Beta decays in investigations and searches for rare effects

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Contents

1. Introduction
2. Classification of beta decays
3. Shapes of beta spectra
4. Investigations of rare β decays
   (^{48}Ca, ^{50}V, ^{96}Zr, ^{113}Cd, ^{113m}Cd, ^{115}In, ^{123}Te, ^{180m}Ta, ^{222}Rn)
5. Forbidden non-unique β decays and g_A and g_V values
6. Semiempirical formulae for β $T_{1/2}$
7. Conclusions

β: $(A,Z) \rightarrow (A,Z\pm1) + e^{\pm} + \nu$
from ^{3}H to superheavy
$T_{1/2}$ from 1.5 ms (^{35}Na) to 10^{16} y (^{113}Cd)

Introduction

Beta radiation was observed long ago (E. Rutherford, Philos. Mag. 47 (1899) 109) but our knowledge still can be and should be improved.

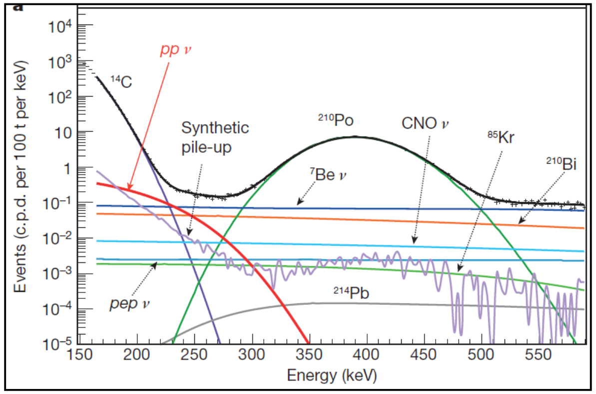
Some rare β decays ($T_{1/2} > 10^{10}$ y) are poorly investigated (spectrum shape is not measured – e.g. ^{50}V) and even not observed (e.g. ^{123}Te, ^{180m}Ta).

Interest to β decays increased during last time because sometimes they constitute significant background in searches for and investigations of rare effects:

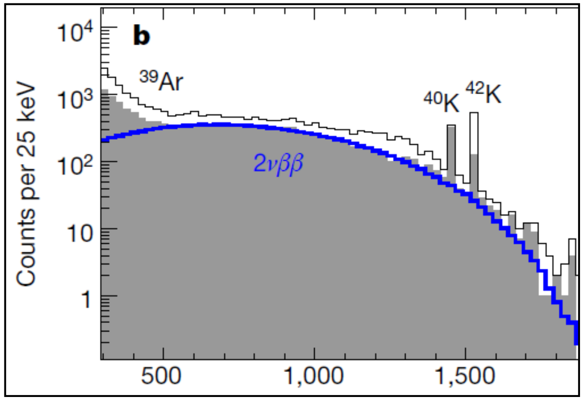
- solar neutrinos (e.g. ^{14}C in Borexino)

- 2β decay (e.g. ^{39}Ar, ^{42}Ar/^{42}K in GERDA)

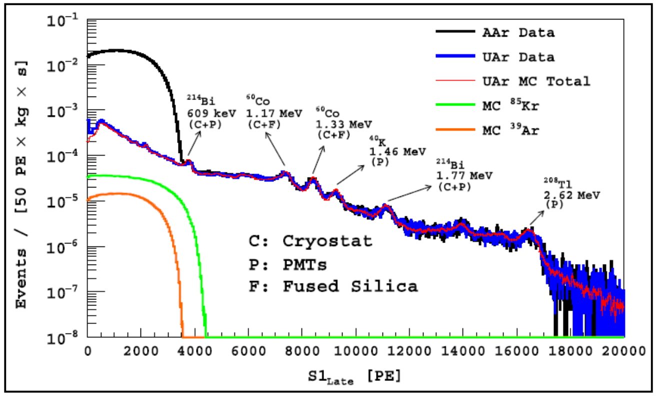
- dark matter experiments, especially based on Ar (e.g. ^{39}Ar, ^{42}Ar in DarkSide)



G. Bellini et al.,
Nature 512 (2014) 383



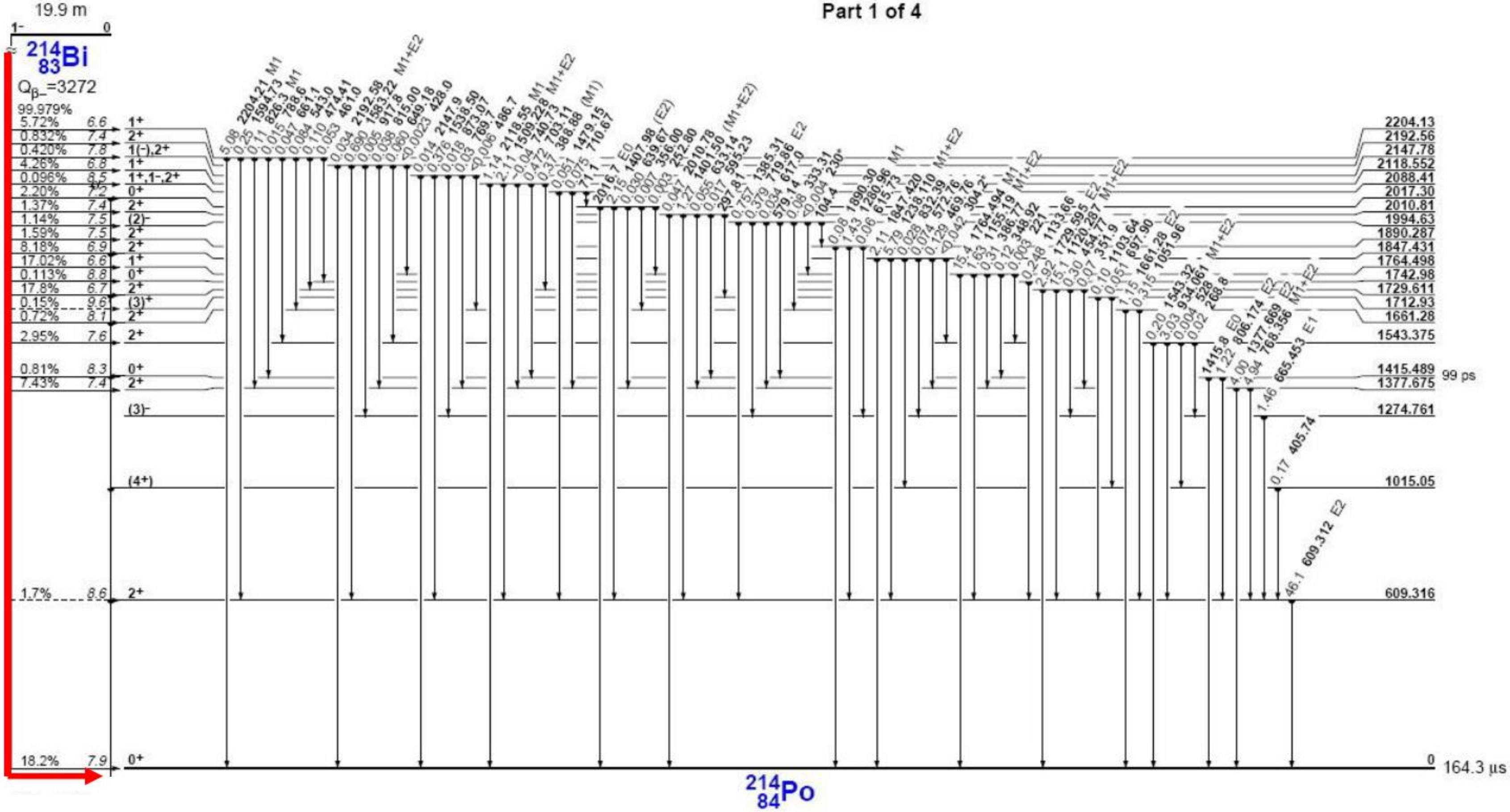
M. Agostini et al.,
Nature 544 (2017) 47



P. Agnes et al.,
PRD 93 (2016) 081101

Some other single β decayers are usual backgrounds in many experiments: ^{40}K, ^{90}Sr/^{90}Y, ^{137}Cs, ^{214}Bi, … - and very often their energy spectrum has not allowed shape.

^{214}Bi – one of the main backgrounds in all 2β experiments, Q_β = 3272 keV, 18.2% g.s. to g.s. transition, $1^- \to 0^+$, 1 FNU – shape is not calculated theoretically and not well measured experimentally (only very old works IANSF 16 (1952) 314; JPSJ 8 (1953) 689; NC 2 (1955) 745 and recent PRC 81 (2010) 034602) – not far from allowed).



