# Beta decay rates of neutron-rich nuclei

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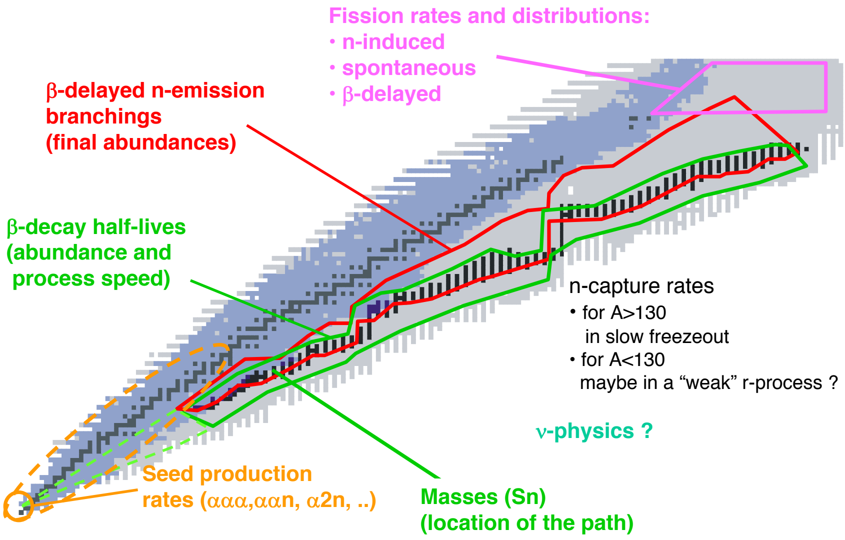
# Introduction



Transitions are obtained by solving the pn-RQRPA equations

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix} = E_\lambda \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} X^\lambda \\ Y^\lambda \end{pmatrix}$$

Residual interaction is derived from the Lagrangian density

$$\mathcal{L}_{\rho+\pi} = -g_\rho \bar{\psi} \gamma_\mu \vec{\rho}^\mu \vec{\tau} \psi - \frac{f_\pi}{m_\pi} \bar{\psi} \gamma_5 \gamma^\mu \partial_\mu \vec{\pi} \vec{\tau} \psi$$

Total strength of a particular transition

$$B_{\lambda,J}(GT) = \left| \sum_{pn} \left\langle p \left\| \hat{O}_J \right\| n \right\rangle \left( X_{pn}^{\lambda,J} u_p v_n - Y_{pn}^{\lambda,J} v_p u_n \right) \right|^2$$

## Decay rate:

$$\lambda_i = D \int_1^{W_{0,i}} W \sqrt{W^2 - 1} \left( W_{0,i} - W \right)^2 F(Z, W) C(W) dW$$

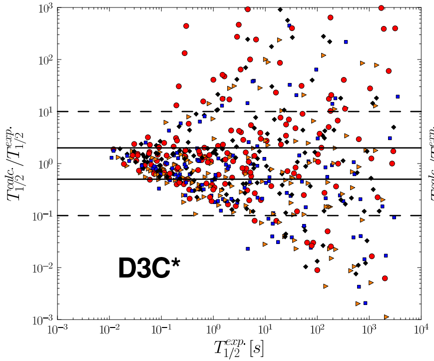
$$T_{1/2} = \frac{\ln 2}{\lambda}, \qquad D = \frac{(G_F V_{ud})^2}{2\pi^3} \frac{\left( m_e c^2 \right)^5}{\hbar}$$

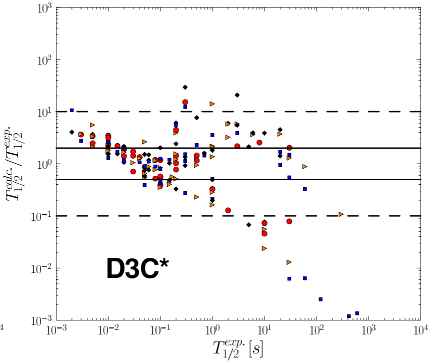
Allowed decays shape factor:

$$C(W) = B(GT)$$

First-forbidden decays shape factor:

