Shell–model half–lives of r–process waiting–point nuclei

G. Martínez–Pinedo, K. Langanke

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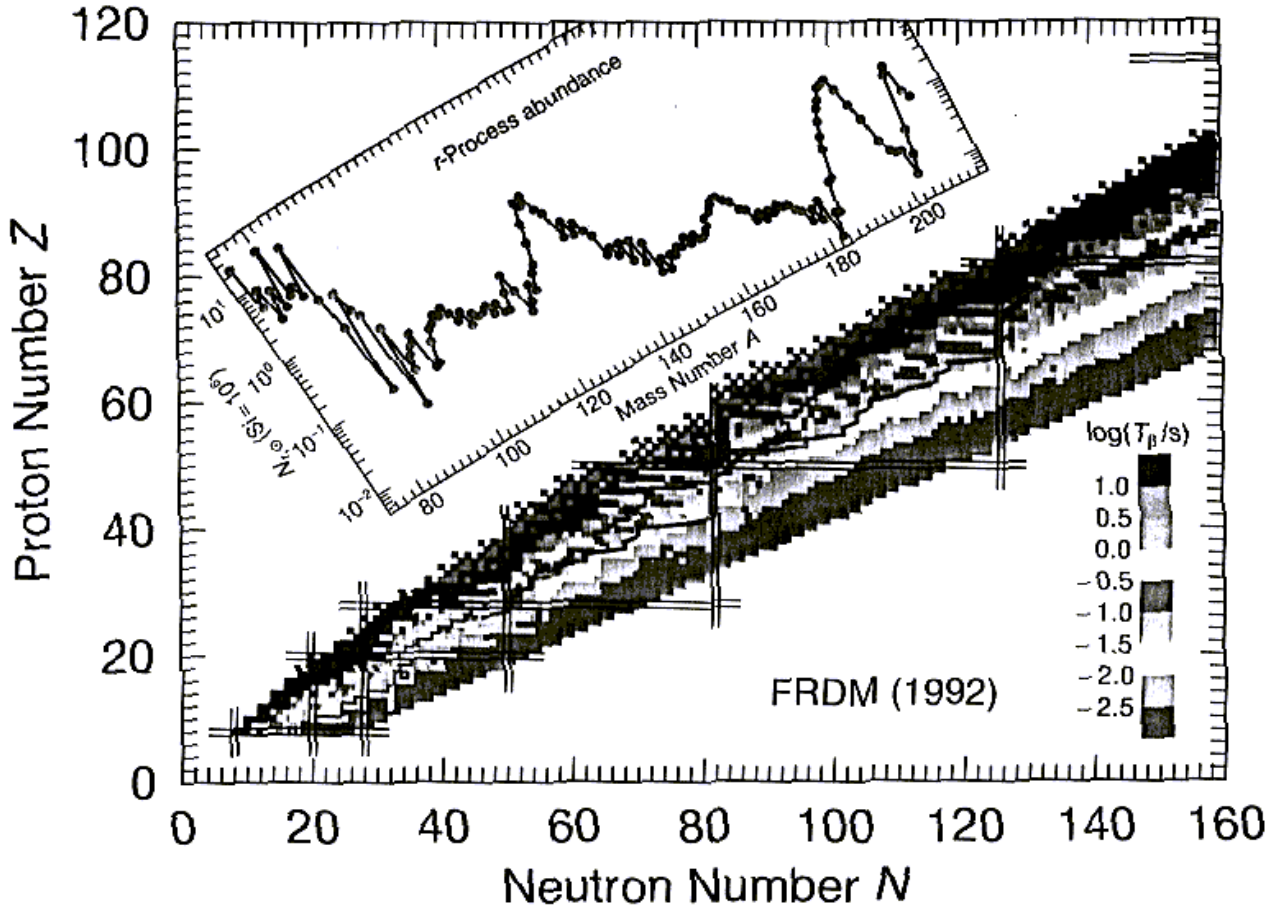
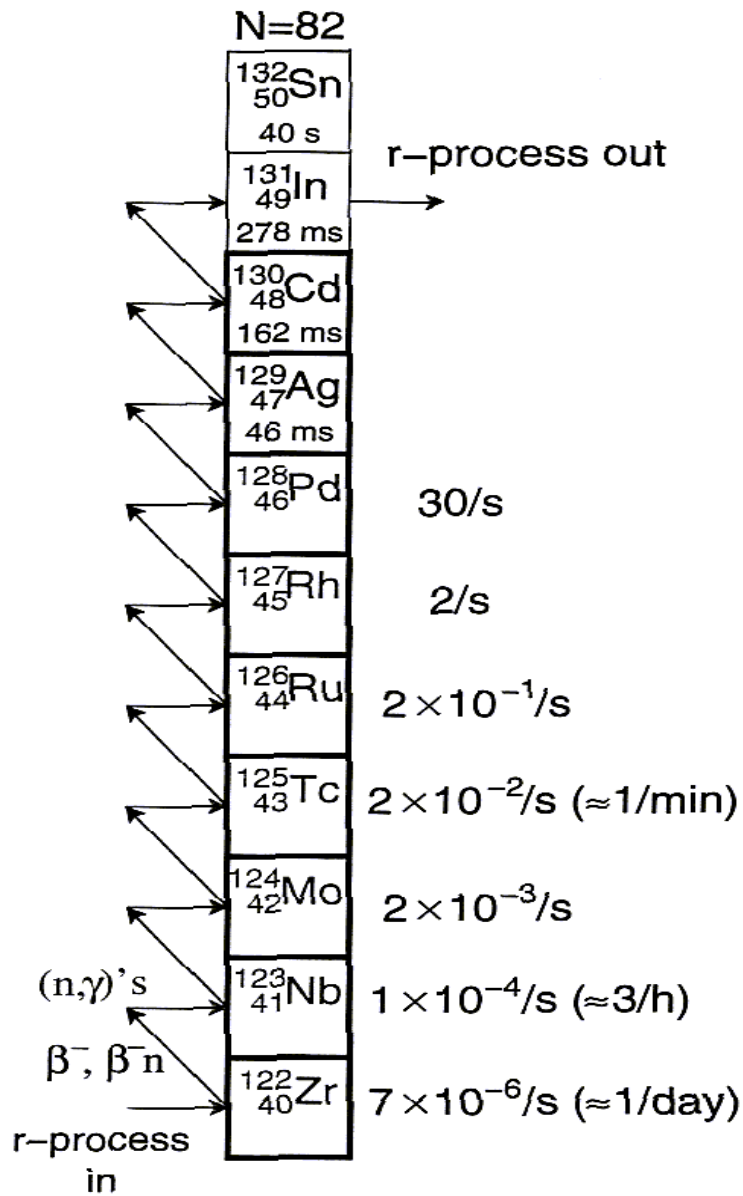
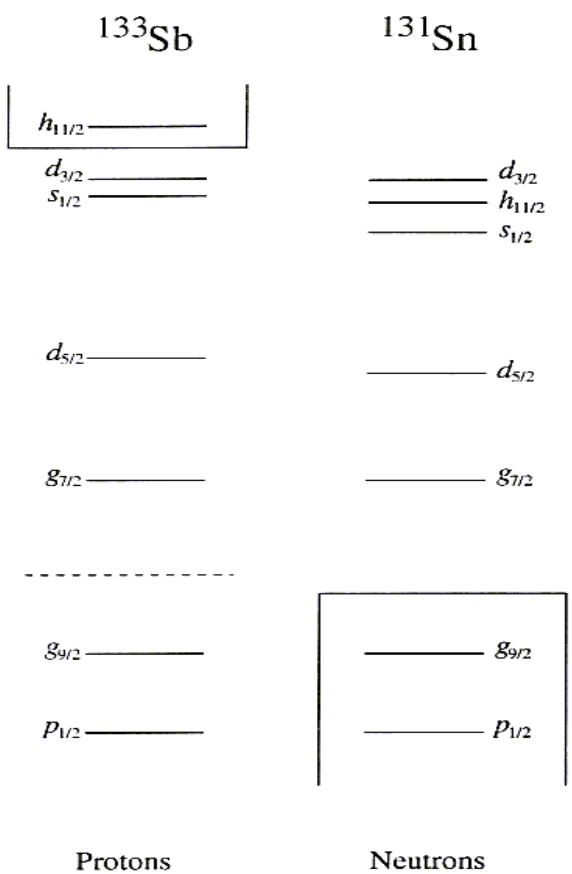


