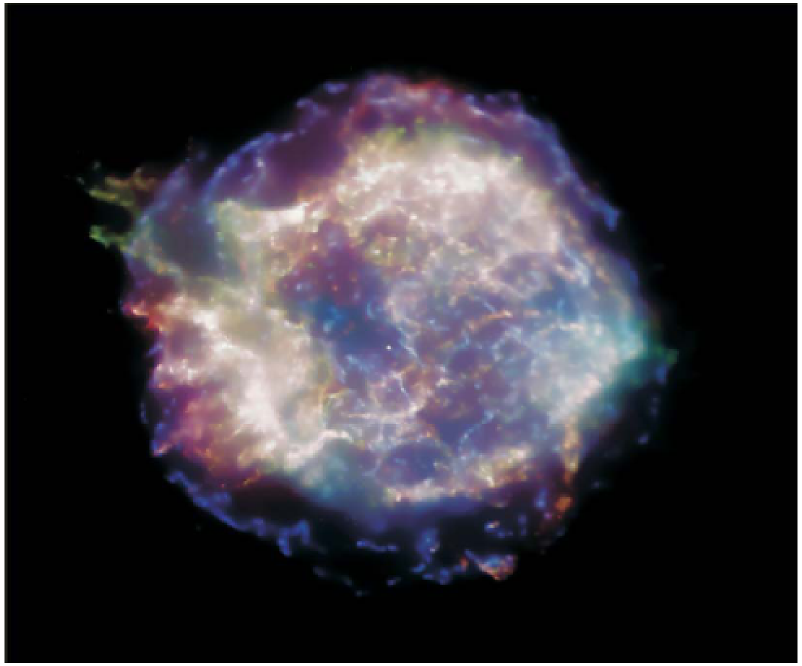
I.N. Borzov

β-decay of neutron-rich nuclei and the r-process nucleosynthesis

NTAA,Dubna, 04.08.05

Astrophysics
R-process modeling



Chandra X-ray Observatory image of the gas remnant of a supernova explosion, Cassiopeia A.
Most of our body mass comes from elements created in stars;
exploding stars like this one are the sources of the iron in your blood,
the calcium in your bones, and the oxygen you breathe

Nuclear
Theory

Structural
evolution
far from
stability

RNB

Current RNB
experiments:
^{78}Ni, ^{132}Sn,
beyond ^{208}Pb

$Nn \geq 10^{20}$ n cm^{-3}

$T9 > 1$

R- process environments

$\tau_{n\gamma} << \tau_{\beta}$

Canonical model B^2FH:

At τ=0:	*multiple n-capture (15 to 30 n) by the seed nuclei transforms the material to very neutron-rich domain;*
At σ(nγ)= σ(γn):	*the r-process "waits" for β-decay at N=50, 82, 126 taking place;*
At Nn→0:	*β-decay and delayed processes return the material back to stability ;*

Starting from A_{seed}=50-80 , the operation of the r-process needs 10-150 n/per/seed nucleus to form Th,U, Pu in the τ ~ sc time.

Which kind of explosive environment can provide such a neutron supply?

Hypothetical r-process sites :

SNII (with postulated n/Nseed ratio)
Neutron star mergers (strong neutron source)

Nuclear input data

Reliable predictions of nuclear properties for few thousands
of unknown nuclei far from stability
demand
the self-consistent approach
based on the universal nuclear density functional.

RNB experiments: validation of the theories.

Ground state properties: ***Bnucl (Z,A)*** ***EDF theory***

Nuclear masses: define the r-process path on (N,Z) plain.

Nuclear response: $S\beta(\omega)$ ***continuum QRPA***

Beta-decay rates: set up the total duration of the r-process.

Beta-delayed processes (β,n), (β,f): *define the production of Th, U, Pu.*

Beta-decay half-life

$$(dW/dt) = T_{1/2}^{-1}\ln 2$$

$$N >> Z$$

$$Gamow-Teller \quad transitions \quad (L=0)$$

$$First- \ forbidden \quad transitions \quad (L=1)$$
$$-m.e.\ are\ reduced\ by \quad (qR)^L,$$
$$but \quad f_0 \quad may \quad be \quad l\arg e!$$

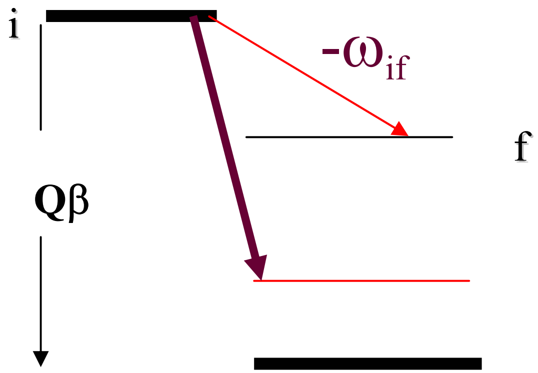
$$Total \quad half-life$$

$$T_{1/2} = \frac{D}{\left(G_A/G_V\right)^2 \int_0^{Q_\beta} S_L(\omega)\ f_0(Z,\omega)\,d\omega}$$

$$D = 2\pi^3 \ln 2 / G_V^2 m_e^5 = 6163s$$
$$G_A/G_V = 1.26$$
$$f_0(Z,A,\omega) = \int_0^\omega F(Z,A,\omega)pW(\omega-W)^2\,dW$$
$$f_0(Z,\omega) \sim \omega^5 \quad \Rightarrow \quad high-energy \quad \beta-decays \quad are \quad amplified!$$

$S_L(\omega)$
$L=0,1$
The main ingredient
to be known at best.
Distribution of
1% of 3(N-Z) !!!

A,Z → A,Z+1+ e-+ υ ^



A,Z+1
daughter

NB! **Q β - HFB**

ω - QRPA

The β-delayed neutron emission

A multi-step process: ***(slow)*** *beta-decay of the precursor,*
(fast) *neutron decay from the states of emitter (* $\omega \leq Q\beta - Bn$

$$P_n = \frac{D^{-1}\left(G_A / G_V\right)^2 \int_{B_n(Z+1)}^{Q_\beta} S(\omega)\ f_0(Z,\omega)\, P_{if}(j_{if}, E_n)\, d\omega}{D^{-1}\left(G_A / G_V\right)^2 \int_0^{Q_\beta} S(\omega)\ f_0(Z,\omega)\, d\omega}$$

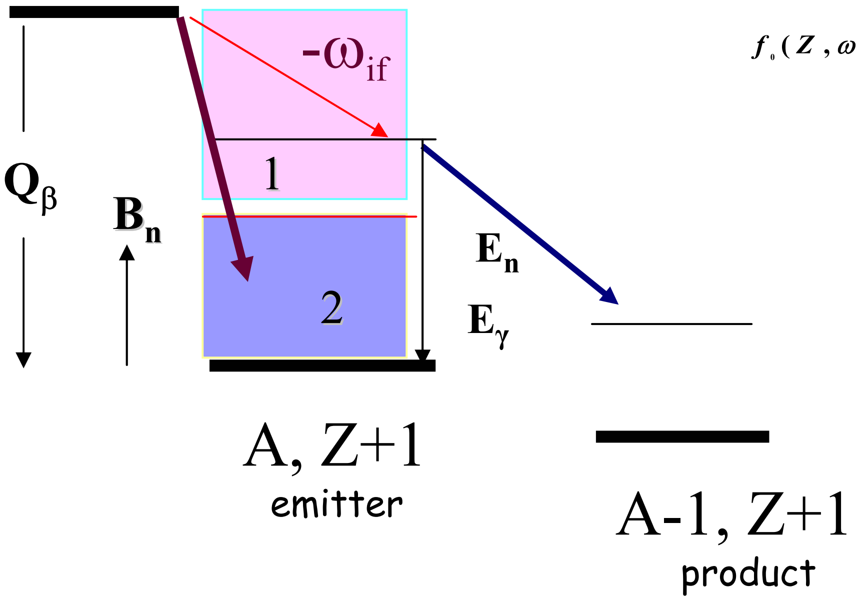
$\sim T_{1/2}$

$S(\omega)$ – *β – strength function*

$P_{if} = \Gamma_n / (\Gamma_n + \Gamma_\gamma), \qquad \Gamma_\gamma \ll \Gamma_n \quad \Rightarrow \quad P \approx 1$

$f_0(Z,\omega) \sim \omega^5 \quad \Rightarrow$ *β – decays to the levels outside the* $Q_\beta - B_n$ *– window are amplified !*

A,Z → A,Z+1+ e-+ υ ^
precursor



Global approaches to nuclear β-decay

1. Empirical systematics, *K.-L. Kratz et al.* ***S(w)=const***

2. "Gross-theories", *Y.Yamada et al, 1975 T.Tachibana et al.,1992, 1997* ***S(w)~ ρ***

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3. Schematic micro-models with the separable forces

BCS+QRPA *H.-V. Klapdor-Kleingrothaus et al., 1992* ***(GT),***
1996 ***(unique FF)***

BSC+RPA *P. Moeller et al., 1997* ***(GT),***
2001 ***(GT-RPA; FF-gross theory)***

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4. Shell- model

SMMC *K. Langanke, G. Martinez-Pinedo 1999* ***(GT)*** ***T1/2 +Pn***

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5. Self-consistent QRPA models *(see I.N.Borzov , S. Goriely PEPAN 34 (6), 1376-1435, 2003)*

M*/M=1

DF3+CQRPA *I.N.Borzov et al., 1995* ***(GT),***
ETFSI +CQRPA *1996* ***(GT),***

HFB+QRPA *W. Nazarewicz et al. 1999* ***(GT)***

DF3+CQRPA *I.N.Borzov , 2003* ***(GT+FF)*** ***T1/2***
2004 ***(GT+FF)*** ***T1/2+Pn***

(DD-ME1* M*/M=0.76)

HFB+RQPA ***T.Nicsic, T.Marketin, D.Vretenar, P. Ring, 2005 T1/2 (GT)***

Self-Consistent ground state (1)

$$E[\rho,\nu] \geq E(exact) \equiv \langle HF | H_{eff} | HF \rangle$$

P.Hohenberg, W.Kohn Phys.Rev. 140 (1964) B864

$$E[\rho,\nu] = Tr\left(\frac{p^2}{2M}\rho\right) + E_{\mathrm{int}}[\rho,\nu]$$

M/M=1*

W.Kohn, L.Sham Phys.Rev. 1409 (1965) A1133

$$E_{\mathrm{int}} = \sum_{main,Coul,sl} \varepsilon_n[\rho] + \frac{1}{2}\nu * F^{\xi}[\rho]\nu$$

$$H = \begin{pmatrix} h-\mu & -\Delta \\ -\Delta & \mu-h \end{pmatrix}$$

$$h = \frac{p^2}{2m} + \frac{\delta E}{\delta\rho} \sim \rho \qquad \Delta = \frac{\delta E}{\delta\nu} \sim \rho,\nu$$

$$\rho_0,\nu_0 \Rightarrow h_0,\Delta_0 \Rightarrow \rho_1,\nu_1 \Rightarrow h_1,\Delta_1$$

Self-Consistent Ground State description(2)

Skyrme-HF

S. Goriely, F. Tondeur, J.M. Pearson ADNDT 77(2001)311

MSk7- 10 parameters Skyrme force, 4 parameters δ-function pairing, 2 parameters Wigner term. The rms error of the fit to 1988 masses (Audi-Wapstra 1995) is **0.738 MeV.**

M/M=1*

DF3

I.N. Borzov, S.A. Fayans, E. Kromer, D. Zawischa Z. Phys. A335(1996) 117

DF3 – local energy-density functional by

S.A. Fayans et al. 3 parameters δ-function pairing. Fitted to the g.s. properties near “magic cross” at ^{132}Sn.

Nuclear response.
Quasiparticle RPA

$$F^{\omega}_{\tau\tau} = \frac{\delta^2 E}{\delta\rho^{\tau}\delta\rho^{\tau}} \qquad F^{\xi}_{\tau\tau} = \frac{\delta^2 E}{\delta\nu^{\tau}\delta\nu^{\tau}}$$

Spin-isospin stable ground state

g’Skyrme ≈ 0.2 **g’empirical ≈ 1**

QRPA based on the self-consistent ground state

Effective NN-interaction (p-h)

$$F_{\sigma\tau} = 2C_0\left(g'_0\,\sigma_1\sigma_2 + g^*_\pi Q^2_\pi \frac{(\sigma_1 k)(\sigma_2 k)}{k^2+m^2_\pi+P_\Delta(k)} + g^*_\rho \frac{[\sigma_1 k][\sigma_2 k]}{k^2+m^2_\rho}\right)(\tau_1\tau_2)$$

REPULSION **ATTRACTION**

$g' > 0$, $g^*_\pi Q^2_\pi = -\frac{4\pi}{C_0}\frac{f^2_\pi}{m^2_\pi} Q_\pi^{2} < 0$, $g^*_\rho = 0.4\, g^0_\rho < 0$

$$S_{GT} = Q^2_{\sigma\tau}\, 3(N-Z)$$

60 ± 10%
(p,n), Ep=120 MeV
IUCF 1980-1990
Qπ≅Qστ=0.8

93 ± 5%
(p,n), E_p=295 MeV
RCNP 1999
Qπ≅Qστ=0.9

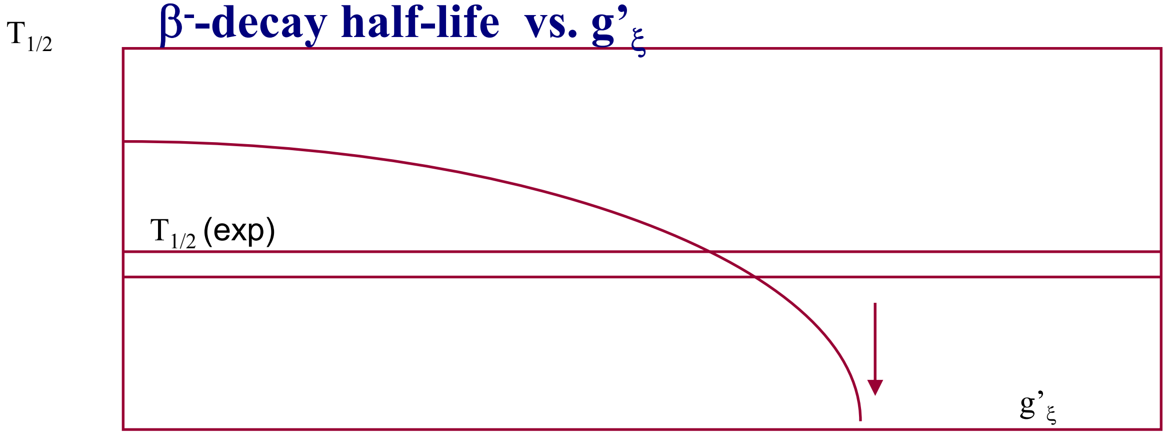
Particle-particle effective interaction (pn T=0)

$$F\sigma\tau^{\xi} = -\,2C_0{}^{*}\, g'_{\xi}\, \delta(r_{12})$$

`g'ξ is fixed from`

```
(n,p), (p,n) spectra
   Ep,n =300 MeV
    54Fe, 60Ni ...
```

β^--decay half-life vs. g'_ξ



CQRPA description of the pn-excited states

$$[\hat{I}-\begin{pmatrix} -F^{\omega} & 0 & 0 & 0 \\ 0 & -F^{\omega} & 0 & 0 \\ 0 & 0 & -F^{\xi} & 0 \\ 0 & 0 & 0 & -F^{\xi} \end{pmatrix}\begin{pmatrix} L(\omega) & M(\omega) & N^{1}(\omega) & N^{2}(\omega) \\ M(\omega) & L(-\omega) & N^{2}(-\omega) & N^{1}(-\omega) \\ N^{1}(\omega) & N^{2}(-\omega) & K(\omega) & -M(\omega) \\ N^{2}(\omega) & N^{1}(-\omega) & -M(\omega) & K(-\omega) \end{pmatrix}]\begin{pmatrix} V \\ V^{h} \\ d^{(1)} \\ d^{(2)} \end{pmatrix}=\begin{pmatrix} V_0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$V_0^{*}(r)=\begin{pmatrix} \sigma\tau, & \varepsilon_{mec}\langle\lambda_5\rangle,\langle\sigma r\rangle, & \langle\alpha\rangle,\langle ir\rangle,[\sigma r]^{1,2} \\ GT & J=0 & J=1,2 \end{pmatrix}$$

$$L(r,r';\varpi)=A(r,r';\varpi)+\Sigma\int\int<n^{*}p\left|L_{pn}-A_{\tilde{\tilde{pn}}}\right|np^{*}>$$

Propagators:

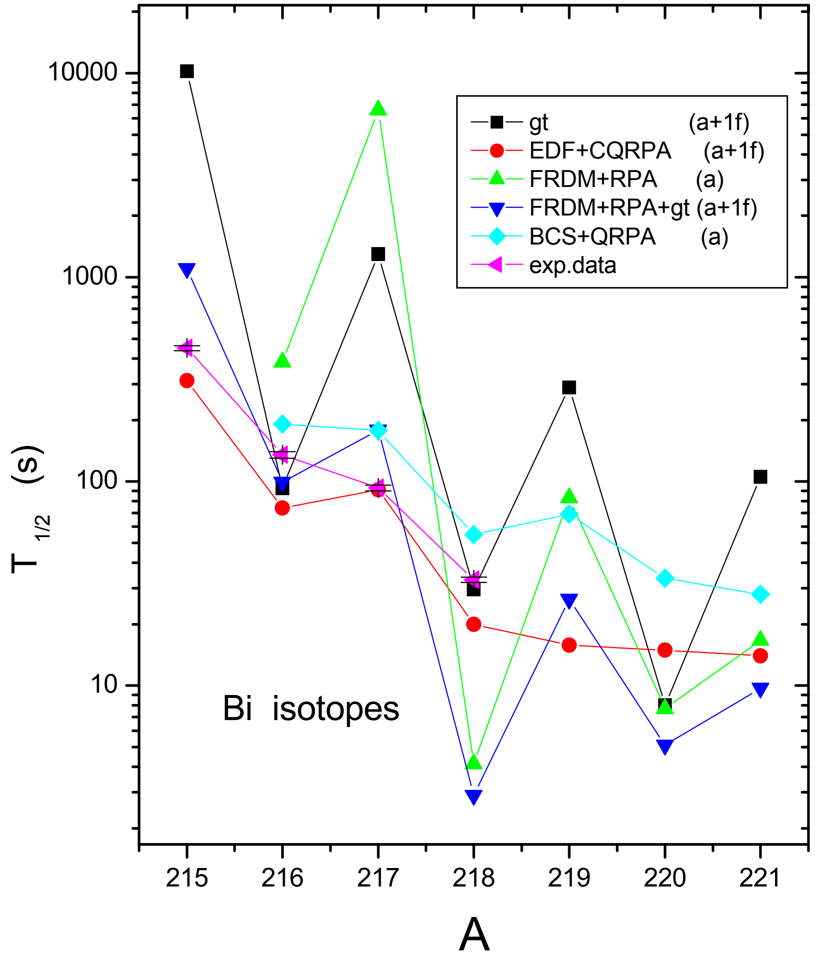
$A(r,r';\varpi)$ **no pairing, continuum**