$$C(W) = k \left( 1 + aW + bW^{-1} + cW^2 \right)$$



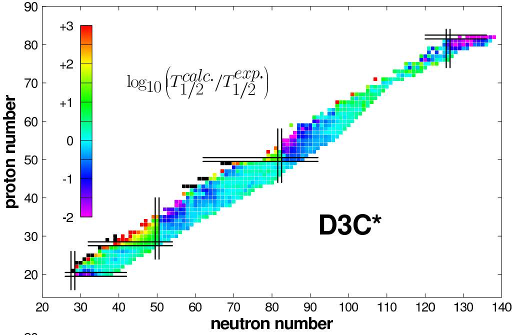




$$\bar{r} = \frac{1}{N}\sum_i \log\frac{T_{\text{th.}}}{T_{\text{exp.}}}$$

$$\sigma = \left[\frac{1}{N}\sum_i (r_i - \bar{r})^2\right]^{1/2}$$

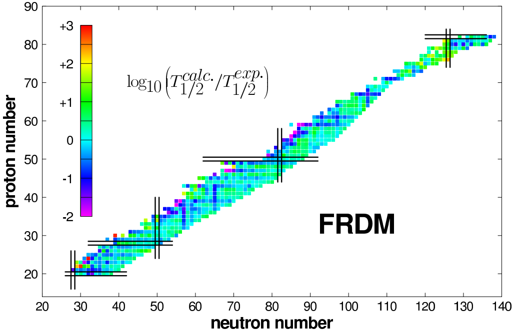
| | D3C* | | FRDM | |
|---|---|---|---|---|
| $T_{\text{exp.}}$ [s] | $\bar{r}$ | $\sigma$ | $\bar{r}$ | $\sigma$ |
| < 1000 | 0.011 | 0.889 | 0.021 | 0.660 |
| < 100 | 0.057 | 0.791 | 0.040 | 0.580 |
| < 10 | 0.061 | 0.645 | 0.046 | 0.515 |
| < 1 | 0.011 | 0.436 | 0.019 | 0.409 |
| < 0.1 | 0.041 | 0.195 | 0.021 | 0.354 |

G. Audi *et al.*, CPC 36, 1157 (2012)



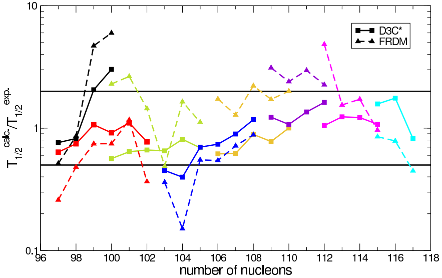

## D3C*

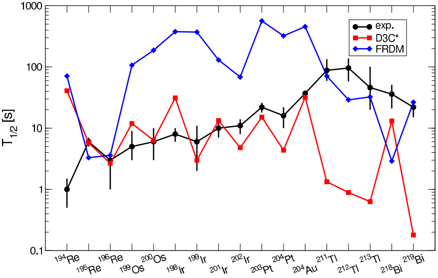
| | $\bar{r}$ | $\sigma$ |
|---|---|---|
| even-even | -0.037 | 0.331 |
| odd-Z | 0.054 | 0.328 |
| odd-N | -0.086 | 0.387 |
| odd-odd | 0.089 | 0.582 |
| total | 0.011 | 0.436 |

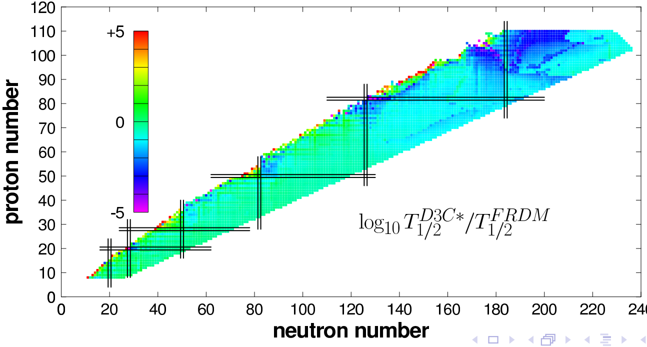


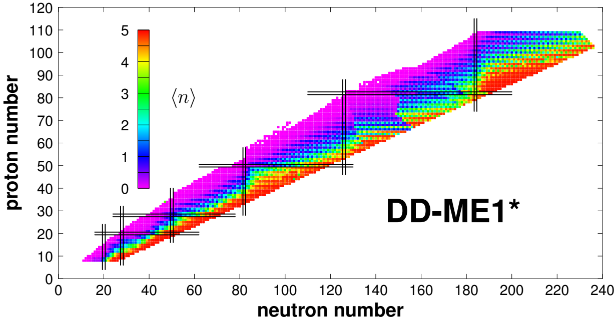

## FRDM

| | $\bar{r}$ | $\sigma$ |
|---|---|---|
| even-even | 0.333 | 0.226 |
| odd-Z | -0.128 | 0.288 |
| odd-N | 0.124 | 0.436 |
| odd-odd | -0.179 | 0.409 |
| total | 0.019 | 0.409 |