General classification of β decays:

in dependence on change in spin and parity between mother and daughter nuclei

$\Delta J^{\Delta\pi}$ =

0^+ 1^+		**– allowed**
0^- 1^- 2^+ 3^- 4^+ …	**$\Delta\pi = (-1)^{\Delta J}$**	**– forbidden non-unique; forbidenness = ΔJ**
2^- 3^+ 4^- …	**$\Delta\pi = (-1)^{\Delta J-1}$**	**– forbidden unique; forbidenness = $\Delta J-1$**

Each next degree of forbidenness in forbidden non-unique (FNU) or forbidden unique (FU) transitions gives 5–6 orders of magnitude in ft value (i.e., in ~$T_{1/2}$) – see B. Singh et al., Nucl. Data Sheets 84 (1998) 487:

1 FNU (0^- 1^-)	**– ft = 7.3**	**1 FU (2^-)**	**– ft = 9.5**
2 FNU (2^+)	**– ft = 12.5**	**2 FU (3^+)**	**– ft = 15.6**
3 FNU (3^-)	**– ft = 17.5**	**3 FU (4^-)**	**– ft = 21.1**
4 FNU (4^+)	**– ft = 23.4**		

(for superallowed ft = ~3, for allowed ft = ~6)

From theoretical point of view, FU β decays are simpler: rate of decay and shape of spectrum is defined by only one nuclear matrix element (what is why “unique”)

Shape of β spectrum in general is described as:

$\rho(E) = \rho_{\text{allowed}}(E) \times C(E)$

$\rho_{\text{allowed}}(E) = F(Z_d,E)WP(Q_\beta - E)^2$ – allowed spectrum
W (P) – total energy (momentum) of β particle
$F(Z_d,E)$ – Fermi function

C – (empirical) correction factor; W – in m_ec^2 units; P,Q – in m_ec units

for FNU $C_1(E) = 1+a_1/W+a_2W+a_3W^2+a_4W^3$
or $C_1(E) = 1+b_1P^2+b_2Q^2$
Q – momentum of (anti)neutrino

For FU $C = C_1C_2$
1 FU $C_2 = P^2+c_1Q^2$
2 FU $C_2 = P^4+c_1P^2Q^2+c_2Q^4$
3 FU $C_2 = P^6+c_1P^4Q^2+c_2P^2Q^4+c_3Q^6$
4 FU $C_2 = P^8+c_1P^6Q^2+c_2P^4Q^4+c_3P^2Q^6+c_4Q^8$
or
1 FU $C_2 = Q^2+\lambda_2P^2$, 2 FU … λ_2, λ_4, …,
where λ_i – Coulomb functions calculated in H. Behrens, J. Janecke, Numerical Tables for Beta-Decay and Electron Capture, 1969

Fermi function $F(Z_d,E)$:

takes into account influence of electric field of daughter nucleus (and atomic shell) on emitted e^- or e^+ particle

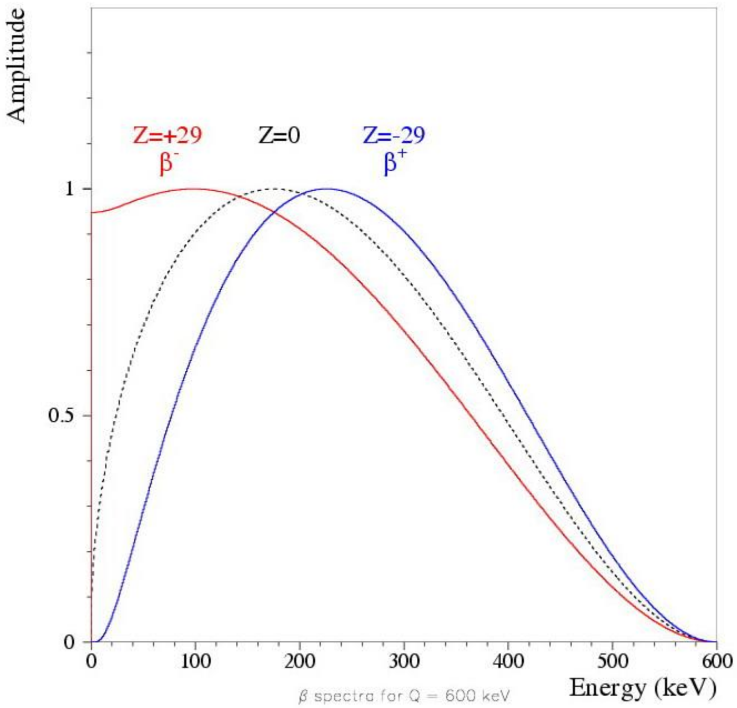
Calculations of F(Z,E) for non-point nucleus, corrections from screening by atomic shell, etc.:

1. **H. Behrens, J. Janecke, Numerical Tables for Beta-Decay and Electron Capture, 1969**
2. **B.S. Djelepov et al., Beta Processes. Functions for the Analysis of Beta-Spectra and Electron Capture, 1972**

R.D. Evans, The Atomic Nucleus, 1955:
β^- and β^+ spectra of ^{64}Cu (Z=29)
$Q(\beta^-)=579$ keV
$Q(\beta^+)=653$ keV

Good approximation is:
$F(Z,E) \sim P^{2(\gamma-1)} e^{\pi y} |\Gamma(\gamma+iy)|^2$
$y=\alpha Z W/P$
$\gamma=[1-(\alpha Z)^2]^{1/2}$
$\alpha=1/137.036$
$Z>0$ for β^- and $Z<0$ for β^+

Primakoff-Rosen approximation (1959) is simple: $F(Z,E) \sim W/P$ but adequate for $Z>0$ (β^- decay)



β spectra for Q = 600 keV

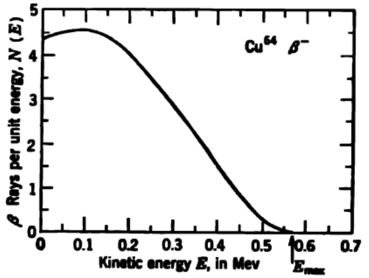


Fig. 1.4 Energy spectrum of the negatron β rays from Cu^{64}.

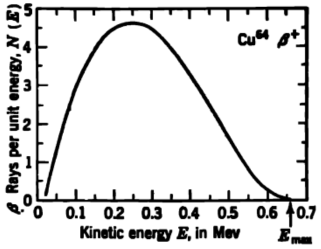
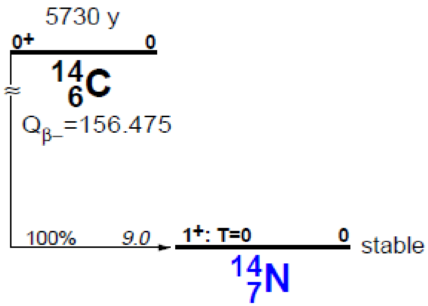


Fig. 1.6 Energy spectrum of the positron β rays from Cu^{64}.

Theoretical calculations of coefficients a_i, b_i, c_i:

they are mixture of products of phase space factors with different nuclear matrix elements – a lot of theoretical efforts

There are sometimes unexpected things even for “simple” cases as f.e. for ^{14}C: while it is allowed beta decay $^{14}C(0^+) \rightarrow {}^{14}N(1^+)$, experimental shape of spectrum is different from allowed, and also $T_{1/2}$ is too long (ft=9 instead of ft~6 for allowed decays)

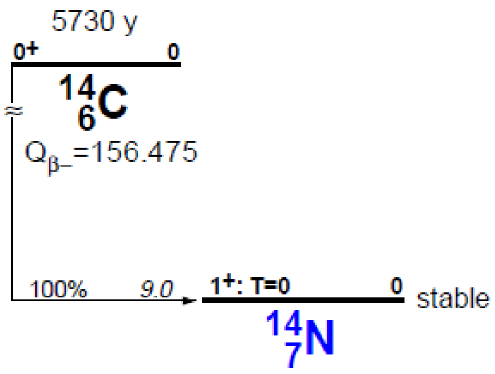


Best of all is to use shape measured experimentally (the problem is that results could be different in different experiments …).