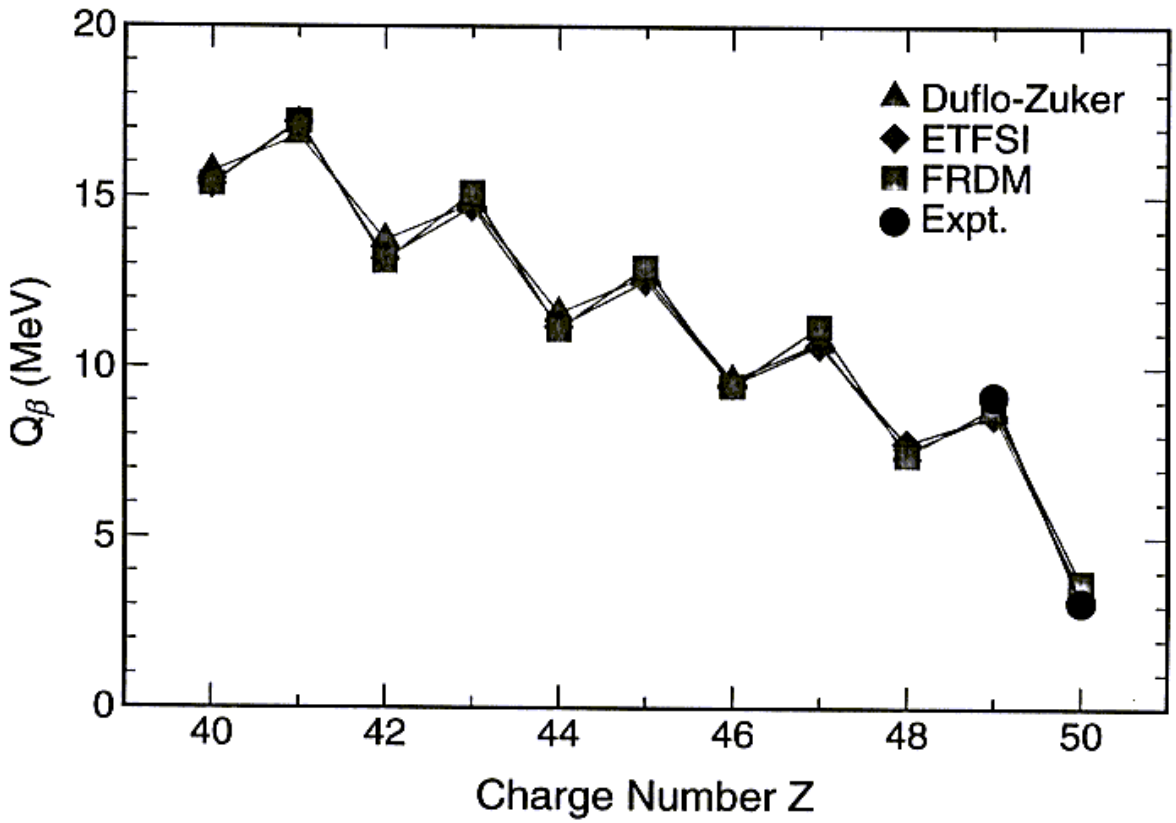
$T \sim 10^9\,K \quad n \gtrsim 10^{20}\,cm^{-3} \quad \Rightarrow \quad \tau_n \ll \tau_\beta$


N=82
$^{132}_{50}$Sn
40 s
$^{131}_{49}$In
278 ms
$^{130}_{48}$Cd
162 ms
$^{129}_{47}$Ag
46 ms
$^{128}_{46}$Pd
$^{127}_{45}$Rh
$^{126}_{44}$Ru
$^{125}_{43}$Tc
$^{124}_{42}$Mo
$^{123}_{41}$Nb
$^{122}_{40}$Zr
r–process out
30/s
2/s
2×10^{-1}/s
2×10^{-2}/s (≈1/min)
2×10^{-3}/s
1×10^{-4}/s (≈3/h)
7×10^{-6}/s (≈1/day)
(n,γ)'s
β^-, β^-n
r–process in

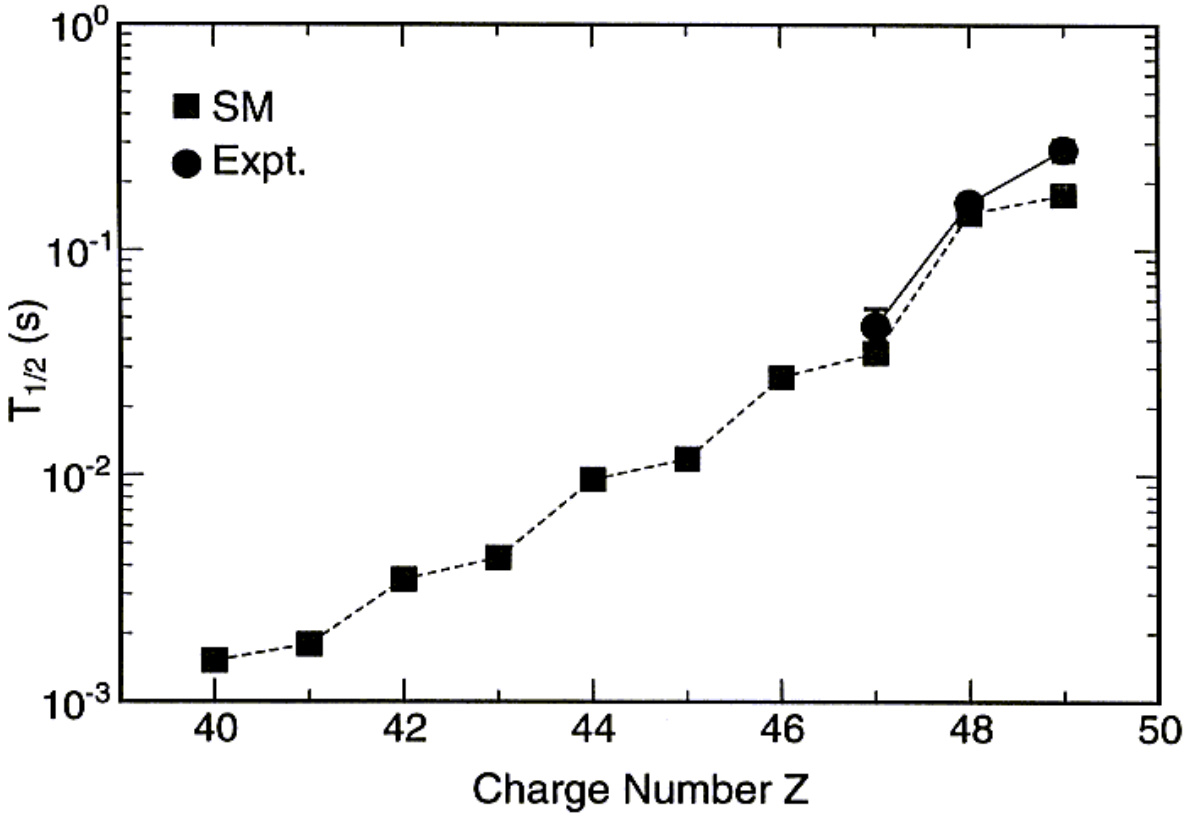
Model Space


^{133}Sb
^{131}Sn
$h_{11/2}$
$d_{3/2}$
$s_{1/2}$
$d_{3/2}$
$h_{11/2}$
$s_{1/2}$
$d_{5/2}$
$d_{5/2}$
$g_{7/2}$
$g_{7/2}$
$g_{9/2}$
$p_{1/2}$
$g_{9/2}$
$p_{1/2}$
Protons
Neutrons