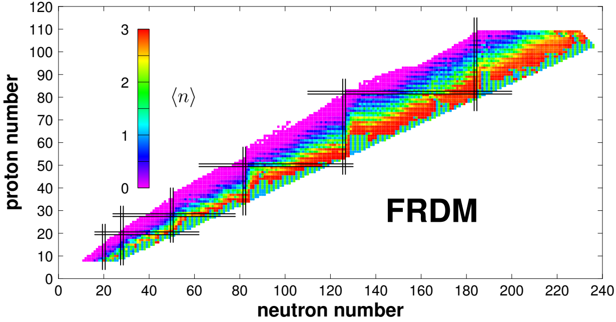

D3C*
FRDM
number of nucleons
T1/2 calc./T1/2 exp.


exp.
D3C*
FRDM
T1/2 [s]
194Re 195Re 196Re 199Os 200Os 198Ir 199Ir 201Ir 202Ir 203Pt 204Pt 204Au 211Tl 212Tl 213Tl 218Bi 219Bi


+5
0
-5
proton number
neutron number
log10 T1/2 D3C* / T1/2 FRDM

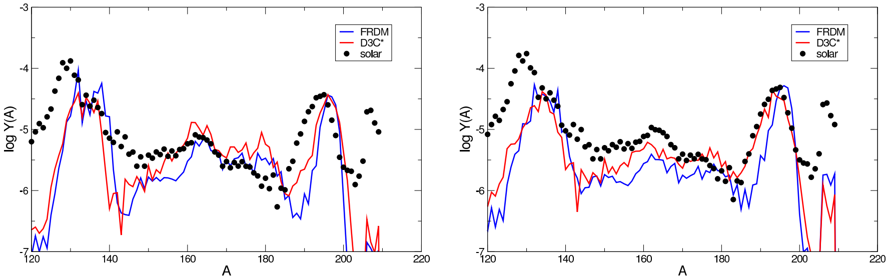



$$P_{xn} = \frac{1}{\lambda_{tot}} \sum_{E_i = S_{xn}}^{S_{(x+1)n}} \lambda_i$$




$$\langle n \rangle = \sum_i i P_{in}$$

# Correlations in r-process




- Half-lives have a significant impact on the r-process abundance pattern
- It is difficult to say which nuclei are important for a particular part of the pattern → a systematic way of performing sensitivity studies is needed

Assuming a model with $N_p$ parameter, adjusted to $N$ observables

$$\chi^2(\boldsymbol{p}) = \sum_{n=1}^{N} \frac{O_n^{th}(\boldsymbol{p}) - O_n^{exp.}}{\Delta O_n^2}$$

- The goal is to find an optimal set of parameters $\boldsymbol{p}_0$ which minimizes the function
- To get more information out of the fit we require the curvature matrix

$$\mathcal{M}_{ij} = \frac{1}{2}\left(\frac{\partial^2 \chi^2}{\partial p_i \partial p_j}\right)_{\boldsymbol{p}_0} \approx \sum_{n=1}^{N} \frac{1}{\Delta O_n^2} \frac{\partial O_n}{\partial p_i} \frac{\partial O_n}{\partial p_j}$$

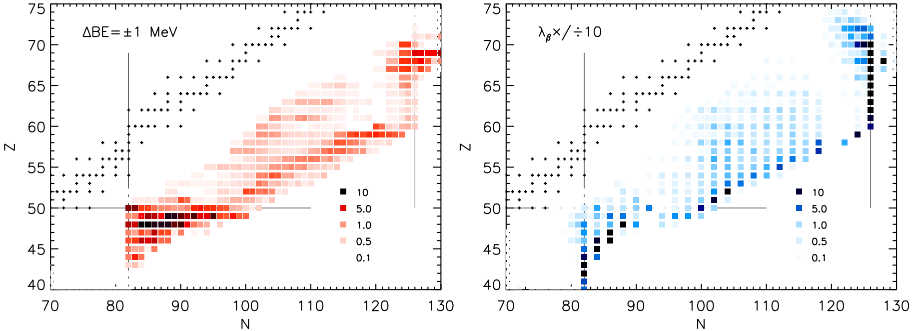
Finally, we obtain the correlation coefficients between observables

$$\rho(A,B) = \frac{\mathrm{cov}(A,B)}{\sqrt{\mathrm{var}(A)\mathrm{var}(B)}},$$

with

$$\mathrm{cov}(A,B) = \mathrm{cov}(B,A) = \sum_{i,j=1}^{N_p} \frac{\partial A}{\partial p_i} \mathcal{M}^{-1} \frac{\partial B}{\partial p_j}$$

- More consistent way of performing sensitivity studies in heavy element nucleosynthesis
- Relatively simple, although computationally intensive




- Final result would be the correlations between r-process abundances and the half-lives of nuclei across the whole nuclear chart

R. Surman, M. Mumpower, J. Cass, and A. Aprahamian, nucl-th:1309.0058

# Evaluation of reactor antineutrino spectra

In reactors, 99% of the electrons come from decay of fission products of 4 nuclei.

