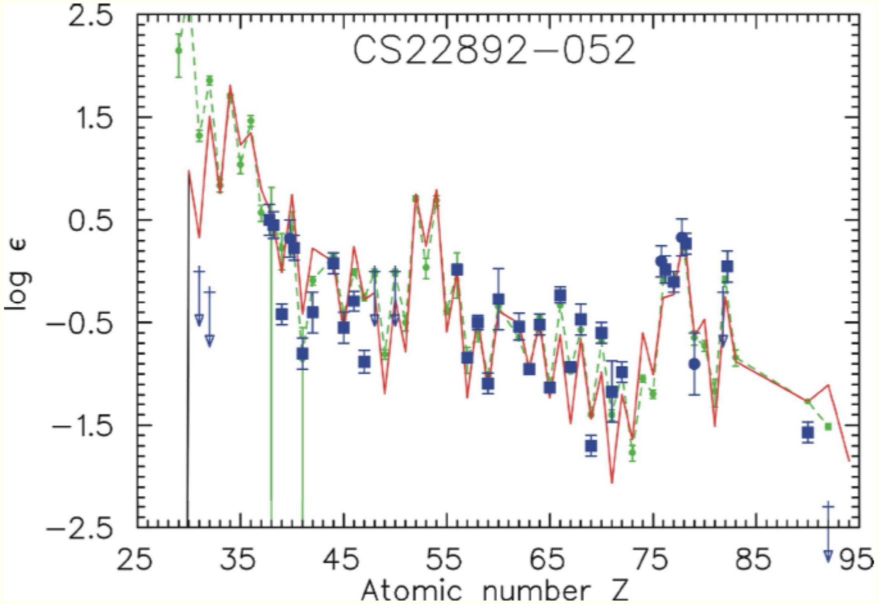
For the following examples, I have chosen the N=82 peak, as the r-process boulevard comes close to stability enabling the performance of nuclear structure experiments on isotopes in the path.

Courtesy Marialuisa Aliotta, Edinburgh

„Classical“ Mz-Bs calculations



Fit to solar r-process *isotopic* abundances obtained as superposition of 16 “canonical” n_n-components. Important is a good fit to the r-process Pb and Bi contributions after summing up the α-decay chains of heavier nuclei.



Observed neutron-capture *elemental* abundances in an ultra-metal-poor halo-star (blue squares and dots) compared to scaled solar values (green dots) and our calculated r-abundances (red line).

K.-L. Kratz et al., Ap.J. 403 (1993) 216; B. Pfeiffer et al., Nucl. Phys. A693 (2001) 282

Importance of **experimental** data

- The r-process abundances depend strongly on nuclear-structure data at the **magic neutron-numbers**,
  nuclei which act as **bottle-necks** for the matter flow.
- Up to present, only neutron-rich nuclei with N=50 and 82 could be observed.
- Future RIB-facilities hopefully will make N=126 (and beyond ?) accessible for experiments.

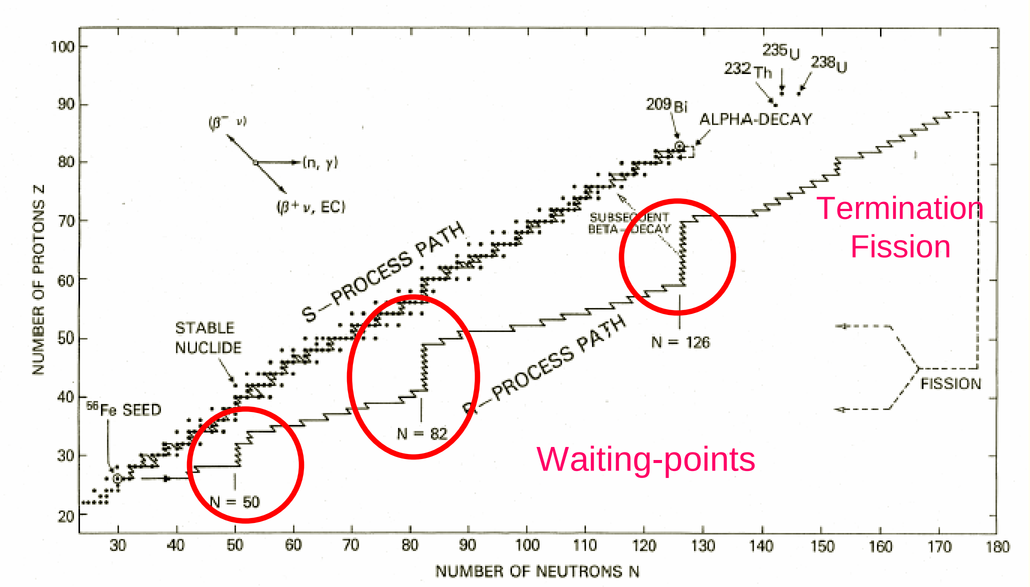
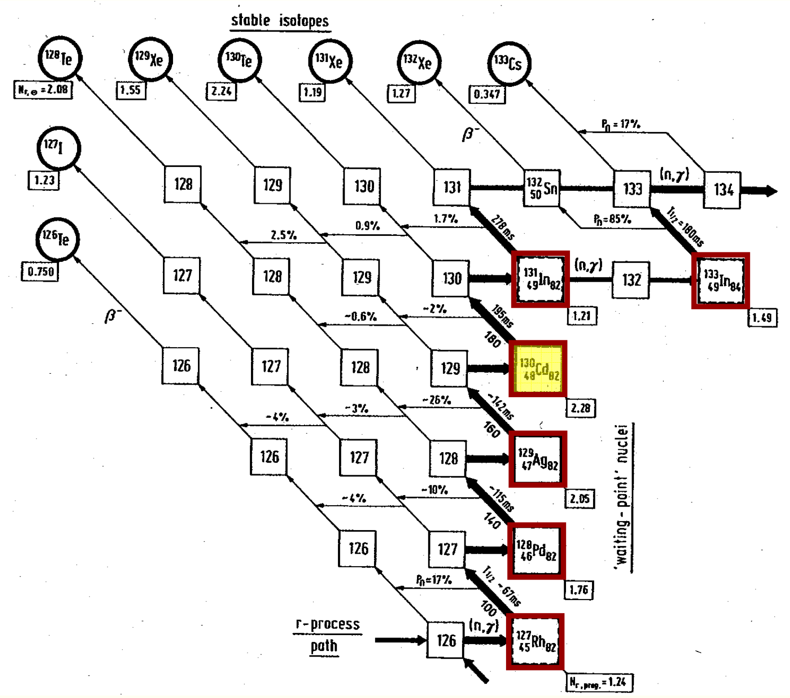
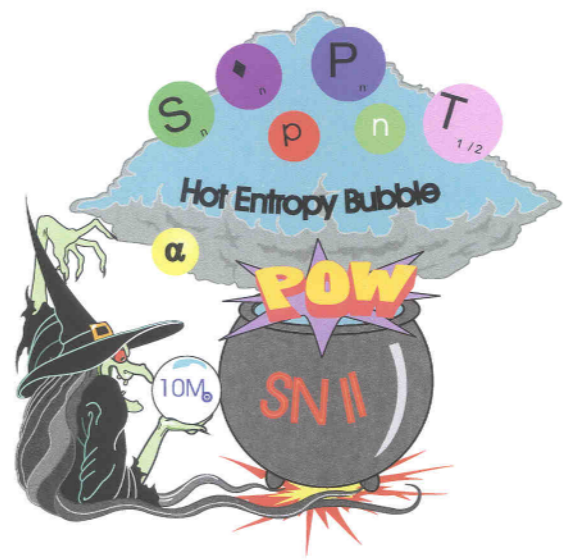


FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The *s*-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (*N*, *Z*)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm^{-3}.



r-process path at N=82

Nuclear physics input data



Data for extremely neutron-rich nuclei, mostly out of reach of actual experimental techniques:

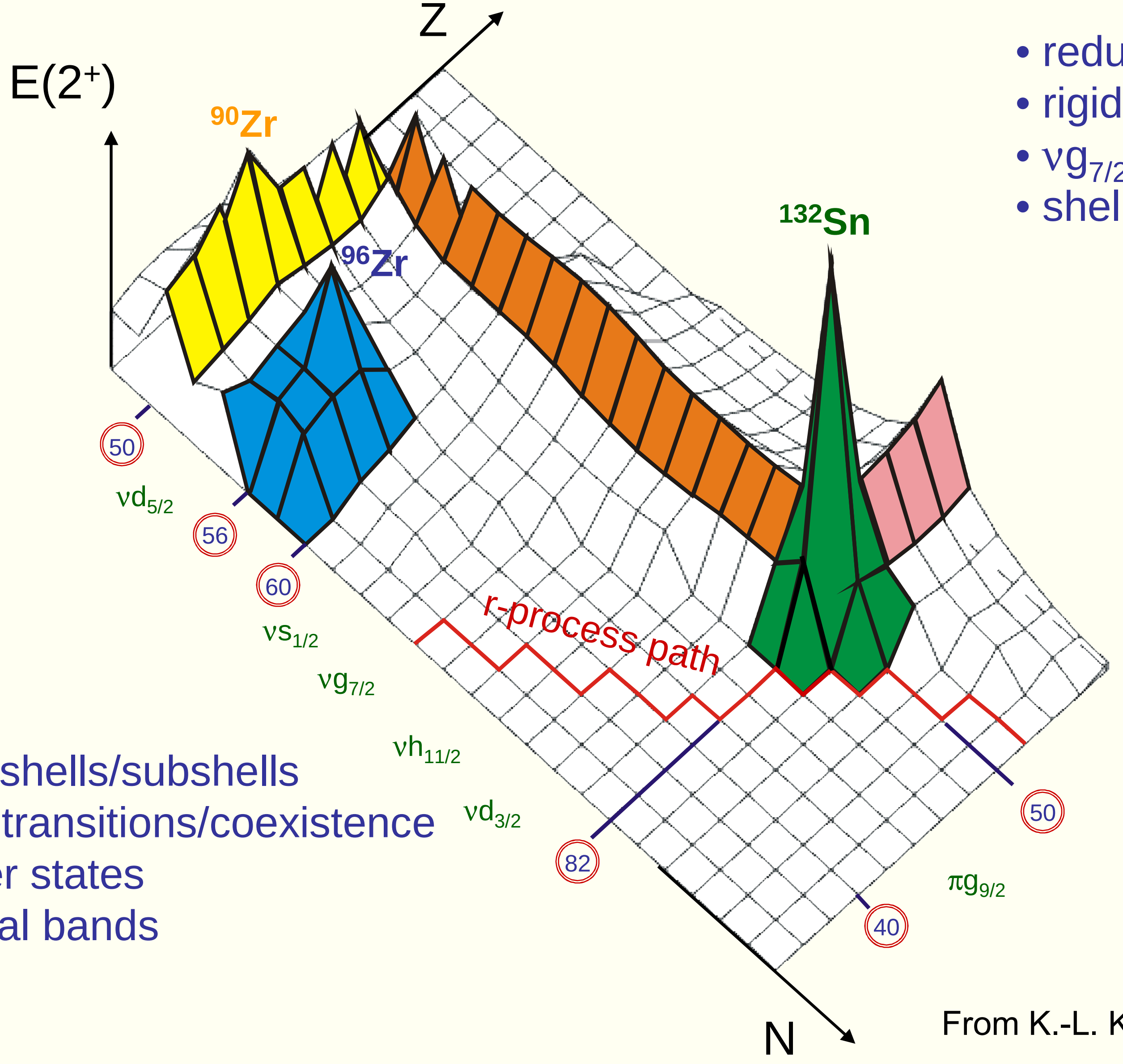
- nuclear masses
- β-decay properties: $T_{1/2}$, P_n, β-delayed/n-induced fission
- (n,γ), (γ,n) rates

Approximation to full network calculations already give insights in decisive data:

“canonical” r-process

- (n,γ)↔(γ,n) equilibrium (“waiting-point”)
- β-flow equilibrium
- Fe seed nuclei
- $Y(Z) \cdot \lambda_\beta = \text{const.}$
- In the simplest case, S_n and $T_{1/2}$ (by given neutron number density and temperature) are sufficient.