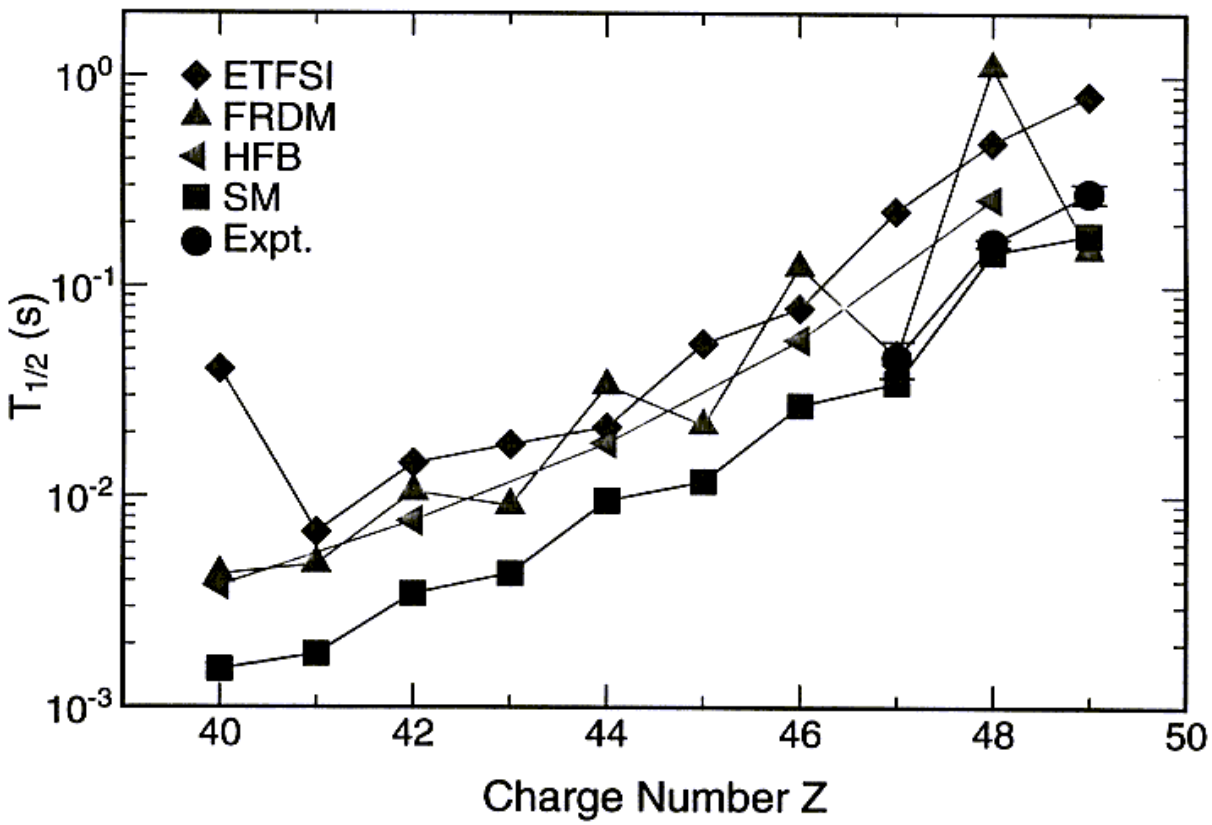
Q_β values for $N = 82$ nuclei

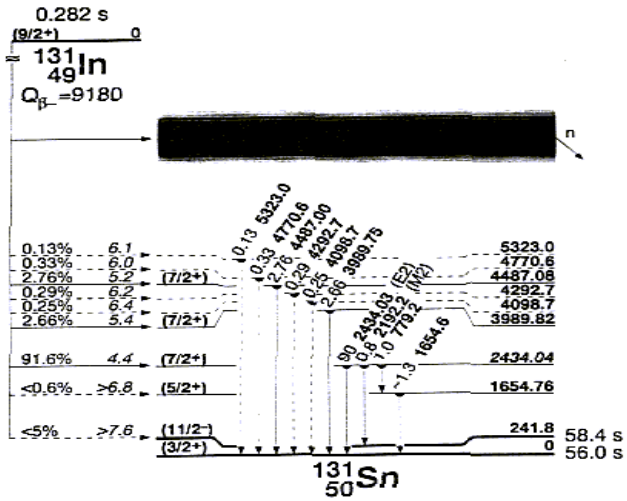


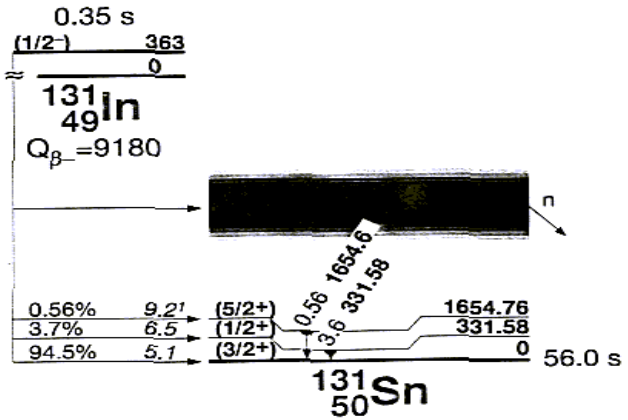
Half-lives for $N = 82$ nuclei

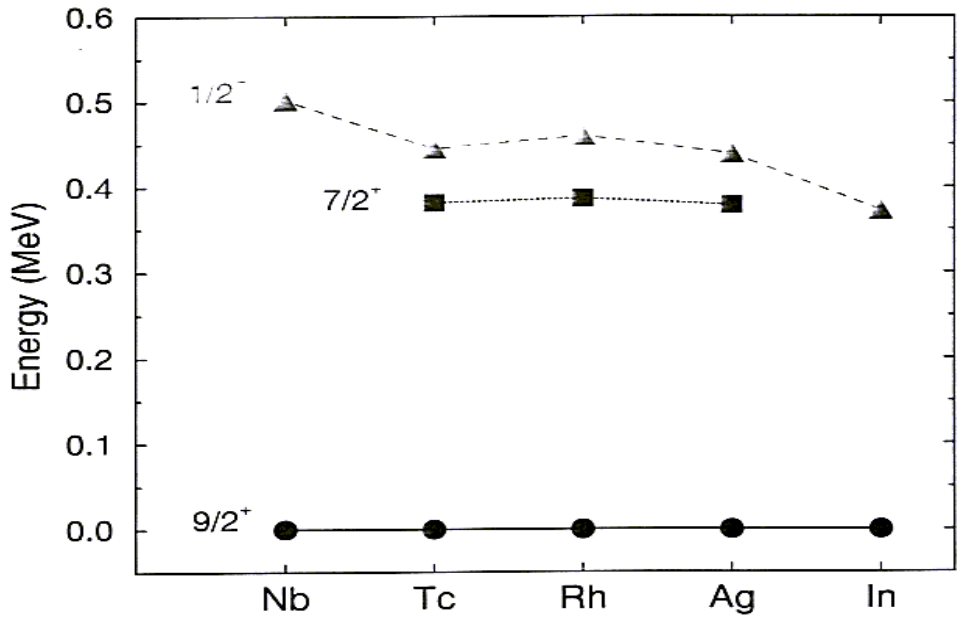


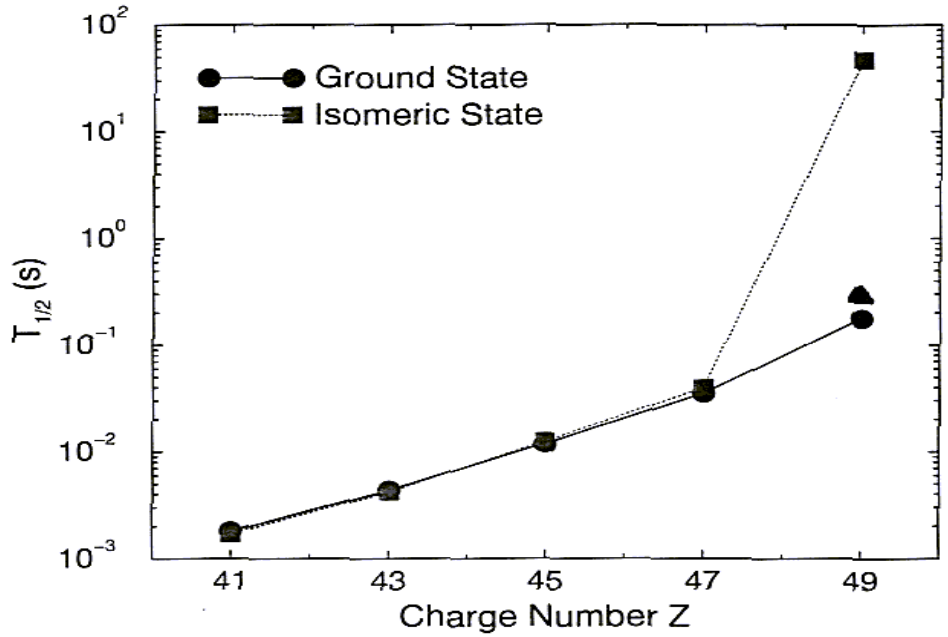
Comparison with other calculations



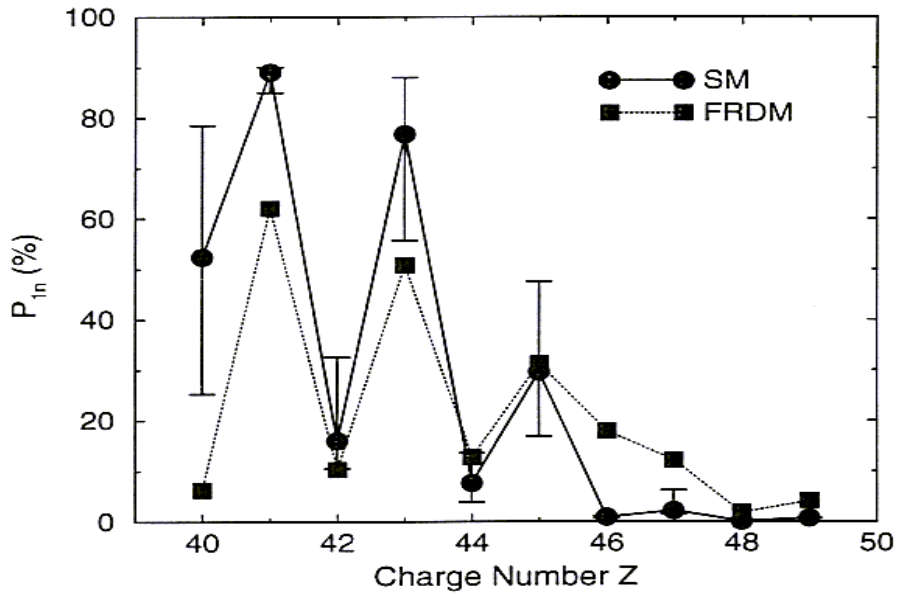

0.282 s
(9/2+) 0
131 49 In
Qβ− =9180
n
0.13% 6.1
0.33% 6.0
2.76% 5.2 (7/2+)
0.29% 6.2
0.25% 6.4
2.66% 5.4 (7/2+)
91.6% 4.4 (7/2+)
<0.6% >6.8 (5/2+)
<5% >7.6 (11/2−)
(3/2+)
0.13 5323.0
0.33 4770.6
2.76 4487.00
0.29 4292.7
0.25 4098.7
2.66 3989.75
(E2)
(M2)
90 2434.03
0.8 2192.2
1.0 779.2
1654.6
~1.3
5323.0
4770.6
4487.08
4292.7
4098.7
3989.82
2434.04
1654.76
241.8
0
58.4 s
56.0 s
131 50 Sn