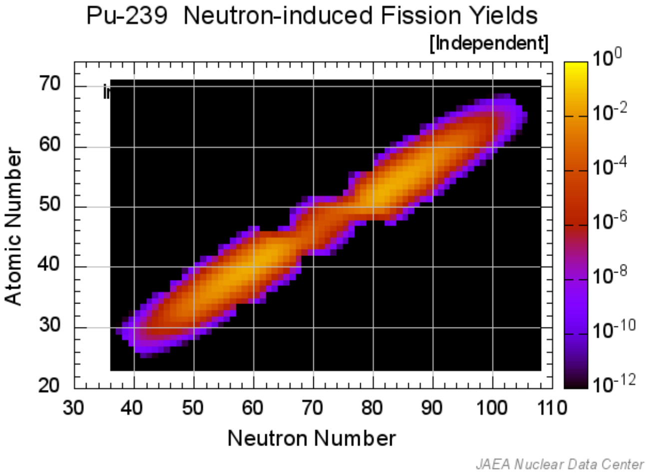
$$S_{tot}(E) = \sum_{k={}^{235}U,{}^{238}U,{}^{239}Pu,{}^{241}Pu} \alpha_k S_k(E),$$

- $\alpha_k$ - number of fissions at considered time
- $S_k(E)$ - $\beta$ spectrum normalized to one fission
- $E$ - kinetic energy of emitted electrons

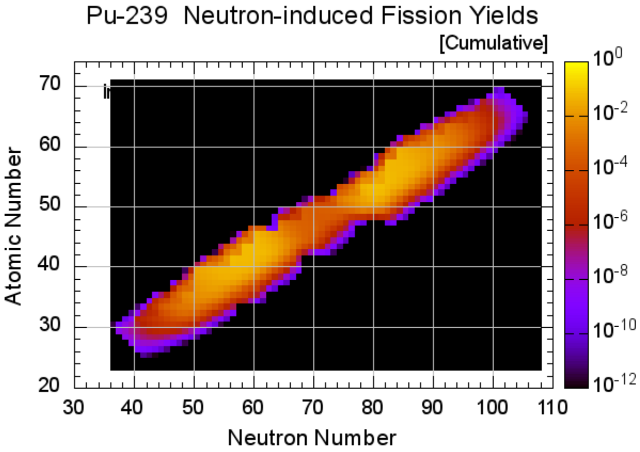
Electrons (and antineutrinos) come from the $\beta$-decay of resulting fission fragments.

$$S_k(E) = \sum_{f=1}^{N_f} Y_f S_f(E)$$

$$S_f(E) = \sum_{i=i}^{N_t} \frac{\lambda_i}{\lambda_{tot}} S_f^i(Z, A, E_{max}, E).$$



$$S_f(E) = \sum_{i=i}^{N_t} \frac{\lambda_i}{\lambda_{tot}} S_f^i(Z, A, E_{max}, E).$$




JAEA Nuclear Data Center

For allowed transitions the spectrum reads

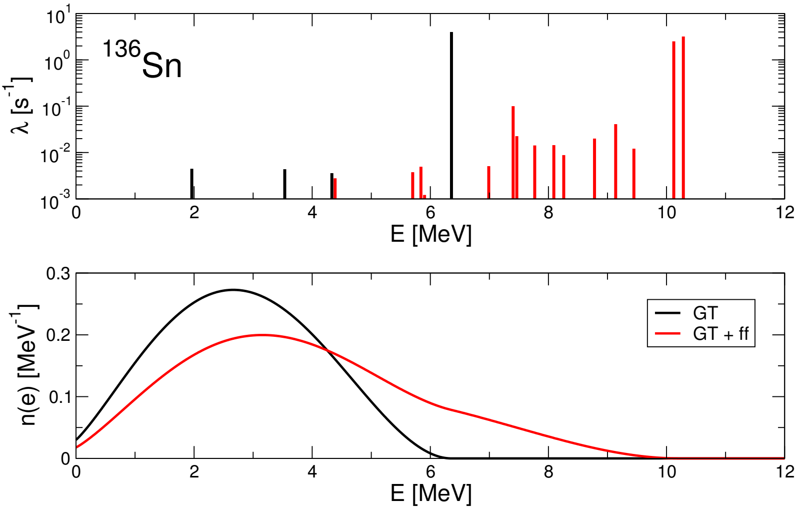
$$S_f^i = F(Z,A,E) \cdot pE(E - E_{max})^2 \cdot L_0(Z,E) \cdot C'(Z,E)$$