L_{pn} **pairing, valence space**

$A_{\tilde{\tilde{pn}}}$ **removes 2-counting.**

T=0	*A.P. Platonov, E.E. Saperstein, ЯФ 1987; Nucl.Phys. A486(1988)63.*
T=0	*N. Van Giai, Nucl. Phys. A482 (1988) 473c.*
|T|=1	*I.N. Borzov, E.L. Trykov Izv.AN SSSR 53(1989) 2468:*
	I.N. Borzov, S.A.Fayans, E.L. Trykov Sov.J.Nucl.Phys. 52(1990) 33

Isotopic behavior
of the beta-decay half-lives



- **Gross theory parametrization**

P.Moller at al. (BCS+RPA)
Δ - no pp-interaction

H.-V.Klapdor et al. (QRPA)
◊ - no FF transitions

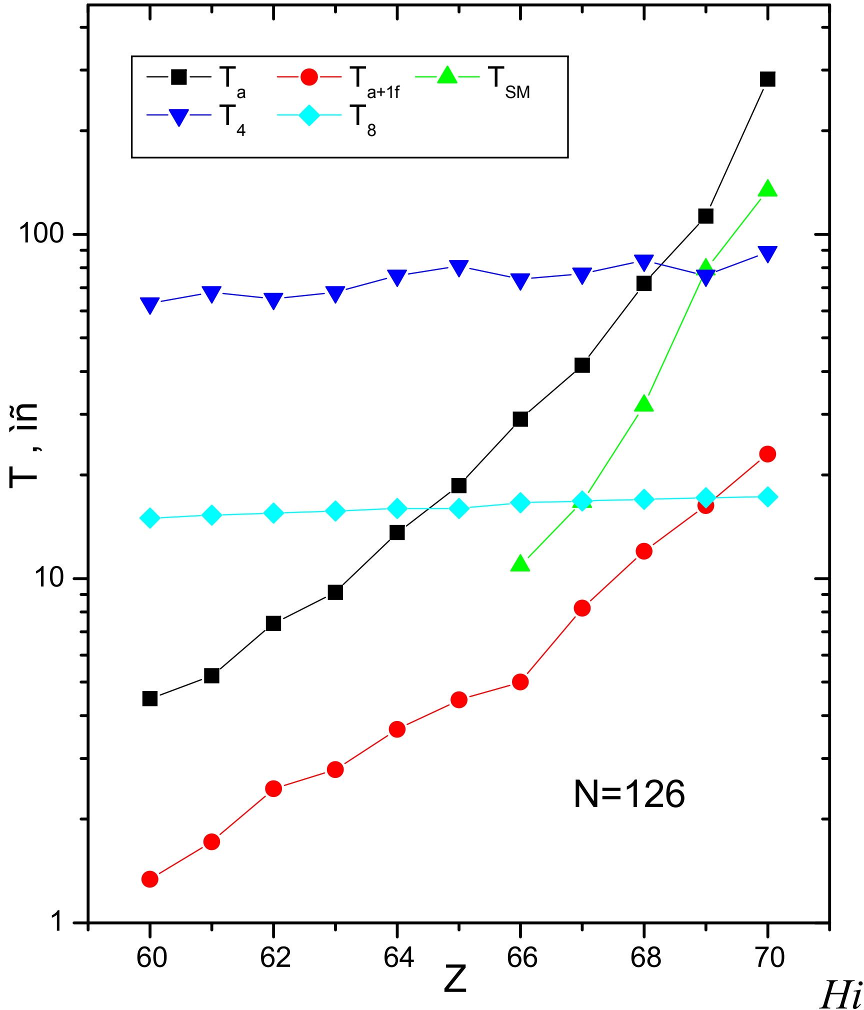
O - cQRPA (ph,pp)

\# - Exp.data

H. DeWitte, A.N. Andreev, I.N. Borzov et al.,
Phys. Rev. C 69 (2004) 044305

Experimental odd-even staggering of the total β-decay half-lives is well described within the full QRPA framework. The latter includes “dynamic paring “ and restores the SO(8) symmetry broken in the BCS+RPA approximation.

Beta-decay in N=126 region



I.N. Borzov Phys. Rev. C67 (2003) 025802

DF3+CQRPA

a -allowed GT approximation
a+1f – with GT+FF transitions

SM – Shell-Model

G.Martinez-Pinedo Nuc.Phys.A668(2000)357c

◊ - effective half-life for Ve_-capture
at T=8 MeV

The calculated beta-rate (GT_FF) is higher than ve_-capture rate at T=4 and 8 MeV

High-energy FF transitions substantially reduce the total β-decay half-lives in N=126 region.. This results in speeding up the r-process.

Competition of the Gamow-Teller (GT) and First Forbidden (FF) β-decays

Where ?

In the nuclei with the neutron-excess bigger than one major-shell

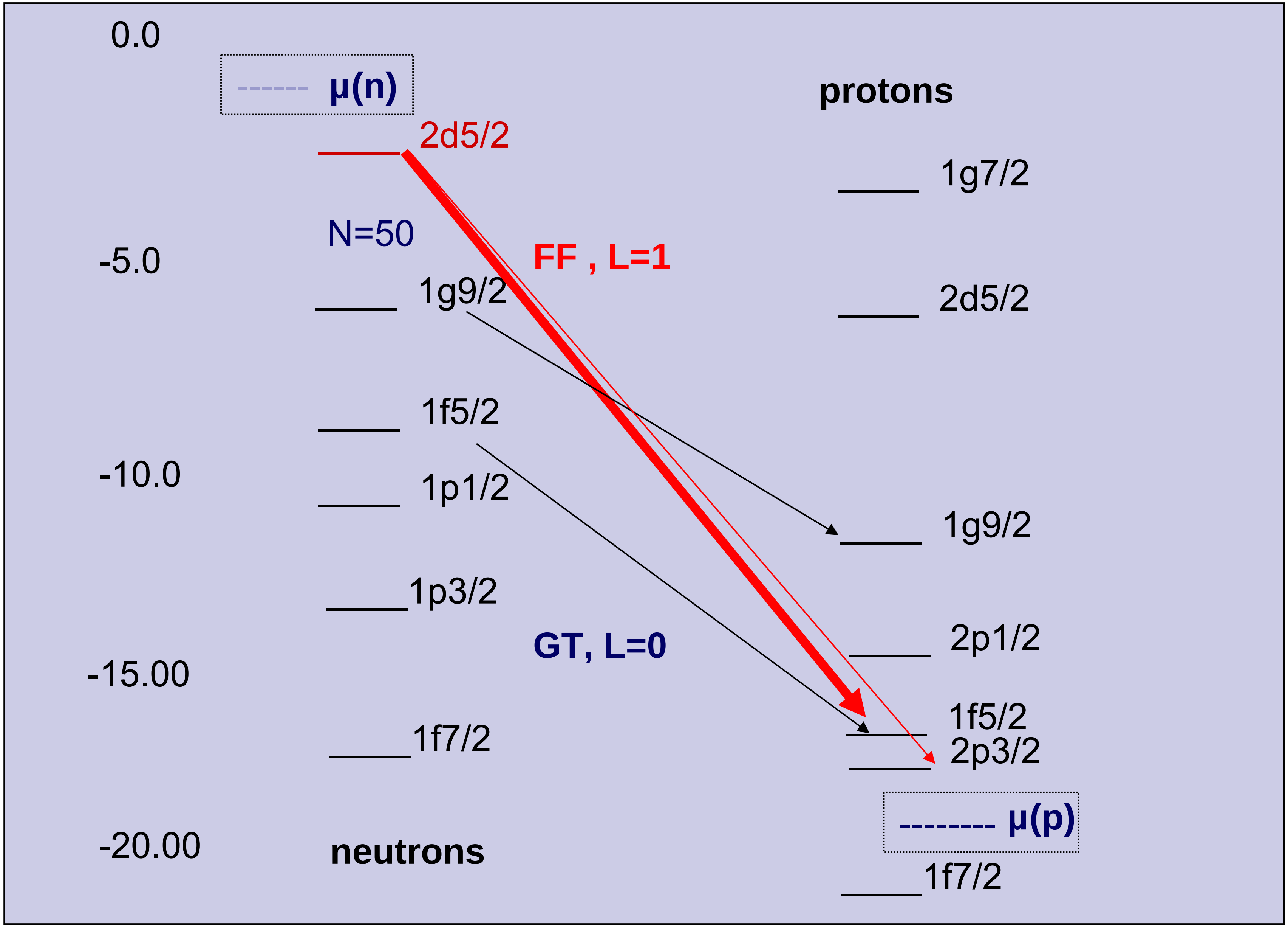
The result.

A suppression of the delayed neutron emission

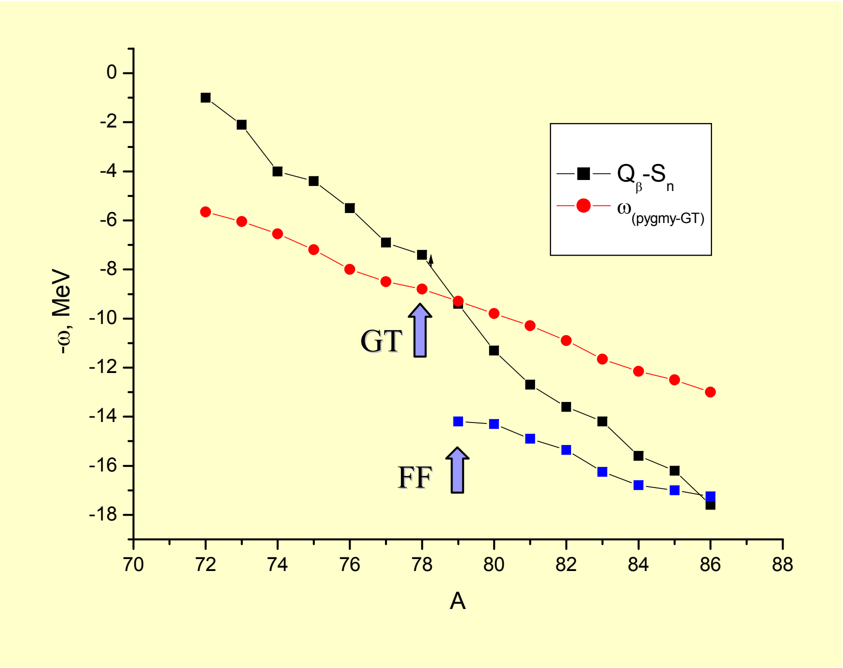
Why?

Due to the high-energy FF transitions
to the states outside the neutron emission window

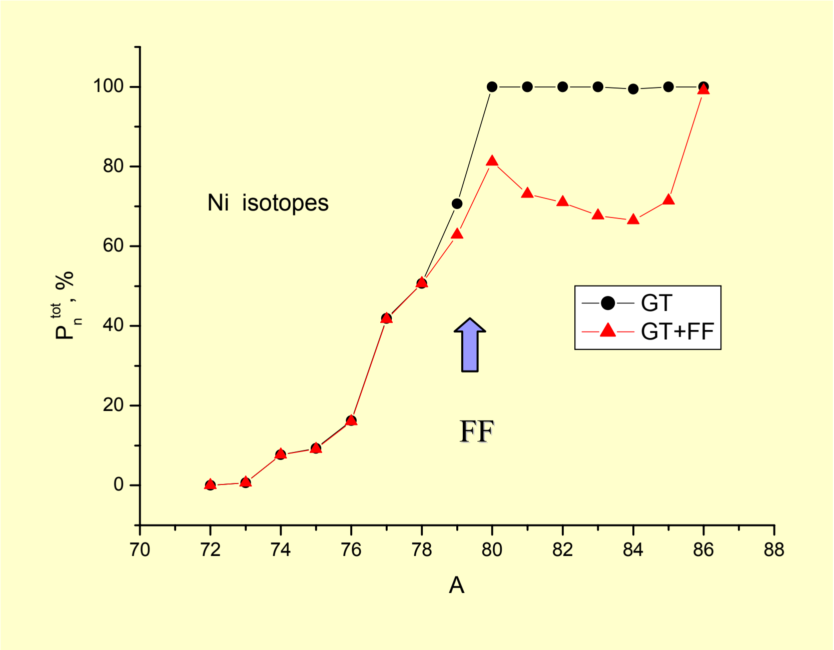
One-quasiparticle levels near Z=28, N≥50



The energies of the $J=0^-$ and 1^+ transitions and the Pn-values
(Ni isotopes)



A≤78 : no high energy FF transitions are open.

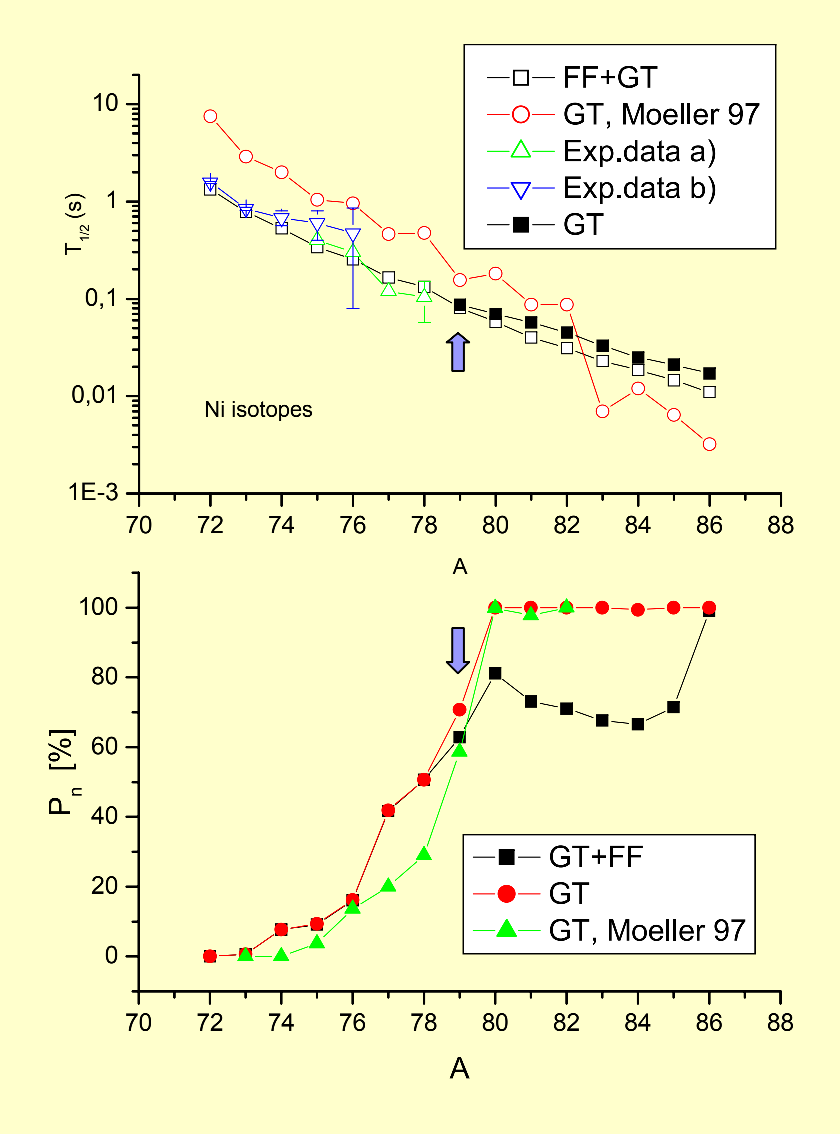


© A "gap-like" pattern in the the Pn-values

© A≥79: the FF transitions dominate in the T1/2. No neutron emission from these levels is possible as $\omega \geq Q_{\beta n}$

I. N. Borzov nucl-th/0409019 (2004)

Half-lives and Pn-values for Ni isotopes



I.N. Borzov nucl-th/0409019 (2004)
Phys.ReV. C71(2005)065801

*The half-lives for A≤78 are well described in the **GT** approximation (DF3+CQRPA)*

(contradicts to P. Moeller – GT+FF+shell quenching!)

a) MSU-05 , P.T.Hosmer et.al.
PRL 94 (2005) 112501

b) CERN 98

A	*Tth, ms*	*MSU-05,ms*
75	*340*	*344+20-24*
76	*255*	*238+15-18*
77	*166*	*128+27-33*
78	***133***	***110+100 -60***

© A regular behavior of the T1/2 for A>78 can be provided if the FF transitions are included.

© The FF transitions outside the Q β n reduce the Pn-values compared to the GT case.