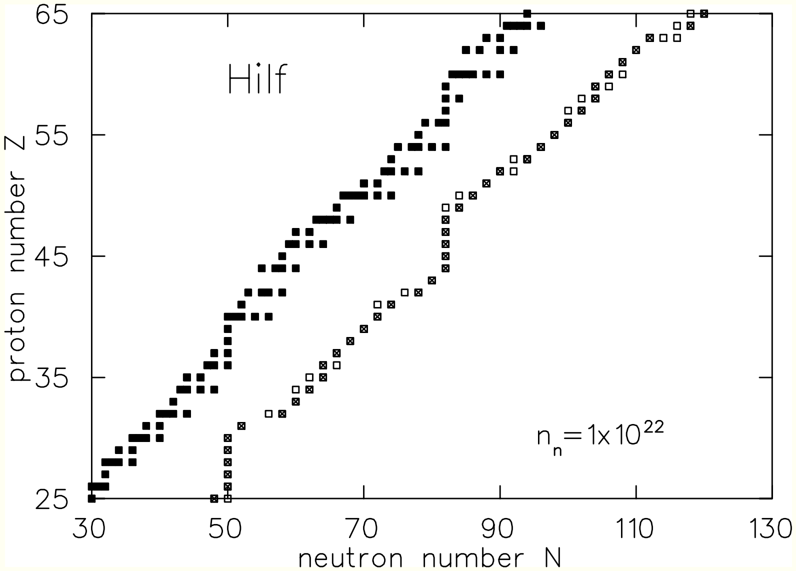
E(2+) - landscape 90 ≤ A ≤ 150

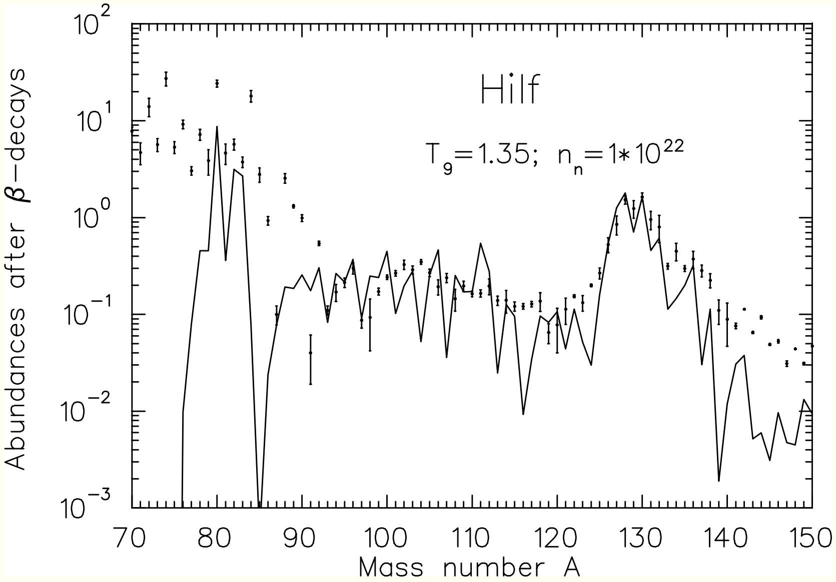


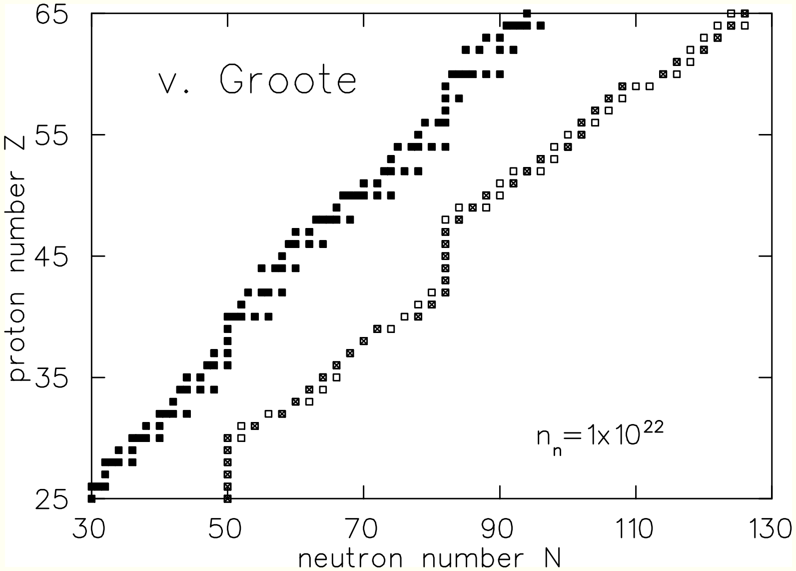
- reduced pairing
- rigid rotors
- $\nu g_{7/2} \otimes \pi g_{9/2}$ interaction
- shell quenching

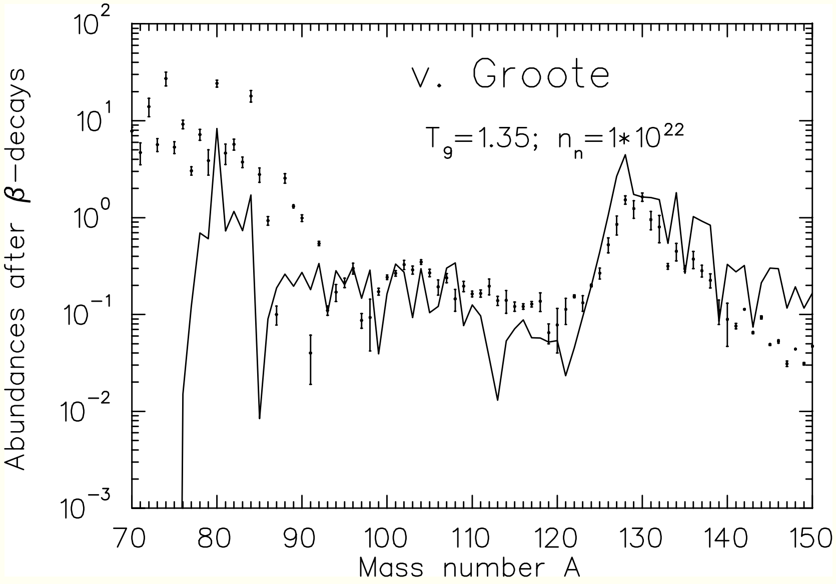
- magic shells/subshells
- shape transitions/coexistence
- intruder states
- identical bands

From K.-L. Kratz 2004

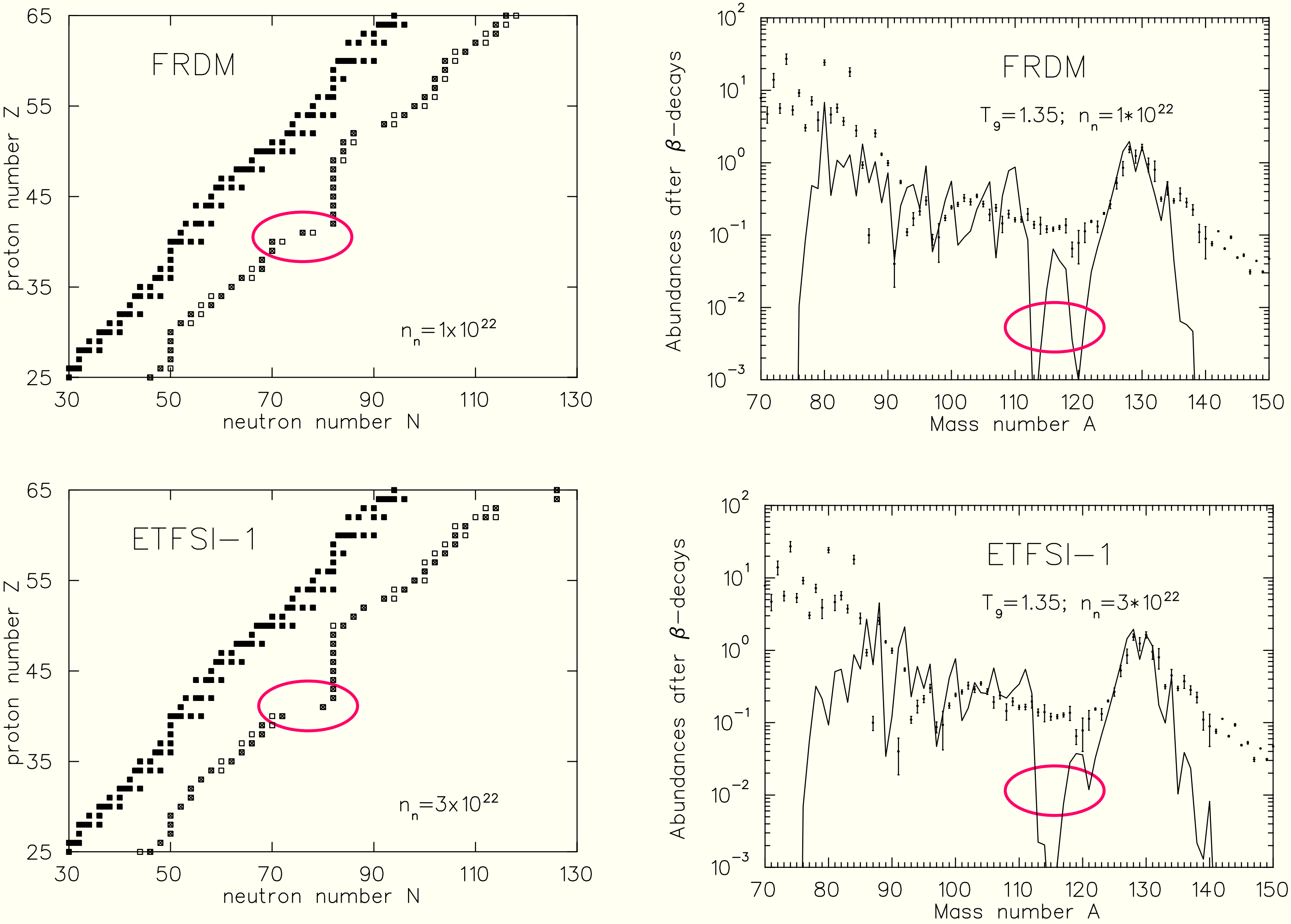








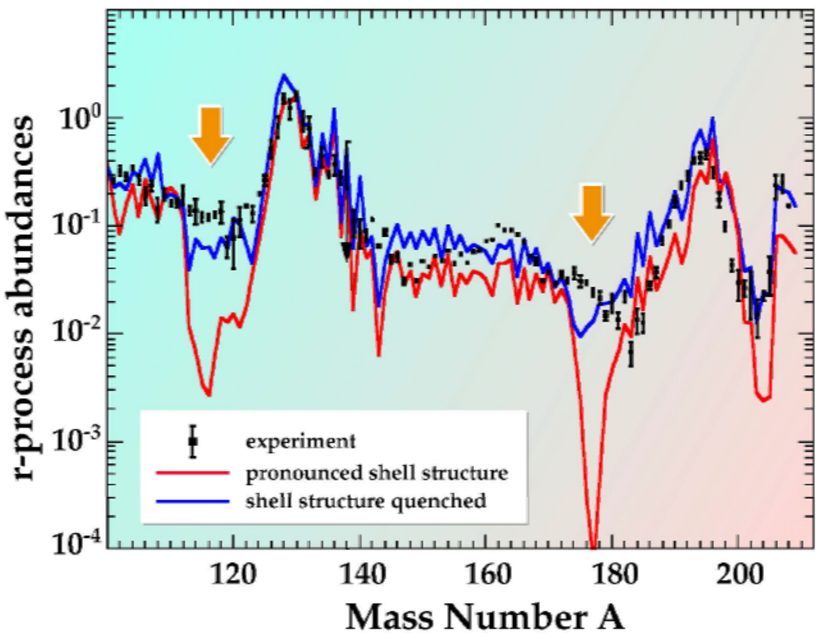
With data sets derived from mass formulas as the ones of “Hilf” or “v. Groote” from the end of the 70’s quite satisfying results were obtained.



Surprisingly, more sophisticated mass models (as from macroscopic-microscopic approaches) run into trouble. Troughs prior to the magic numbers indicated to the treatment of shell gaps.

New nuclear structure at drip-lines, as “shell quenching”?

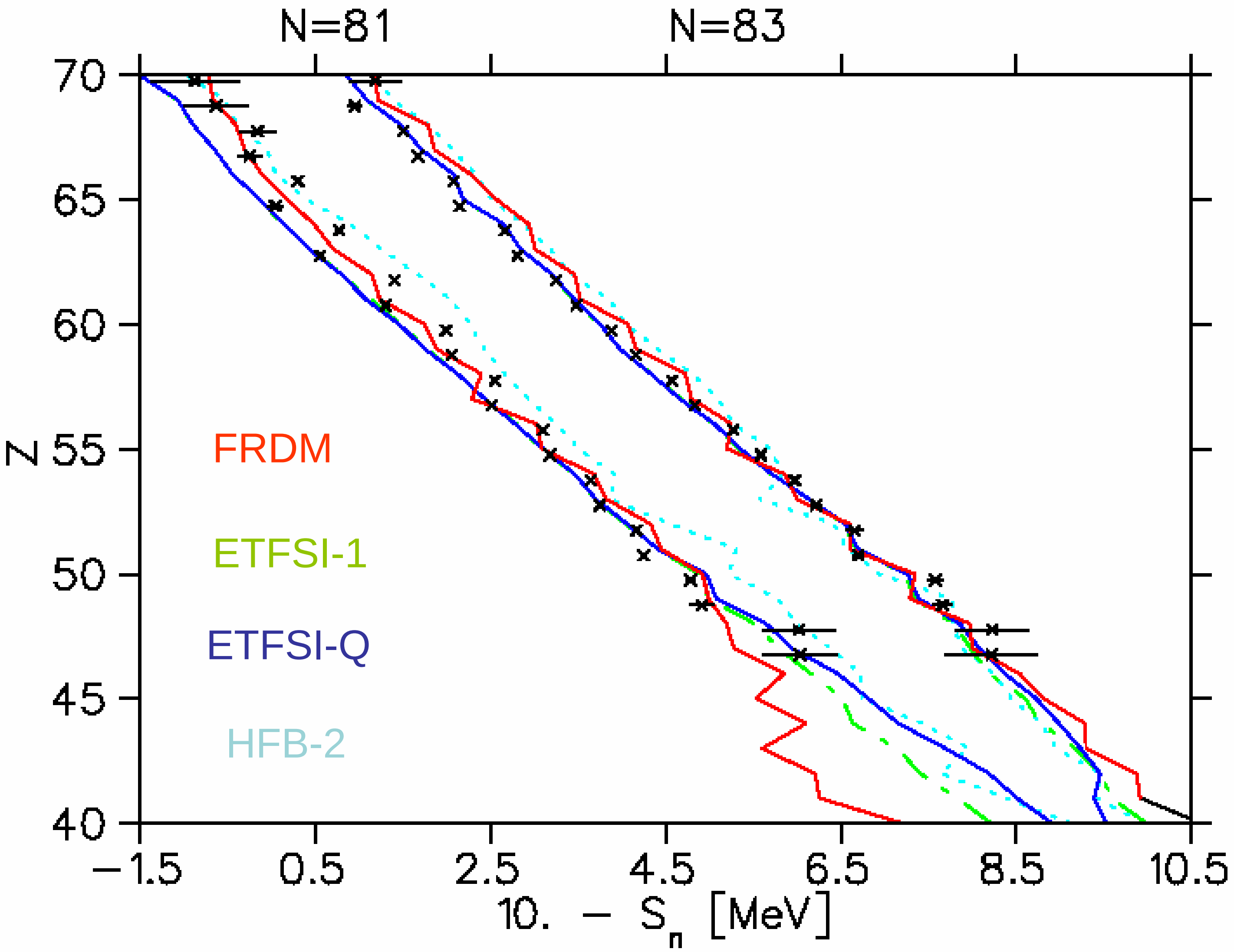
Defiencies prior to the main peaks were attributed by our group to nuclear structure effects:
- too strong shell strength for extremely neutron-rich magic nuclei far from stability
- nuclear models adjusted to stable nuclides
- weakening of N=28 and 50 shell gaps had been observed previously
- mass model based on SkP force yielded “quenching” [Dobaczewski, PRL 72 (1996) 981]