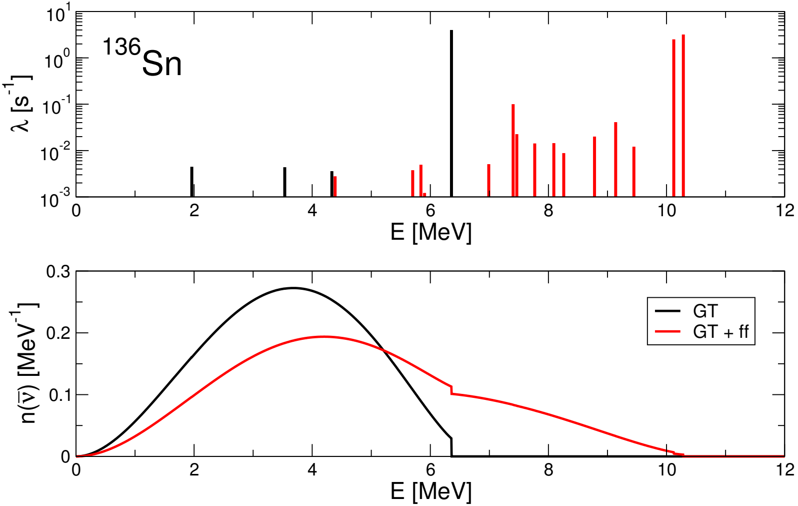
- $F(Z,A,E)$ - Fermi function, correction for the Coulomb field
- $L_0(Z,E)$ - correction for the finite size of the charge distribution
- $C'(Z,E)$ - correction for the nucleon moving within a nuclear potential
- other corrections are neglected

but if we include first-forbidden transitions

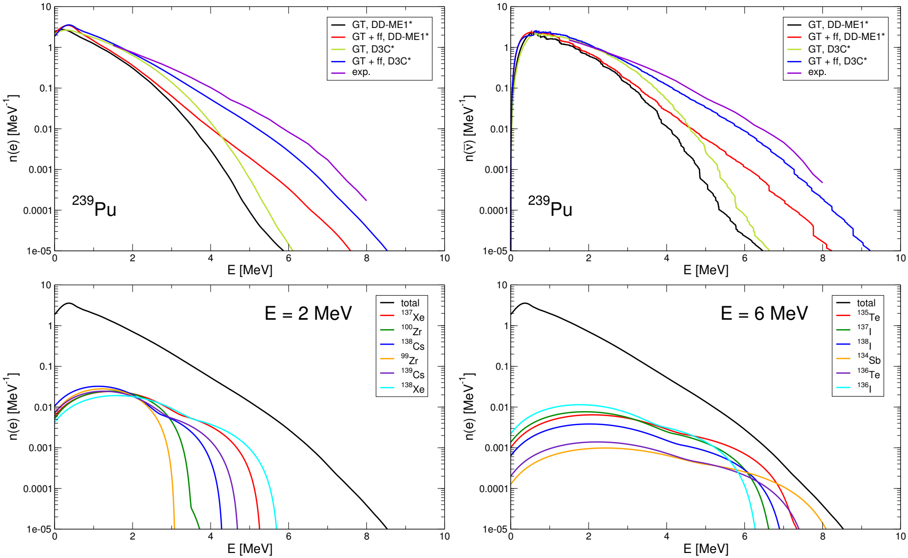
$$S_f^i = F(Z,A,E) \cdot pE(E - E_{max})^2 \cdot C(E) \cdot L_0(Z,E) \cdot C(Z,E)$$

where $C(E)$ is the *shape factor*


$^{136}$Sn
λ [s$^{-1}$]
$10^{1}$
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
0
2
4
6
8
10
12
E [MeV]
n(e) [MeV$^{-1}$]
0.3
0.2
0.1
0
GT
GT + ff