Beta-decay in $Z>28$ region

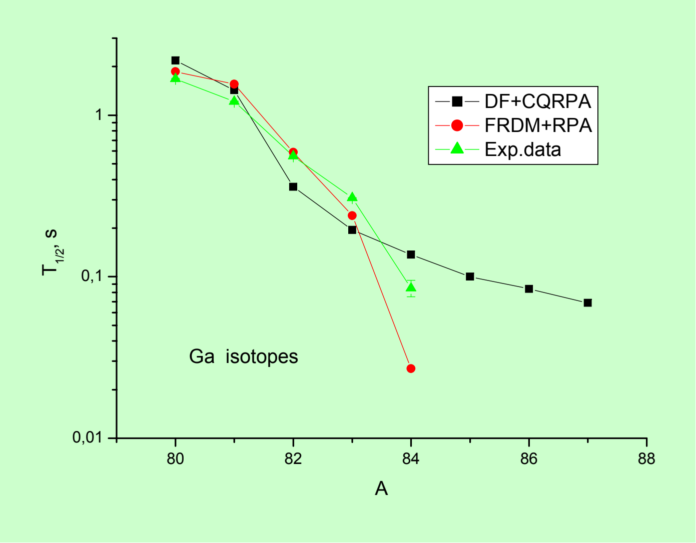
1. $Q_{\beta n}$-value is high enough.

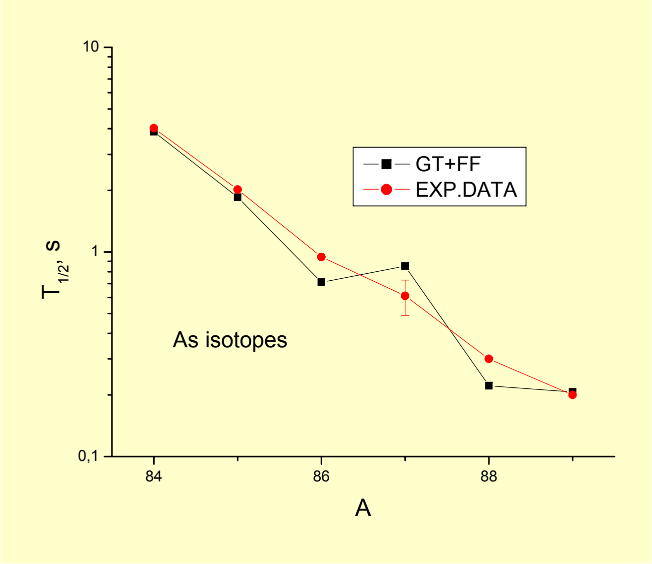
2. For $N - Z > N_0$ nuclei, a suppression of the Pn-values increases with Z.

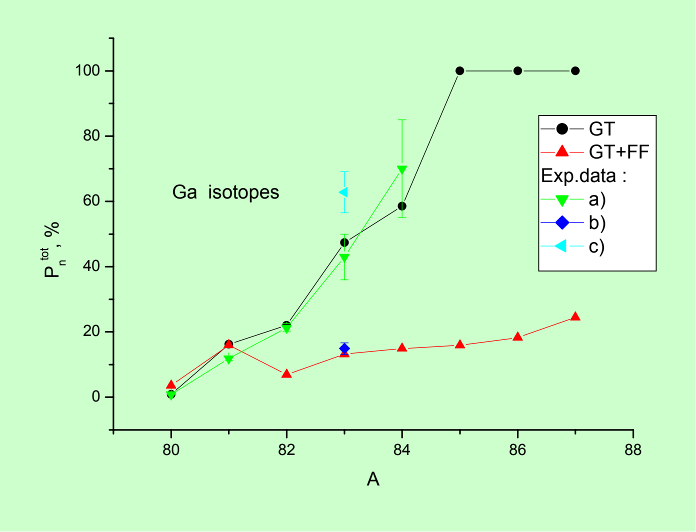
3. Predicted suppression of the Pn-values for Zn-Kr will be verified in the current RNB – experiments:

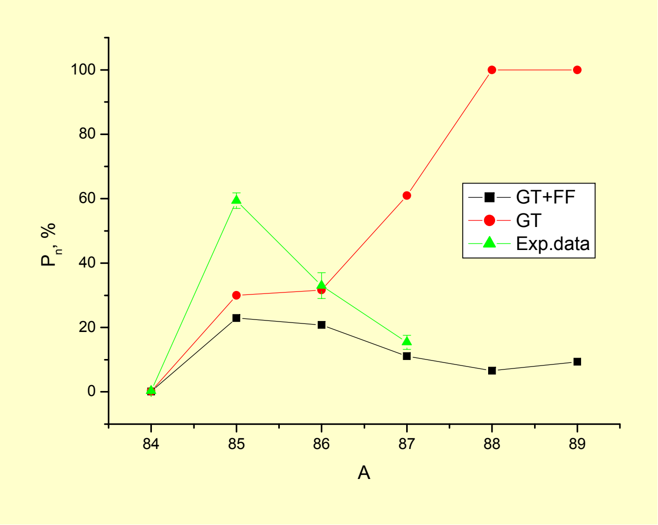
   ISOLDE CERN-05, ALTO-05 …

Half-lives and Pn-values for Ga and As isotopes



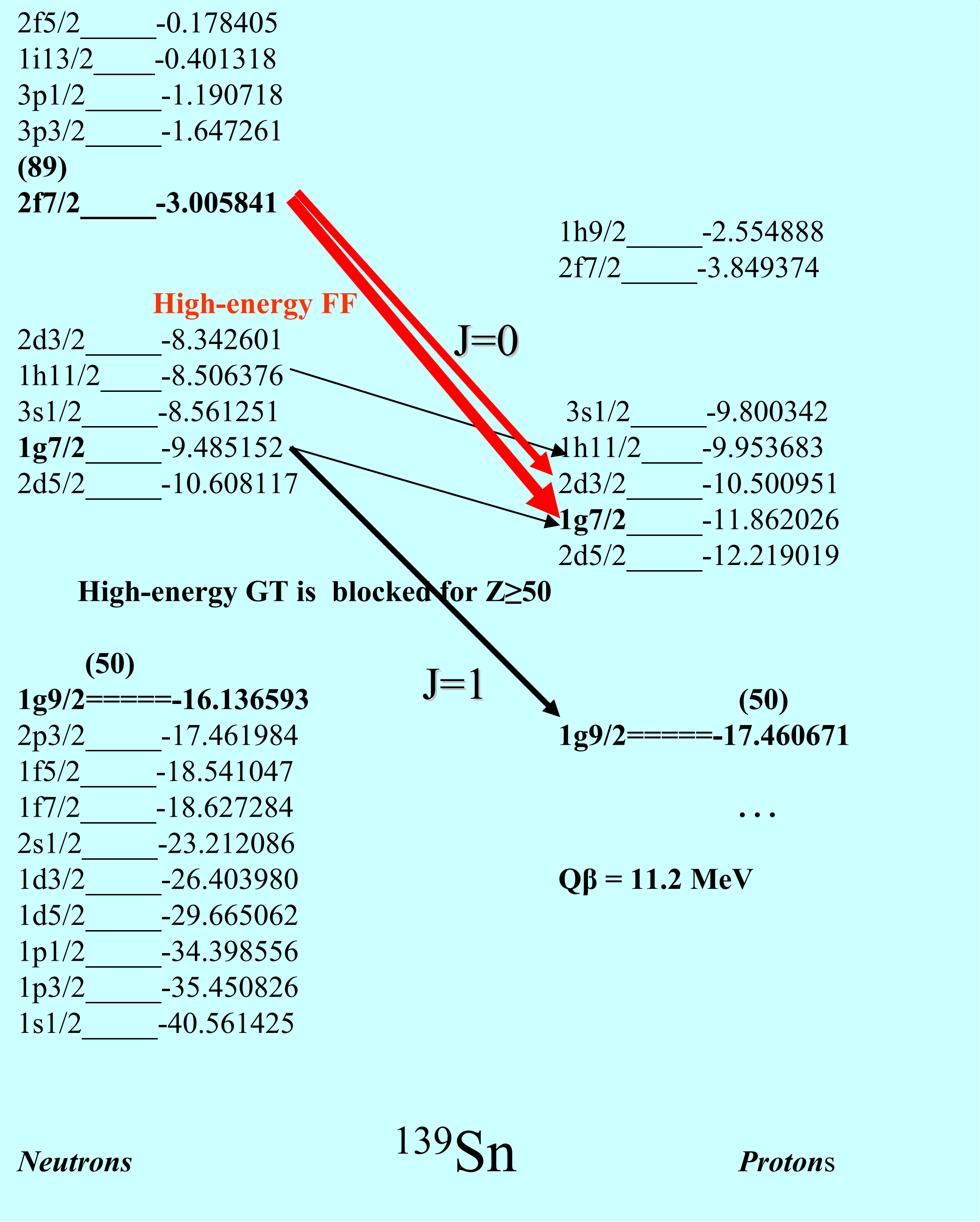






I. N. Borzov nucl-th/0409019 (2004), Phys.Rev. C 71 (2005)

Blocking of the π1g9/2- orbit Z ≥ 50



2f5/2_____-0.178405
1i13/2____-0.401318
3p1/2_____-1.190718
3p3/2_____-1.647261
(89)
2f7/2_____-3.005841

High-energy FF

2d3/2_____-8.342601
1h11/2____-8.506376
3s1/2_____-8.561251
1g7/2_____-9.485152
2d5/2_____-10.608117

J=0

1h9/2_____-2.554888
2f7/2_____-3.849374

3s1/2_____-9.800342
1h11/2____-9.953683
2d3/2_____-10.500951
1g7/2_____-11.862026
2d5/2_____-12.219019

High-energy GT is blocked for Z≥50

J=1

(50)
1g9/2=====-16.136593
2p3/2_____-17.461984
1f5/2_____-18.541047
1f7/2_____-18.627284
2s1/2_____-23.212086
1d3/2_____-26.403980
1d5/2_____-29.665062
1p1/2_____-34.398556
1p3/2_____-35.450826
1s1/2_____-40.561425

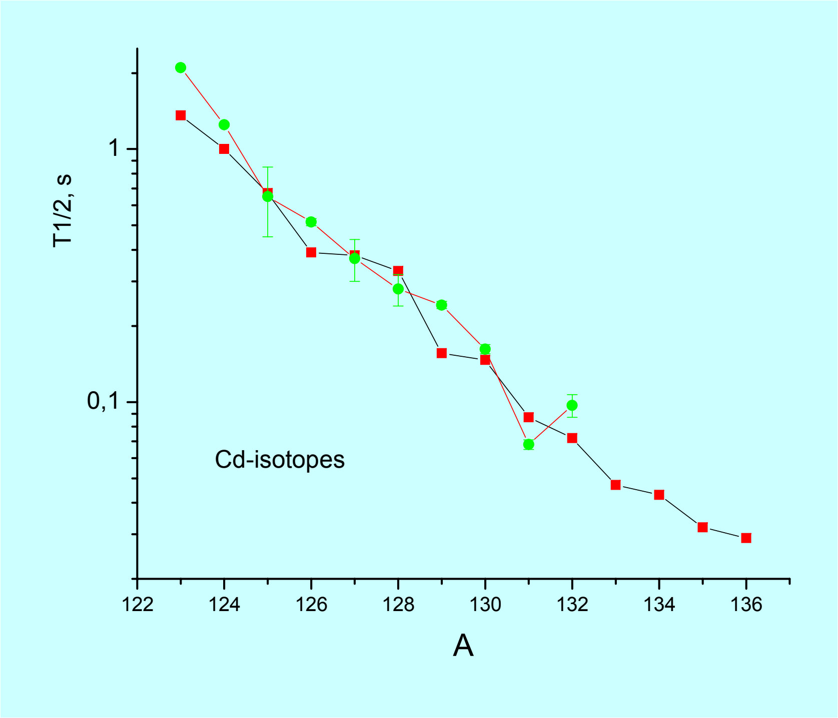
(50)
1g9/2=====-17.460671

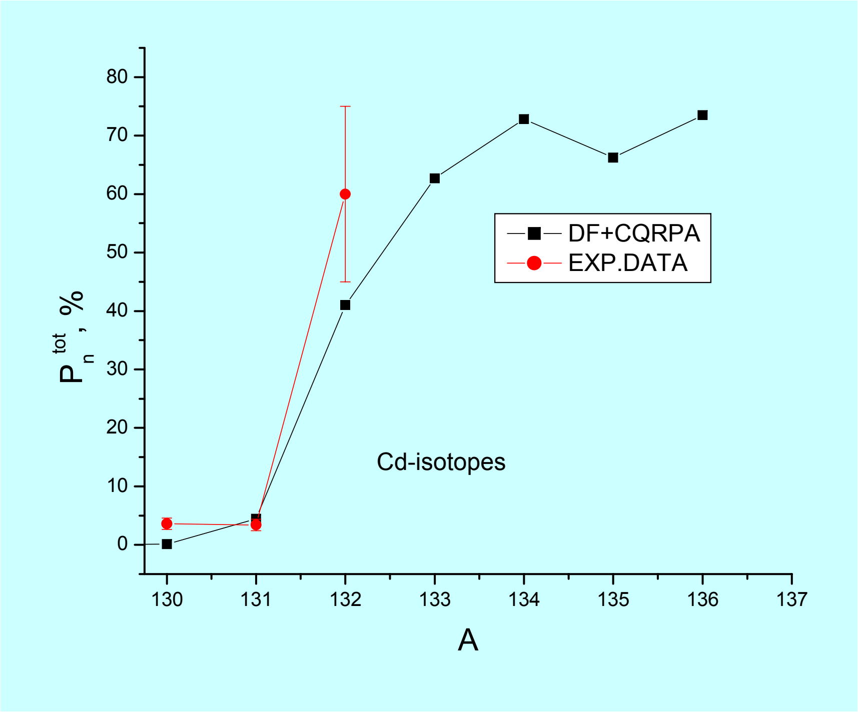
. . .

Qβ = 11.2 MeV

Neutrons ^{139}Sn ***Protons***

$_{48}Cd^{130\text{-}136}$

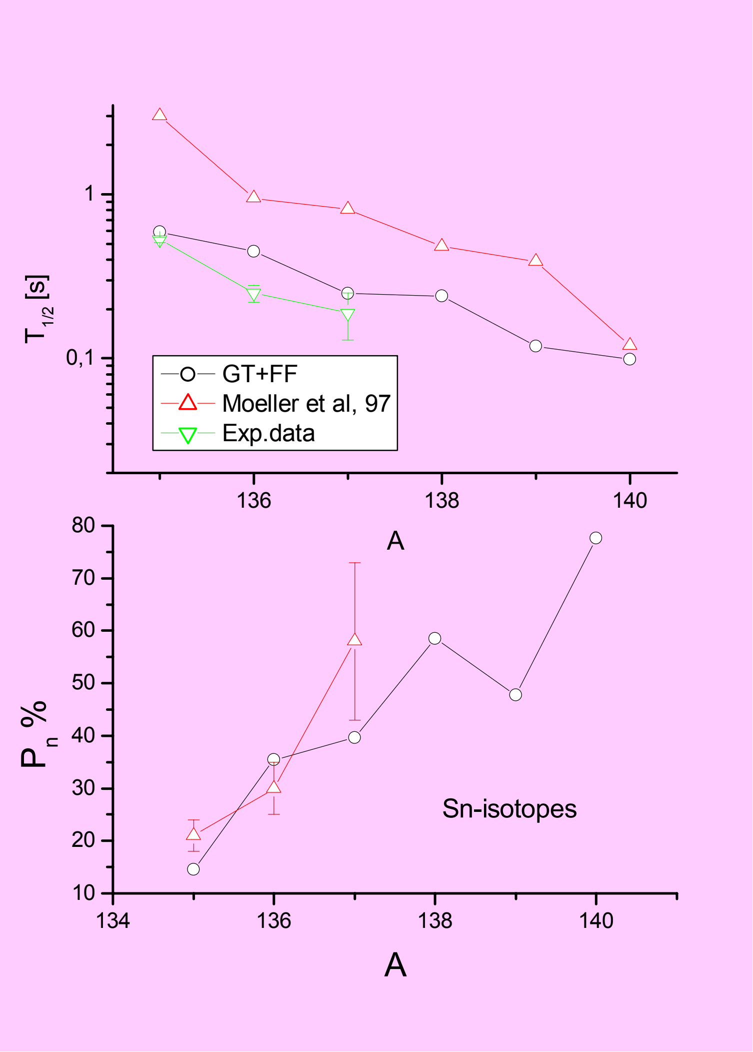


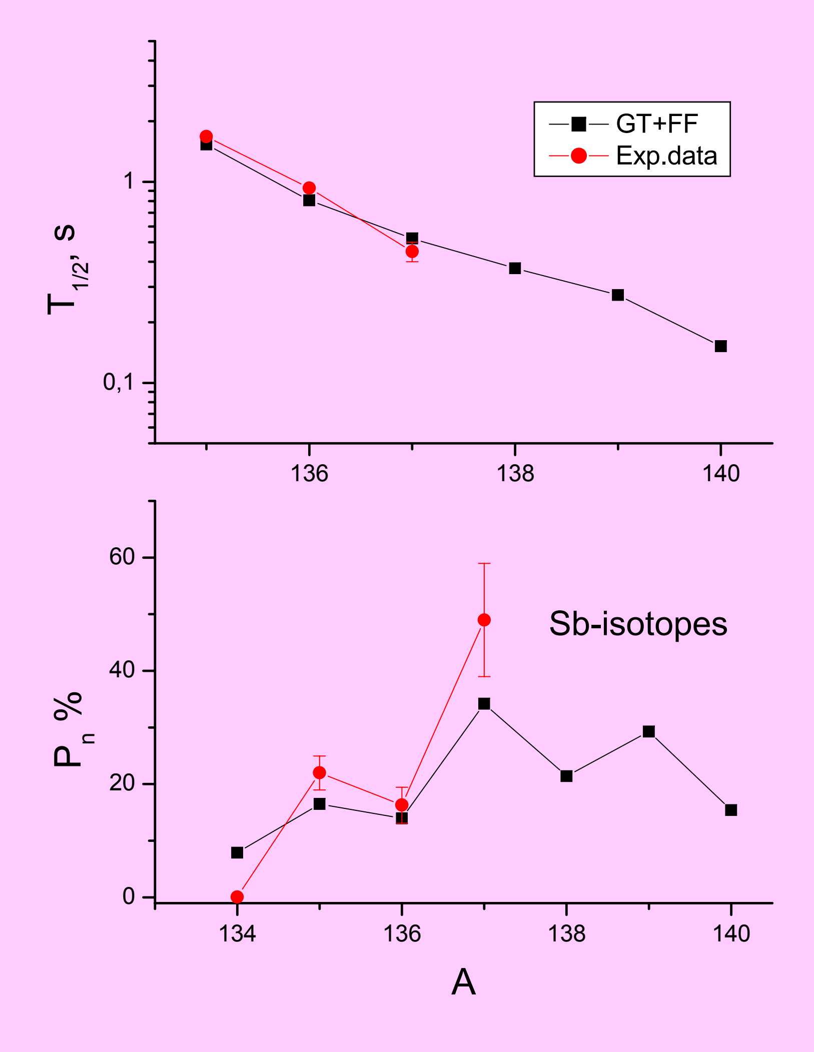


I.N.Borzov, Nucl.Phys. A , 2005
(Special Volume “Nuclear Astrophysics”, invited paper, in print)