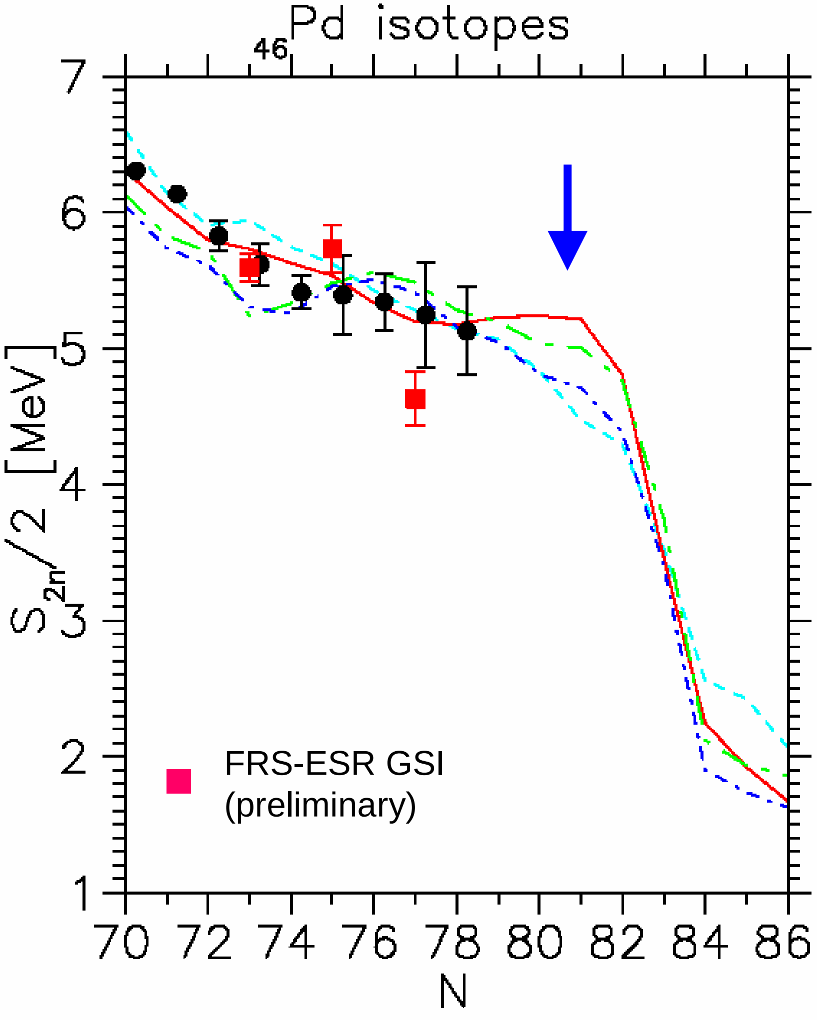


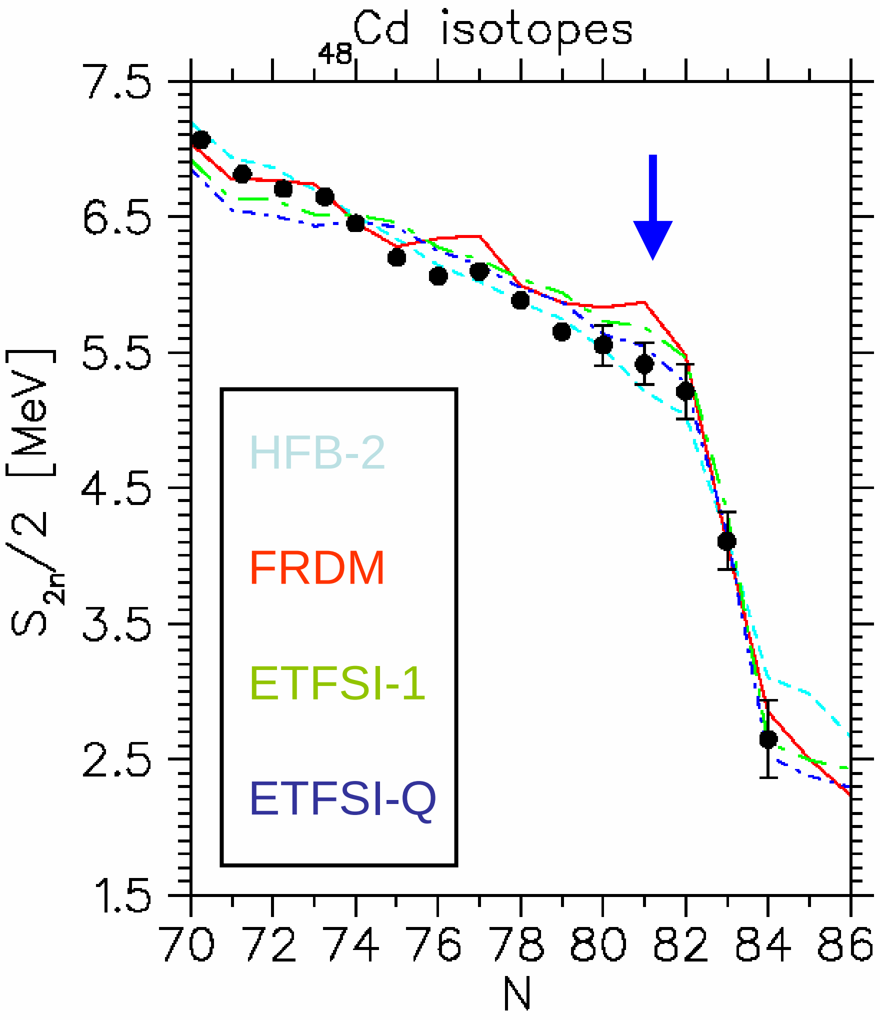
Question:
Can one learn neutron-dripline physics from astrophysical observables?

K.-L. Kratz, Ap.J. 403 (1993) 216

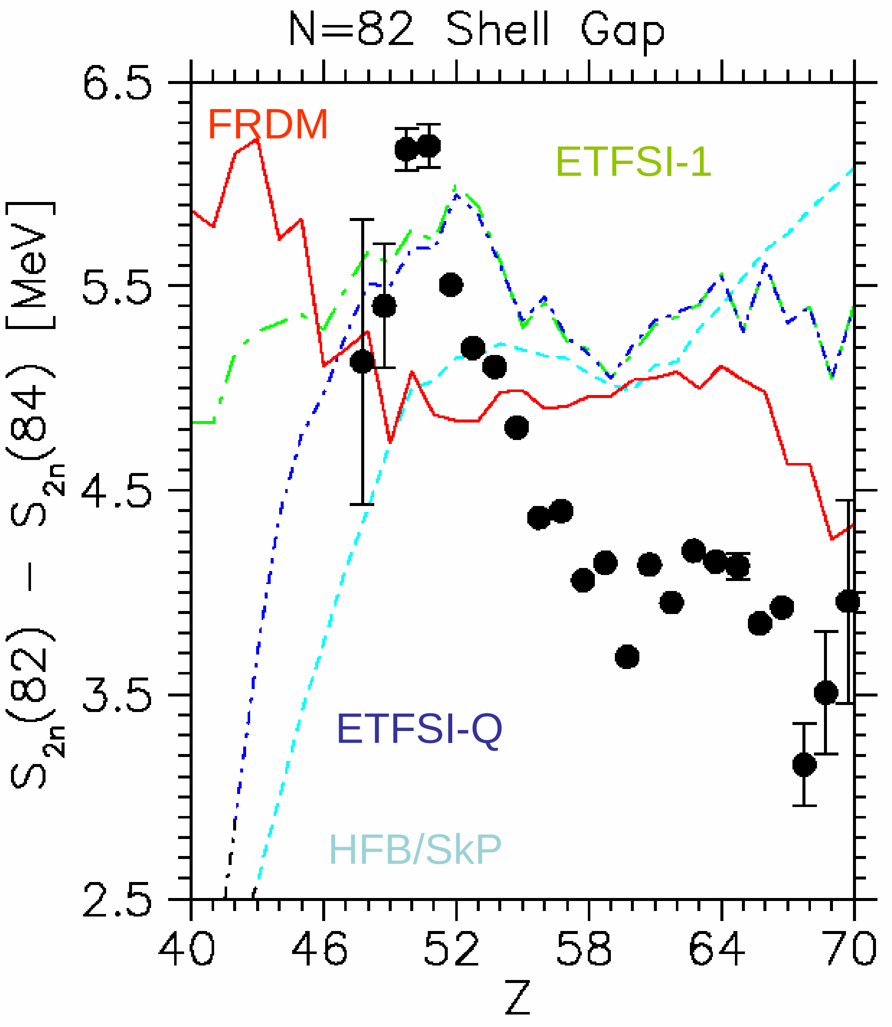
N=82 Shell Gap



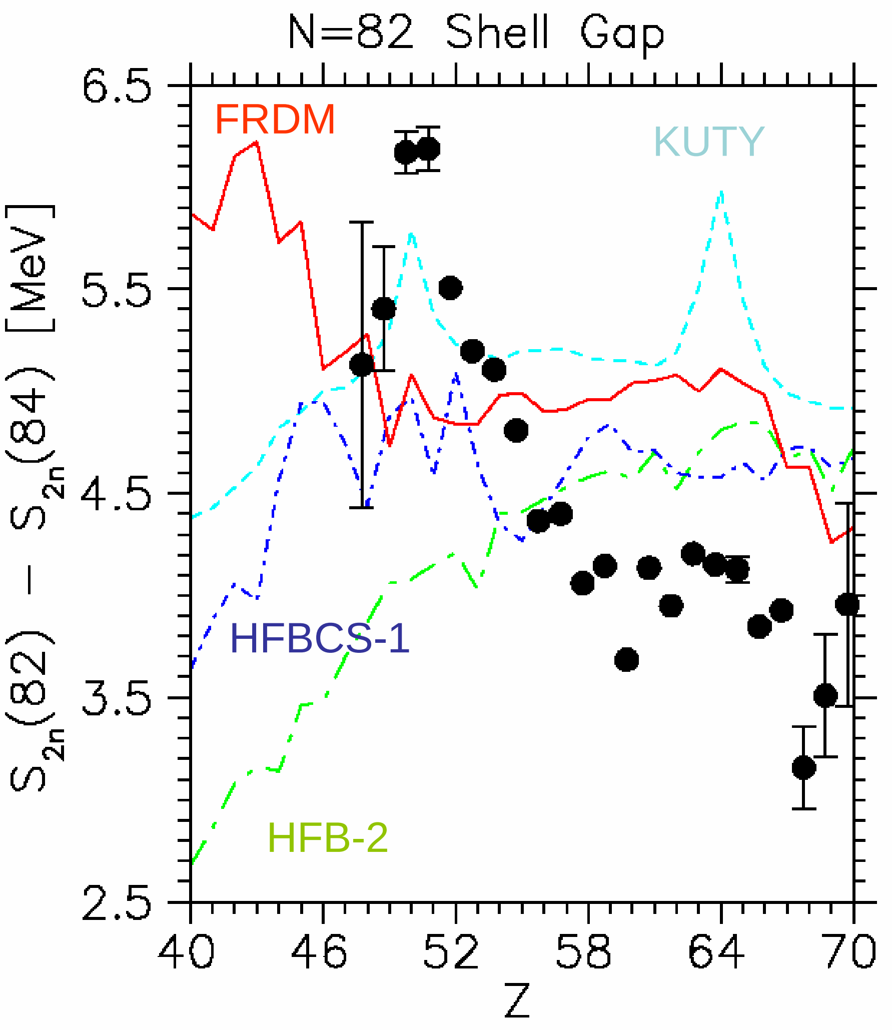

46Pd isotopes
S2n/2 [MeV]
7
6
5
4
3
2
1
70 72 74 76 78 80 82 84 86
N
🟥 FRS-ESR GSI
(preliminary)