0.35 s
(1/2−) 363
0
131 49 In
Qβ− =9180
n
0.56% 9.21 (5/2+)
3.7% 6.5 (1/2+)
94.5% 5.1 (3/2+)
0.56 1654.6
3.6 331.58
1654.76
331.58
0
56.0 s
131 50 Sn


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Energy (MeV)
1/2⁻
7/2⁺
9/2⁺
Nb
Tc
Rh
Ag
In


Ground State
Isomeric State
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$T_{1/2}$ (s)
41
43
45
47
49
Charge Number Z

P_{1n} estimates



Beta-flow equilibrium

$(n,\gamma) \rightleftarrows (\gamma,n) \Rightarrow n(Z,A)$ (depend on n_n, T, S_n)

$$n(Z) = \sum_A n(Z,A)$$

$$\lambda_\beta(Z) = \frac{1}{n(Z)} \sum_A n(Z,A)\lambda_\beta(Z,A)$$

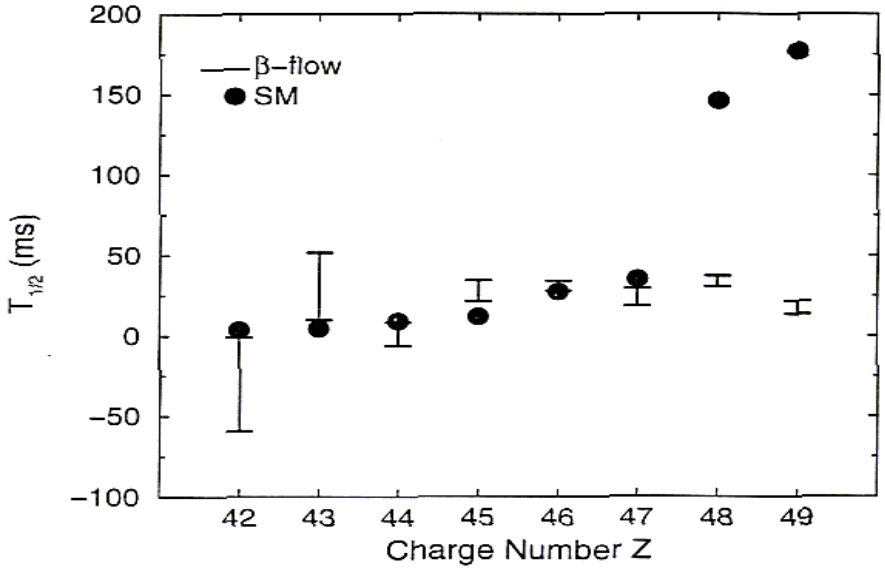
$$\dot{n}(Z) = n(Z-1)\lambda_\beta(Z-1) - n(Z)\lambda_\beta(Z)$$

r-process time $\gg$ individual half-lives $\Rightarrow \dot{n}(Z) = 0$

$$\frac{n(Z)}{n(Z-1)} = \frac{T_{1/2}(Z)}{T_{1/2}(Z-1)}$$

From observed abundances and $P_n \Rightarrow n(Z)$.

Beta flow equilibrium



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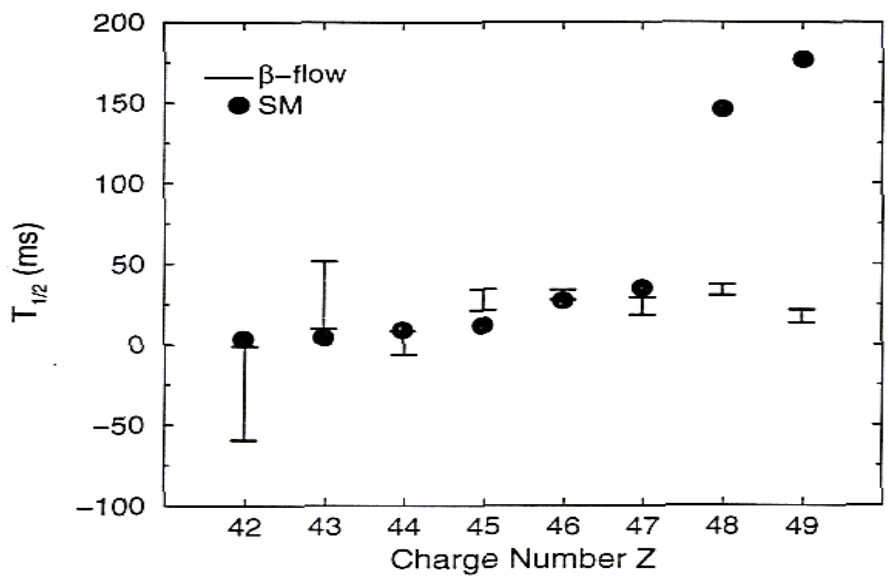
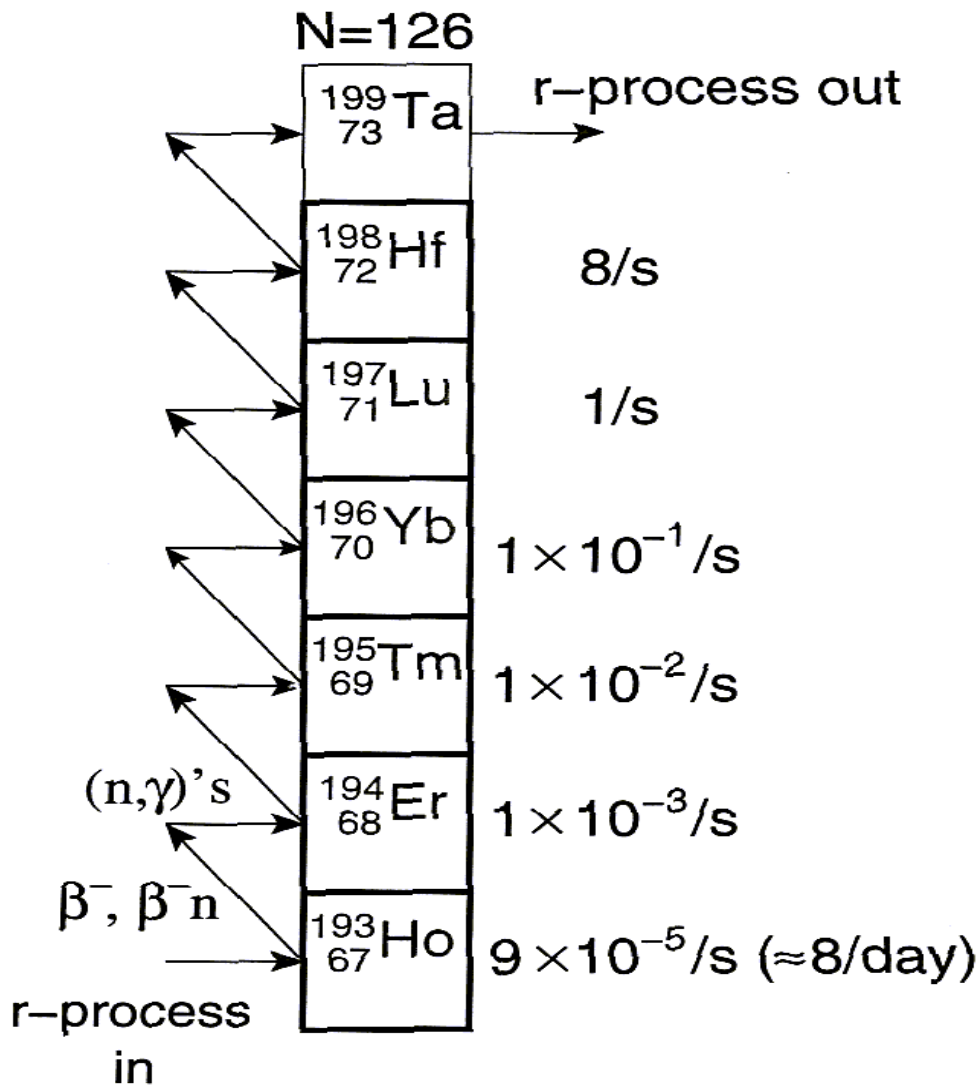
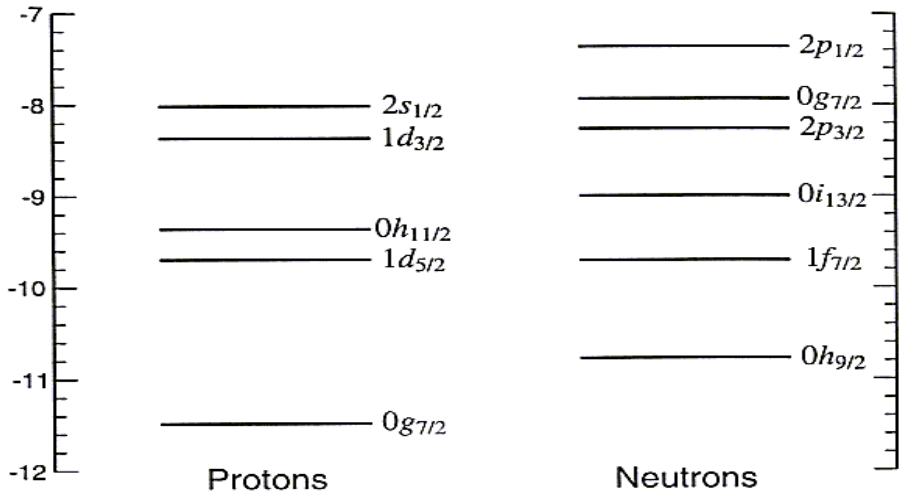
Beta flow equilibrium