Experimental data : M. Hannawald et al. 2000, Phys. ReV. C62, 054301

The isotopes at $Z \geq 50$

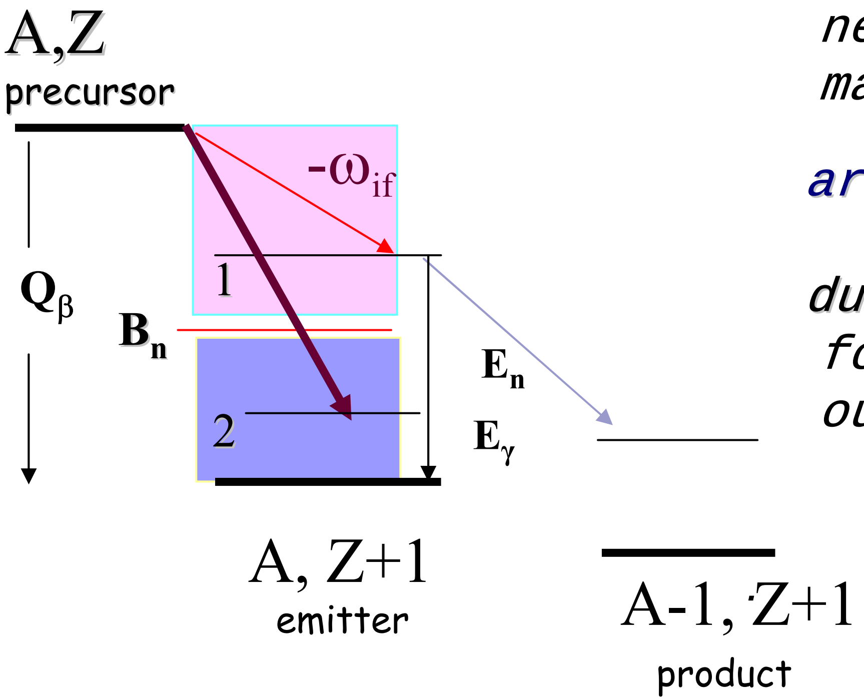




I.N.B,   Nucl.Phys. (npa 10142, 2005)

Experimental data :
G. Rudstam et al. 1993, ADNDT 53, 1
R. Shergur et al. 2002,Phys. ReV. C 65, 034313

Suppression of the Pn-values



In the nuclei with the neutron-excess bigger than one major-shell, the Pn –values

are suppressed

due to the high-energy first-forbidden decays to the states outside the Q_β – B_n-window.

GT + FF

The effect should be taken into account in the r-process calculations

The self-consistent DF+CQRPA approach is used to improve the β–decay characteristics for the r-process relevant nuclei at N=50,82,126

Perspectives

Deformed DF+QRPA

T1/2, Pn
Beta-delayed fission
Neutrino-induced fission

Conclusions (I)

Experimental odd-even staggering of the total β-decay half-lives is well described within the full QRPA framework.

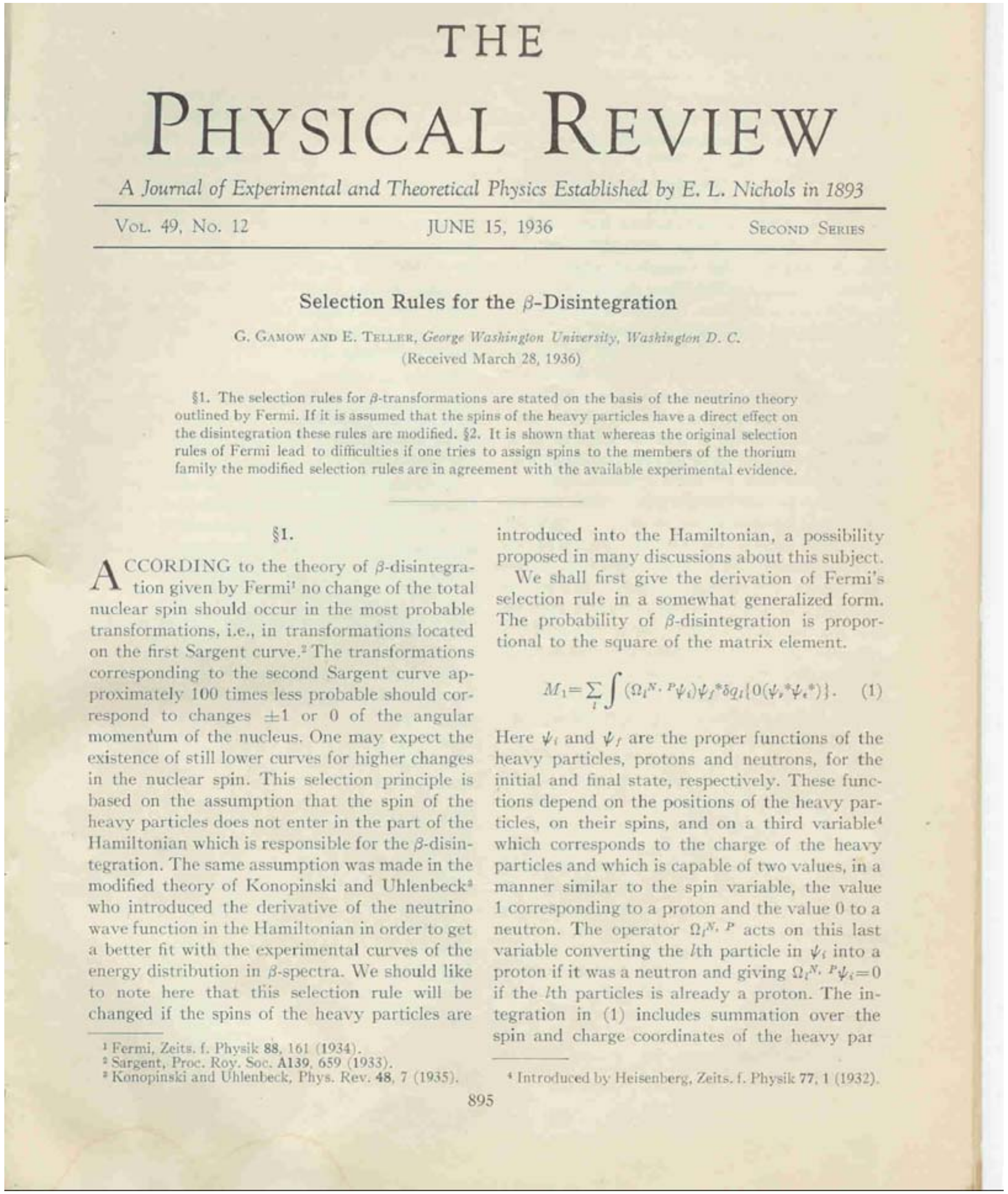
The latter includes "dynamic paring " and restores the

SO(8) symmetry broken in the BCS+RPA approximation.

High-energy FF transitions substantially reduce the total

β-decay half-lives for $Z \geq 50$, $N \geq 82$ nuclei and in $N=126$ region.

This results in speeding up the r-process.



THE
PHYSICAL REVIEW
A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893
VOL. 49, NO. 12 JUNE 15, 1936 SECOND SERIES

Selection Rules for the β-Disintegration

G. GAMOW AND E. TELLER, *George Washington University, Washington D. C.*

(Received March 28, 1936)

§1. The selection rules for β-transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

§1.

ACCORDING to the theory of β-disintegration given by Fermi[1] no change of the total nuclear spin should occur in the most probable transformations, i.e., in transformations located on the first Sargent curve.[2] The transformations corresponding to the second Sargent curve approximately 100 times less probable should correspond to changes ±1 or 0 of the angular momentum of the nucleus. One may expect the existence of still lower curves for higher changes in the nuclear spin. This selection principle is based on the assumption that the spin of the heavy particles does not enter in the part of the Hamiltonian which is responsible for the β-disintegration. The same assumption was made in the modified theory of Konopinski and Uhlenbeck[3] who introduced the derivative of the neutrino wave function in the Hamiltonian in order to get a better fit with the experimental curves of the energy distribution in β-spectra. We should like to note here that this selection rule will be changed if the spins of the heavy particles are introduced into the Hamiltonian, a possibility proposed in many discussions about this subject.

We shall first give the derivation of Fermi's selection rule in a somewhat generalized form. The probability of β-disintegration is proportional to the square of the matrix element.

$$M_1=\sum_l \int (\Omega_l^{N,P}\psi_i)\psi_f^*\delta q_l\{O(\psi_\nu^*\psi_e^*)\}. \quad (1)$$

Here ψ_i and ψ_f are the proper functions of the heavy particles, protons and neutrons, for the initial and final state, respectively. These functions depend on the positions of the heavy particles, on their spins, and on a third variable[4] which corresponds to the charge of the heavy particles and which is capable of two values, in a manner similar to the spin variable, the value 1 corresponding to a proton and the value 0 to a neutron. The operator $\Omega_l^{N,P}$ acts on this last variable converting the lth particle in ψ_i into a proton if it was a neutron and giving $\Omega_l^{N,P}\psi_i=0$ if the lth particles is already a proton. The integration in (1) includes summation over the spin and charge coordinates of the heavy par

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[1] Fermi, Zeits. f. Physik **88**, 161 (1934).
[2] Sargent, Proc. Roy. Soc. **A139**, 659 (1933).
[3] Konopinski and Uhlenbeck, Phys. Rev. **48**, 7 (1935).
[4] Introduced by Heisenberg, Zeits. f. Physik **77**, 1 (1932).

T1/2, Pn
Far from stability…

Beyond the Gamow-Teller transitions approximation.

?

Driving operators of First-Forbidden Decay

$$V_{J=1,L=1,S=0,1} = {}^{1}\!/\!_{\sqrt{3}}\left(i\mathbf{r} - \frac{\mathbf{p}}{2M}\right) + \hat{e}_{qs}\sqrt{2}[\boldsymbol{\sigma}\mathbf{r}]^{(1)}$$

$$V_{J=0,L=1,S=1} = \hat{e}_{qs}(i\boldsymbol{\sigma}\otimes\mathbf{r}) - \hat{e}_{q5}\frac{\boldsymbol{\sigma}\otimes\mathbf{p}}{2M}$$

$$\hat{e}_{qs} = e_q[\sigma\tau] = {}^{g_A}\!/\!_{G_A} \approx 0.8 - 0.9$$

$$\hat{e}_{q5} = e_q[\gamma_5] \approx (1+R)(1+{}^{2}\!/\!_{3}\, g_1') \approx 1.5$$

Reduction of the relativistic operators $\alpha,\gamma_5 \sim P \quad \rightarrow \quad r, \sigma r$

$$\lambdabar\langle\alpha\rangle = \xi\Lambda_1\langle i\mathbf{r}\rangle$$

$$\lambdabar\langle\gamma_5\rangle = \xi\Lambda_0\langle i\boldsymbol{\sigma}\mathbf{r}\rangle$$

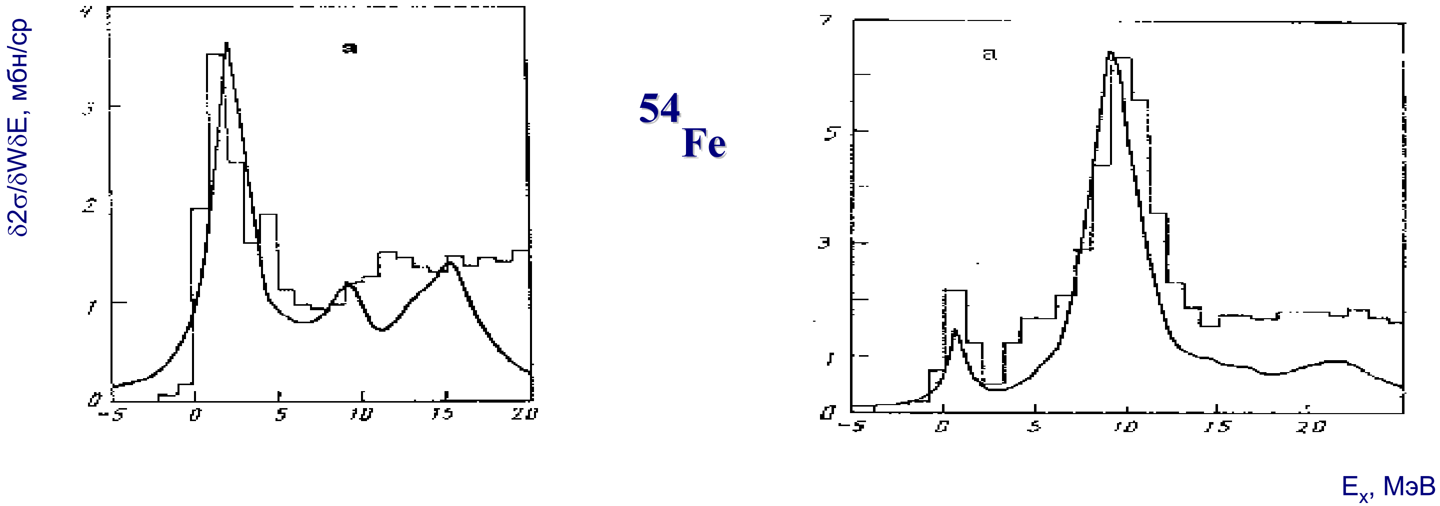
$$\xi\Lambda_1 = \omega_{if} + \overline{U}_C$$

$$\xi\Lambda_0 = \omega_{if} + \overline{U}_C + (\overline{w}_{sl} - \overline{u}_{sl})$$

I.N. Borzov Phys. Rev. C67 (2003) 025802

Gamow-Teller Strength, ΔT= ± 1

(n,p) & (p,n)
reactions spectra at E~ 300 MeV



$2C0*g'_{\xi} = 120–180\ \mathrm{MeV*fm}^3$

The pp-strength was constrained using (p,n) and (n,p) reactions spectra TRIUMF, 1989-1998, (1998 data on Fe,Ni isotopes ≤ 180 MeV·fm^3). Tested in the calculations of the β^+-strength of neutron-deficient nuclei and on the β^--decay half-lives of neutron-rich nuclei.

I.N.Borzov, E.L.Trykov Sov.J.Nucl.Phys. 52 (1990) 33

I.N.Borzov, F.A.Gareev, S.N.Ershov et.al. Sov.J. Nucl.Phys.55 (1992) 60 DWIA

Conclusions

Nuclei far from stability

The half-lives and A-behavior of the Pn-values deviate from the one predicted within the GT decay approximation

High-energy first-forbidden transitions to the states outside the $Q_{\beta n}$- window suppress the Pn-values .

The r-process nucleosynthesis

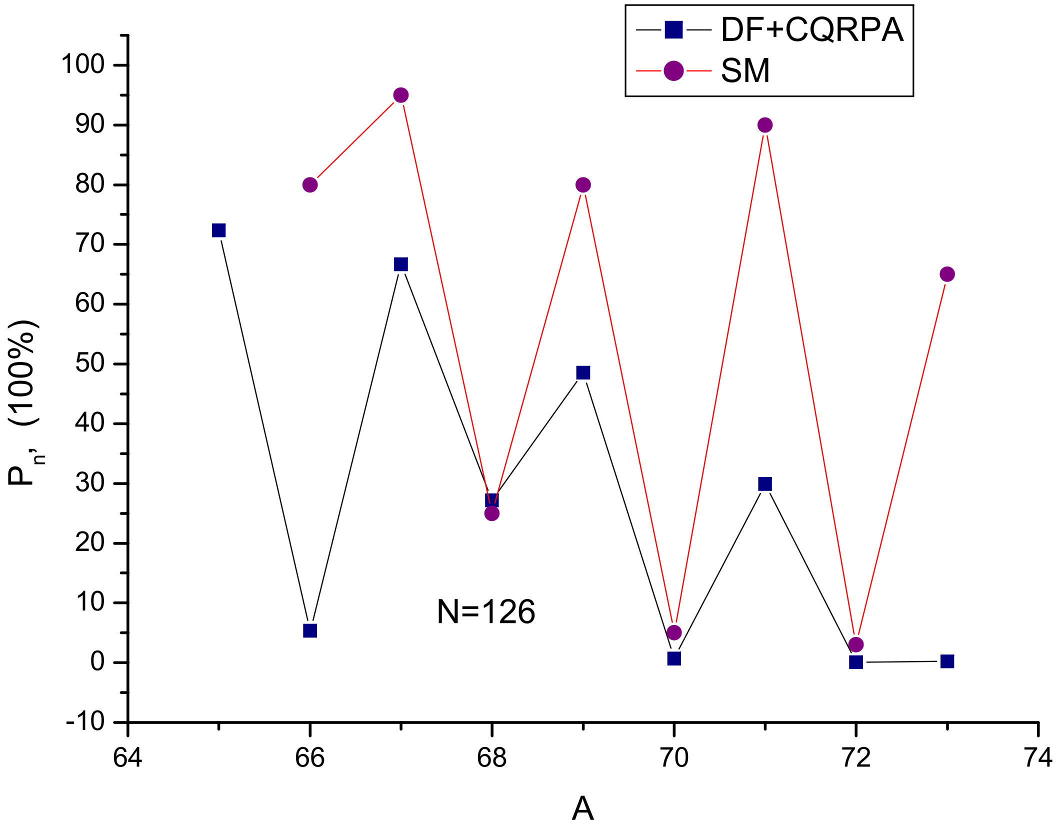
FF transitions lead to shorter time-scale.