48Cd isotopes
S2n/2 [MeV]
7.5
6.5
5.5
4.5
3.5
2.5
1.5
70 72 74 76 78 80 82 84 86
N
HFB-2
FRDM
ETFSI-1
ETFSI-Q

N=82 Shell Gap

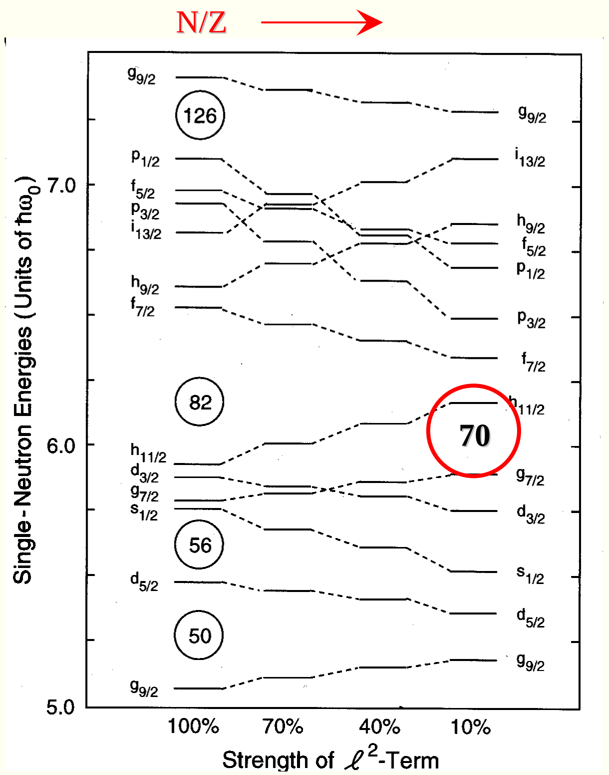


N=82 Shell Gap

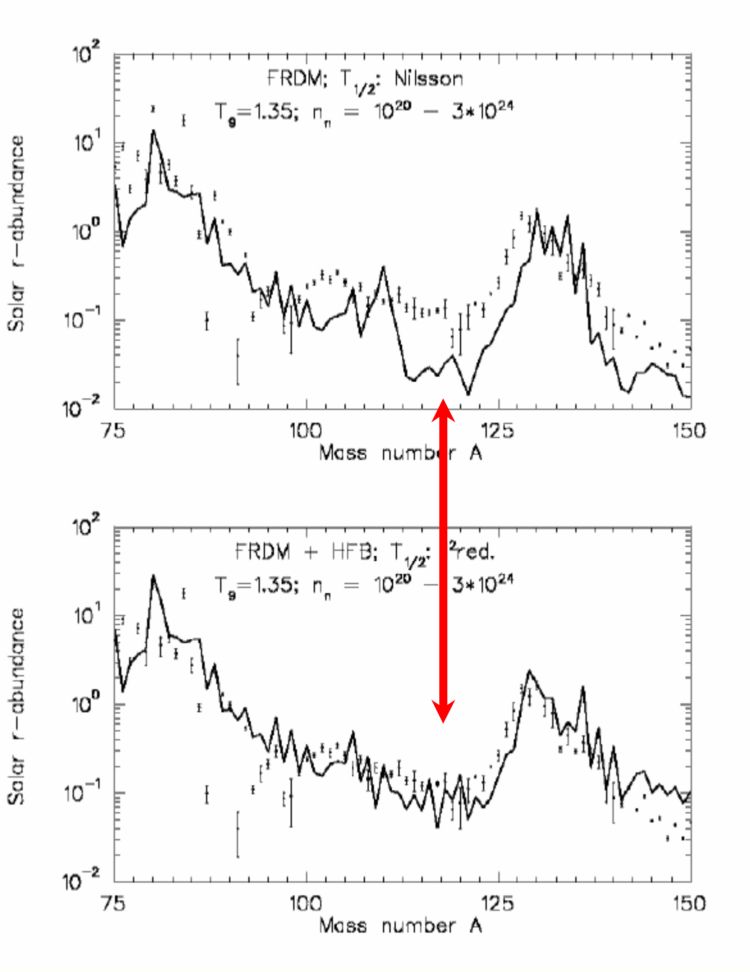


KUTY: H. Koura, M. Uno, T. Tachibana, and M. Yamada
Nucl. Phys. A674 (2000) 47

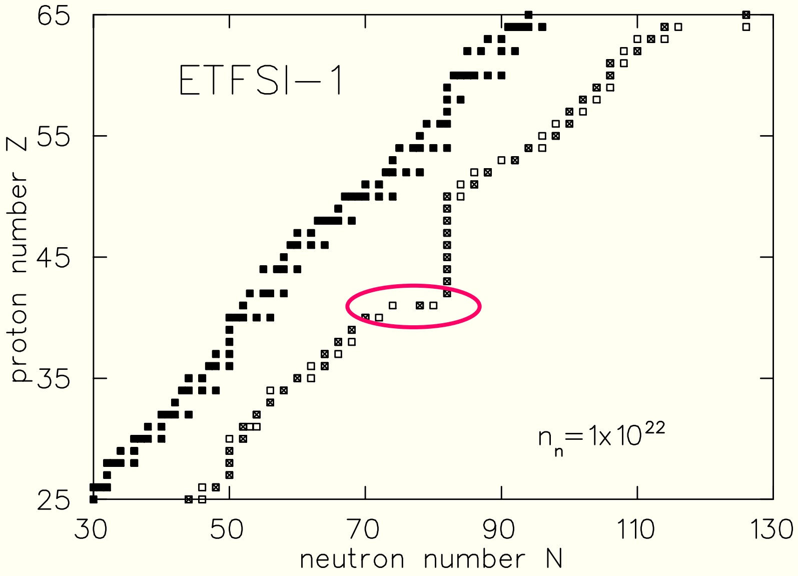
- The weakening (quenching) of the shell gaps can be simulated by reducing the l^2-term in the Nilsson potential
- The trough in the abundances prior to N=82 vanishes

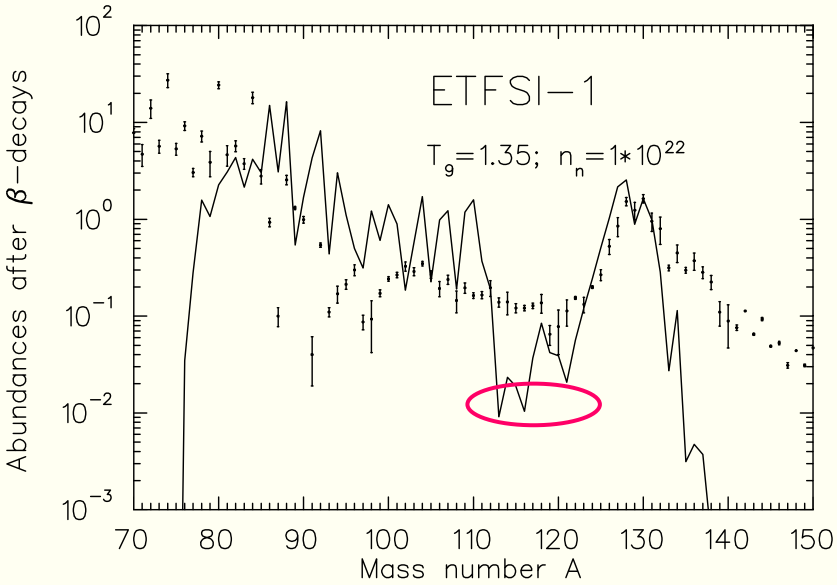


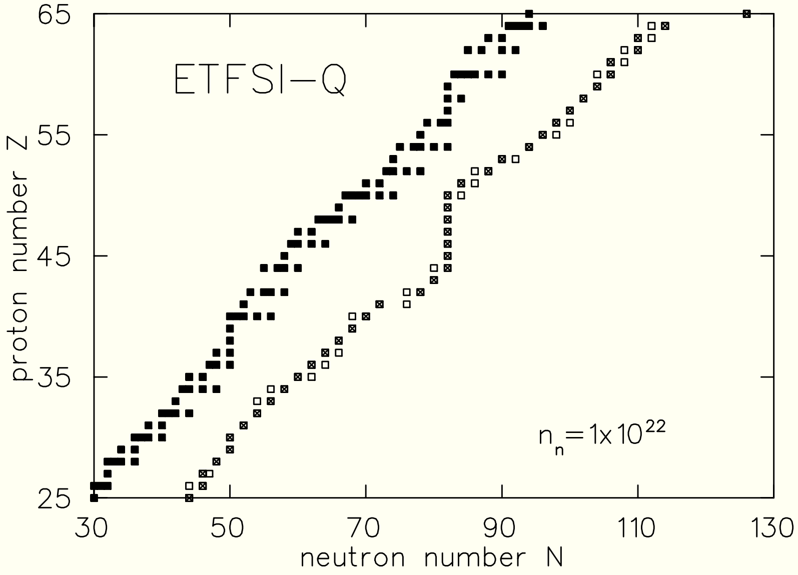
New magic numbers at the drip-line?