N=126
$^{199}_{73}$Ta
r–process out
$^{198}_{72}$Hf
8/s
$^{197}_{71}$Lu
1/s
$^{196}_{70}$Yb
1×10^{-1}/s
$^{195}_{69}$Tm
1×10^{-2}/s
(n,γ)'s
$^{194}_{68}$Er
1×10^{-3}/s
β⁻, β⁻n
$^{193}_{67}$Ho
9×10^{-5}/s (≈8/day)
r–process
in

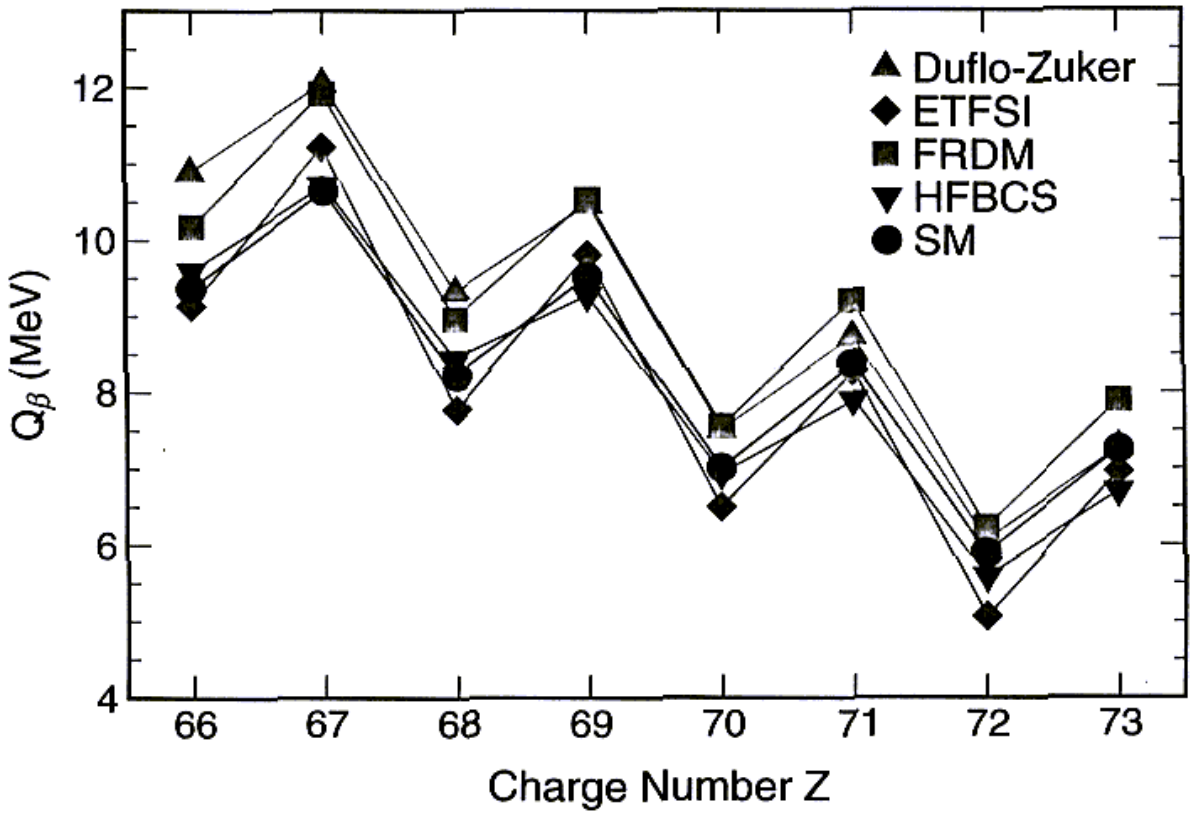
Model space



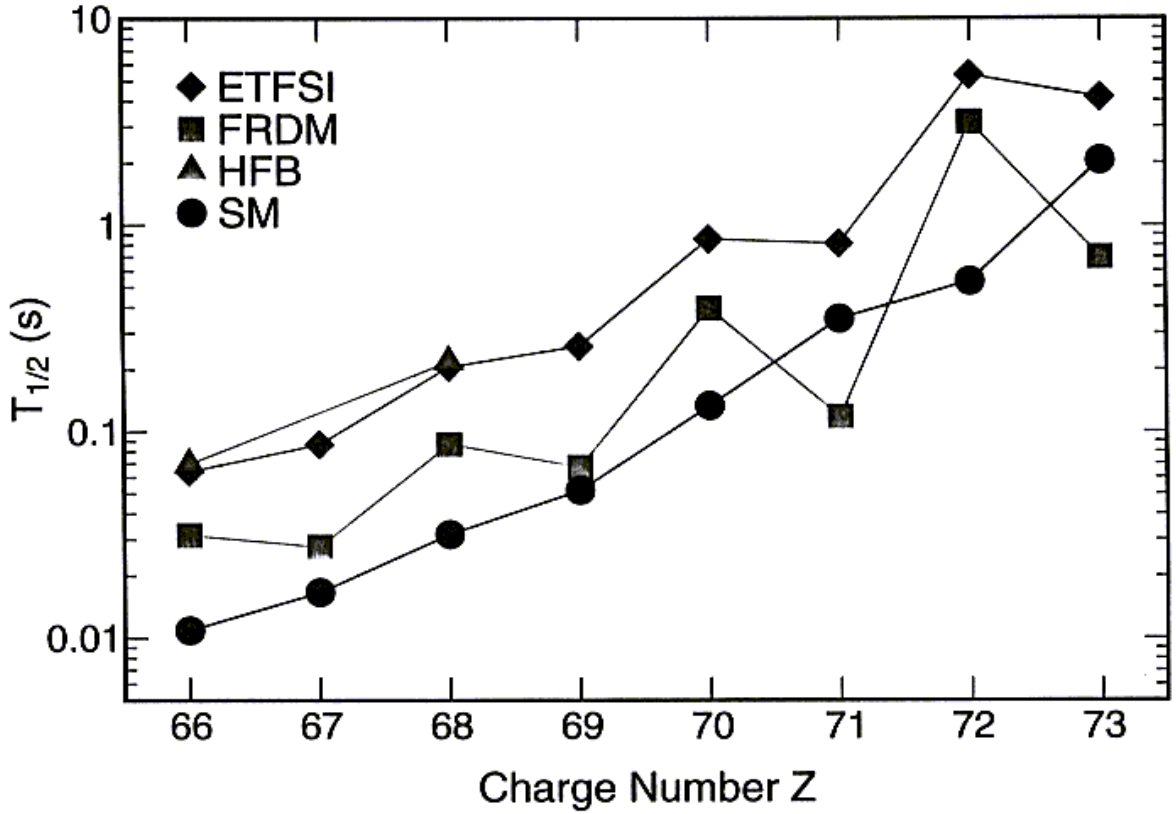
- Kuo-Herling (1972) interaction with the improvements of Rydström, Blomqvist, and Liotta (1990).