The existing **T1/2, Pn-libraries** have to be revised.

RNB-experiments in the region of ^{78}Ni,

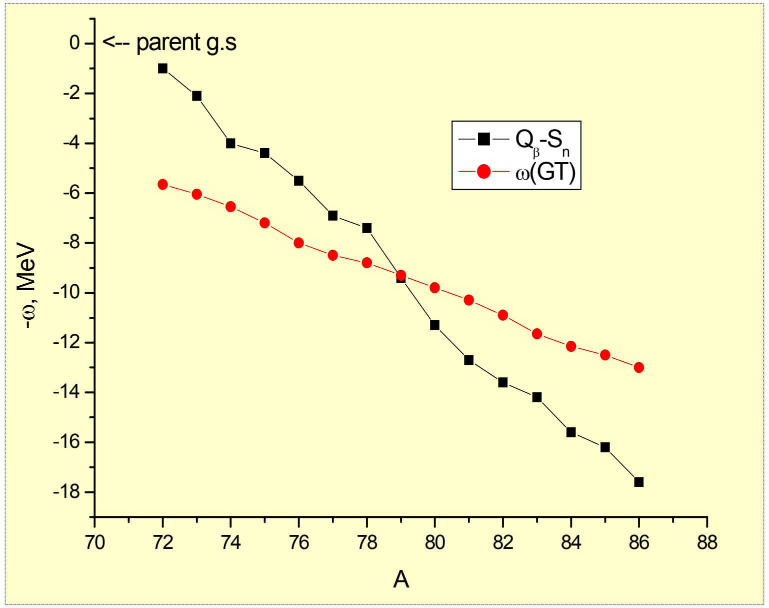
Predicted suppression of the Pn-values for Zn-Kr will be verified in the **RNB – experiments**: ISOLDE CERN-05,
ALTO - 05,
MSU - 05...

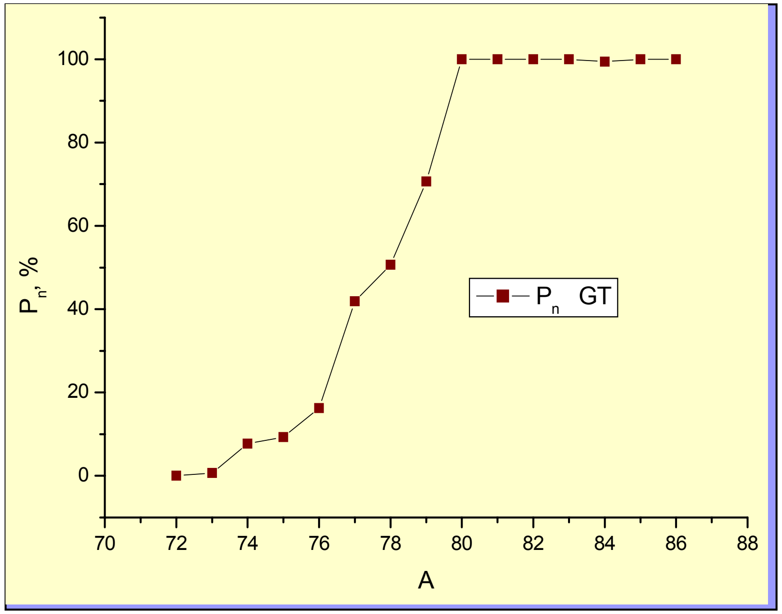
N=126 isotones

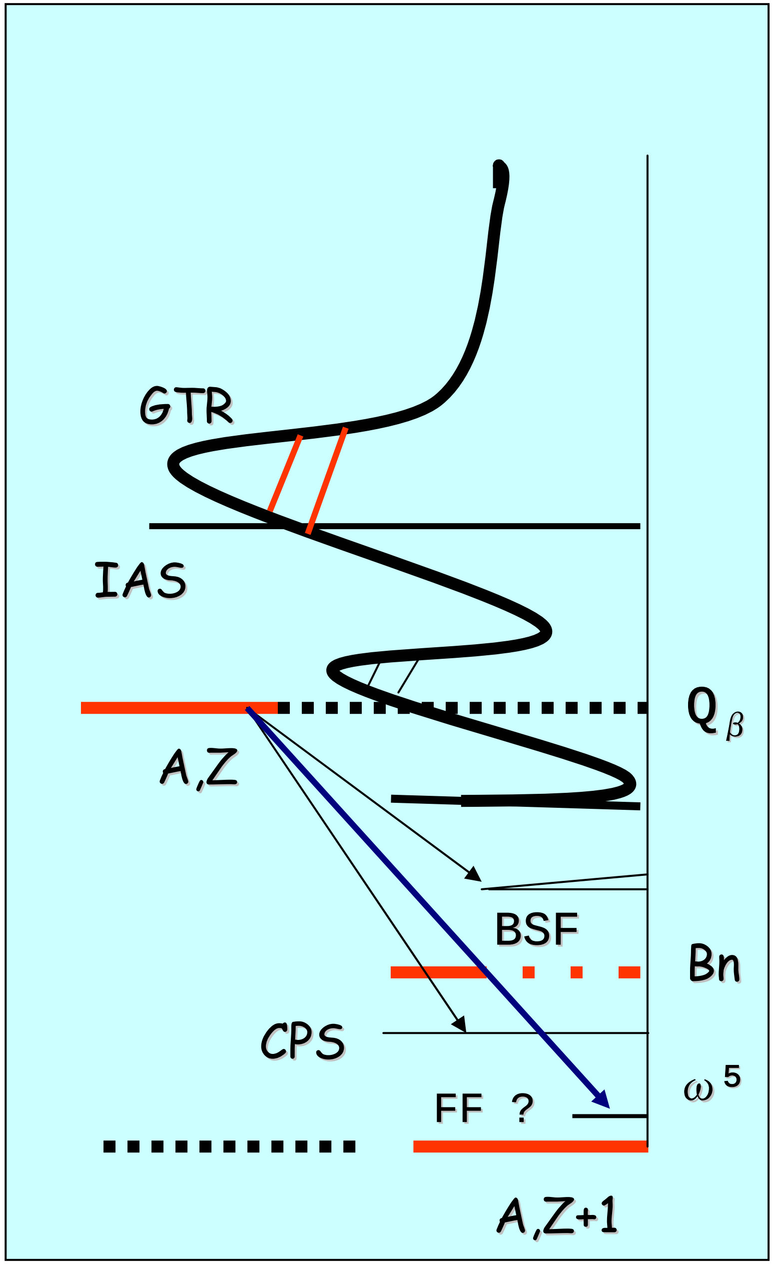


SM calculations – Martinez-Pinedo, Langanke 2002

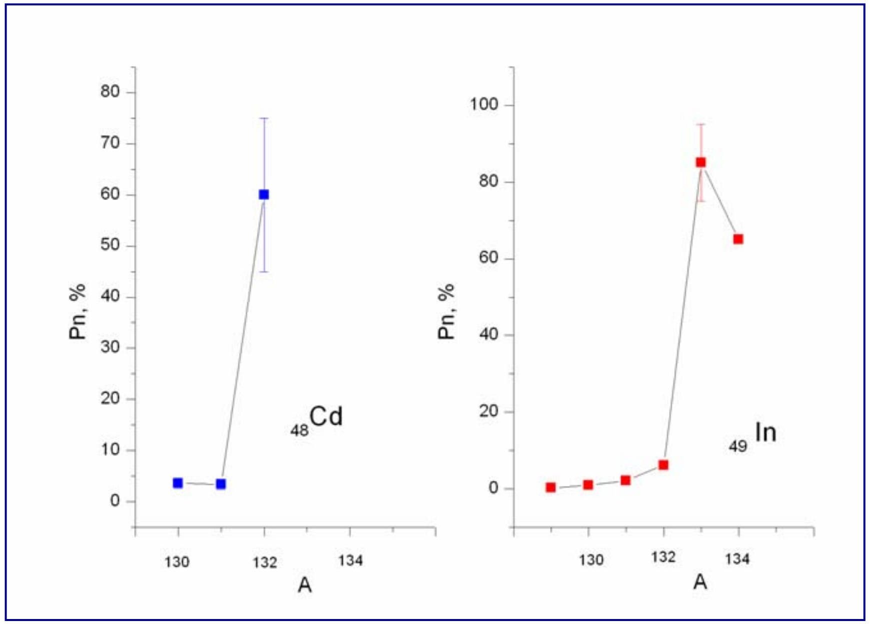
Gamow-Teller decay

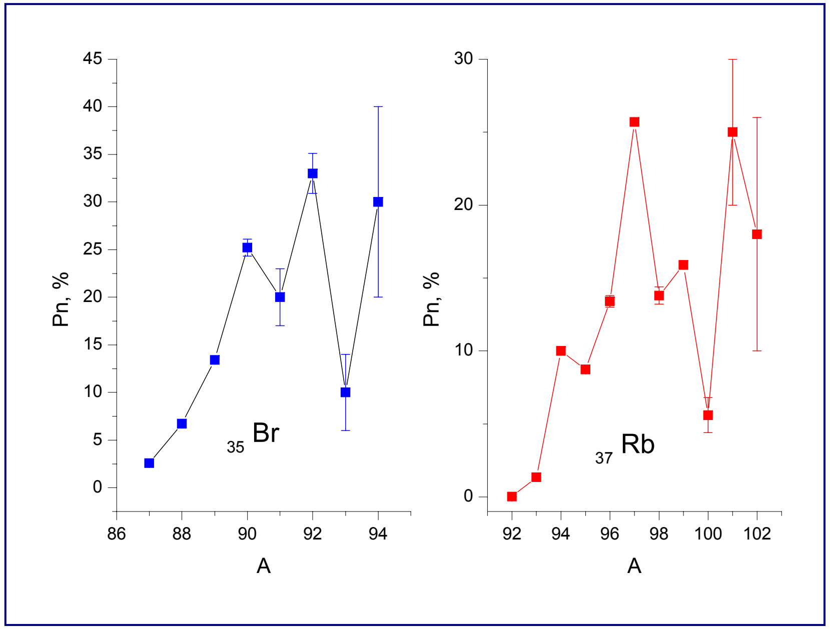




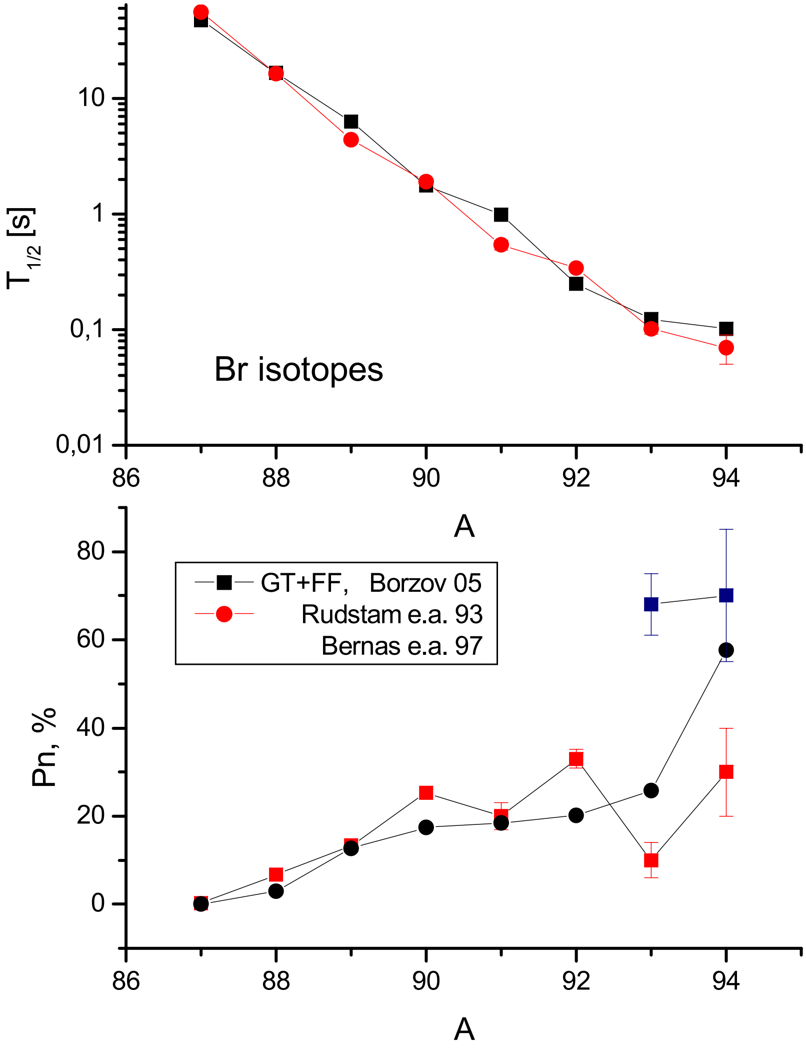


G. Rudstam et al., 1993 compilation



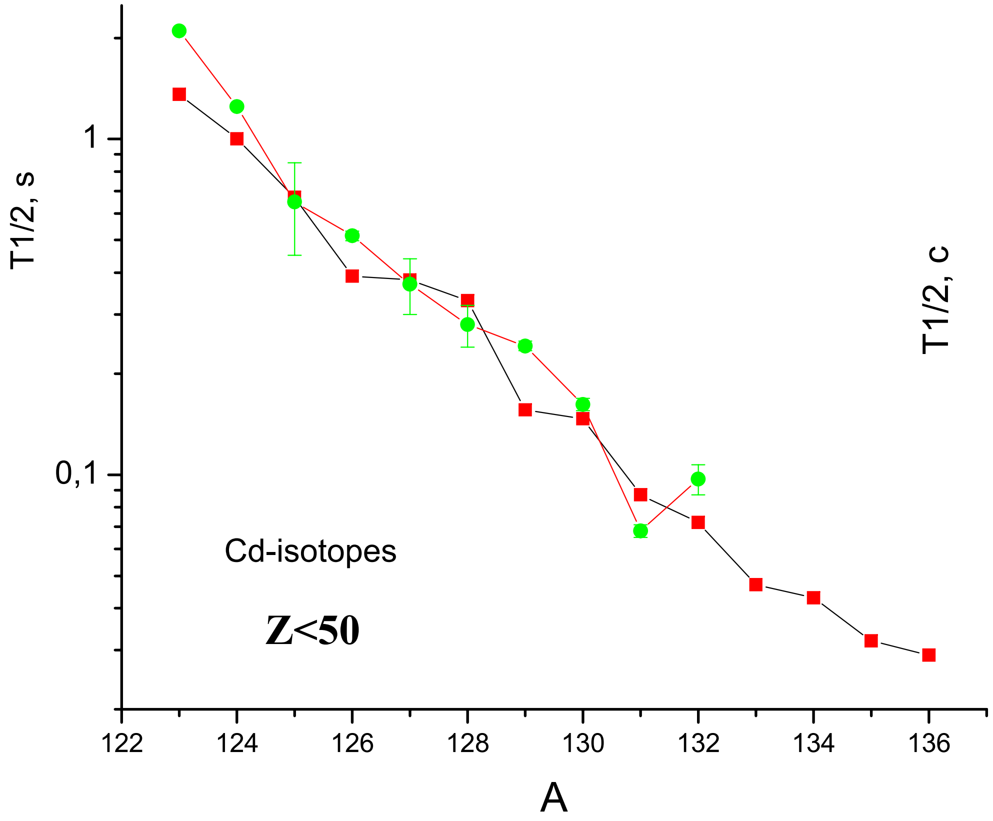


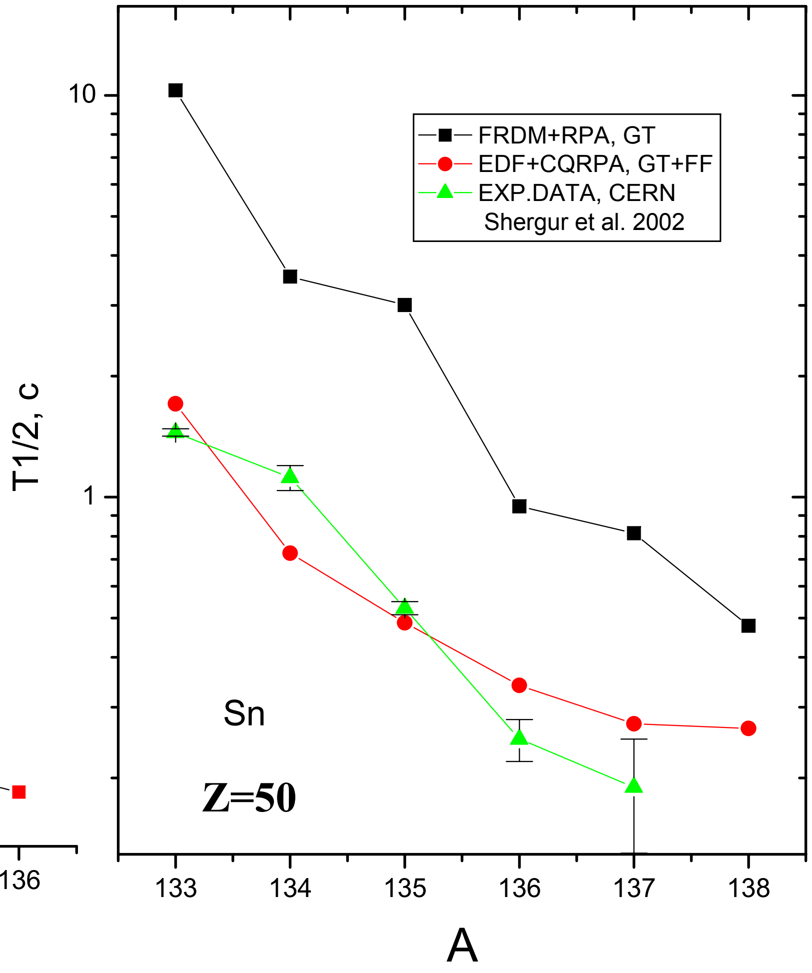
$_{35}Br^{87-94}$



	T1/2, s		Pn %		gr.
	Exp.	Th.	Exp.	Th.	
87 Br	55,6(0,13)	47,7	0,20(0.04)	0,15	(I)
90 Br	1,91(0,01)	1,77	25,2(0,9)	17,5	(IV)