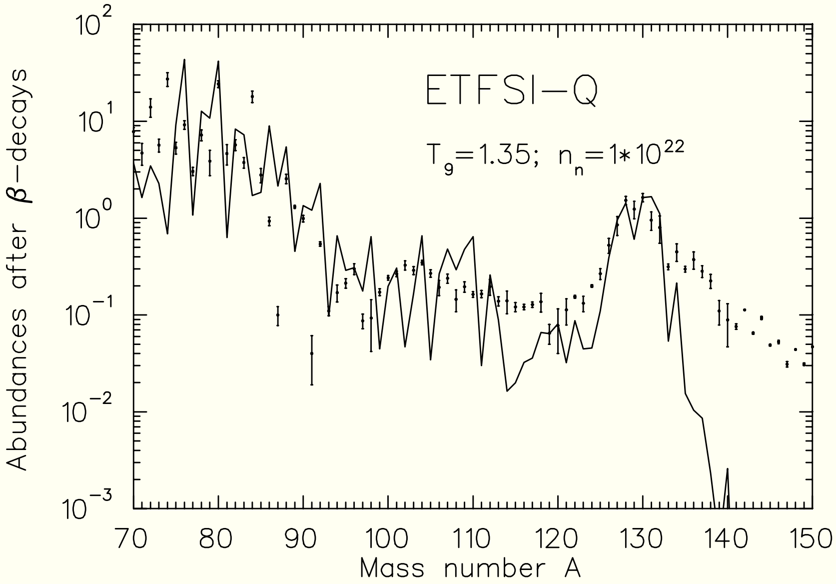


B. Pfeiffer et al., Acta Physica Polonica B27 (1996) 475



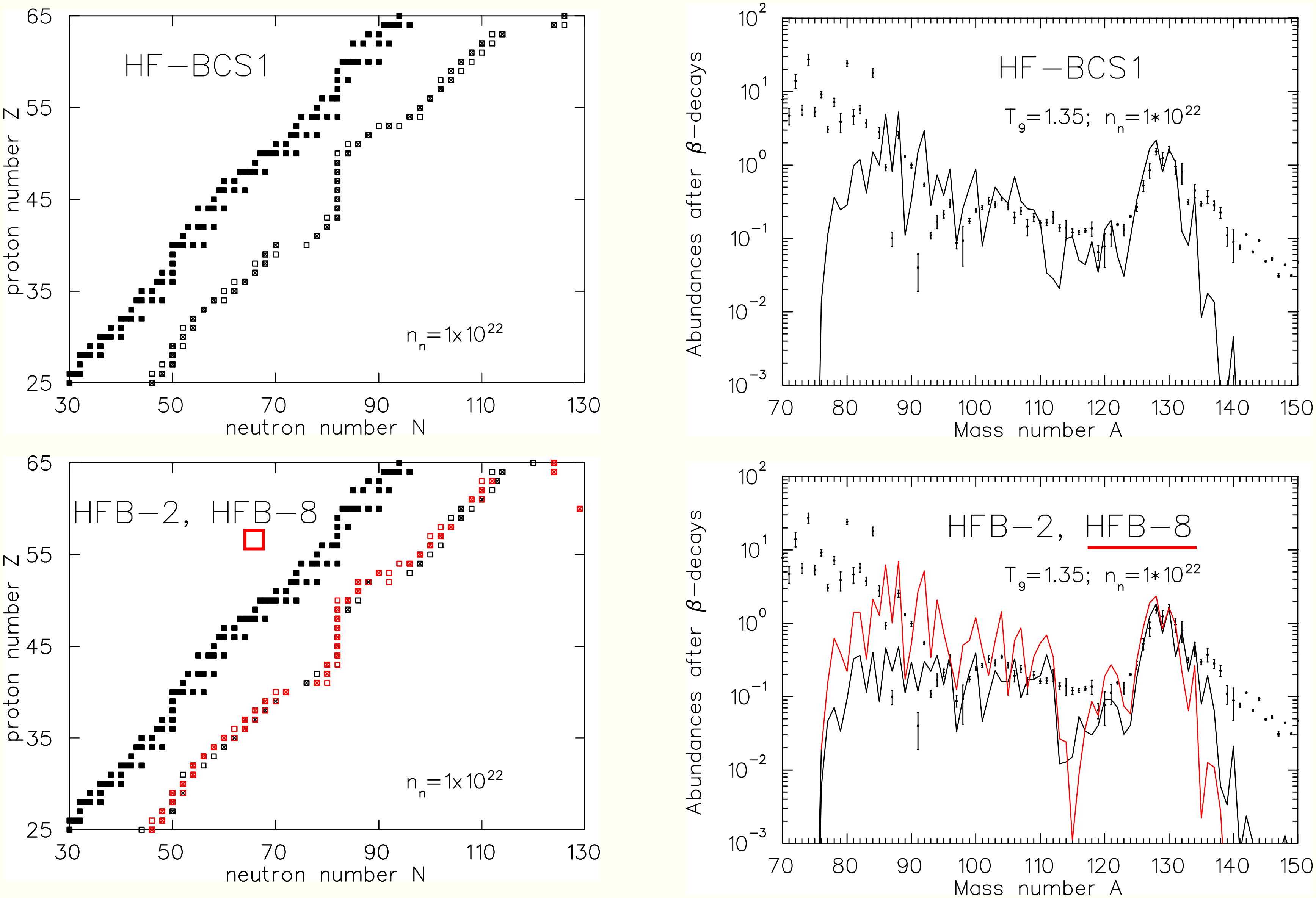




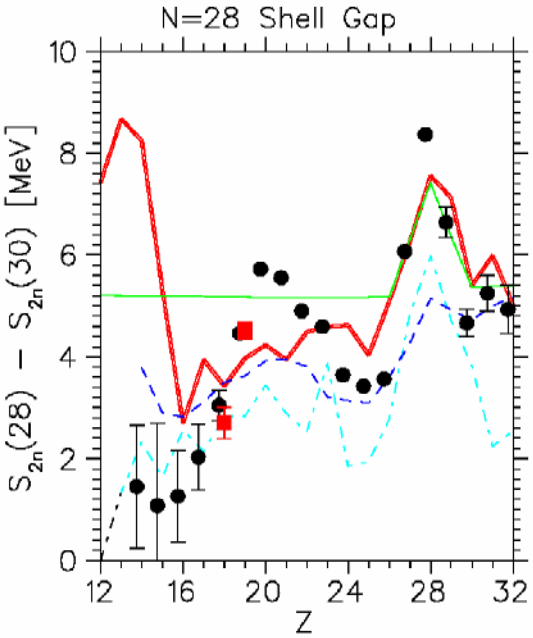


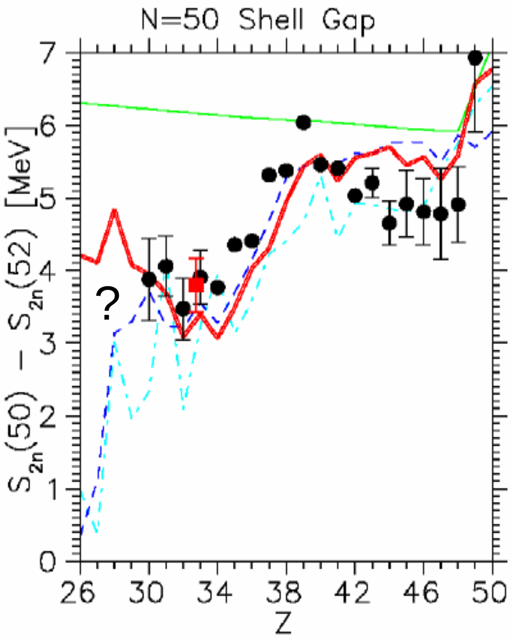
The “shell quenching” of the HFB/SkP model was heuristically overlaid to the ETFSI-1 model

ETFSI-Q



In the last years, the Brussel-Montreal group has released several selfconsistent mass models.


N=28 Shell Gap

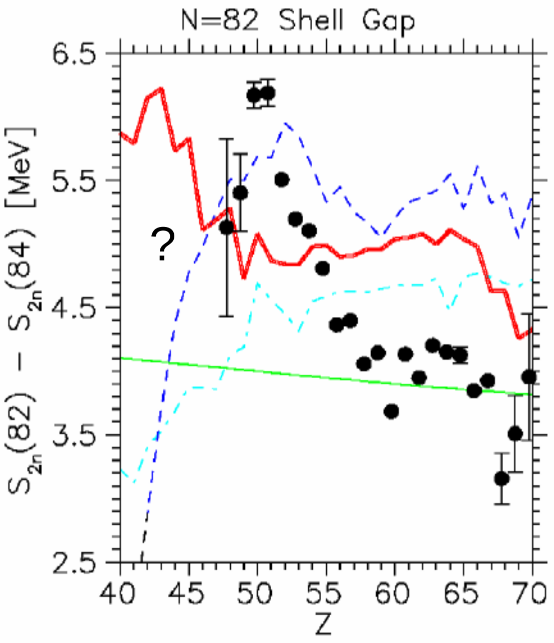

N=50 Shell Gap

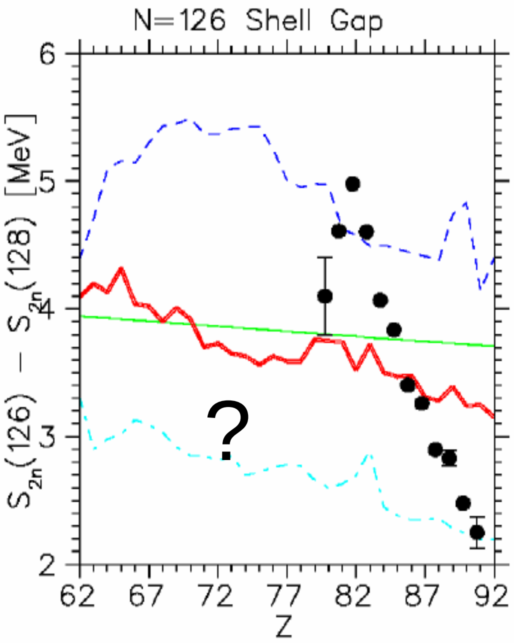
FRDM

Hilf

ETFSI-Q

HFB-8

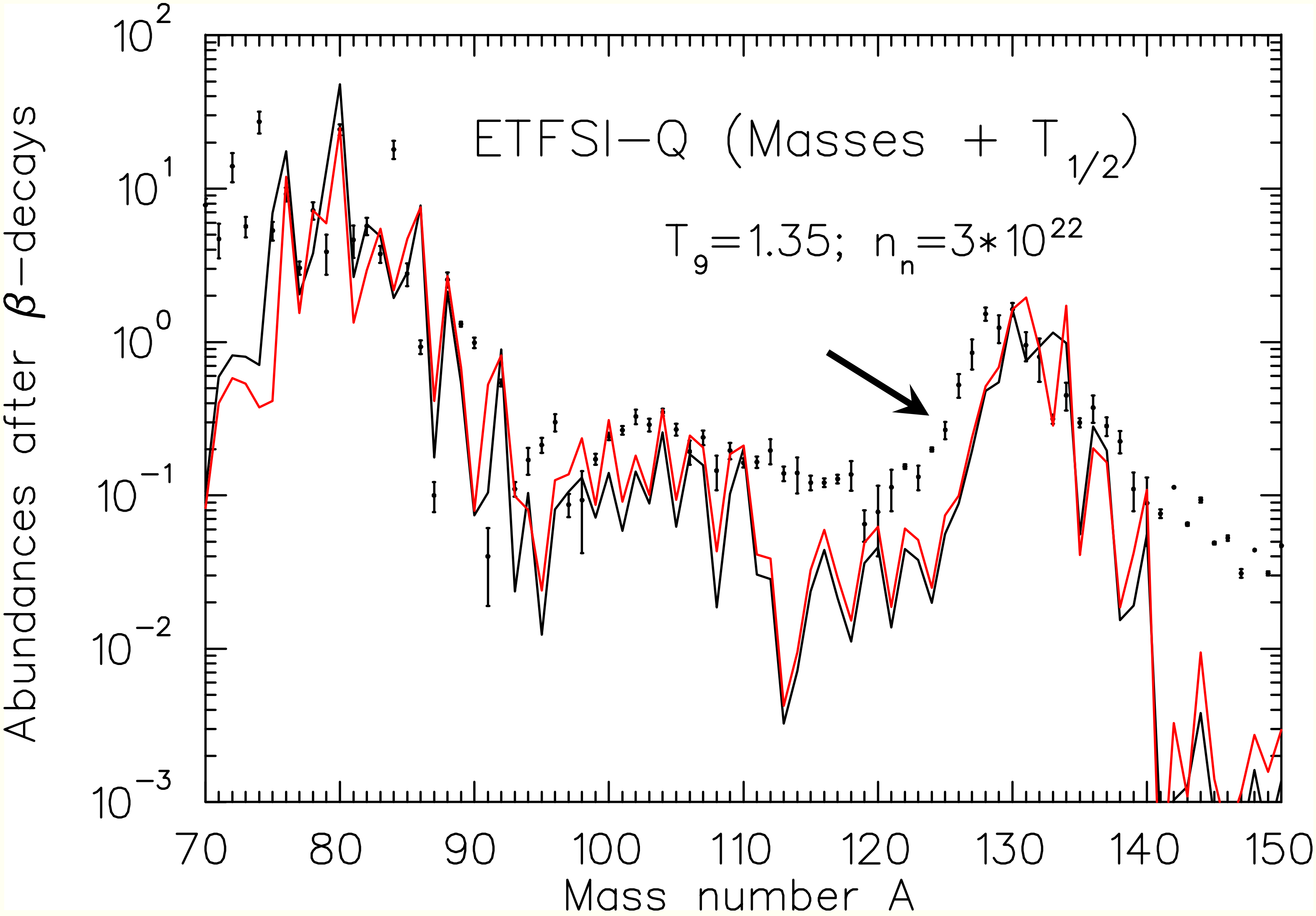

N=82 Shell Gap


N=126 Shell Gap

There is an urgent need for mass measurements of neutron-rich nuclei.

Black line: theoretical masses and $T_{1/2}$, P_n (GT+ff)

Red line: overlay of experimental $T_{1/2}$, P_n

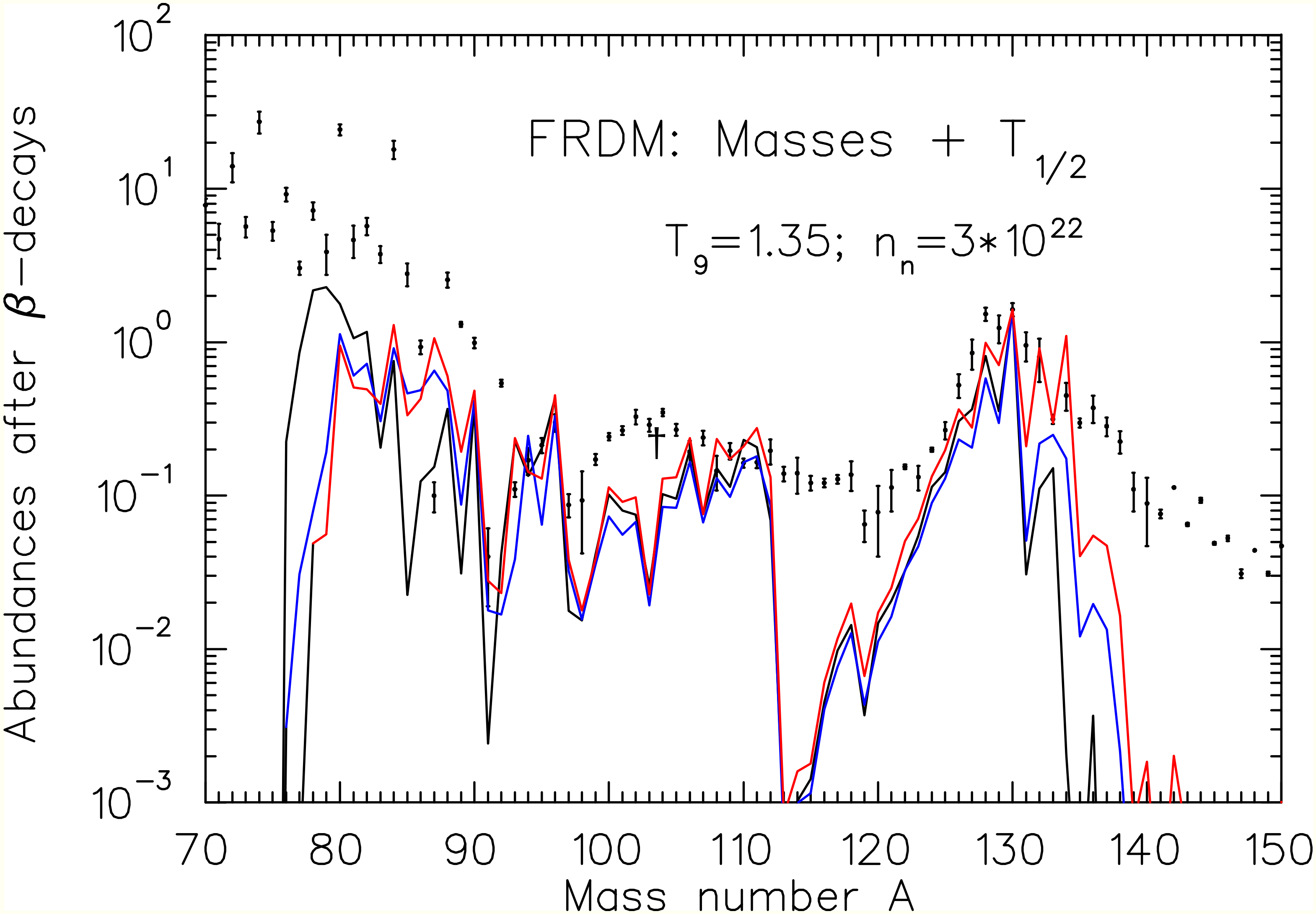


There is a problem with the left wing of the A=130 peak. $T_{1/2}$ too short.