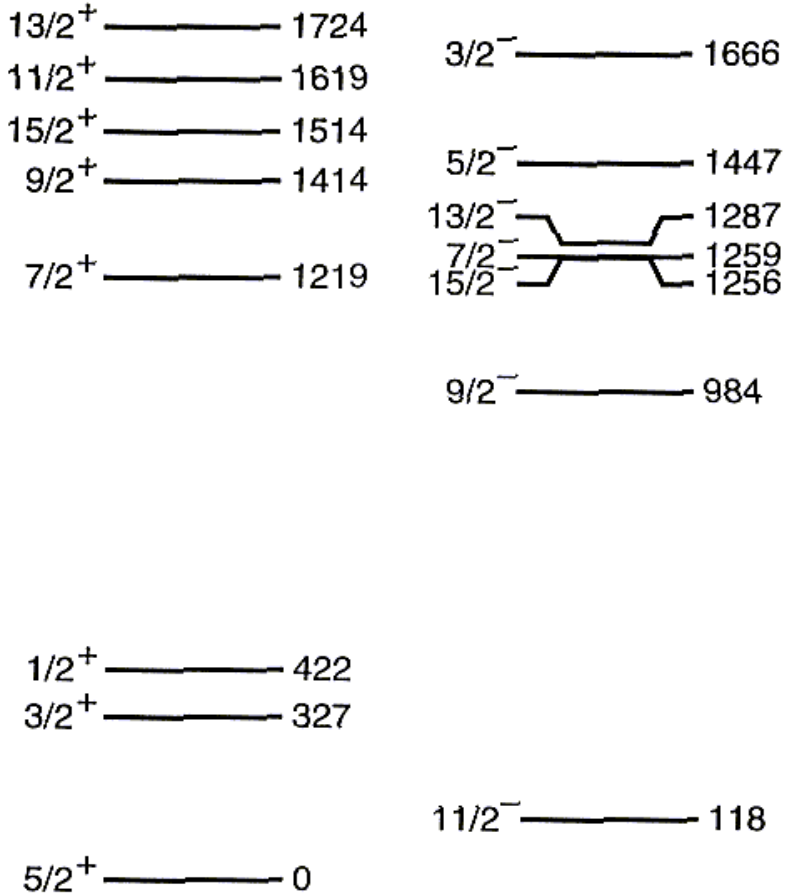
- SM calculations with truncation in seniority
  $v = 8$ for even isotones
  $v = 7$ for odd isotones

Q_β values for $N = 126$

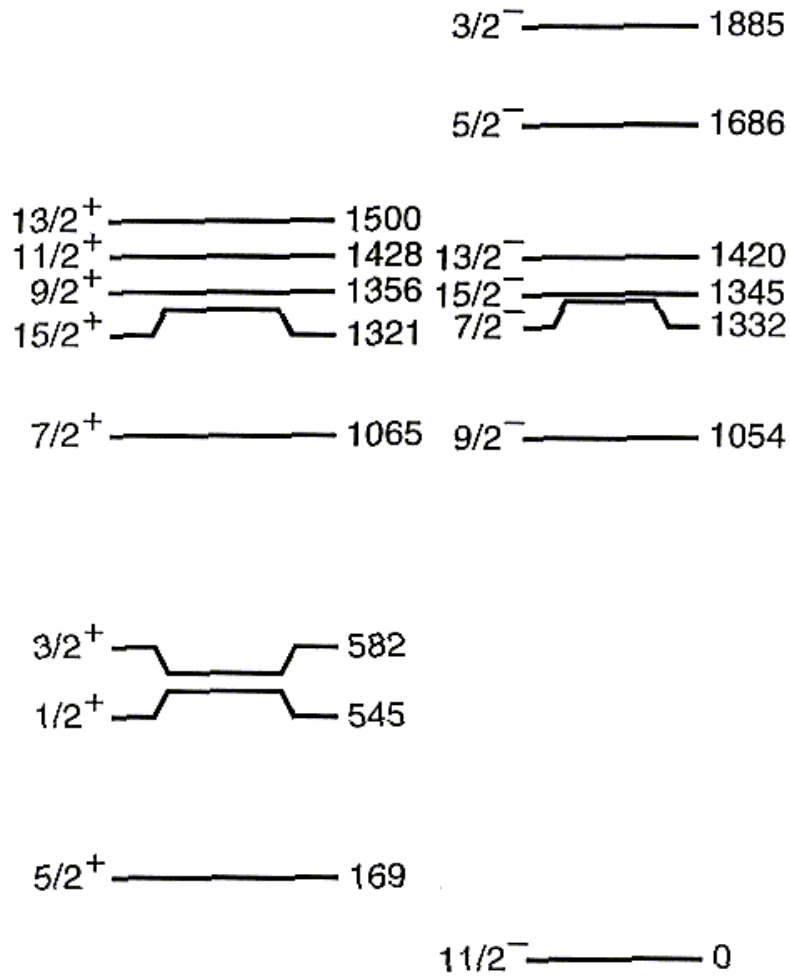


Half-lives for $N = 126$ nuclei




13/2+ 1724
11/2+ 1619
15/2+ 1514
9/2+ 1414
7/2+ 1219
3/2− 1666
5/2− 1447
13/2− 1287
7/2− 1259
15/2− 1256
9/2− 984
1/2+ 422
3/2+ 327
5/2+ 0
11/2− 118

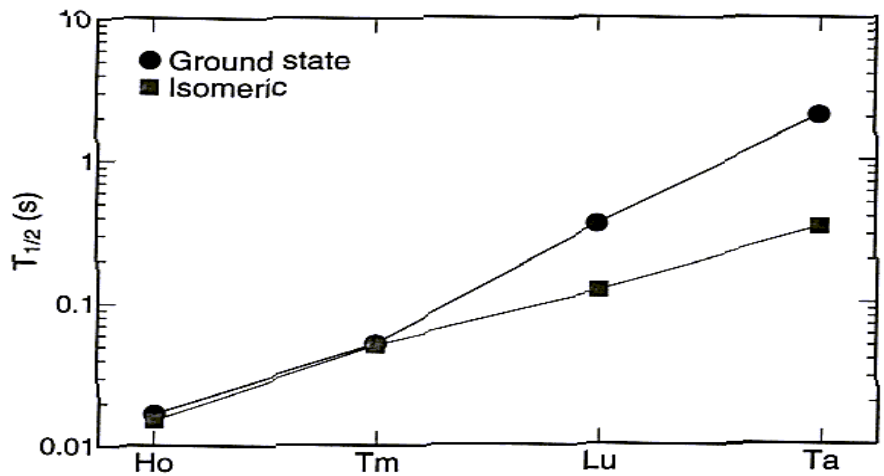
^{197}Lu


3/2− 1885
5/2− 1686
13/2+ 1500
11/2+ 1428
9/2+ 1356
15/2+ 1321
7/2+ 1065
13/2− 1420
15/2− 1345
7/2− 1332
9/2− 1054
3/2+ 582
1/2+ 545
5/2+ 169
11/2− 0