Compilations of a_i, b_i, c_i:

1. **H. Paul, Shapes of beta spectra, Nucl. Data Tables A 2 (1966) 281;**
2. **H. Daniel, Shapes of beta-ray spectra, Rev. Mod. Phys. 40 (1968) 659 (in fact, incorporates all data from Paul’1966);**
3. **H. Behrens, L. Szybisz, Shapes of beta spectra, Phys. Data 6-1 (1976);**
4. **X. Mougeot, Realibility of usual assumptions in the calculation of β and ν spectra, Phys. Rev. C 91 (2015) 055504; Appl. Rad. Isot. 109 (2016) 177.**

Shapes: ^{14}C β spectrum



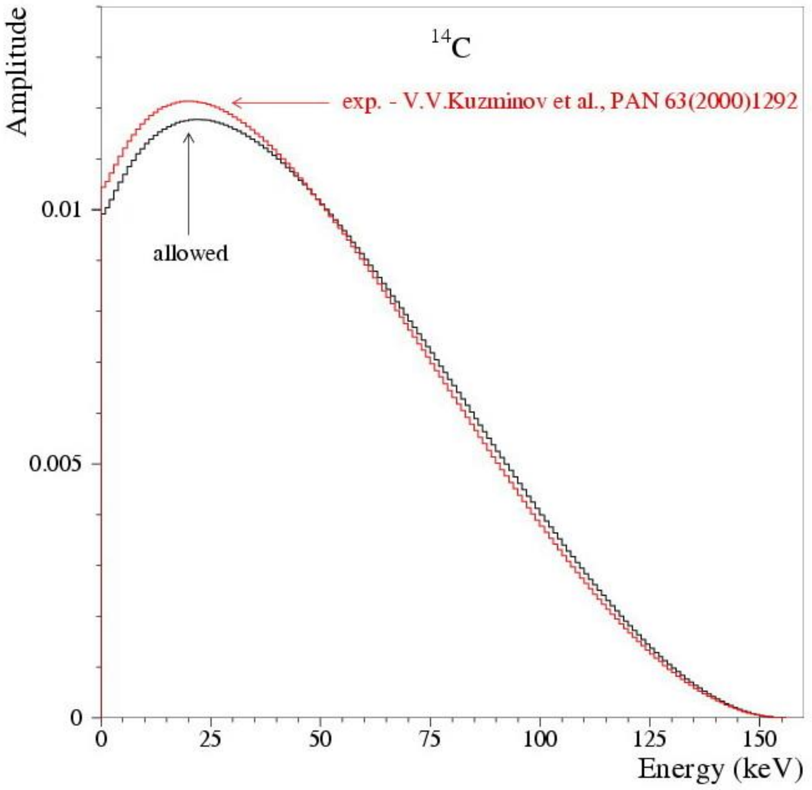
$0^+ \rightarrow 1^+$ $\Delta J^{\Delta\pi} = 1^+$ classified as allowed

However, ft=9.0 instead of usual ft~6 for allowed decays ($T_{1/2}$ is too big).

It is explained by accidental cancellation of the 1-st order nuclear matrix elements, so second order effects start to be important

C(E) – measured in few works (including Ge detector with implanted ^{14}C!)

The last one is:
C(E) = 1+aW with a=–0.347
[V.V. Kuzminov et al.,
Phys. At. Nucl. 63 (2000) 1292]

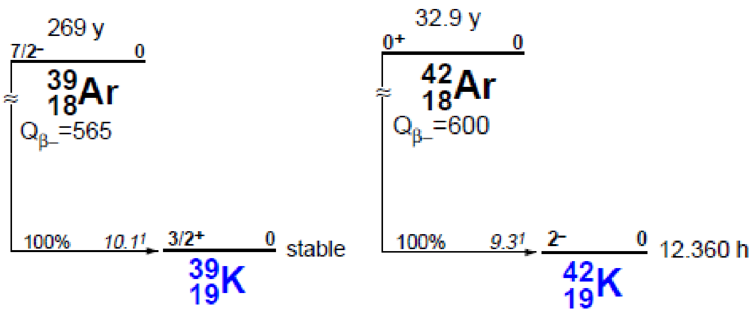


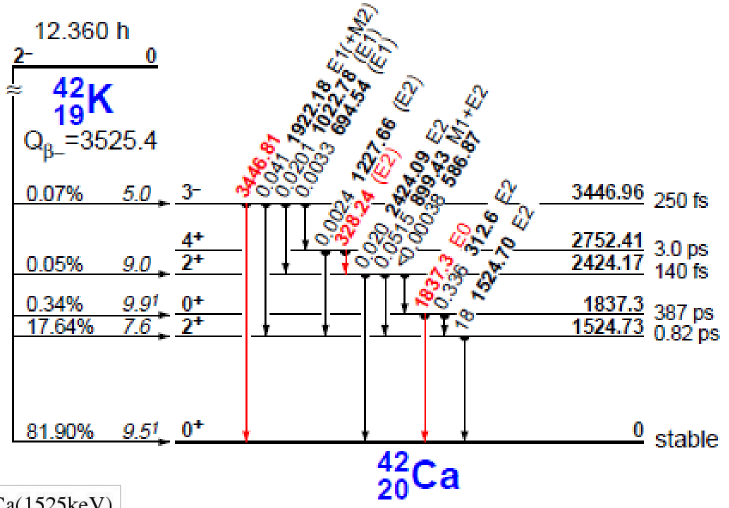
Shapes: ^{39}Ar and ^{42}Ar/^{42}K β decays

^{39}Ar, ^{42}Ar: $\Delta J^{\Delta\pi} = 2^-$ classified as 1 FU
$C(E) = (Q^2+\lambda_2 P^2)(1+aW)$, a = 0

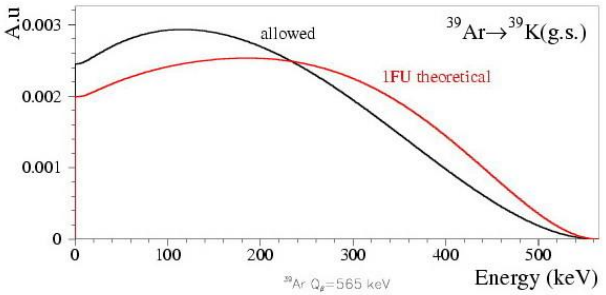
^{42}K (to g.s., 81.90%): $\Delta J^{\Delta\pi} = 2^-$ 1 FU
$C(E) = (Q^2+\lambda_2 P^2)(1+aW)$, $a \neq 0$

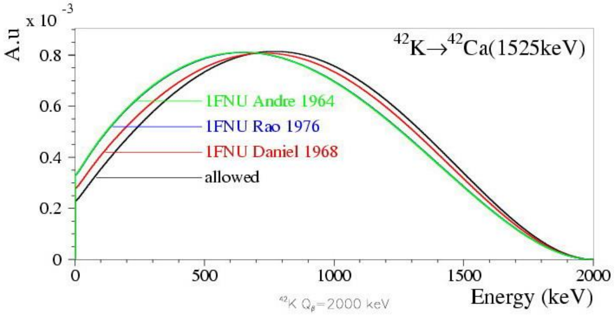
^{42}K (to 1525 keV, 17.64%): $\Delta J^{\Delta\pi} = 0^-$ 1 FNU
$C(E) = 1+a_1/W+a_2W+a_3W^2$
a, a_i – see Behrens’1976

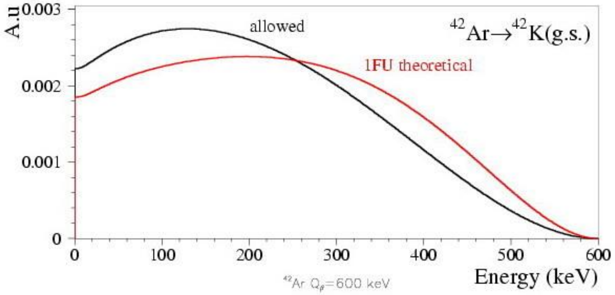


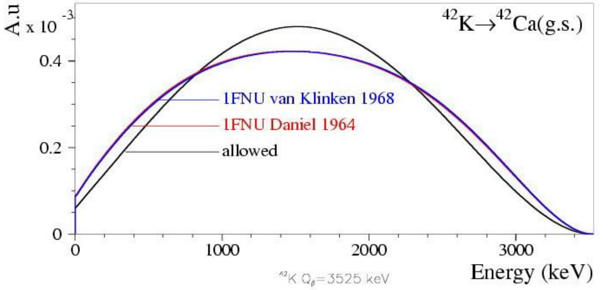


DECAY0:



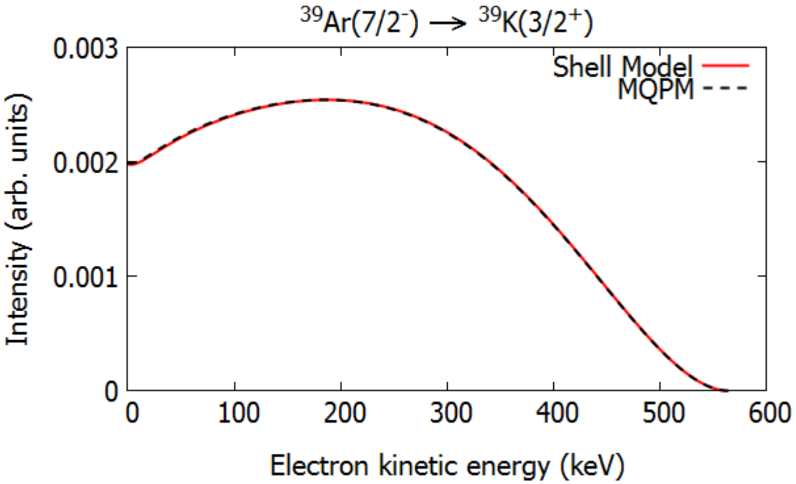


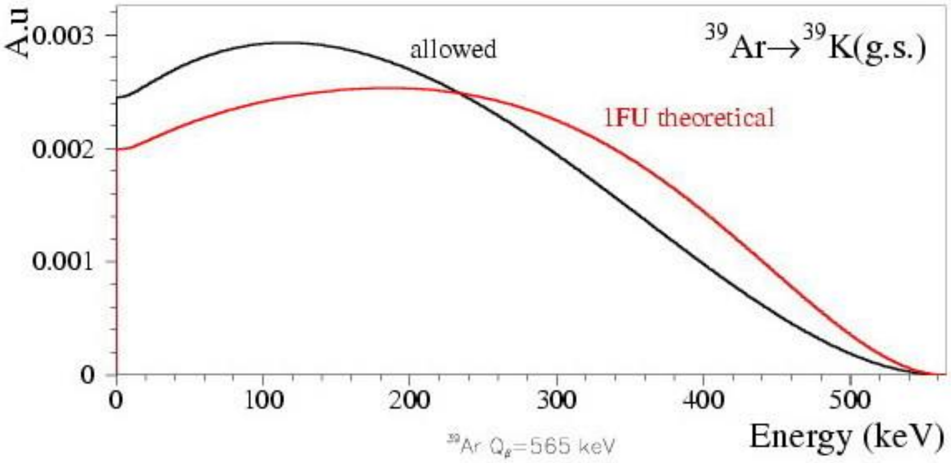


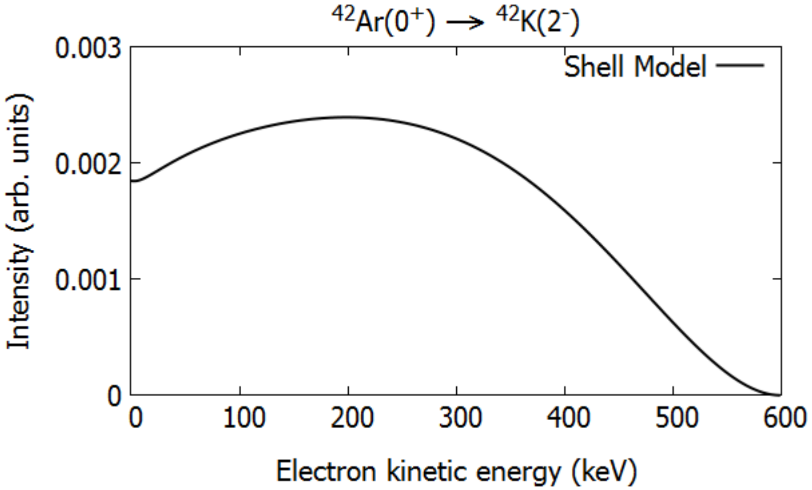


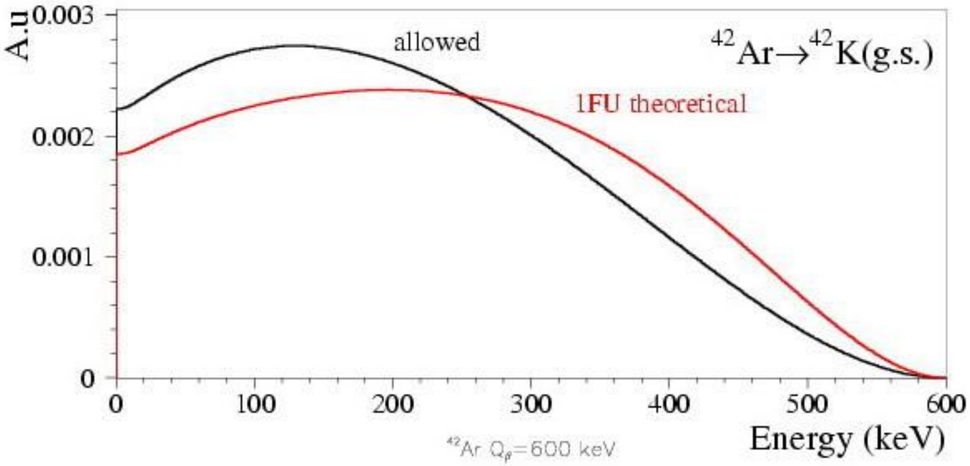
Recent calculations for ^{39}Ar and ^{42}Ar:
J. Kostensalo et al., arXiv:1705.05726

Shapes in DECAY0:

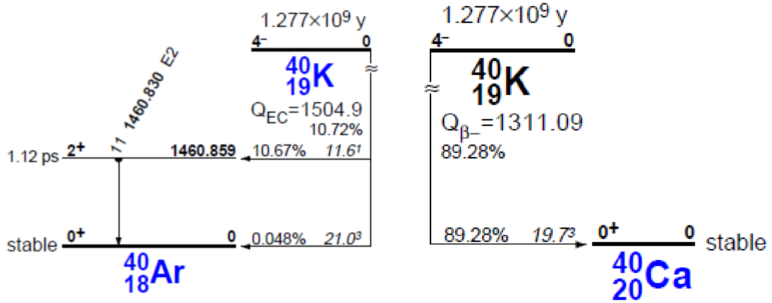








Shapes: ^{40}K β spectrum



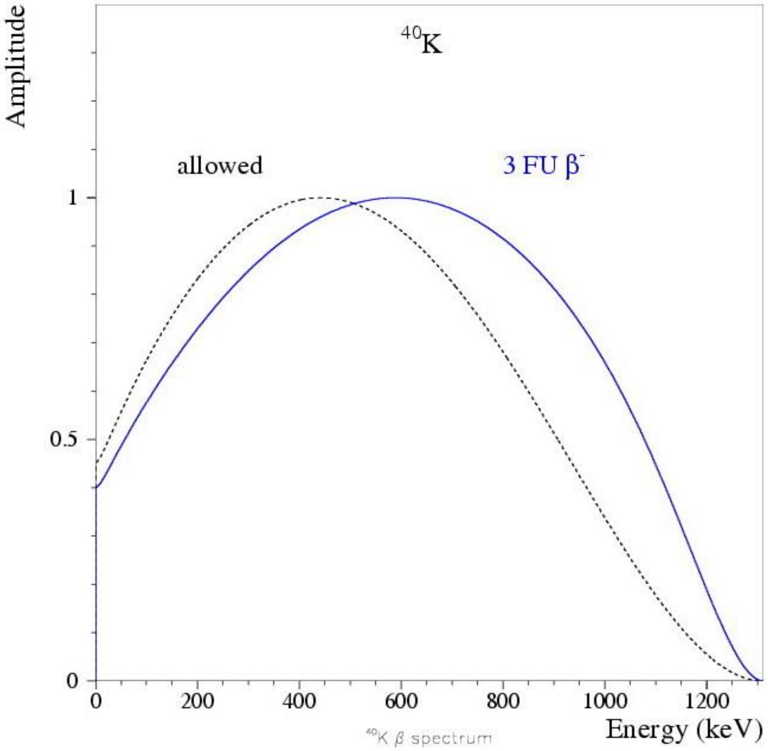
^{40}K: 10.7% EC, 89.3% β decay

$4^- \rightarrow 0^+$ $\Delta J^{\Delta\pi} = 4^-$ classified as 3 FU

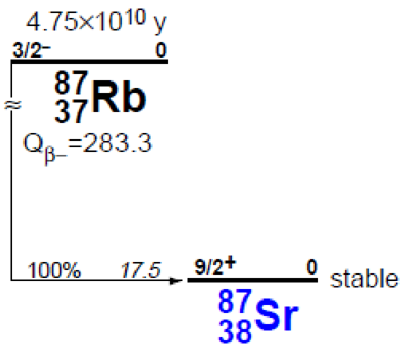
$C(E) = P^6+c_1P^4Q^2+c_2P^2Q^4+c_3Q^6$

$c_1 = 7$, $c_2 = 7$, $c_3 = 1$

[W.H. Kelly et al., Nucl. Phys. 11 (1959) 492]