Beta-decay in N=82 region





I.N. Borzov Phys. Rev. C67 (2003) 025802

Light nuclei

1. CMB consistent modeling of the BBN

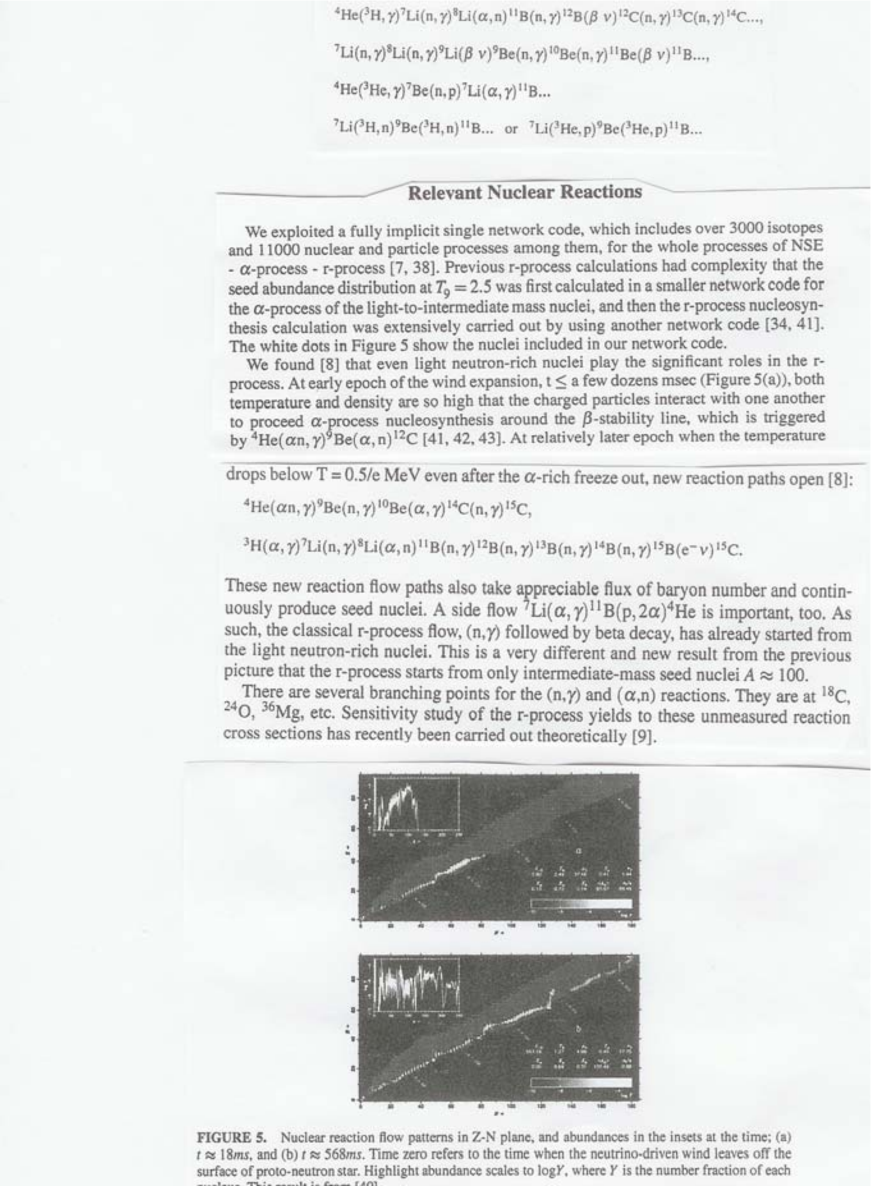
2. Related α – r – process (3000 isotopes)

α : $^{4}He(\alpha n,\gamma)^{9}Be(\alpha,\gamma)$ …

r: $^{4}He(\alpha n,\gamma)^{9}Be(n,\gamma)^{10}Be(\alpha,\gamma)^{14}C(n,\gamma)^{15}C$ …

(n, γ), (α,n) branching points: ^{18}C, ^{24}O,^{36}M

3. β-delayed emission brings additional branchings.



$^{4}He(^{3}H,\gamma)^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B(n,\gamma)^{12}B(\beta\ \nu)^{12}C(n,\gamma)^{13}C(n,\gamma)^{14}C\ldots,$

$^{7}Li(n,\gamma)^{8}Li(n,\gamma)^{9}Li(\beta\ \nu)^{9}Be(n,\gamma)^{10}Be(n,\gamma)^{11}Be(\beta\ \nu)^{11}B\ldots,$

$^{4}He(^{3}He,\gamma)^{7}Be(n,p)^{7}Li(\alpha,\gamma)^{11}B\ldots$

$^{7}Li(^{3}H,n)^{9}Be(^{3}H,n)^{11}B\ldots$ or $^{7}Li(^{3}He,p)^{9}Be(^{3}He,p)^{11}B\ldots$

Relevant Nuclear Reactions

We exploited a fully implicit single network code, which includes over 3000 isotopes and 11000 nuclear and particle processes among them, for the whole processes of NSE - α-process - r-process [7, 38]. Previous r-process calculations had complexity that the seed abundance distribution at $T_9 = 2.5$ was first calculated in a smaller network code for the α-process of the light-to-intermediate mass nuclei, and then the r-process nucleosynthesis calculation was extensively carried out by using another network code [34, 41]. The white dots in Figure 5 show the nuclei included in our network code.

We found [8] that even light neutron-rich nuclei play the significant roles in the r-process. At early epoch of the wind expansion, t $\leq$ a few dozens msec (Figure 5(a)), both temperature and density are so high that the charged particles interact with one another to proceed α-process nucleosynthesis around the β-stability line, which is triggered by $^{4}He(\alpha n,\gamma)^{9}Be(\alpha,n)^{12}C$ [41, 42, 43]. At relatively later epoch when the temperature drops below $T = 0.5/e$ MeV even after the α-rich freeze out, new reaction paths open [8]:

$^{4}He(\alpha n,\gamma)^{9}Be(n,\gamma)^{10}Be(\alpha,\gamma)^{14}C(n,\gamma)^{15}C,$

$^{3}H(\alpha,\gamma)^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B(n,\gamma)^{12}B(n,\gamma)^{13}B(n,\gamma)^{14}B(n,\gamma)^{15}B(e^{-}\nu)^{15}C.$

These new reaction flow paths also take appreciable flux of baryon number and continuously produce seed nuclei. A side flow $^{7}Li(\alpha,\gamma)^{11}B(p,2\alpha)^{4}He$ is important, too. As such, the classical r-process flow, (n,γ) followed by beta decay, has already started from the light neutron-rich nuclei. This is a very different and new result from the previous picture that the r-process starts from only intermediate-mass seed nuclei $A \approx 100$.

There are several branching points for the (n,γ) and (α,n) reactions. They are at ^{18}C, ^{24}O, ^{36}Mg, etc. Sensitivity study of the r-process yields to these unmeasured reaction cross sections has recently been carried out theoretically [9].

FIGURE 5. Nuclear reaction flow patterns in Z-N plane, and abundances in the insets at the time; (a) $t \approx 18ms$, and (b) $t \approx 568ms$. Time zero refers to the time when the neutrino-driven wind leaves off the surface of proto-neutron star. Highlight abundance scales to $\log Y$, where Y is the number fraction of each

BBN (IBM)

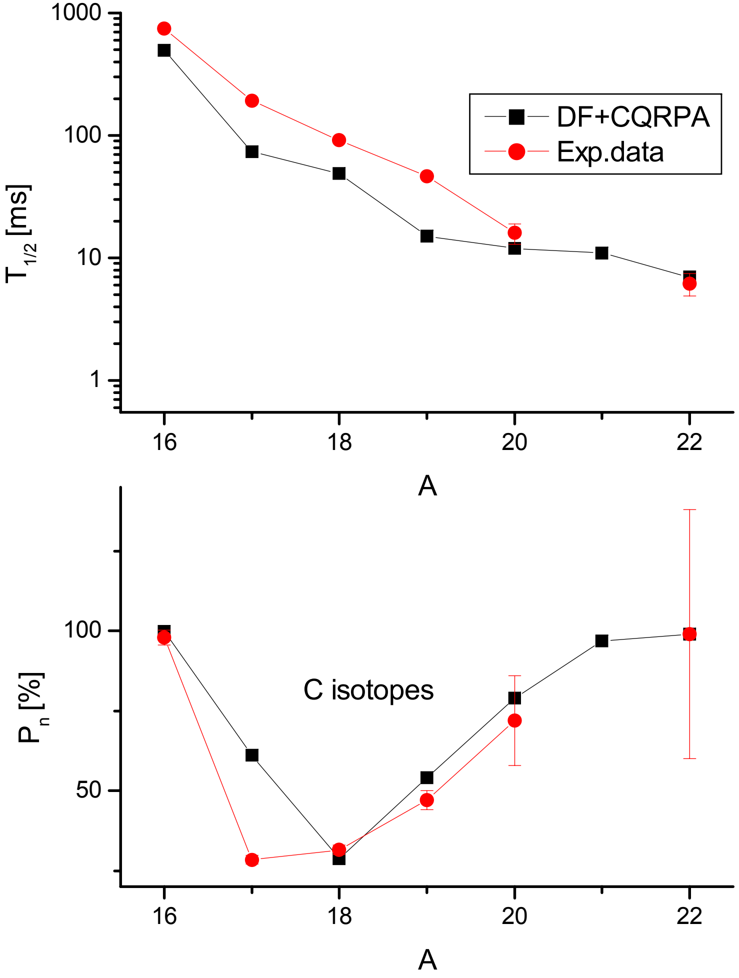
$0.01 \leq \Omega_B h^2 \leq 0.05$

CMB

$\Omega_B = 0.044 + 0.03 - 0.02$

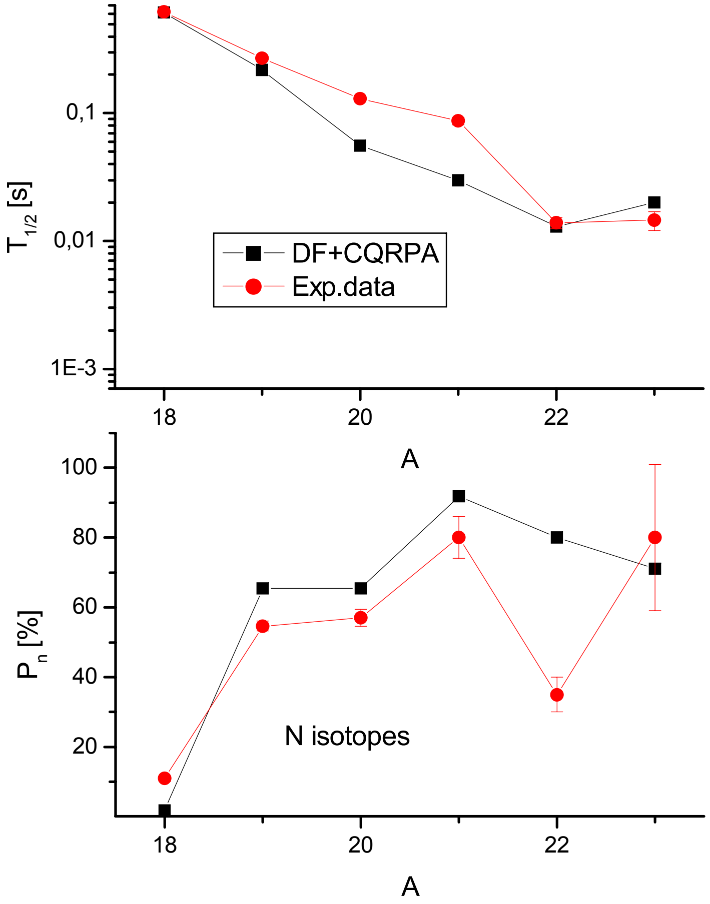
α - r-process (SN-II)

C isotopes



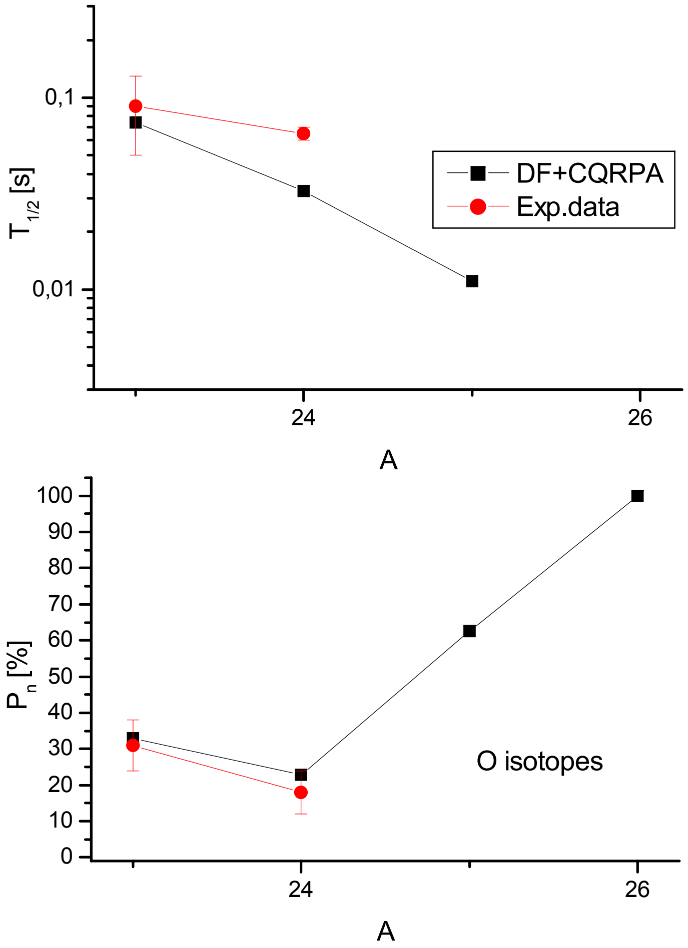
1000
100
10
1
$T_{1/2}$ [ms]
DF+CQRPA
Exp.data
16
18
20
22
A
100
50
P_n [%]
C isotopes
16
18
20
22
A

N isotopes



T$_{1/2}$ [s]
0,1
0,01
1E-3
■ DF+CQRPA
● Exp.data
18
20
22
A
P$_n$ [%]
100
80
60
40
20
N isotopes
18
20
22
A

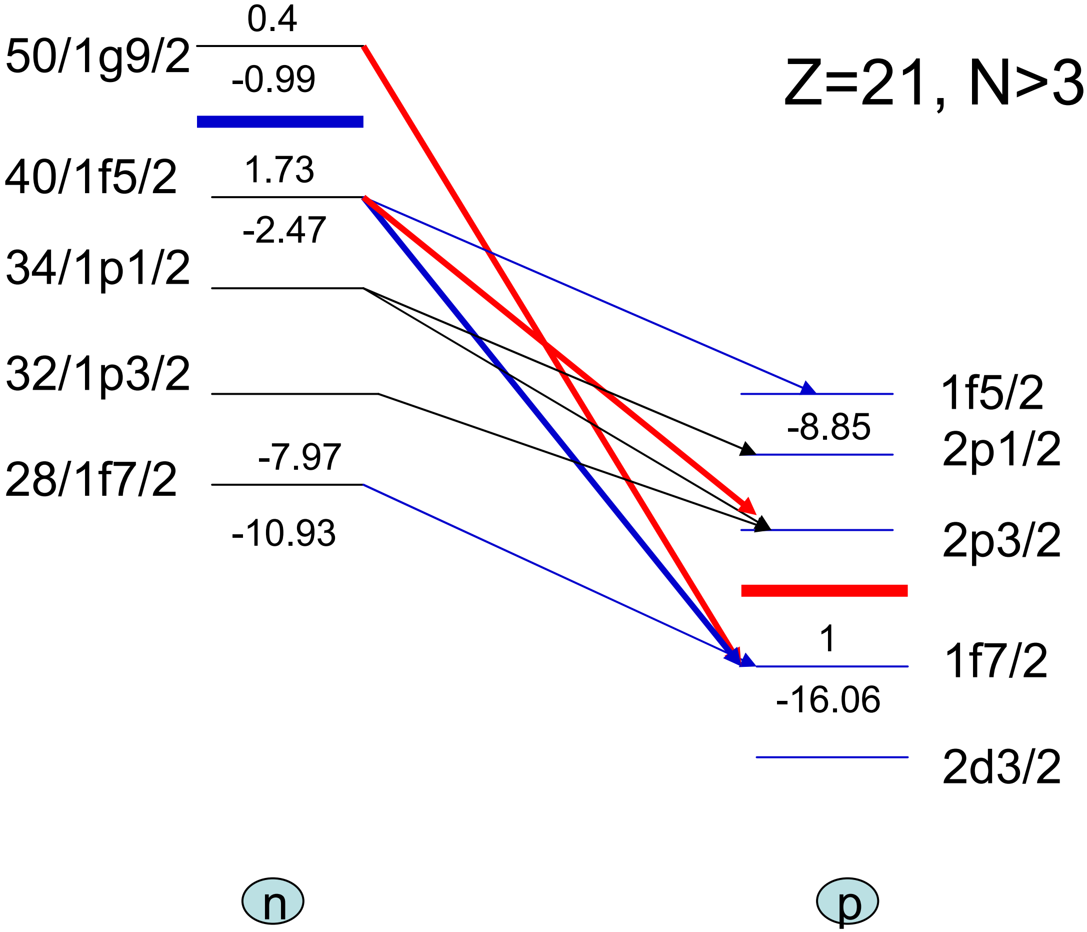
O isotopes



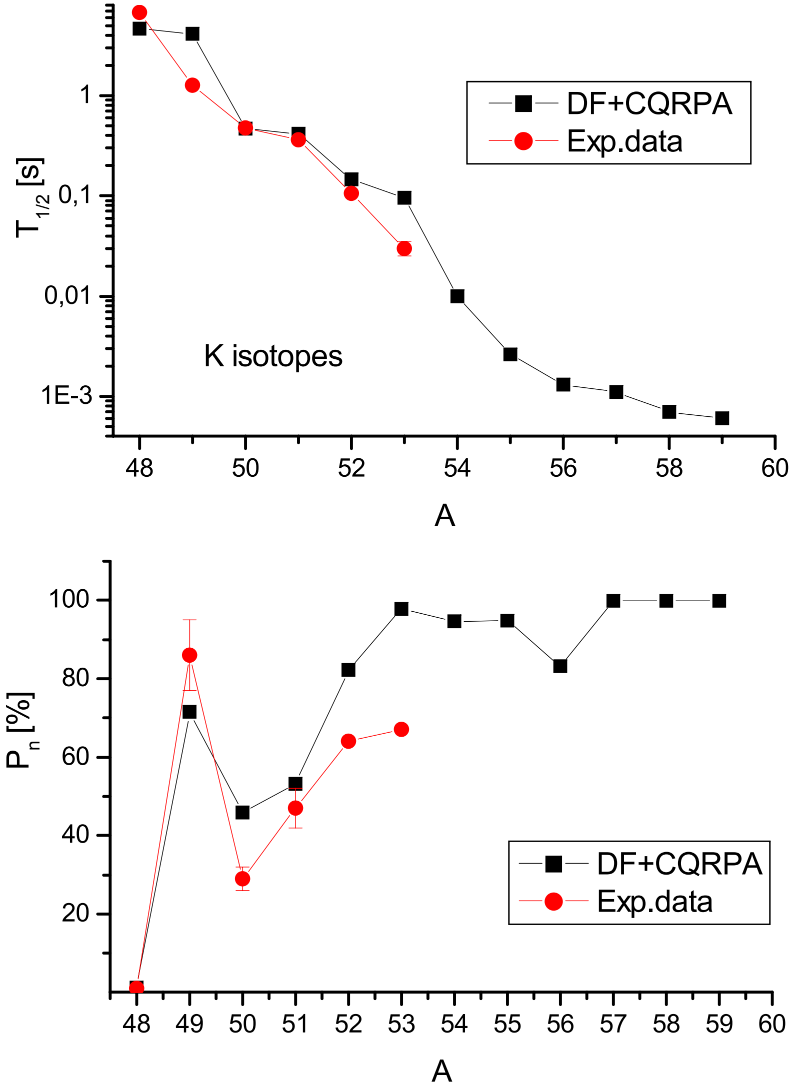
T_{1/2} [s]
0,1
0,01
DF+CQRPA
Exp.data
24
26
A
P_n [%]
100
90
80
70
60
50
40
30
20
10
0
O isotopes
24
26
A