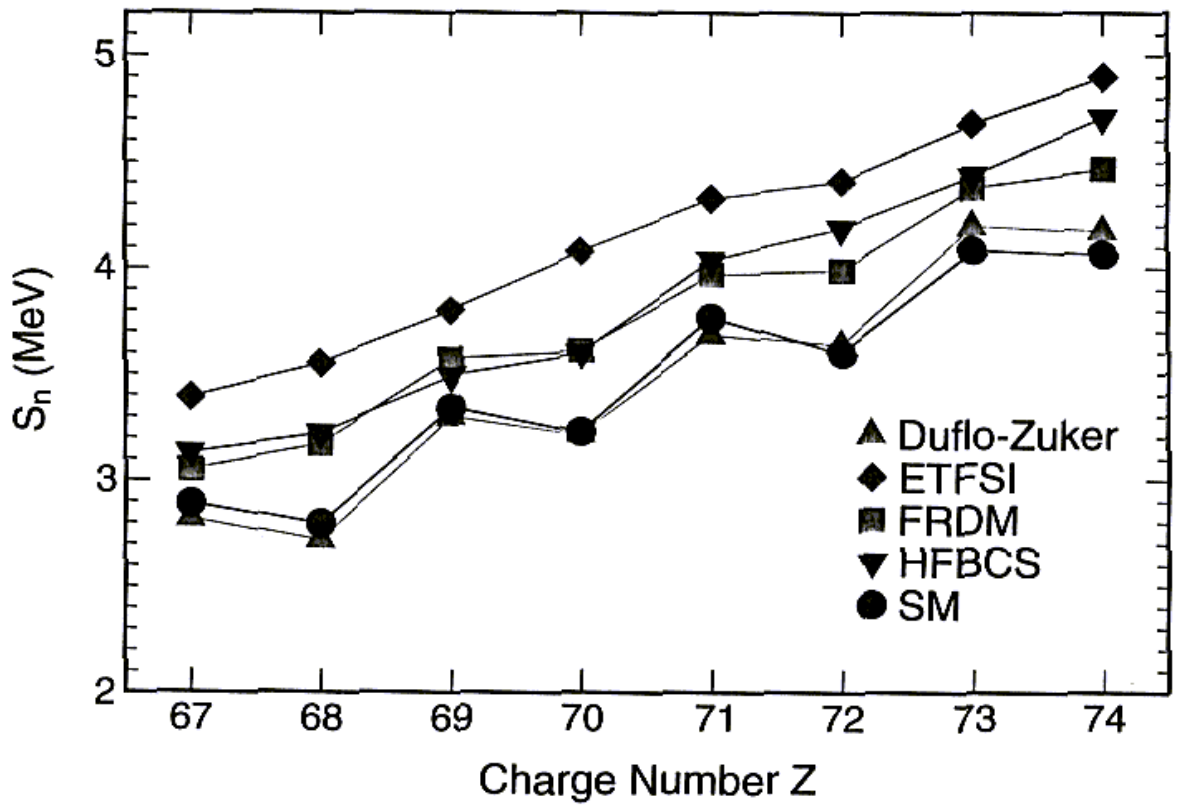
^{195}Tm

$N = 126$ isomeric states

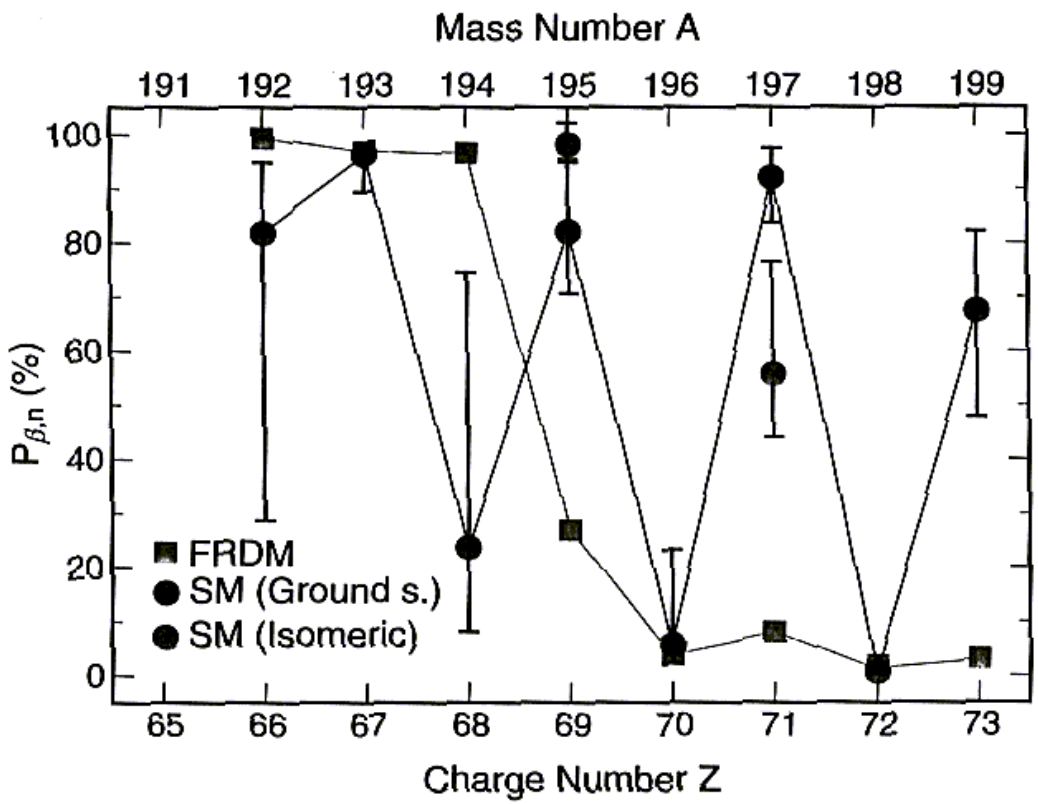
Nucleus	J^π	E^* (keV)	$B(E3)$ (W.u.)	$T_{1/2}$ $E3$ (s)	$T_{1/2}$ GT (s)
^{199}Ta	$11/2^-$	161	2.1	0.090	0.34
^{197}Lu	$11/2^-$	119	0.86	1.8	0.12
^{195}Tm	$5/2^+$	170	0.0054	25	0.051
^{193}Ho	$5/2^+$	300	0.64	0.0038	0.015



S_n values for $N = 125$ nuclei

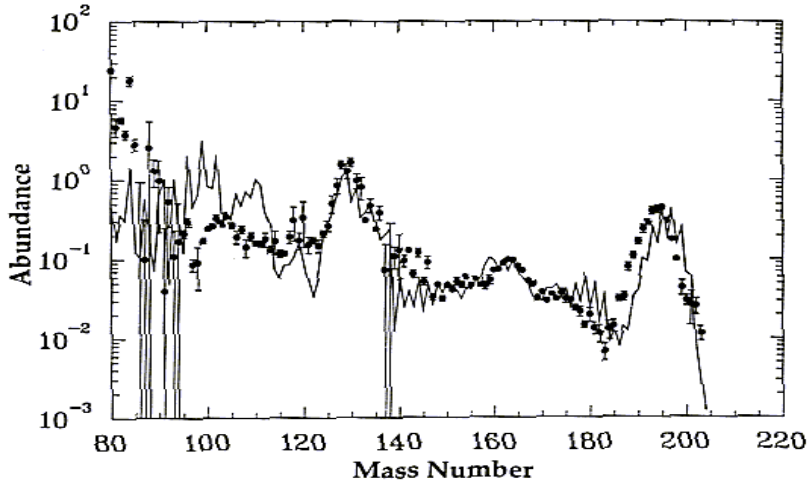


Beta delayed neutron emision probabilities



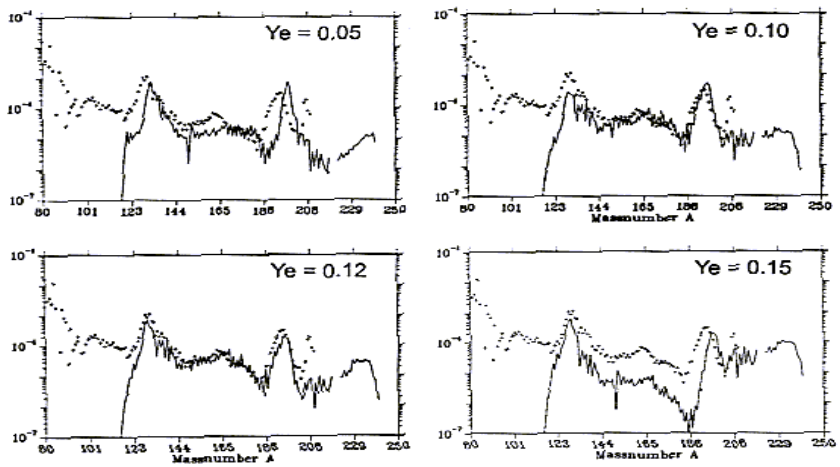
Neutrino driven wind

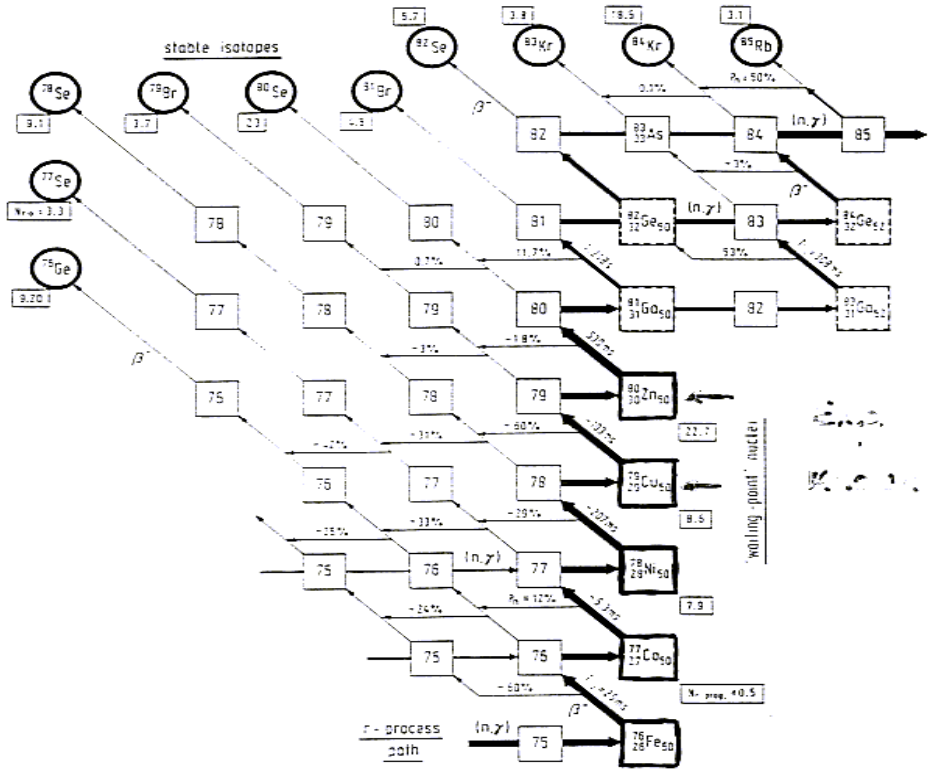
(S. E. Woosley et al., 1994)