Shapes: ^{87}Rb β spectrum



$3/2^- \to 9/2^+$ $\Delta J^{\Delta\pi} = 3^-$ classified as 3 FNU

Was measured in old works:

1. K. Egelkraut, H. Leutz, Z. Phys. 161 (1961) 13 (in German) – only exp. spectrum
2. G.B. Beard, W.H. Kelly, Nucl. Phys. 28 (1961) 570 – exp. spectrum + FK plot
3. B. Rüttenauer, E. Huster, Z. Phys. 258 (1973) 351 (in German)

and in the recent ones:

4. K. Kossert, Appl. Radiat. Isot. 59 (2003) 377 – fitting old experimental data
   $C_1(E) = 1$, $C_2 = P^4+118.00P^2Q^2+333.33Q^4$ (described as 2 FU, $\Delta J^{\Delta\pi} = 3^+$)
5. A.G. Carles et al., Nucl. Phys. A 767 (2006) 248 – new experimental data
   $C_1(E) = 1$, $C_2 = P^4+27.73P^2Q^2+90.91Q^4$ (described as 2 FU, $\Delta J^{\Delta\pi} = 3^+$)
   (also A.G. Carles et al., Nucl. Instrum. Meth. A 572 (2007) 760)

K. Kossert, Appl. Radiat. Isot. 59 (2003) 377:
(as one can see, very good agreement with experimental data)

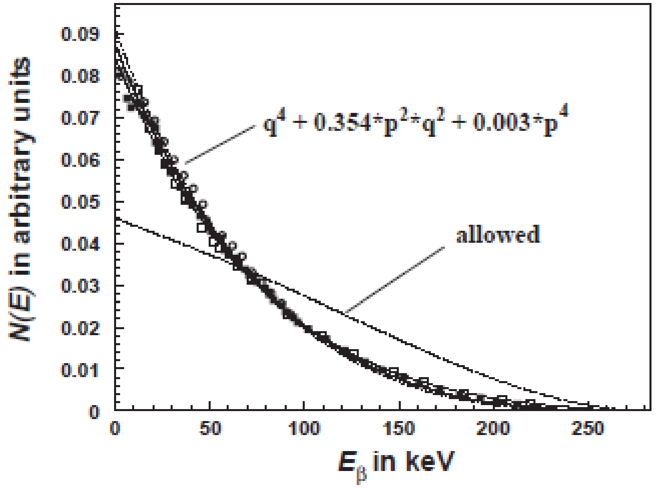


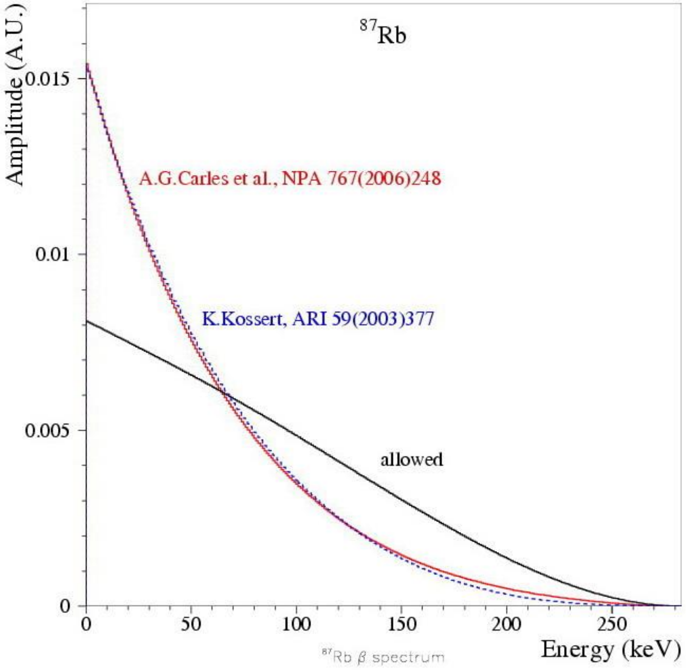
Fig. 1. Calculated β-spectrum $N(E)$ of ^{87}Rb and measured data from Egelkraut and Leutz (1961) (filled squares), Ruettenhauer and Huster (1973) (open circles) and Lewis (1952) (open squares). The dotted and dashed-dotted lines are calculated

Comparison of ^{87}Rb β spectra:

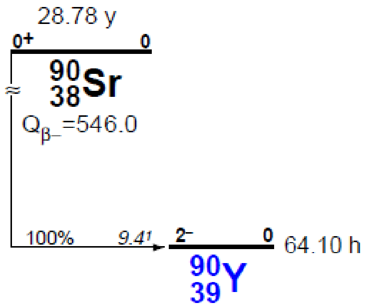
- **allowed**
- **parameterization ARI 59 (2003) 377**
- **parameterization NPA 767 (2006) 248**

step = 1 keV

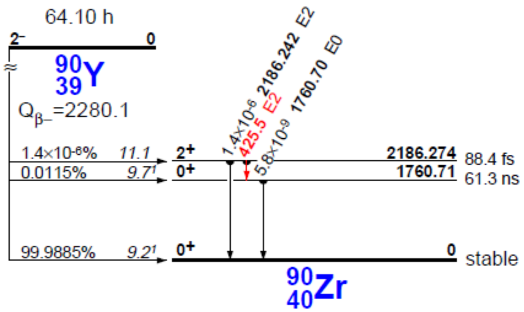
normalized to area = 1 for all spectra



Shapes: ^{90}Sr and ^{90}Y β spectra

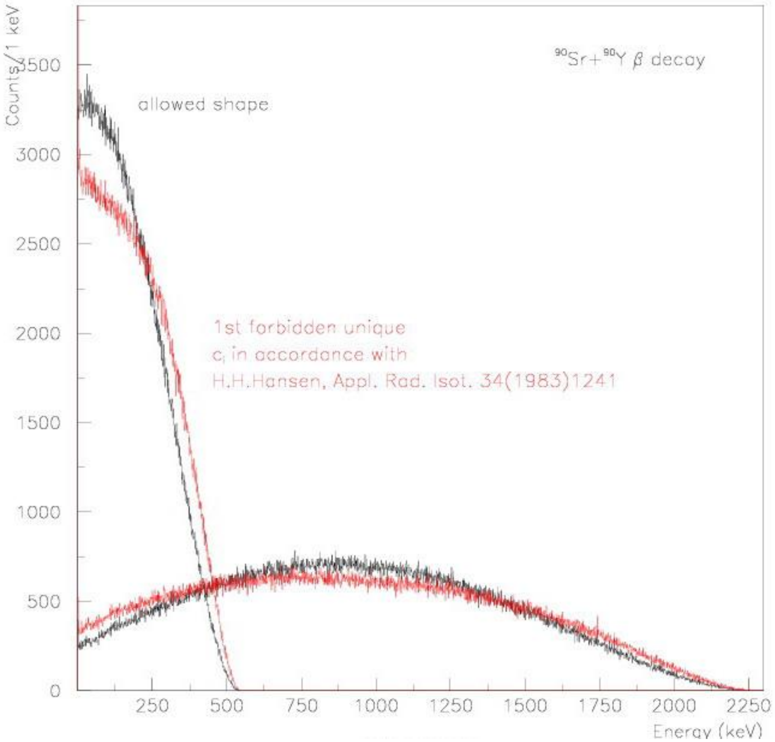


Both are (practically) pure β decayers
$\Delta J^{\Delta\pi} = 2^{-}$ classified as 1 FU

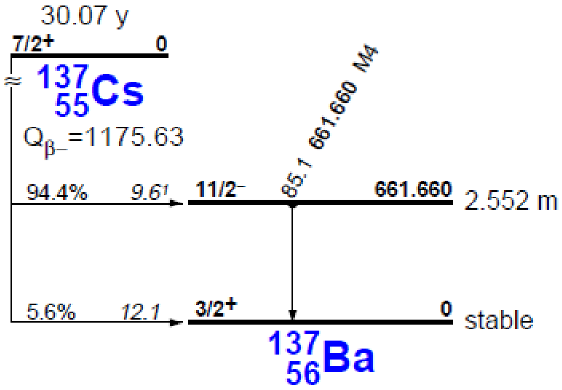


$C(E) = (Q^2+\lambda_2 P^2)(1+aW)$
λ_2 – Coulomb function from BJ'1969
a = –0.032 for ^{90}Sr
a = –0.0078 for ^{90}Y
[H.H. Hansen, Appl. Rad. Isot. 34 (1983) 1241]

Spectra of ^{90}Sr and ^{90}Y generated with DECAY0 event generator:



Shapes: ^{137}Cs β decay



(1) 94.4% $7/2^+ \rightarrow 11/2^-$ $\Delta J^{\Delta\pi} = 2^-$ classified as 1 FU

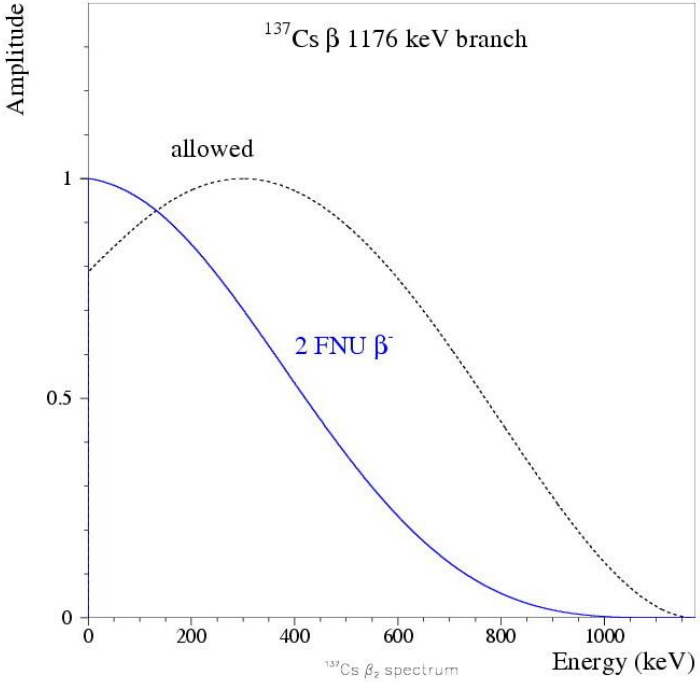
(2) 5.6% $7/2^+ \rightarrow 3/2^+$ $\Delta J^{\Delta\pi} = 2^+$ classified as 2 FNU

(1) $C(E) = Q^2+\lambda_2 P^2$

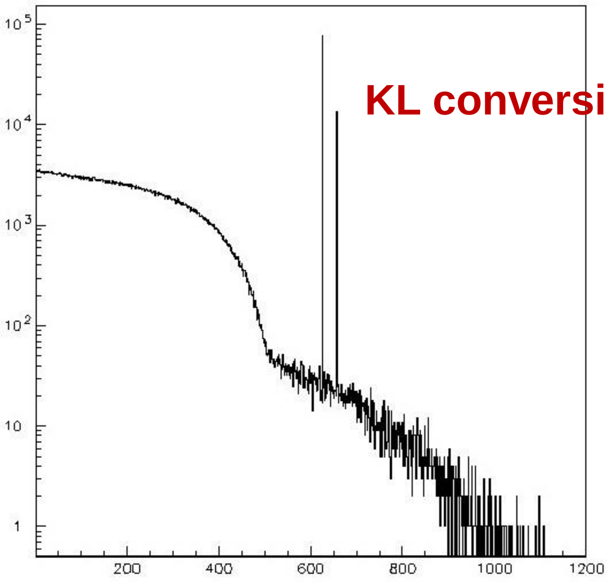
(2) $C(E) = 1+c_1/W+c_2W+c_3W^2$

$c_1 = 0$, $c_2 = -0.6060315$, $c_3 = 0.0921520$

[S.T. Hsue et al., Nucl. Phys. 86 (1966) 47]



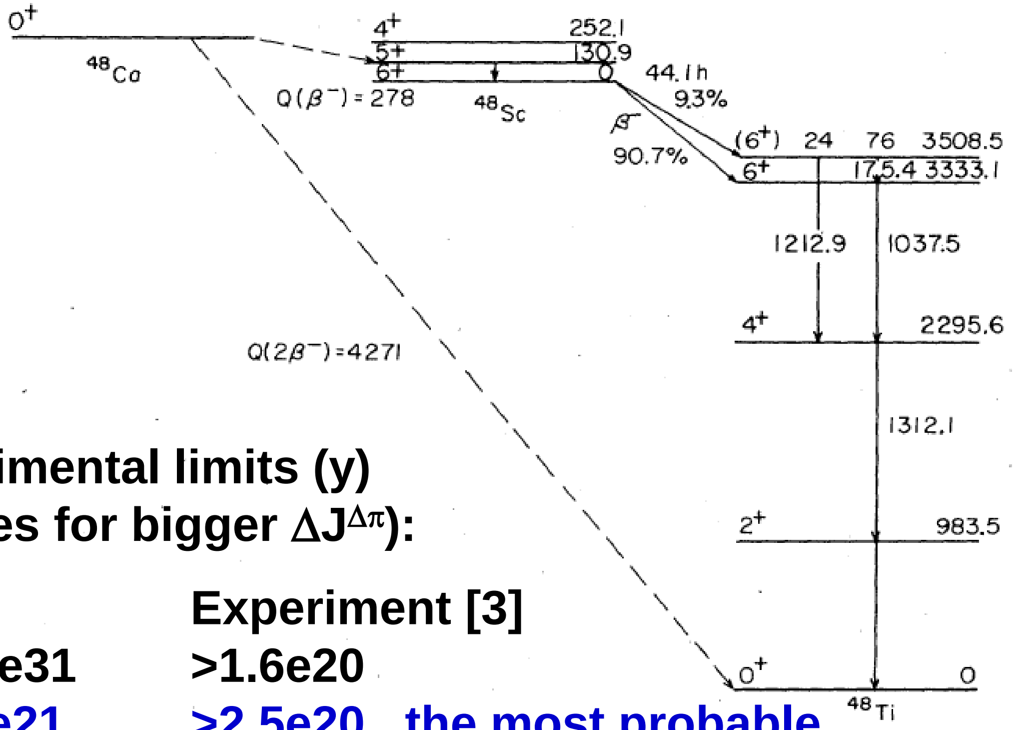
“Real” spectrum of electrons emitted by ^{137}Cs (generated with DECAY0)



KL conversion e⁻

Searches: ^{48}Ca

Q_β=279(5) keV, $\delta(^{48}Ca)$=0.187%



Could be populated:

ground state $\Delta J^{\Delta\pi}=6^+$
level 131 keV $\Delta J^{\Delta\pi}=5^+$
level 252 keV $\Delta J^{\Delta\pi}=4^+$

$T_{1/2}$ - theoretical estimates and experimental limits (y)
($T_{1/2}$ decreases as ~$1/Q^5$, but increases for bigger $\Delta J^{\Delta\pi}$):

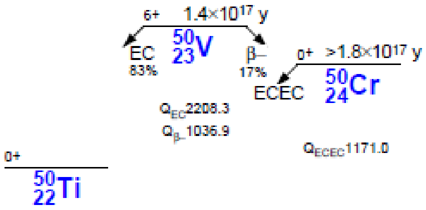
	Theory [1]	Theory [2]	Experiment [3]
6^+(g.s.)	=4.0e25	=1.5e29-1.3e31	>1.6e20
5^+(131)	=4.0e22	=$(1.1^{+0.8}_{-0.6})$e21	>2.5e20
4^+(252)	=3.0e23	=8.8e23-5.2e26	>1.9e20

the most probable
(also M. Haaranen et al.,
PRC 89 (2014) 034315:
(2.6-7.0)e20)

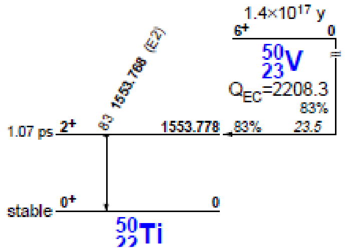
[1] R.K. Bardin et al., NPA 158 (1970) 337
[2] M. Aunola et al., Europhys. Lett. 46 (1999) 577
[3] A. Bakalyarov et al., JETP Lett. 76 (2002) 545
(search for deexcitation γ's of ^{48}Sc, ^{48}Ti with Ge detector)

^{48}Ca can decay also through 2β decay to ^{48}Ti (2nd order process) – already observed in few experiments; NEMO-3'2016: $T_{1/2}(2\beta2\nu$, g.s.) = 6.4e19 y.
Thus single β decay occurs even with lower probability than 2β - due to big ΔJ

Searches: ^{50}V δ=0.250%

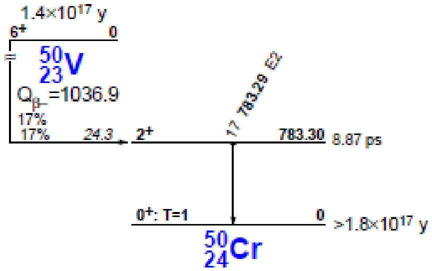


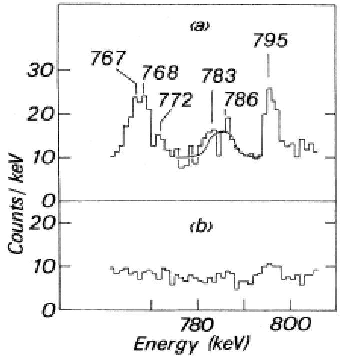
One of only 3 nuclei where β processes with $\Delta J^{\Delta\pi}=4^+$ were observed (other two are ^{113}Cd and ^{115}In)