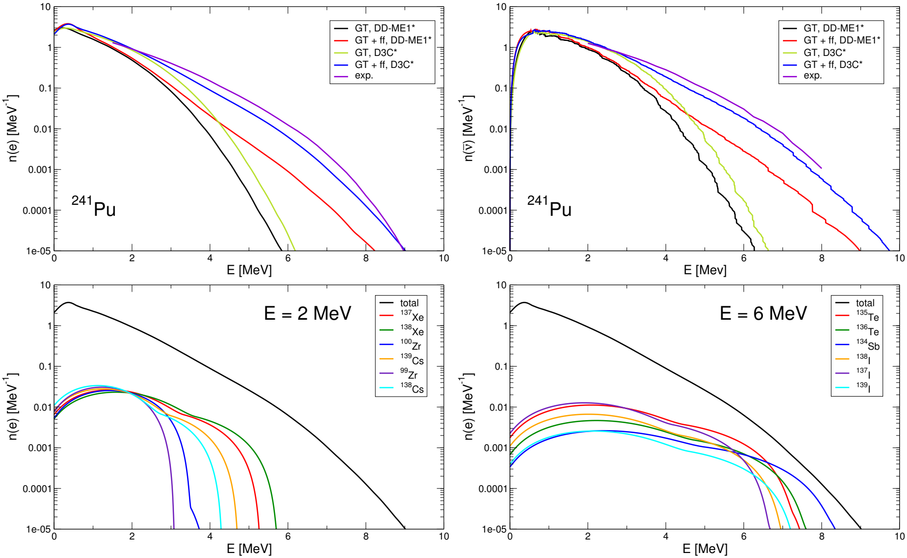

136Sn
λ [s-1]
E [MeV]
n(ν̄) [MeV-1]
E [MeV]
GT
GT + ff

# $^{239}$Pu

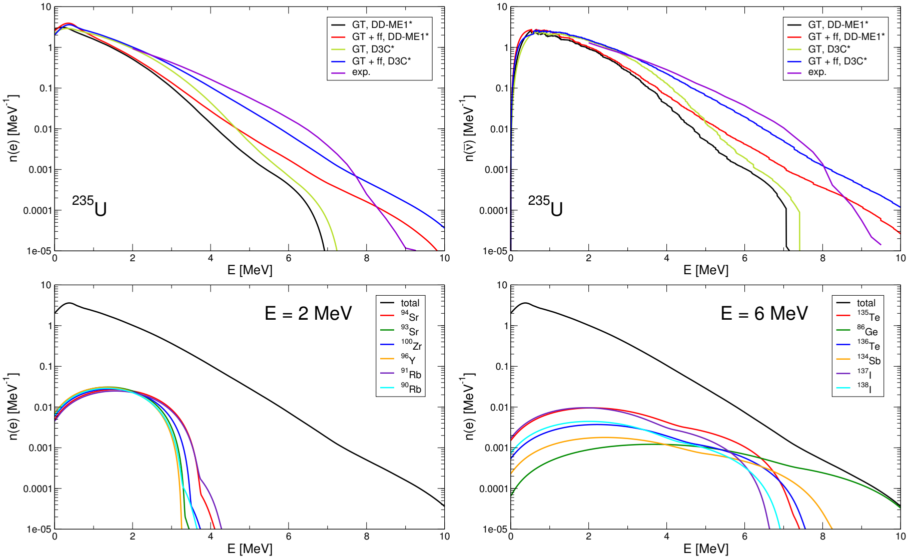


GT, DD-ME1*
GT + ff, DD-ME1*
GT, D3C*
GT + ff, D3C*
exp.
239Pu
n(e) [MeV-1]
n(ν̄) [MeV-1]
E [MeV]
E = 2 MeV
total
137Xe
100Zr
138Cs
99Zr
139Cs
138Xe
E = 6 MeV
135Te
137I
138I
134Sb
136Te
136I