Quasiparticle levels
^{57}Sc

Z=21, N>34



$Z \approx 20$ shell



?

1. ***Neutron source for the r-process***
2. ***Уточнения по сравнению с 80гг***

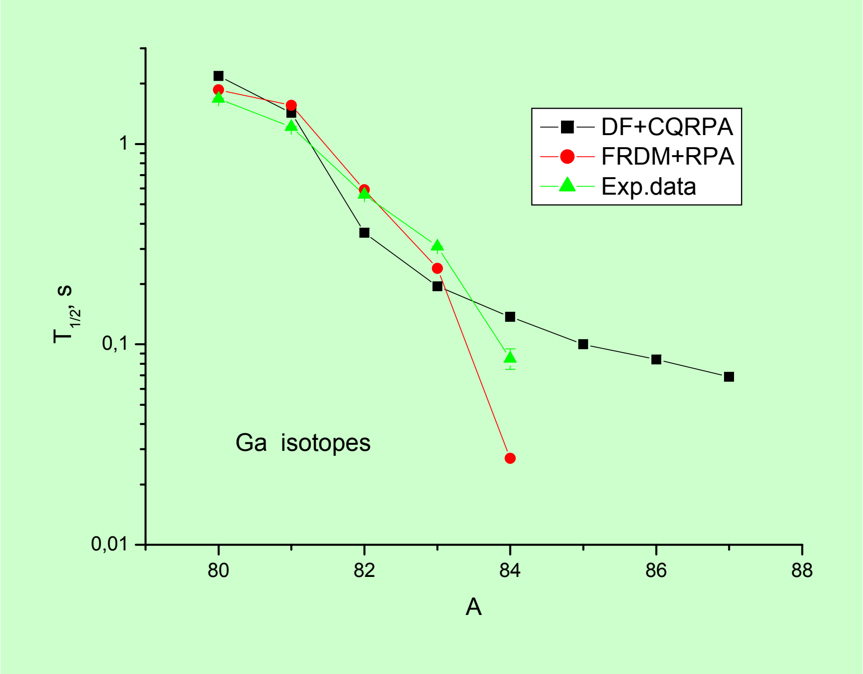
a) Self-consisitent cQRPA : pairing, ph, pp.

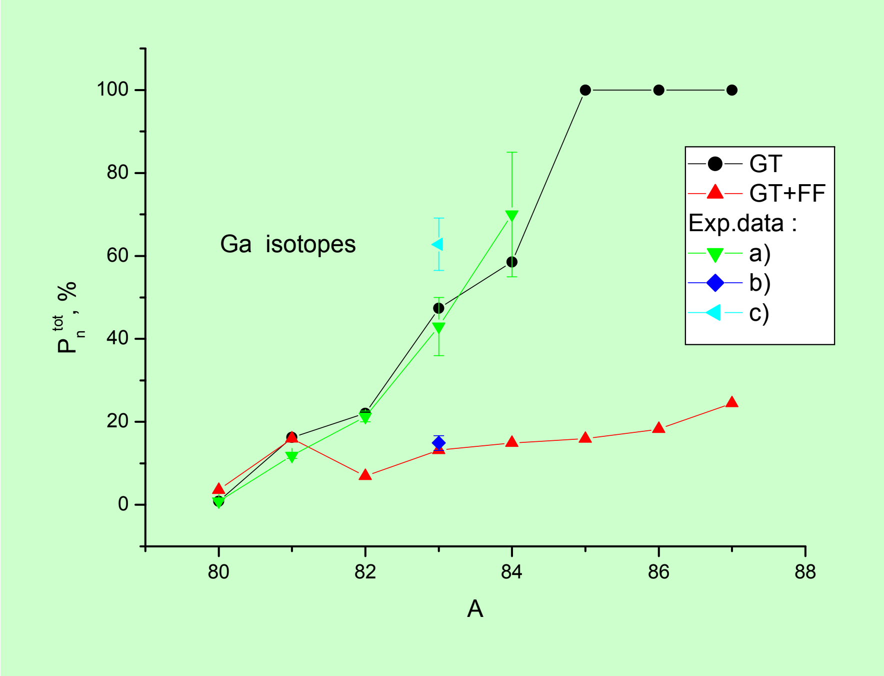
Необходимj для описания четно-нечетного эффекта в T1/2

b) GT+FF

Exotic flowers

Half-lives and Pn-values for Ga isotopes





A≤81 : no high energy FF transitions

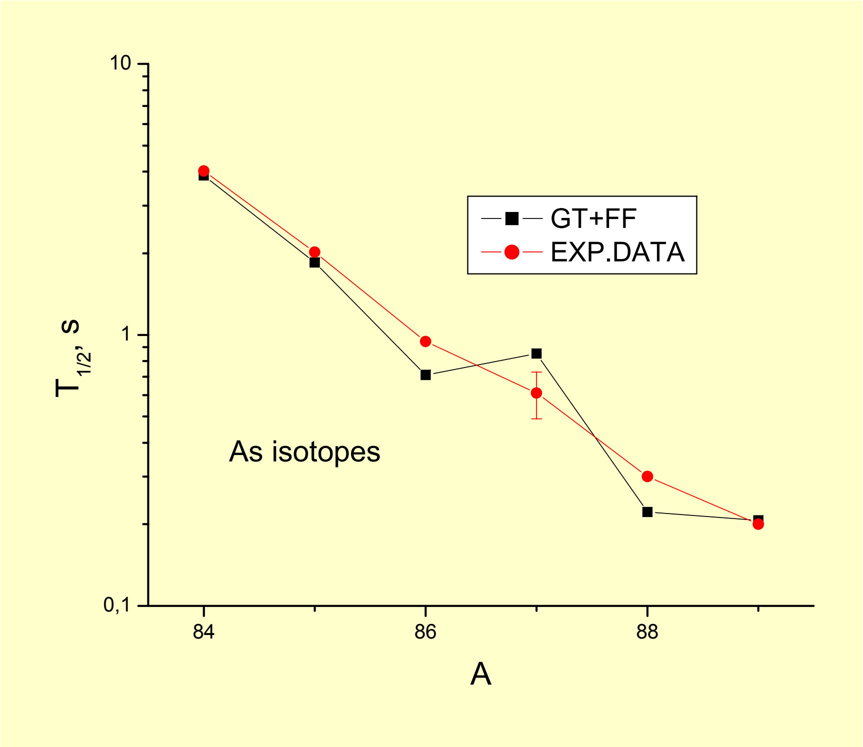
© A≥82: the contribution of the FF transitions dominates in the T1/2.

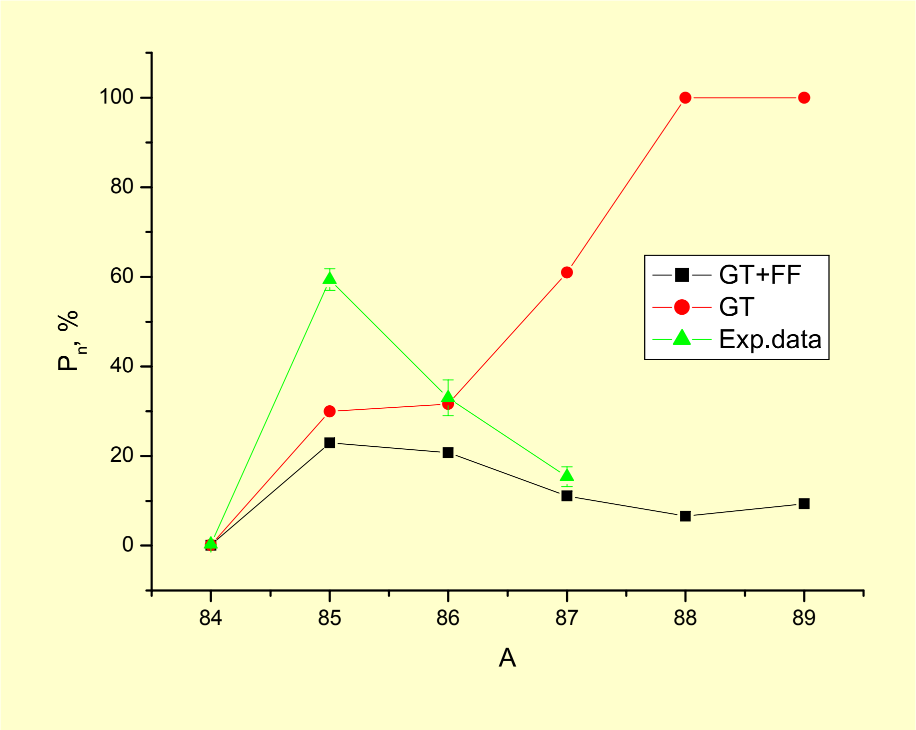
I. N. Borzov nucl-th/0409019 (2004)

© A≥82: due to the FF transitions to the states outside the Qβn-window, the Pn-values are suppressed.

The exp. data a,b,c) -Rudstam et al 1993 for A=83 differ significantly.

$_{33}As^{84-89}$





Experimental data : G. Rudstam et al. 1993, At.Dat. Nucl.Dat. Tables 53, 1

Эффект подавления P_n

1. В ядрах с нейтронным избытком, превышающем одну главную оболочку, высокоэнергетические запрещенные бета-переходы в состояния вне окна нейтронной эмиссии приводят к уменьшению полной вероятности бета-задержанной эмиссии нейтронов (Pn).

2. Для таких ядер расчеты Pn в приближении разрешенных переходов некорректны.

Schematic micro-models with the separable forces
Separable forces are not fitted for non-unique first-forbidden transitions (FF)

BCS+QRPA	***H.-V. Klapdor-Kleingrothaus et al.,***	***1992***	***(GT),***
		1996	***(unique FF)***
BSC+RPA	***P. Moeller et al.,***	***1997***	***(GT),***
		2001	***(GT-RPA; FF-gross theory)***

Short-lived β-unstable nuclei (s - ms)

- ▼ ***Structural evolution far from stability***
- ▼ ***Supernovae explosion modeling (N=50, 82, 126)***
- ▼ ***Current RNB experiments: ^{78}Ni, ^{132}Sn, east of ^{208}Pb***
- ▼ *Technological applications: reactor physics (7-8 gr) ...*

▲ ***β-decay observables: T1/2, Pn***

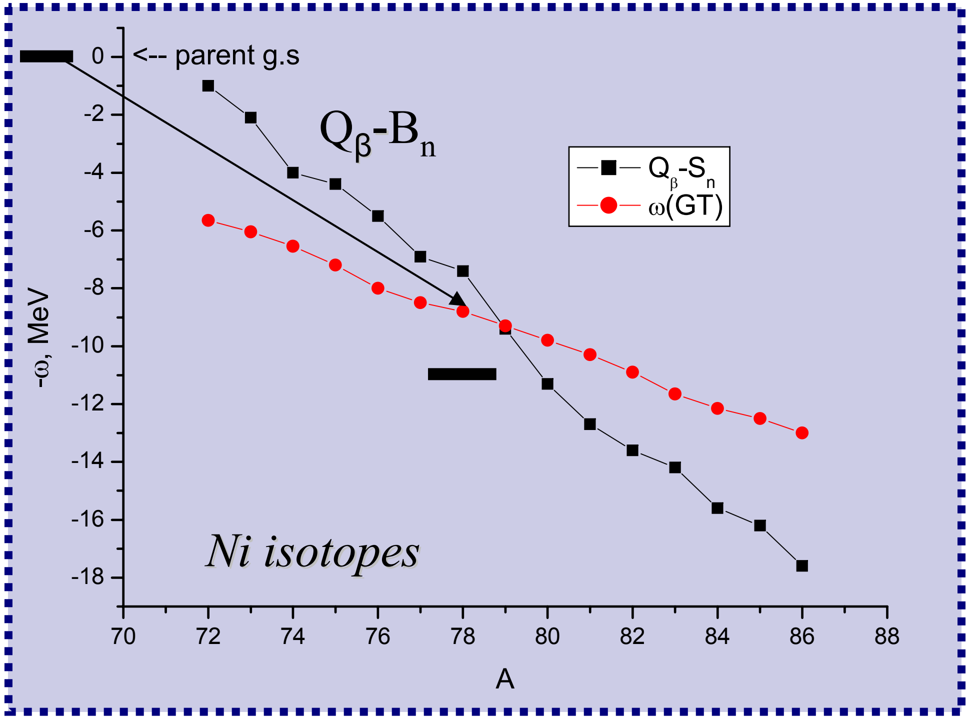
(An insight into the β-strength function)

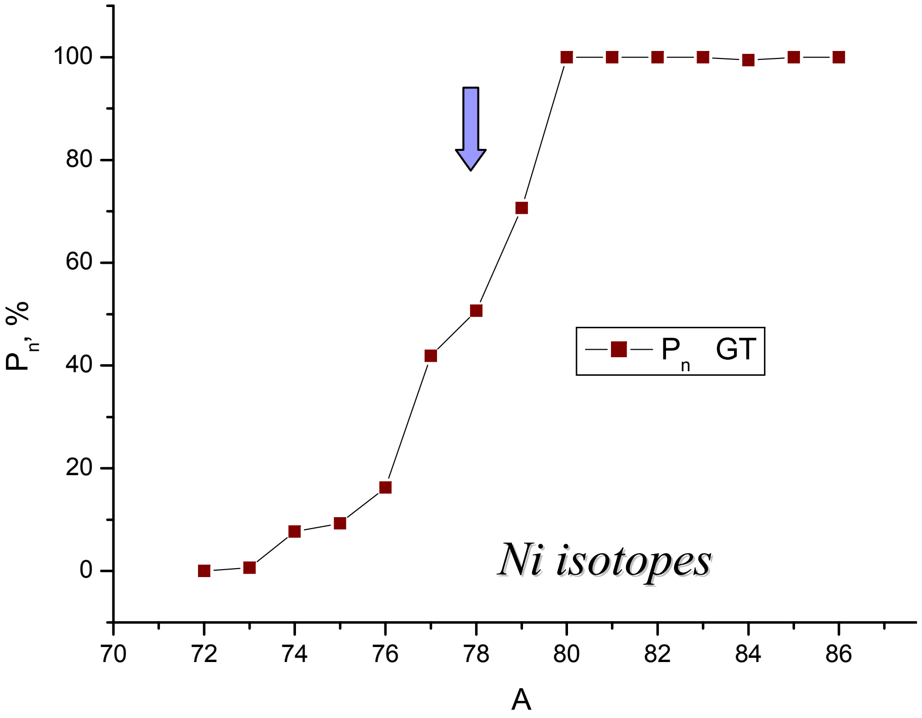
▲ ***Beyond the allowed β-decay approximation***

(Competition of the Gamow-Teller (GT) and First Forbidden (FF) decay channels far from stability)

P_n (Z=const, A)
Allowed Transitions Approximation

- ω ! Opposite sign





Decay to the GT-pygmy resonance dominates.

(The so-called back spin-flip & core-polarized states in the emitter nucleus.)