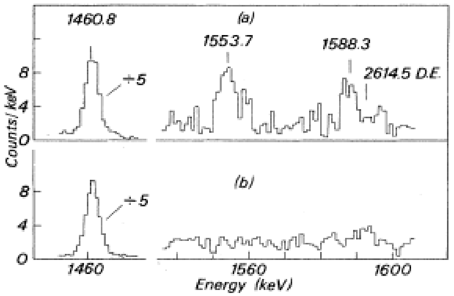


Low natural abundance (δ=0.250%), big $T_{1/2}$ (difficult to study)

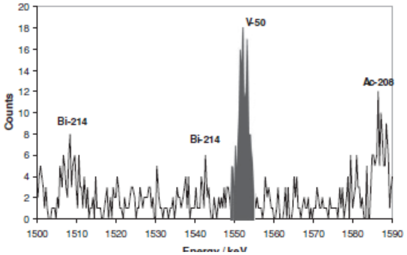
Experiment 1989: J.J. Simpson et al., PRC 39 (1989) 2367
3 Ge detectors, 337.5 g of natural V, salt mine, 1109 h
Search for γ's of 1554 keV (EC) and 783 keV (β^- decay)

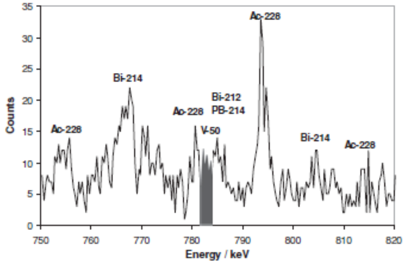






Experiment 2011: H. Dombrowski et al., PRC 83 (2011) 054322
Ge detector, 255.8 g of natural V, Asse salt mine (1200 m w.e.), 2347 h
Peak 783 keV is not observed:
$T_{1/2}$(EC)=(2.3±0.3)e17 y, $T_{1/2}(\beta^-)$>1.7e18 y

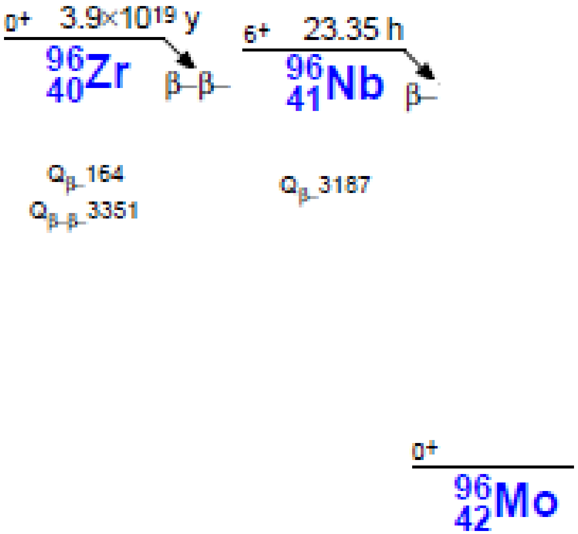




Only γ's are detected;
$T_{1/2}$ is measured but not shape of β spectrum

Searches: ^{96}Zr

Q_β=163.97(10) keV, δ(^{96}Zr)=2.80%



Could be populated:

ground state	$\Delta J^{\Delta\pi}=6^+$
level 44 keV	$\Delta J^{\Delta\pi}=5^+$
level 146 keV	$\Delta J^{\Delta\pi}=4^+$

$T_{1/2}$ - theoretical estimates and experimental limits:

	Theory [1]	Experiment [2]
6^+(g.s.)	=1.2e29	>3.8e19
5^+(44)	=2.4e20	>3.8e19 the most probable
4^+(146)	=4.9e22	>3.8e19

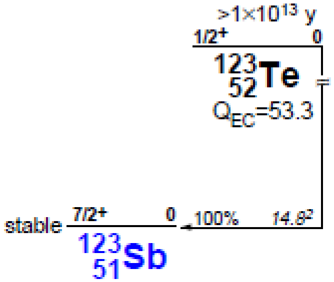
[1] H. Heiskanen et al., J. Phys. G 34 (2007) 837

[2] M. Arpesella et al., Europhys. Lett. 27 (1994) 29
(search for deexcitation γ's of ^{96}Mo with Ge detector; δ(^{96}Zr)=2.80% - much higher than that for ^{48}Ca; worth to remeasure with higher sensitivity?)

2β decay of ^{96}Zr to ^{96}Mo: $T_{1/2}$(2β2ν, g.s.) =(2.3±0.2)e19 y (NEMO-3'2015).
Geochemical 2β $T_{1/2}$: =(3.9±0.9)e19 Kawashima'1993 and =(0.9±0.3)e19 Wieser'2001.

Contribution of single β decay to geochemical $T_{1/2}$?

Searches: ^{123}Te $\delta(^{123}\mathrm{Te})=0.89\%$



Many puzzling experimental situations (only K EC was searched for):

1. D.N. Watt et al., Philos. Mag. 7 (1962) 105: detection of Sb X rays E_X=26.1 keV after EC with prop. counter, $T_{1/2}=(1.24\pm0.10)$e13 y
This result was present in all nuclear tables many years

2. A. Alessandrello et al., PRL 77 (1996) 3319: four 340 g TeO_2 bolometers, underground measurements (LNGS, 3600 m w.e.), 1548 h
Peak at total energy release of 30.5 keV (E_K of Sb) is observed,
$T_{1/2}^K=(2.4\pm0.9)$e19 y - 6 orders of magnitude higher!
Result of Watt'1962 was explained by excitation of Te atoms by cosmic rays and nat. radioactivity that gives E_X=27.3 keV, and by not enough good resolution of prop. counter

3. A. Alessandrello et al., PRC 67 (2003) 014323: twenty 340 g TeO_2 bolometers, LNGS (3600 m w.e.), peak at 30.5 keV is not present, $T_{1/2}^K>5.0$e19 y !

However, this peak appeared once more after all crystals were dismounted for surface cleaning at the sea level for ~2 months period and reinstalled underground.
Explanation of Alessandrello'1996: peak at 30.5 keV is due to EC of ^{121}Te (Q=1036 keV, $T_{1/2}$=16.78 d); ^{121}Te is produced by neutron capture on ^{120}Te ($\delta=0.09\%$) !

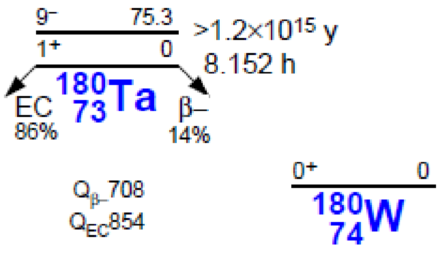
Searches: ^{180m}Ta

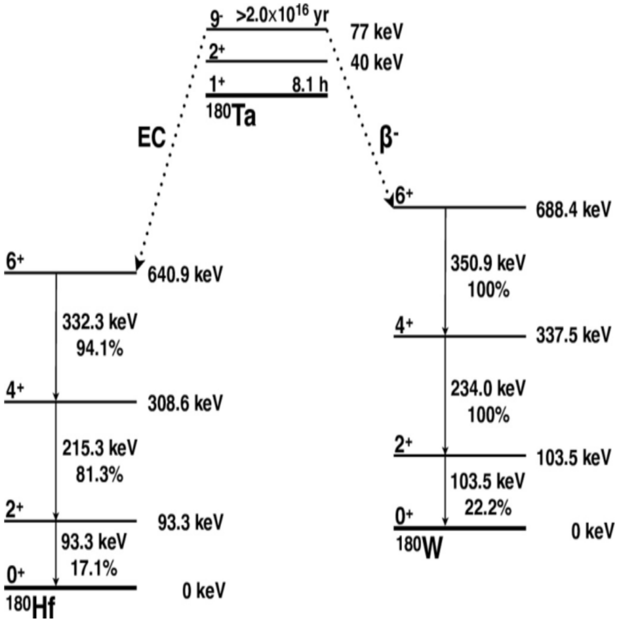
Extremely interesting case:
g.s. state quickly decays ($T_{1/2}$~8 h);
isomeric state (E_{exc}=77 keV) has big $T_{1/2}$>4.5e16 y
δ(^{180m}Ta)=0.012%

EC	**$\Delta J^{\Delta\pi}=3^-$**	**3 FNU**
β^-	**$\Delta J^{\Delta\pi}=3^-$**	**3 FNU**

Last experimental limits:

B. Lehnert et al., PRC 95 (2017) 044306
1500 g of natural Ta, sandwich HP Ge,
underground HADES laboratory (500 m w.e.)
$T_{1/2}$(EC) > 2.0e17 y
$T_{1/2}$(β^-) > 5.8e16 y





Theoretical $T_{1/2}$ estimations:

E.B. Norman, PRC 24 (1981) 2334:	**IT > 1e27 y**
H. Ejiri et al., JPG 44 (2017) 065101:	**IT = 1.4e31 y (8e18 with convers. el.)** **EC = 1.4e20 y** **β^- = 5.4e23 y**

Searches: ^{222}Rn

P. Belli et al., Eur. Phys. J. A 50 (2014)134

BaF_2 scintillator, 1.714 kg, LNGS (3600 m w.e.), 101 h.
High contamination by ^{226}Ra – 7.8 Bq/kg.