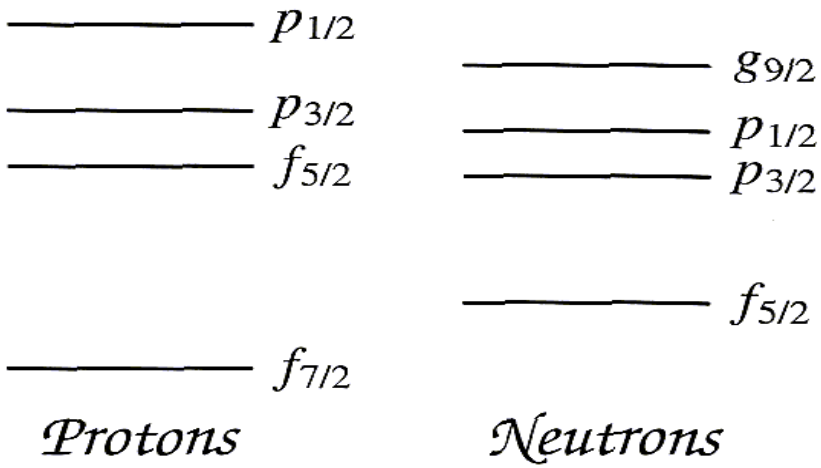
Neutron star mergers

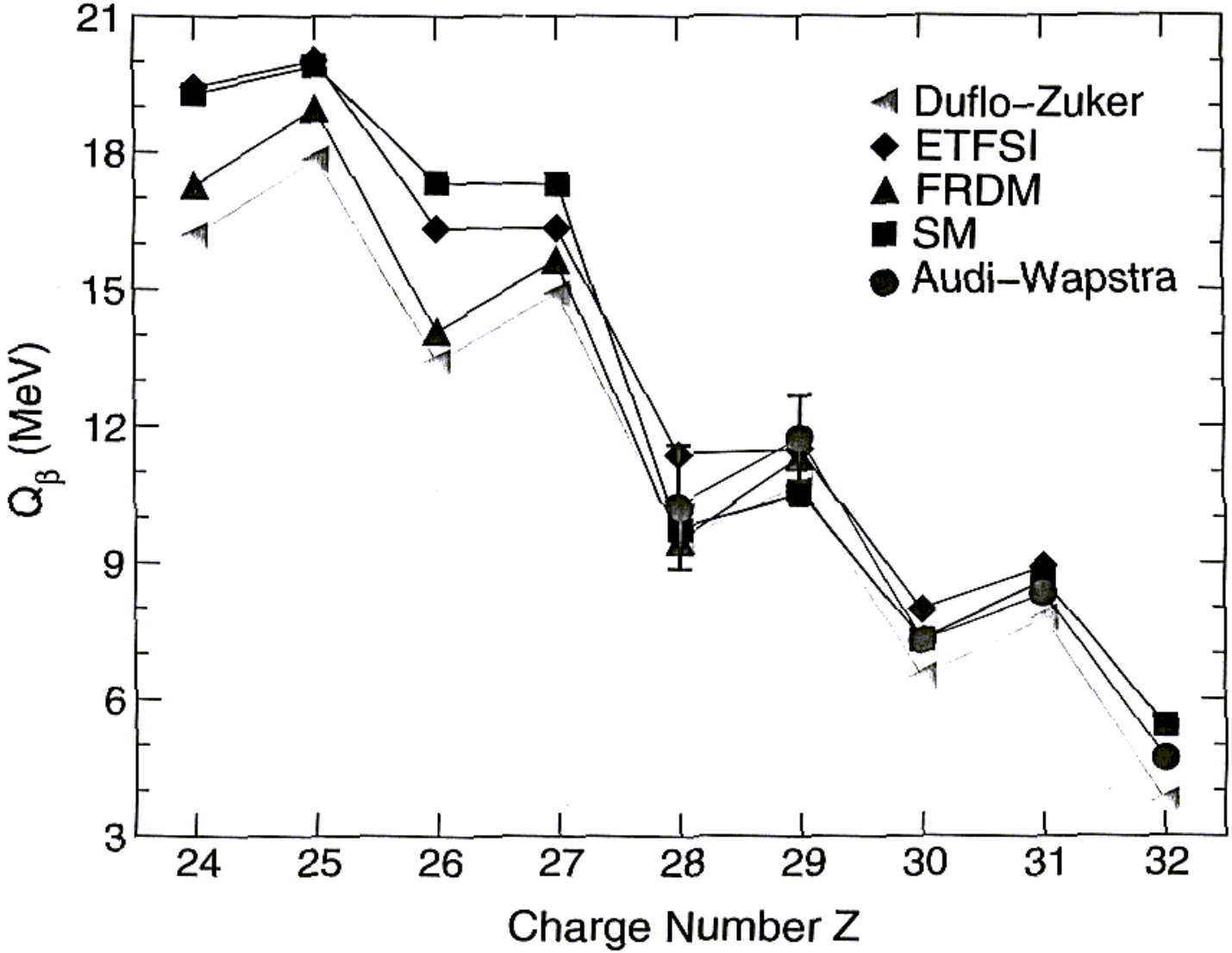
(C. Freiburghaus et al., 1999)

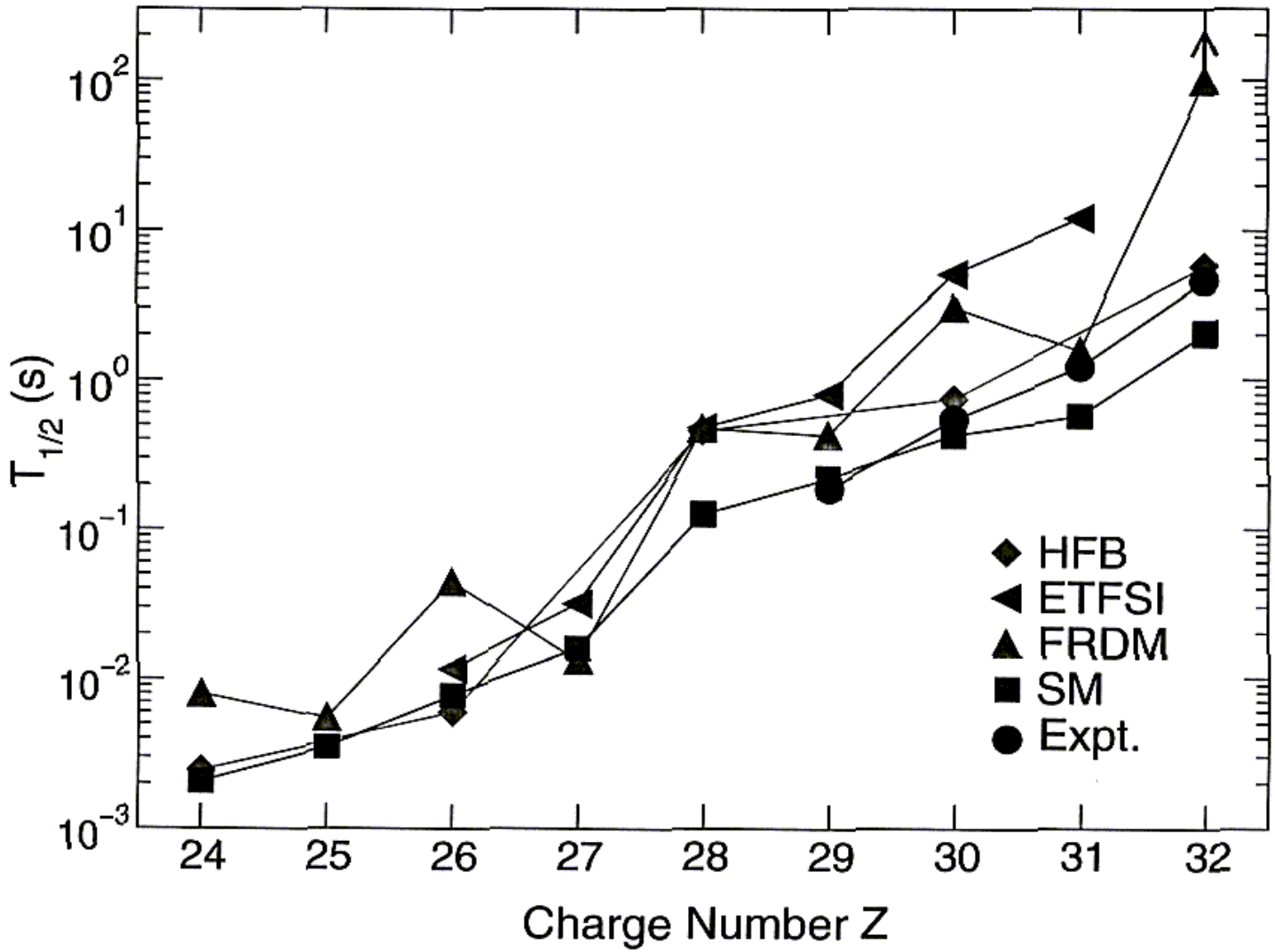



stable isotopes
r - process path
waiting-point nuclei
(n,γ)
β⁻

Model Space N=50




Duflo–Zuker
ETFSI
FRDM
SM
Audi–Wapstra
Q_β (MeV)
Charge Number Z
21
18
15
12
9
6
3
24
25
26
27
28
29
30
31
32


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
$T_{1/2}$ (s)
24
25
26
27
28
29
30
31
32
Charge Number Z
HFB
ETFSI
FRDM
SM
Expt.

Conclusions

N=82

- ^{130}Cd is not produced in β-flow equilibrium
- As ^{130}Cd is expected to be in the r-process path then the N=82 and N=126 are not produced under the same physical conditions. Consistent with recent observations of metal poor stars (Sneden *et al.*, 2000)

N=126

- Larger probabilities for beta delayed neutron emission seem consistent with realistic r-process simulations.

N=50

- Work in progress