P_n tends to 100% once the GT-pygmy resonance enters the $Q_{\beta n}$- window

First-Forbidden Decay

$$V_{J=1,L=1,S=0,1} = {}^{1}\!/_{\sqrt{3}}\,(i\mathbf{r} - \frac{\mathbf{p}}{2M}) + \hat{e}_{qs}\sqrt{2}\,[\sigma\mathbf{r}]^{(1)}$$

$$V_{J=0,L=1,S=1} = \hat{e}_{qs}(i\boldsymbol{\sigma}\otimes\mathbf{r}) - \hat{e}_{q5}\frac{\boldsymbol{\sigma}\otimes\mathbf{p}}{2M}$$

$$\hat{e}_{qs} = e_q[\sigma\tau] = {}^{g_A}\!/_{G_A} \approx 0.8-0.9$$

$$\hat{e}_{q5} = e_q[\gamma_5] \approx (1+R)(1+{}^{2}\!/_{3}\,g') \approx 1.5$$

Reduction of the relativistic operators α, γ_5

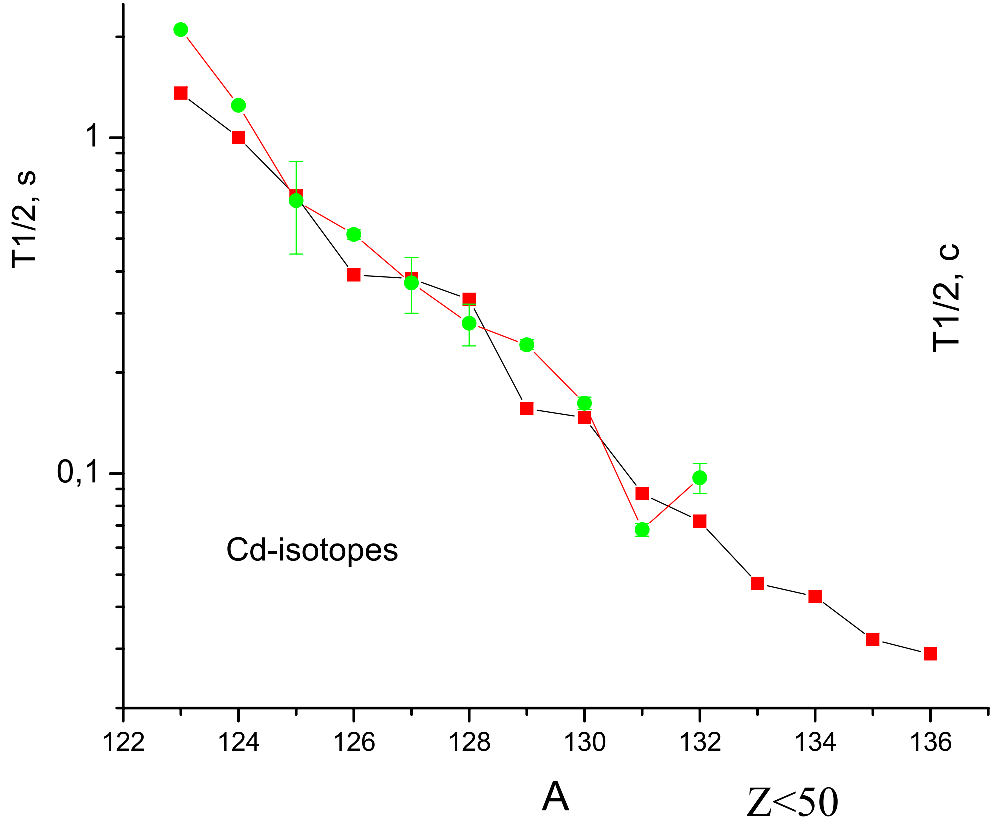
$$\lambda\langle\alpha\rangle = \xi\Lambda_1\langle i\mathbf{r}\rangle$$

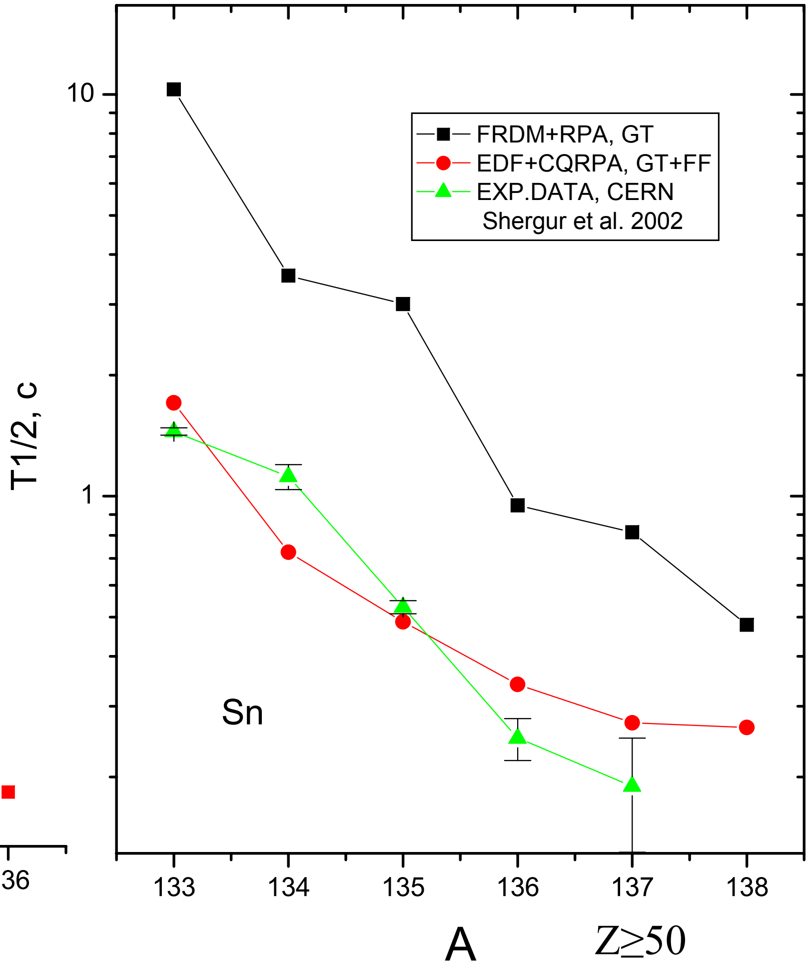
$$\lambda\langle\gamma_5\rangle = \xi\Lambda_0\langle i\boldsymbol{\sigma}\mathbf{r}\rangle$$

$$\xi\Lambda_1 = \omega_{if} + \overline{U}_C$$

$$\xi\Lambda_0 = \omega_{if} + \overline{U}_C + (\overline{w}_{sl} - \overline{u}_{sl})$$

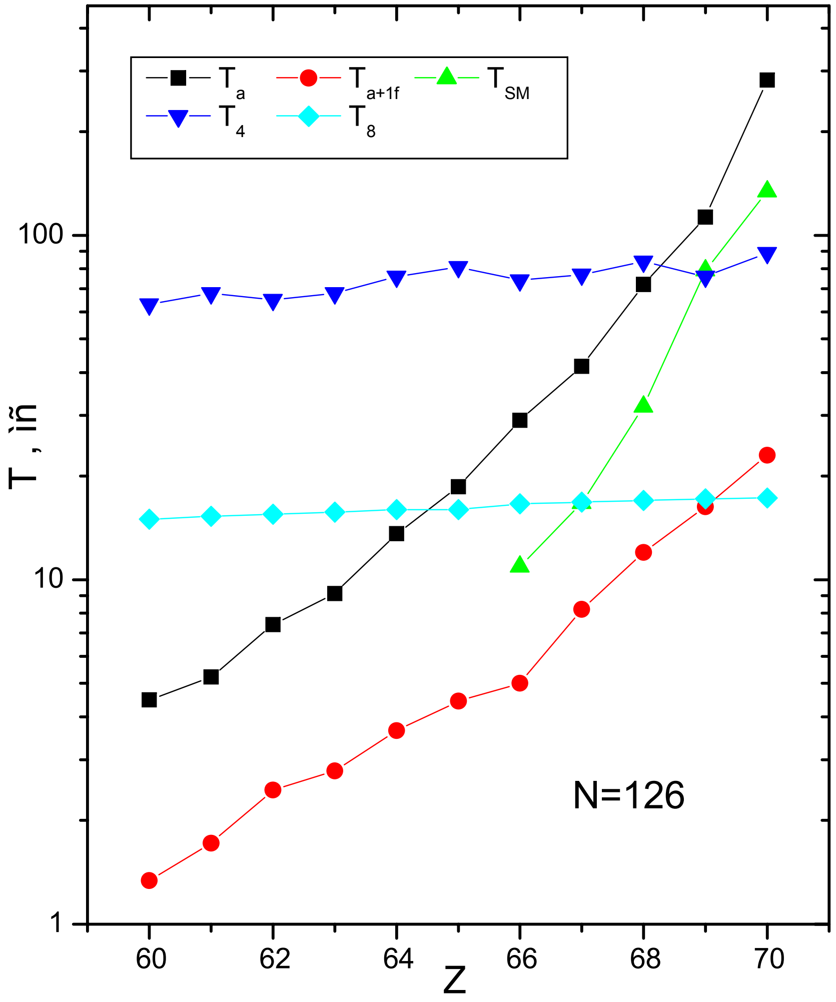
Периоды β-распада ядер с N=82



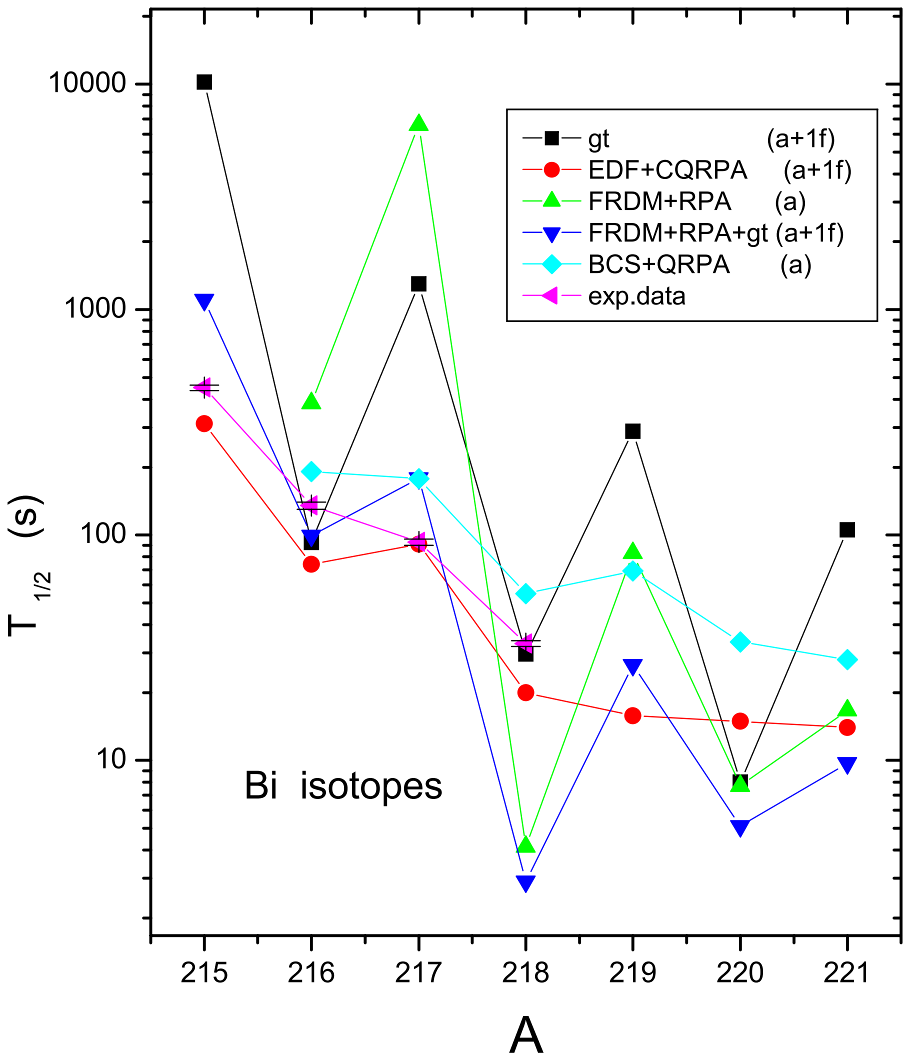


I.N. Borzov Phys. Rev. C67 (2003) 025802

N=126



I.N. Borzov Phys. Rev. C67 (2003) 025802



H. DeWitte, A.N. Andreev, I.N. Borzov Phys. Rev. C 69 (2004) 044305

Spin-Isospin Interaction

Skyrme-like EDF

$$E_{Sk} = a\rho + \frac{1}{2} V_{Sk}(\rho)\rho^{2}$$

$$F_{Sk} = \frac{\delta^{2} E_{Sk}}{\delta\rho^{2}} = \frac{\delta V_{Sk}}{\delta\rho} = F(0) + F(\rho)$$

At $\varepsilon_{\text{Fermi}}$ → F_{Sk} → Landau-Migdal interaction :

$$F_{LM}^{\sigma\tau} = N_{0}^{-1} G_{0}^{1} (\sigma_{1}\sigma_{2})(\tau_{1}\tau_{2})$$

Skyrme forces give a spin-stable ground state at g’<0.45

$$g_{0}' = N_{0} G_{0}' = -N_{0}\left[\frac{t_{0}}{4} + \frac{t_{3}\rho}{24} - \frac{p}{8}(t_{1} - t_{2})\right]$$

$g_0' \ll g_0'(\text{empirical}) \cong 1.8 - 2.0$

S. Krewald et al,Nucl.Phys.A281(1977) 166.
J. Engel et al.Phys.ReV. C60 (1999) 14302,

Spin-isospin interaction is-introduced independently :

$$F_{\sigma\tau}^{ph} \rightarrow g'_{0}\,\delta(r_{12}) + \pi + \rho\,, \qquad F_{\sigma\tau}^{pp} = g'_{\xi}\,\delta(r_{12})$$

I. Borzov, S.Fayans et al. Z.Phys. A335(1996) 117
I. Borzov Phys.Rev. C67 (2003) 025802

Self-Consistent Ground State

$$E[\rho,\nu] = Tr\left(\frac{p^2}{2M}\rho\right) + E_{int}[\rho,\nu]$$

$$\varepsilon_{int} = \sum_{main,Coul,sl} \varepsilon_n[\rho] + \frac{1}{2}\nu * F^{\xi}[\rho]\nu$$

$$F^{\xi}(r_{12}) = -2C_0 f^{\xi}(x)\delta(r_{12})$$

$$f^{\xi}(x) = f_{ex} + h^{\xi}x^{q}(r)$$

$$x = {}^{\rho_+}\!/_{2\rho},\ q \geq 2/3;\ f_{ex} < 0,\ h_{\xi} > 0$$

$$H = \begin{pmatrix} h-\mu & -\Delta \\ -\Delta & \mu-h \end{pmatrix}$$

M*/M=1

$$h = \frac{p^2}{2m} + \frac{\delta E}{\delta\rho} \sim \rho$$

$$\Delta = \frac{\delta E_{\text{int}}}{\delta\nu}$$

$$\rho_0,\nu_0 \Rightarrow h_0,\Delta_0 \Rightarrow \rho_1,\nu_1 \Rightarrow h_1,\Delta_1$$

Skyrme-HF

S. Goriely, F. Tondeur, J.M. Pearson ADNDT 77(2001)311

MSk7- 10 parameters Skyrme force, 4 parameters δ-function pairing, 2 parameters Wigner term. The rms error of the fit to 1988 masses (Audi-Wapstra 1995) is **0.738 MeV.**

EDF

I.N. Borzov, S.A. Fayans, E. Kromer, D. Zawischa Z. Phys. A335(1996) 117

DF3 – local energy-density functional by S.A. Fayans et al. 3 parameters δ-function pairing.

Fitted to the g.s. properties near “magic cross” at ^{132}Sn.

Beta-decay half-life

A,Z → A,Z+1+ e^- + υ ^

$$(dW/dt) = t_{1/2}^{-1} \ln 2$$

$$N >> Z$$

$$Gamow - Teller \quad transitions \quad (L=0)$$

$$Partial \quad half - life$$

$$t_{1/2} = \frac{D}{f_0 (G_A/G_V)^2 B_{GT}}$$

$$D = 2\pi^3 \ln 2 / G_V^2 m_e^5 = 6163s$$

$$G_A/G_V = 1.26$$

$$f_0(Z,A,\omega) = \int_0^{\omega} F(Z,A,\omega) pW (\omega - W)^2 dW$$

$$f_0(Z,\omega) \sim \omega^5 \quad \Rightarrow \quad high - energy \quad \beta - decays \quad are \quad amplified\,!$$

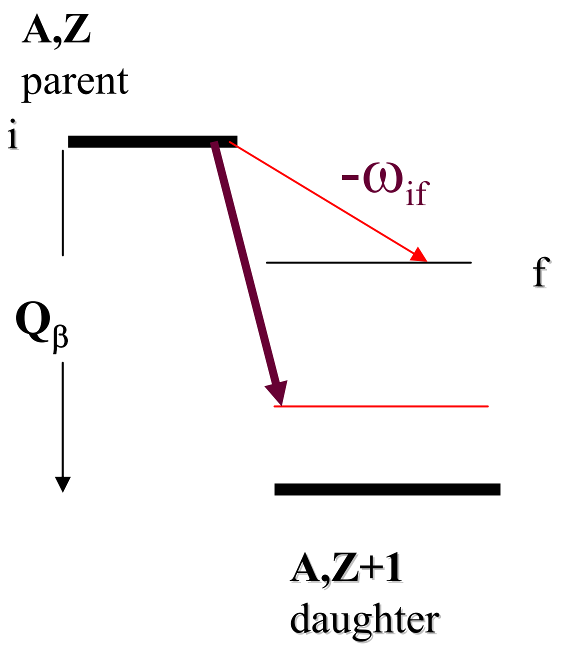
$$First - forbidden \quad transitions \quad (L=1)$$

$$- m.e. \, are \, reduced \, by \quad (qR)^L, \quad but \quad f_0 \quad may \quad be \quad big!$$

$$Total \quad half - life$$

$$\boxed{T_{1/2} = \frac{D}{\left(\frac{G_A}{G_V}\right)^2 \int_0^{Q_\beta} S_L(\omega)\, f_0(Z,\omega)\, d\omega}}$$

$S^L(\omega)$
$L=0,1$
The main ingredient to be known at our best!



NB! **Q β - HFB**

ω **- QRPA**