Black line: theoretical masses and $T_{1/2}$, P_n (GT) †

Blue line: plus ff-decay

Red line: overlay of experimental $T_{1/2}$, P_n



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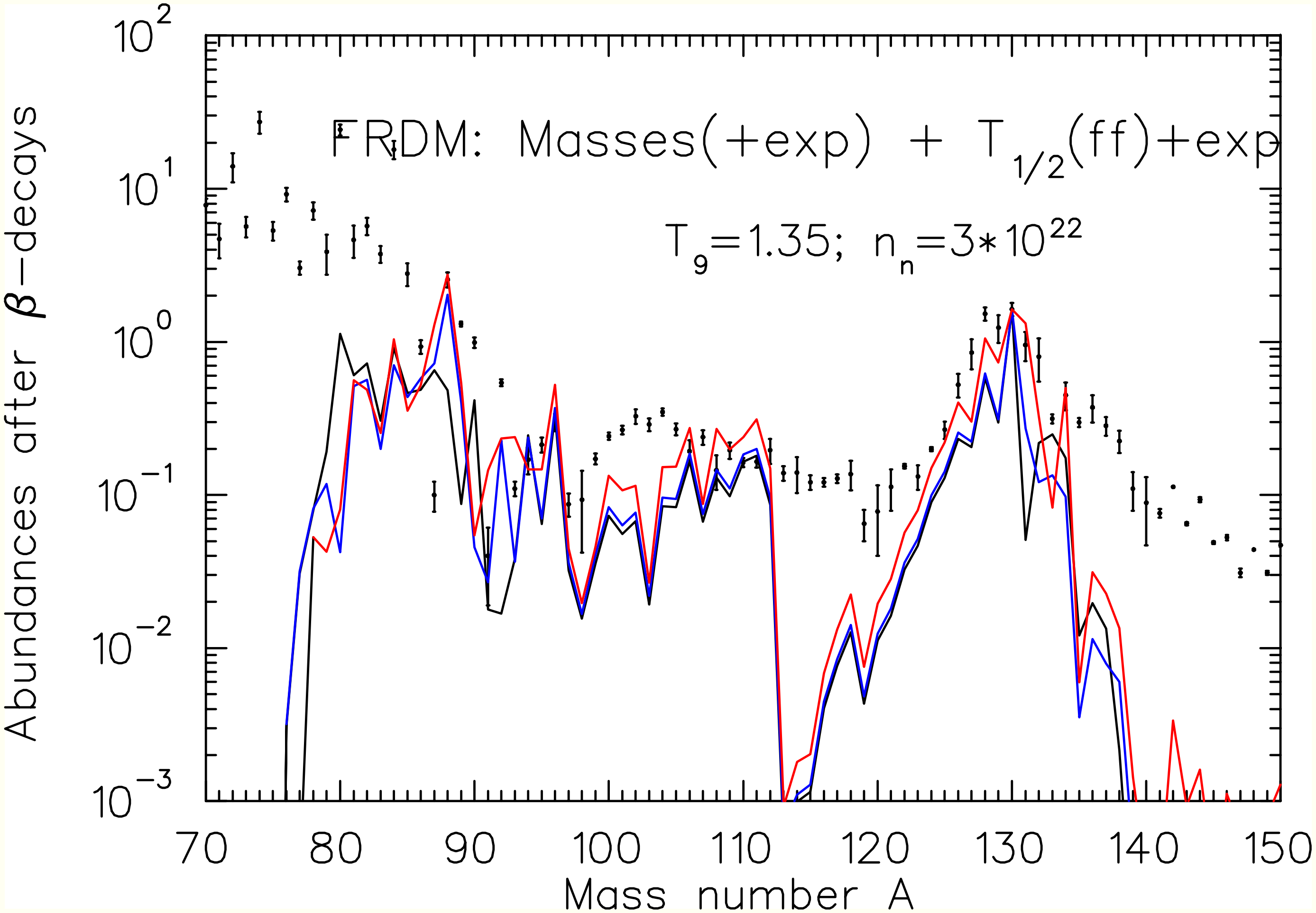
† Möller, Nix, Kratz; ADNDT 66 (1997) 131

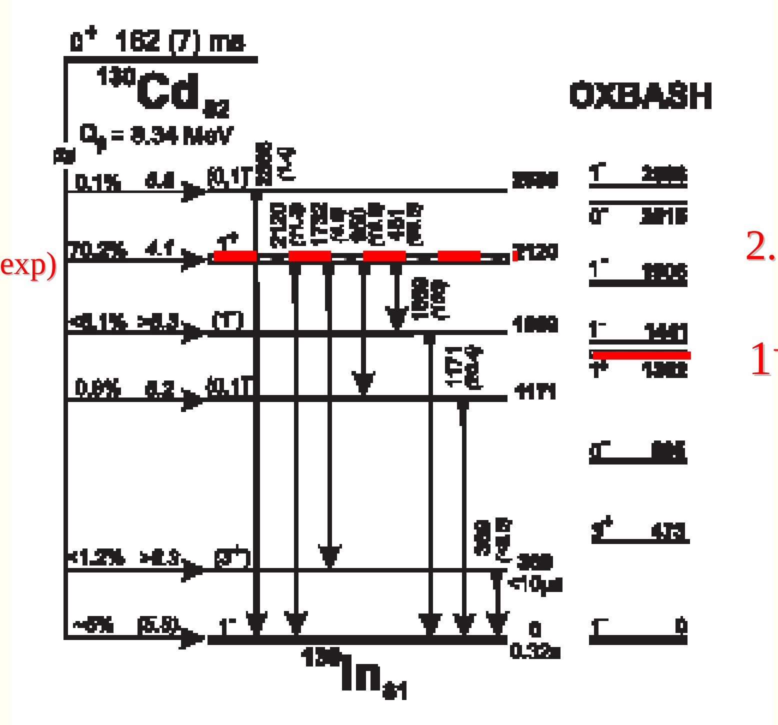
Black line: theoretical masses and $T_{1/2}$, P_n (Gt+ff)
Blue line: overlay of experimental masses
Red line: plus overlay of experimental $T_{1/2}$, P_n



Detailed spectroscopy of r-process “waiting-point” nucleus ^{130}Cd: N=82 shell-quenching

Nuclear-physics “surprises”

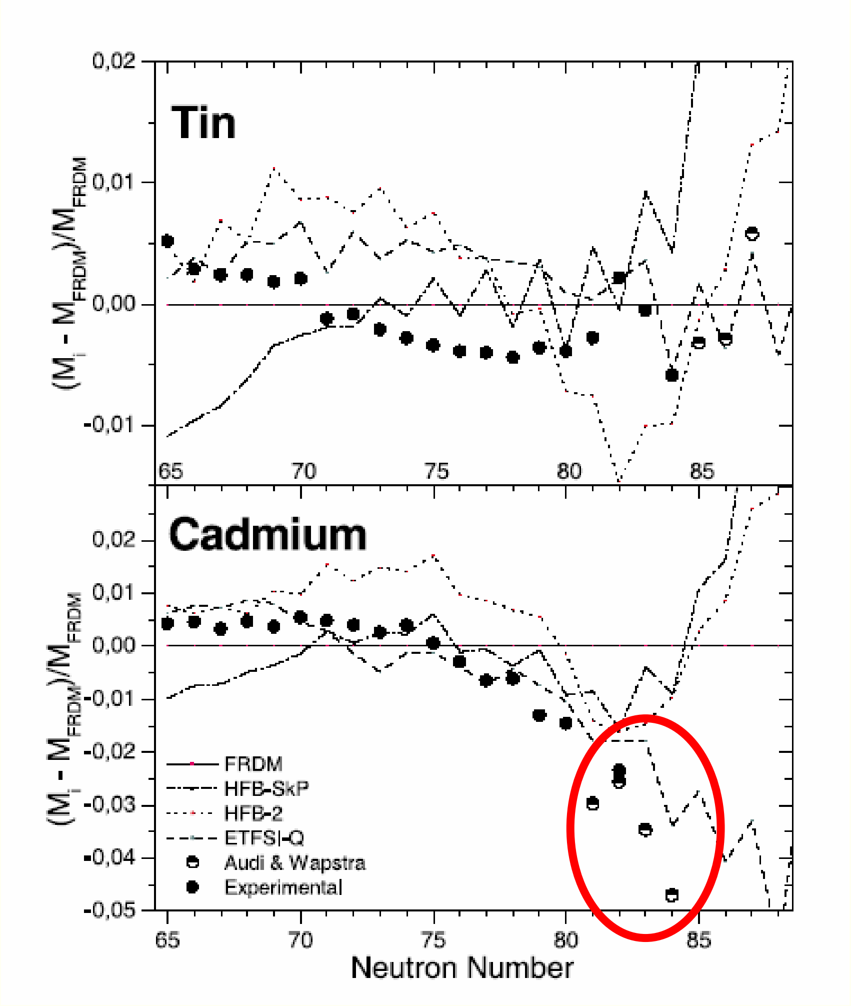
- high excitation energy of 1^+ level
- high Q_β -value of 8.34 MeV



1^+ (exp)

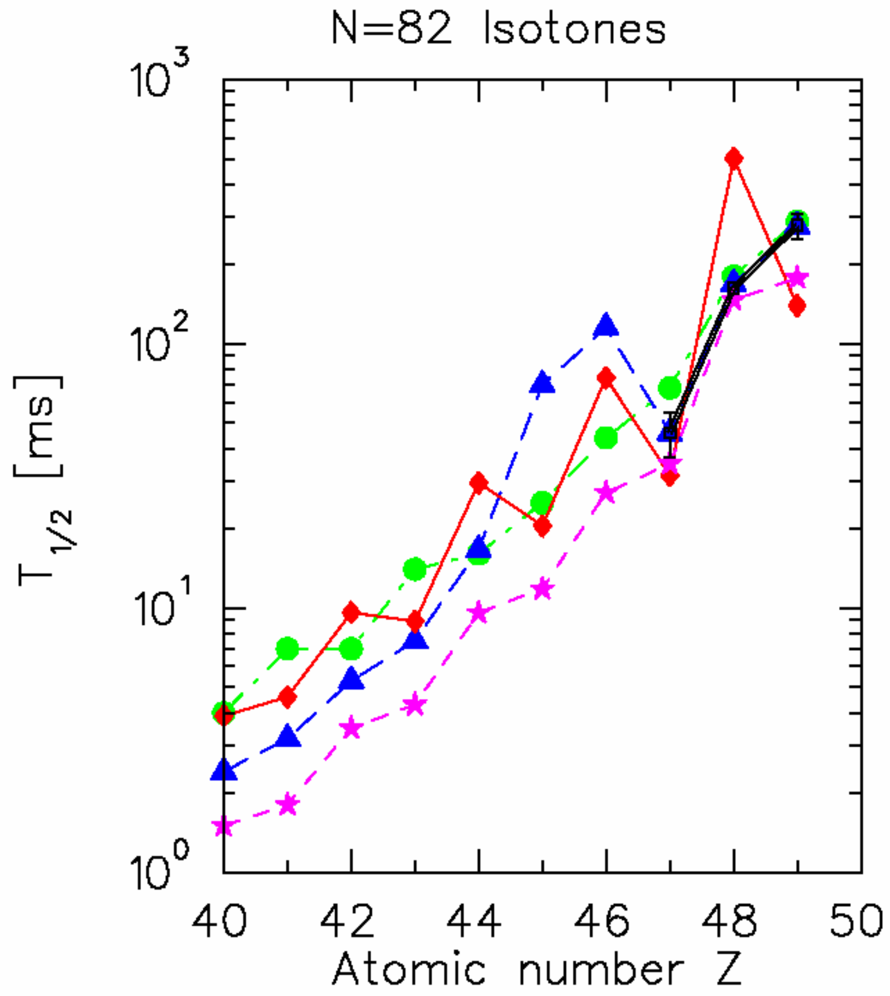
2.12 MeV

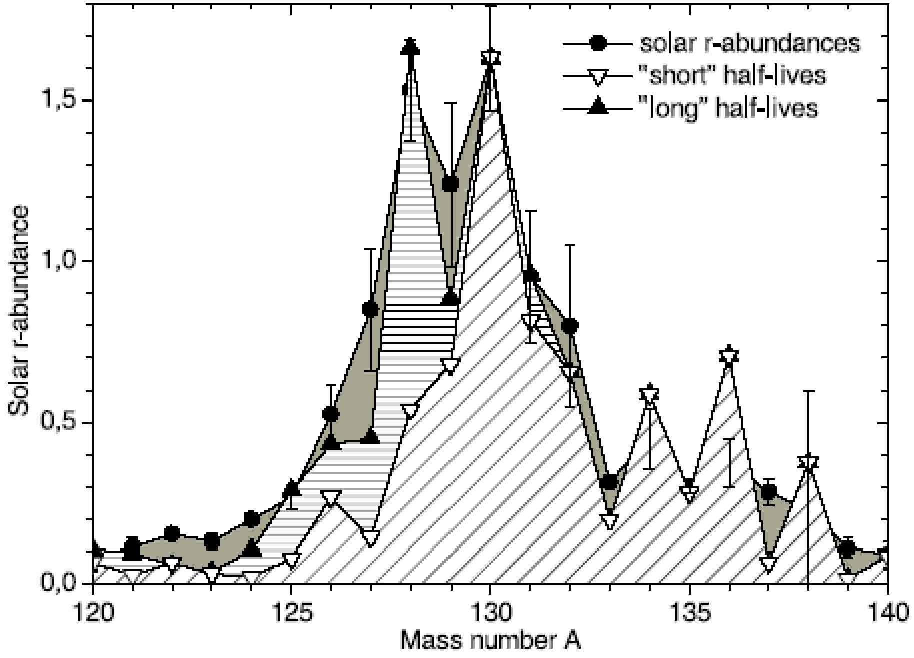
1^+ (theor.)