# $^{241}$Pu

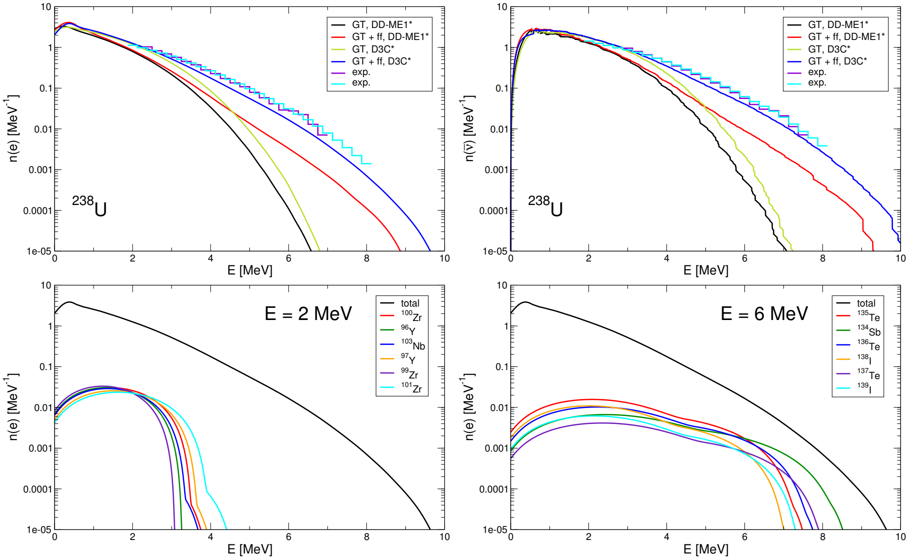

GT, DD-ME1*
GT + ff, DD-ME1*
GT, D3C*
GT + ff, D3C*
exp.
241Pu
n(e) [MeV-1]
E [MeV]
n(ν̄) [MeV-1]
E [Mev]
E = 2 MeV
total
137Xe
138Xe
100Zr
139Cs
99Zr
138Cs
E = 6 MeV
135Te
136Te
134Sb
138I
137I
139I

# $^{235}$U

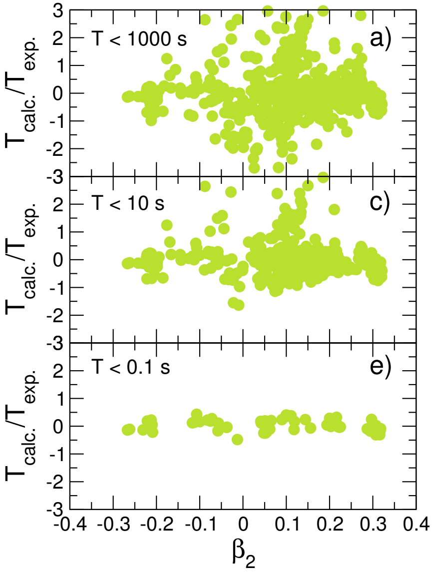


n(e) [MeV$^{-1}$]
n($\bar{\nu}$) [MeV$^{-1}$]
E [MeV]
235U
GT, DD-ME1*
GT + ff, DD-ME1*
GT, D3C*
GT + ff, D3C*
exp.
E = 2 MeV
total
94Sr
93Sr
100Zr
96Y
91Rb
90Rb
E = 6 MeV
135Te
86Ge
136Te
134Sb
137I
138I