Comparison with mass models

I. Dillmann et al., Phys. Rev. Lett.91, 162503 (2003)





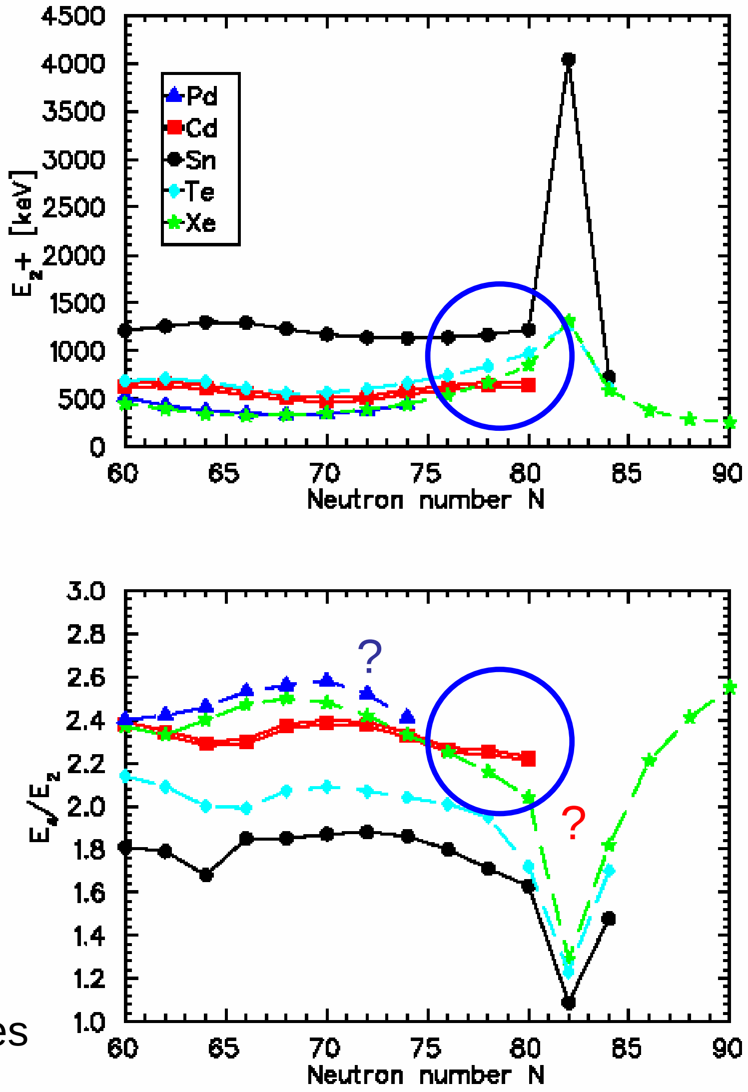
Applying the s-p energies, which reproduce the high-lying 1^+ state in ^{130}Cd, to the N=82 isotones lying in the left-wing of the A=130 abundance peak, leads to longer $T_{1/2}$ than from large-scale calculations, yielding a much better fit to the observed abundances.

Black line: experimental values
Red diamonds: Möller et al., Phys.Rev. C67, 055802 (2003)
Green circles: A. Brown, to be published
Magenta stars: Martinez-Pinedo, Langanke, PRL 83, 4502 (1999)
Blue triangles: KCh Mz, int. rep.

I. Dillmann et al., Phys. Rev. Lett.91, 162503 (2003)

Indications to “shell quenching” from γ-spectroscopy

E_2+ and E_4+/E_2+ for neutron-rich Cd isotopes show a different trend compared to neighbouring elements. Cd-130 and higher-mass Pd ?
[T. Kautzsch et al., EPJ A9 (2000) 201]



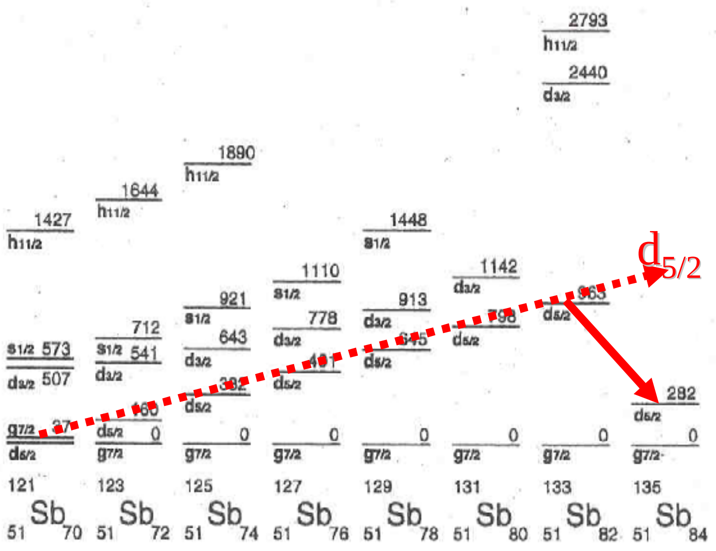


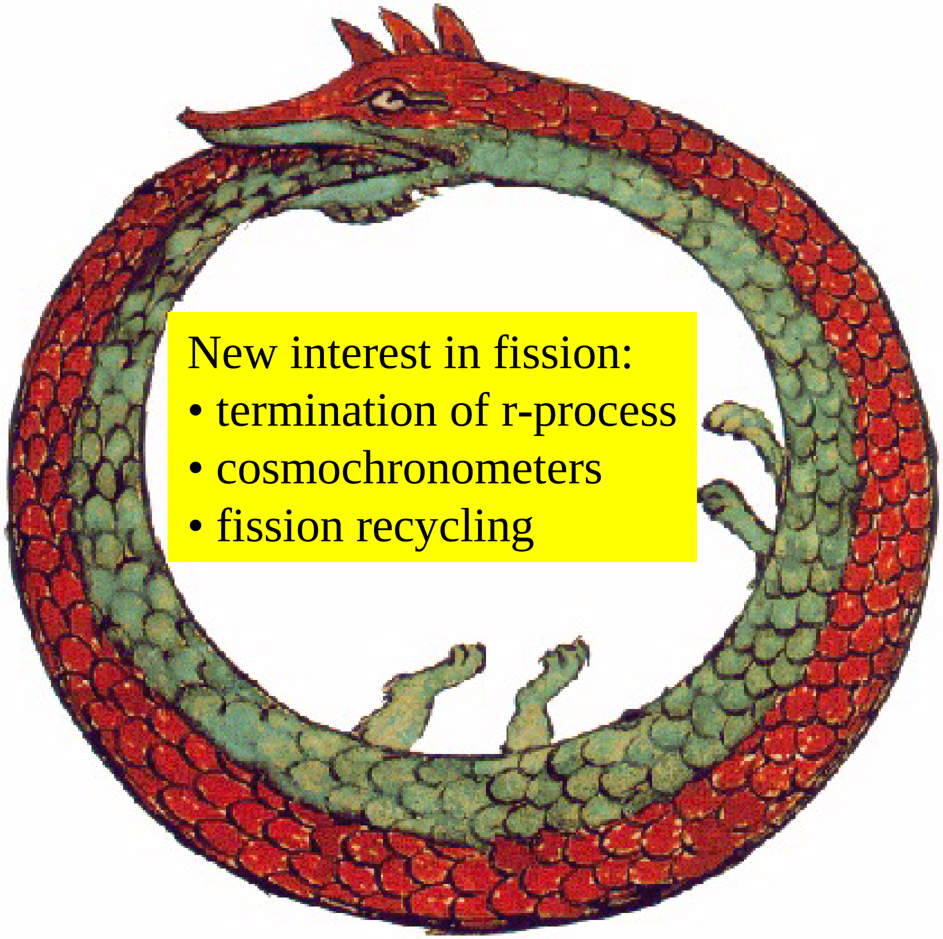
FIG. 13. Level systematics of the neutron-rich odd-mass Sb isotopes.

$T_{1/2}$ of very neutron-rich Sn isotopes were unexpectedly short due to a change in the systematic of low-lying states
[J. Shergur et al., Phys. Rev. C65 (2002) 034313]

universität mainz

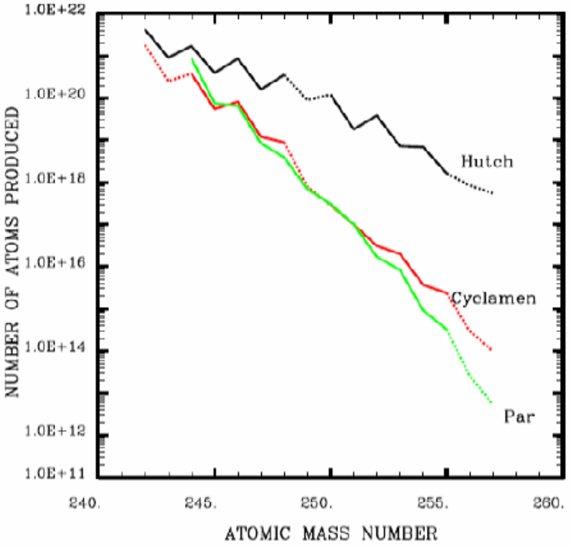
Program Plowshare
“Atoms for Peace”

Sedan test, 1962



New interest in fission:

- termination of r-process
- cosmochronometers
- fission recycling



Up to 19 successive neutron captures yielded Fm-257.

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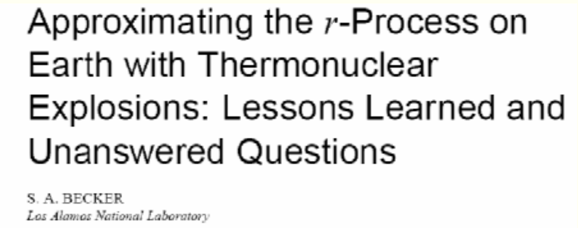


Approximating the r-Process on Earth with Thermonuclear Explosions: Lessons Learned and Unanswered Questions

S. A. BECKER
Los Alamos National Laboratory

Prior to the “Test Ban Treaty” subterranean nuclear tests often involved experiments on the “prompt capture process”.
As long as there are no further experiments possible, one has to rely on theoretical predictions.

http://www.ociw.edu/ociw/symposia/series/symposium4/proceedings.html)

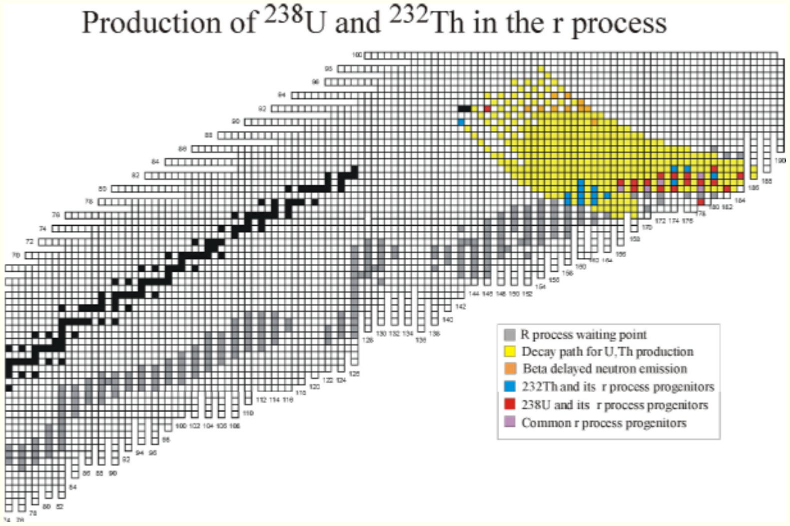
Parisinus graecus 2327, fol. 279 Bibl. Nat., Paris

JINA

Progenitors of the Actinides

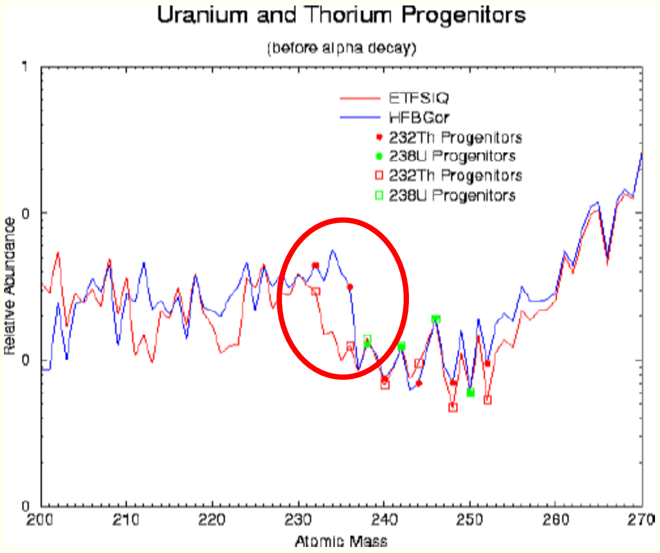
After freeze-out, the extremely neutron-rich nuclei undergo β-, β-del. n-, β-del. fission-, sp. fission decay