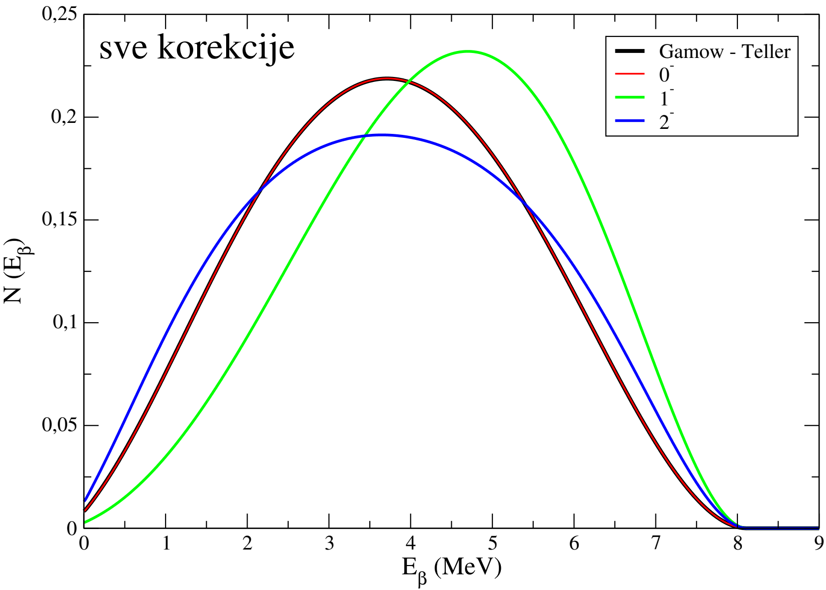
# $^{238}$U

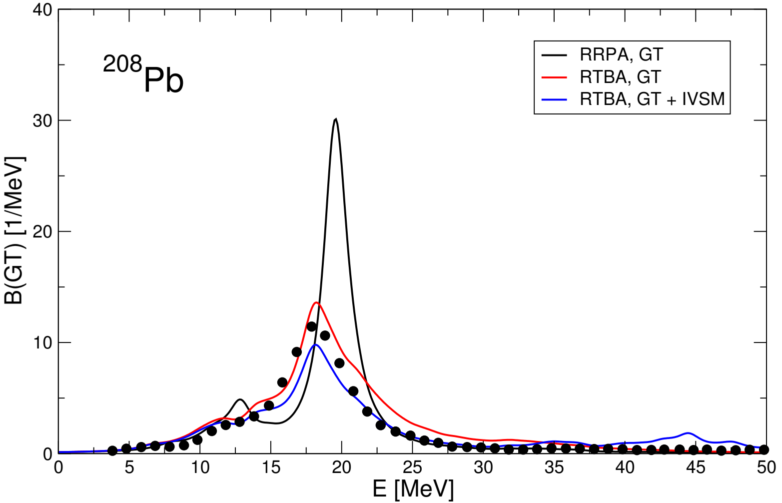


GT, DD-ME1*
GT + ff, DD-ME1*
GT, D3C*
GT + ff, D3C*
exp.
exp.
238U
n(e) [MeV-1]
n(ν̄) [MeV-1]
E [MeV]
E = 2 MeV
total
100Zr
96Y
103Nb
97Y
99Zr
101Zr
E = 6 MeV
135Te
134Sb
136Te
138I
137Te
139I

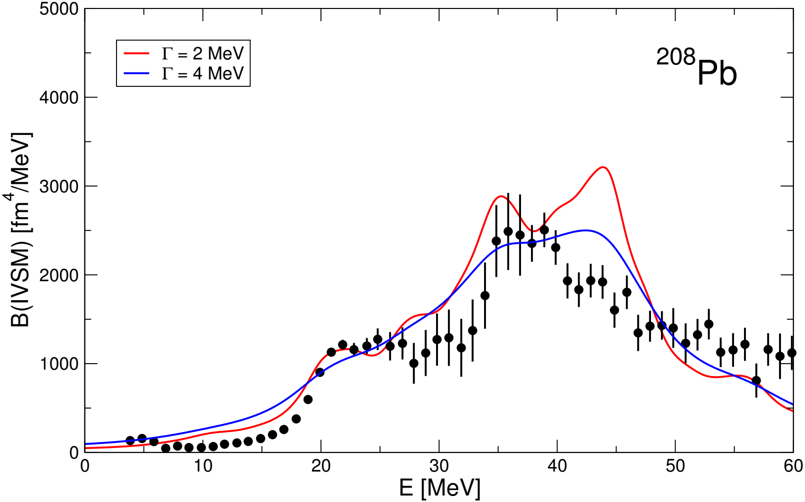


T < 1000 s
a)
T < 100 s
b)
T < 10 s
c)
T < 1 s
d)
T < 0.1 s
e)
$T_{calc.}/T_{exp.}$
$\beta_2$

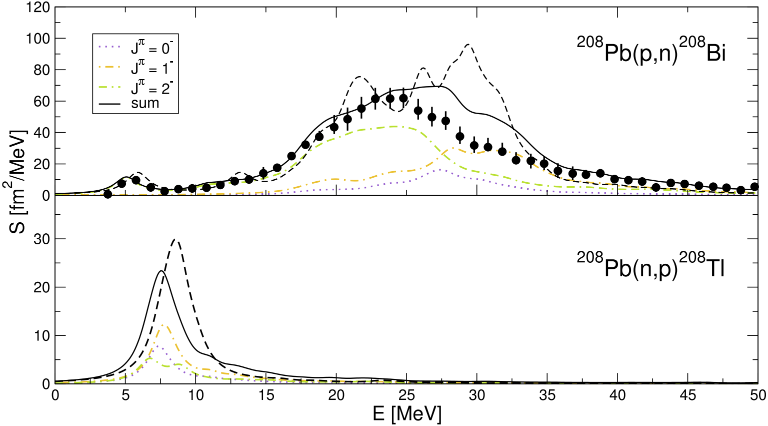

sve korekcije
Gamow - Teller
0-
1-
2-
0,25
0,2
0,15
0,1
0,05
0
N (Eβ)
0
1
2
3
4
5
6
7
8
9
Eβ (MeV)




T. Wakasa *et al.*, Phys. Rev. C 85, 064606 (2012)



5000
4000
3000
2000
1000
0
B(IVSM) [fm$^4$/MeV]
Γ = 2 MeV
Γ = 4 MeV
$^{208}$Pb
0
10
20
30
40
50
60
E [MeV]


$^{208}$Pb(p,n)$^{208}$Bi
$^{208}$Pb(n,p)$^{208}$Tl
$J^\pi = 0^-$
$J^\pi = 1^-$
$J^\pi = 2^-$
sum
S [fm$^2$/MeV]
E [MeV]