- New attempts to include β-del. fission decay by Schatz et al., I.V. Panov et al., …
- Extended studies underway



Progress in mass modeling required:

- Production ratios even of close-lying nuclides as ^{232}Th and ^{238}U differ considerably when applying different mass models. (ETFSI-Q versus HFBCS-1)

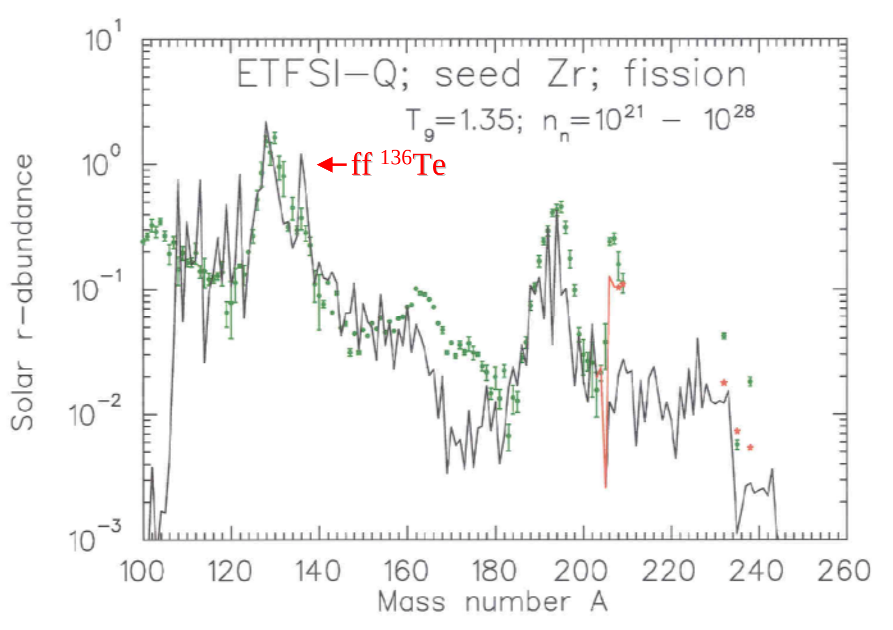


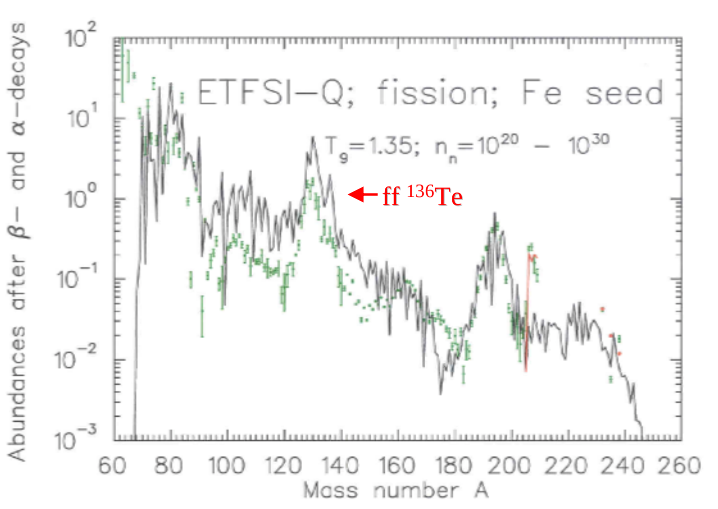
H. Schatz et al., Ap. J. 579 (2002) 628; I.V. Panov et al., Nucl. Phys. A747 (2005) 633

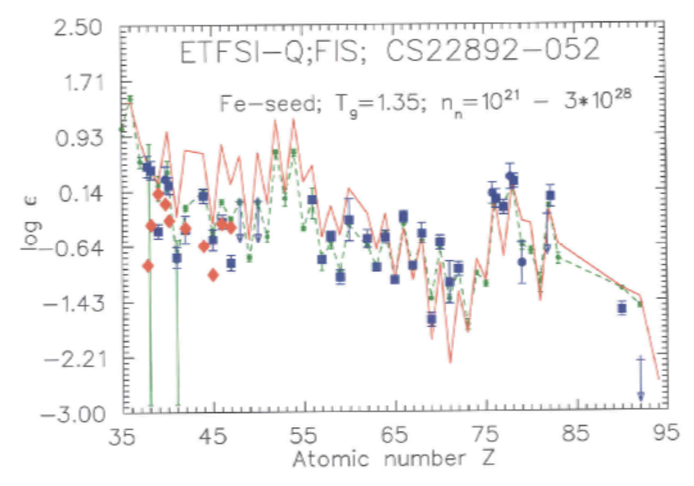
Examples for influence of fission

Attempt to include spontaneous and β-delayed fission modes

- very old data set
- no mass distribution of fission fragments
- no fission recycling





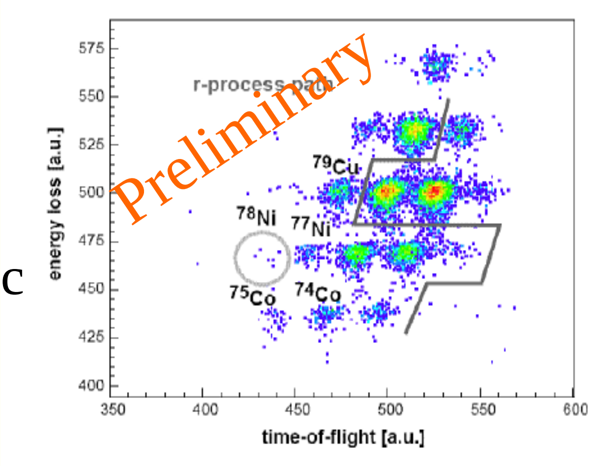


- No strong influence for SNII site for r-process
- Neutron star merger scenario has higher fluxes: Mass flow to fission region and recycling

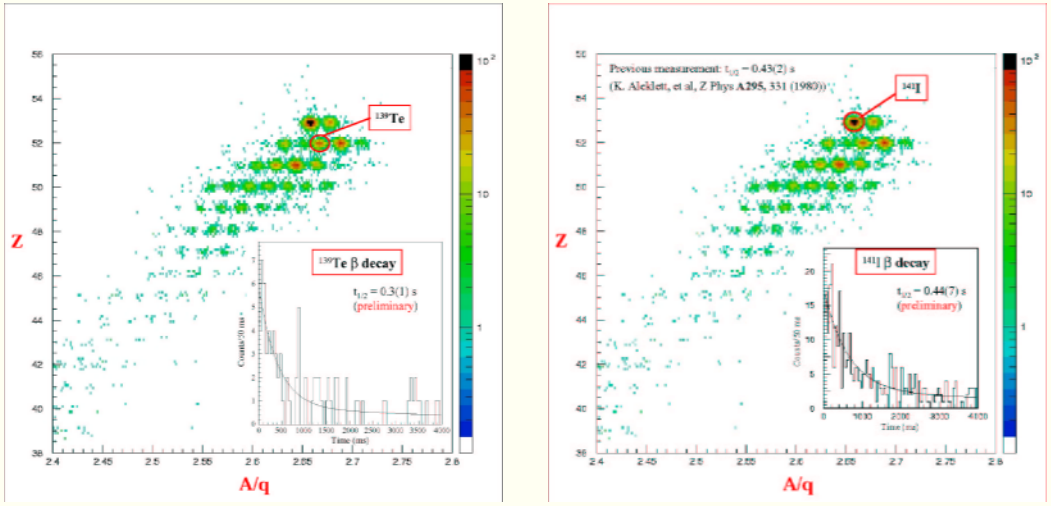
See, e.g. F.-K. Thielemann, J. Metzinger, H.V. Klapdor, Z. Phys. A309 (1983) 301

Radioactive Ion Beam Facilities

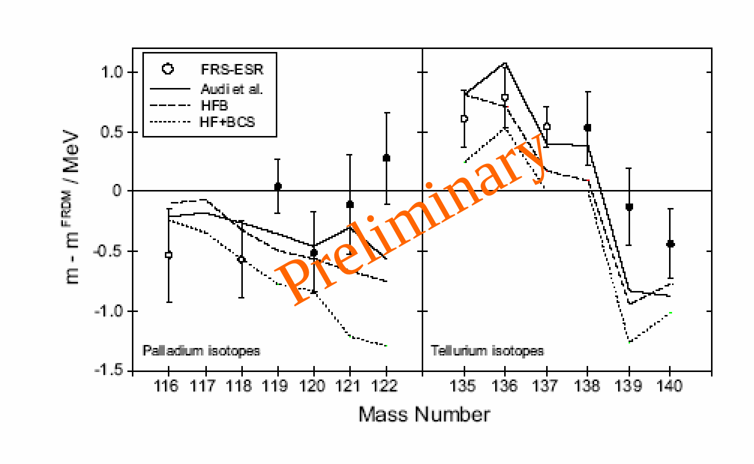
- In-flight separation of reaction (and fission) products offers new possibilities.
- Neutron-rich nuclei at N=50 and 82 have already been studied.
- Refractory elements in region of (low-yield) symmetric low-energy fission accessible.
- Future facilities will (hopefully) extend the studies to N=126 and beyond.



Decay of Ni-78 at NSCL



Decay of Te-139 and I-141 at FRS at GSI



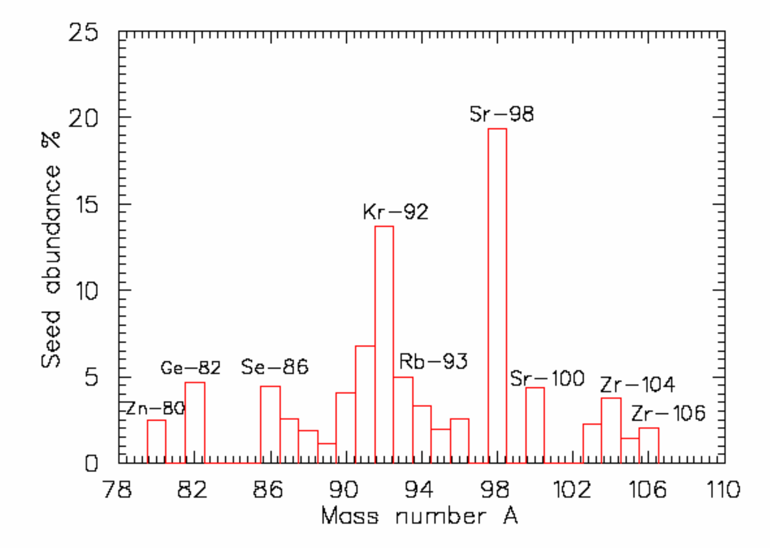
Masses of neutron-rich nuclei at FRS-ESR

This is a "recycled" page! In Session 4 (r-process experiments) we will hear about progress achieved in a short time.

Right figures from Proc. of RNB6; Nucl. Phys. A746 (2004)

Network calculations

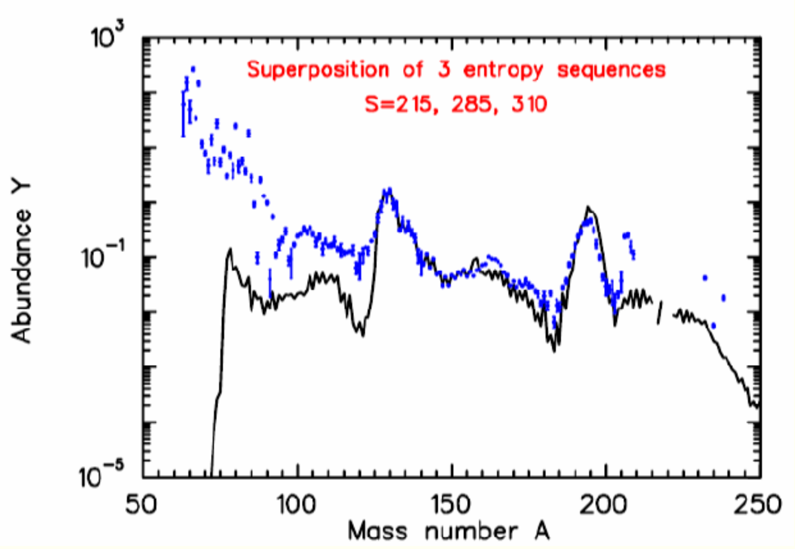
The approximations in the “canonical” model can now be refined by network calculations using the charged particle network of Thielemann and the r-process code of Freiburghaus (ApJ 516 (99) 381).



The seed nuclei composition after an α-rich freeze-out lies beyond the first “bottle-neck” at N=50 enabling a very “fast” r-process with time duration in the order of 200 ms.

First results are promising. The fit to the Solar distribution (blue) with the superposition of only 3 entropy components can reproduce the observations beyond A≈120, the region of the “main” r-process component.

See, K. Farouqi, Ph.D. Mainz, in preparation



K. Farouqi et al., Nuclei in the Cosmos VIII, in print

Future developments

- Further technological advances in production and selective separation of extremely neutron-rich isotopes needed,
  as has been achieved since the detection of the first r-process isotopes 20 years ago.
- First experiments in “critical” mass ranges as A ≈ 115 will be reported in this meeting
- Exploratory experiments in the region of N = 126 (the A ≈ 195 abundance peak) ought be feasible with existing facilities.
- Breakthrough to extremely neutron-rich isotopes will only occur with the advent of the future RIB facilities.
- Peaceful uses of subterranean atomic explosions might again be possible after 2006 (?)
- Further developments in mass modeling will be presented by Peter Möller

RIA at MSU

FAIR at GSI