In all nuclear tables, ^{222}Rn (in chain of ^{238}U) is 100% α decaying. Usual chain:

$$^{222}_{86}\mathrm{Rn} \xrightarrow[5590\ \mathrm{keV}]{\alpha\quad 3.82\ \mathrm{d}} {}^{218}_{84}\mathrm{Po} \xrightarrow[6115\ \mathrm{keV}]{\alpha\quad 3.10\ \mathrm{m}} {}^{214}_{82}\mathrm{Pb} \xrightarrow[1024\ \mathrm{keV}]{\beta\quad 26.8\ \mathrm{m}} {}^{214}_{83}\mathrm{Bi} \xrightarrow[3272\ \mathrm{keV}]{\beta\quad 19.9\ \mathrm{m}}$$

$$^{214}_{84}\mathrm{Po} \xrightarrow[7833\ \mathrm{keV}]{\alpha\quad 164.3\ \mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}\ (22.3\ \mathrm{y}).$$

However, β decay of ^{222}Rn also is energetically allowed with Q=24±21 keV.
In this case:

$$^{222}_{86}\mathrm{Rn} \xrightarrow[24\ \mathrm{keV}]{\beta?\quad \simeq 4.8\times 10^{5}\ \mathrm{y}} {}^{222}_{87}\mathrm{Fr} \xrightarrow[2028\ \mathrm{keV}]{\beta\quad 14.2\ \mathrm{m}} {}^{222}_{88}\mathrm{Ra} \xrightarrow[6679\ \mathrm{keV}]{\alpha\quad 38.0\ \mathrm{s}} {}^{218}_{86}\mathrm{Rn} \xrightarrow[7263\ \mathrm{keV}]{\alpha\quad 35\ \mathrm{ms}}$$

$$^{214}_{84}\mathrm{Po} \xrightarrow[7833\ \mathrm{keV}]{\alpha\quad 164.3\ \mu\mathrm{s}} {}^{210}_{82}\mathrm{Pb}\ (22.3\ \mathrm{y}).$$

^{222}Rn(0^+) → ^{222}Fr(2^-), $\Delta J^{\Delta\pi}=2^-$; $T_{1/2}$ can be estimated using average (for 216 known 1 FU β decays) log ft = 9.5 and LOGFT tool at NNDC as $T_{1/2} = 4.8\times10^5$ y (for Q=24 keV; 6.7×10^4 y for Q=45 keV and 2.4×10^8 y for Q=3 keV).

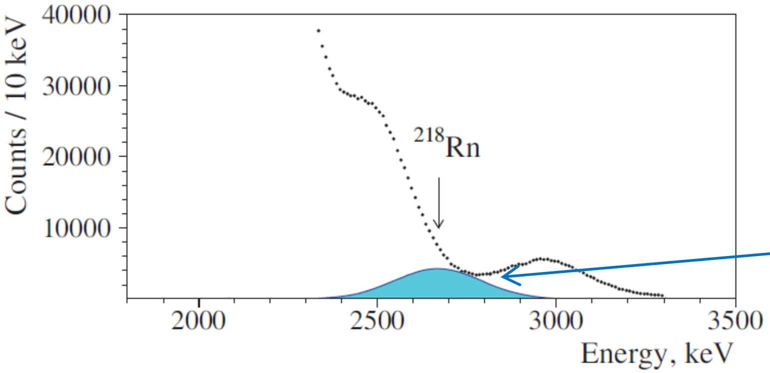
Expected E and Δt are known, and it is possible to distinguish between α and β events in BaF_2 scintillator because of difference in their time shapes.

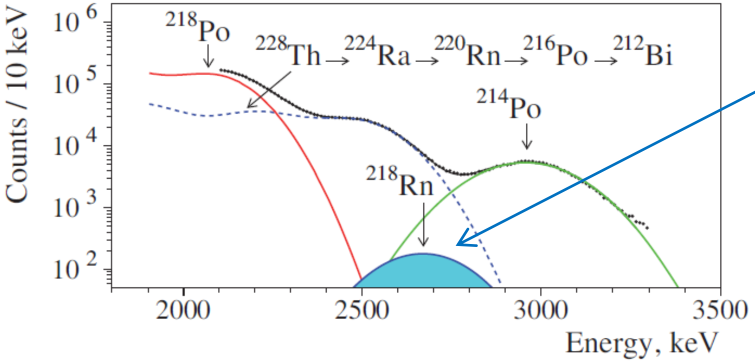
Following sequence of events was searched for ($^{222}Fr \rightarrow {}^{222}Ra \rightarrow {}^{218}Rn \rightarrow {}^{214}Po$):

(1) event at 30 – 2207 keV (^{222}Fr Q_β + $FWHM_\beta$) and with β time shape;

(2) next event at 2109 – 2623 keV (^{222}Ra E_α + $FWHM_\alpha$ in γ scale), with α time shape and in time interval [1.65 ms, 1.65 ms + 5×38.0 s];

(3) last event at 2398 – 2946 keV (^{218}Rn E_α + $FWHM_\alpha$ in γ scale), with α time shape and in time interval [1.65 ms, 1.65 ms + 5×35 ms].



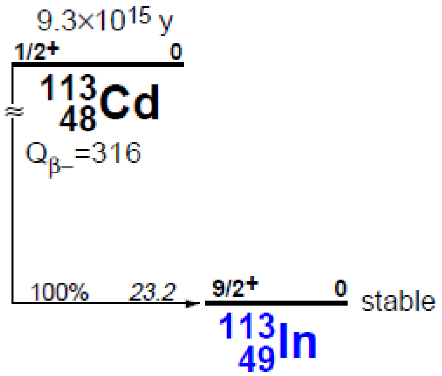


7.0×10^5 selected potential ^{218}Rn events.

Maximal effect consistent with exp. data, $T_{1/2}^{\beta}$ > 122 d (too conservative limit)

Limit from fit by model (known α peaks from contamination), $T_{1/2}^{\beta}$ > 8.0 y.

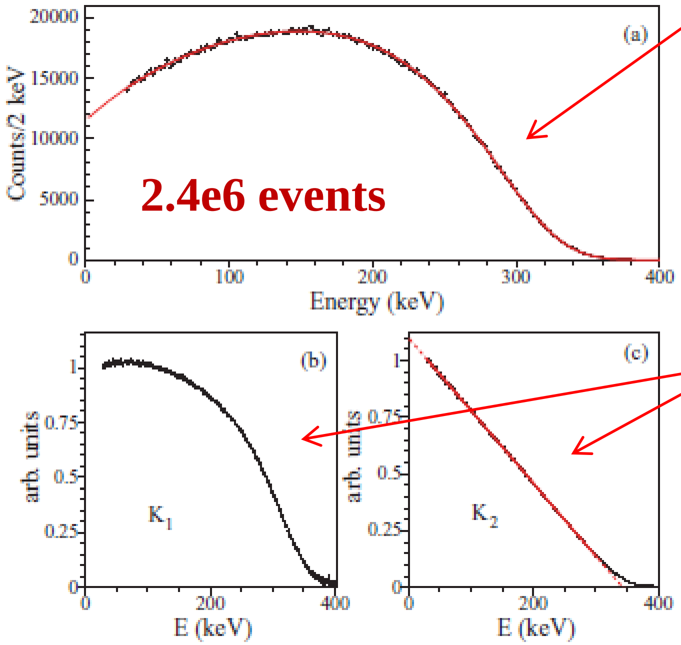
Recent investigations: ^{113}Cd δ=12.22%



1/2$^+$ → 9/2$^+$ $\Delta J^{\Delta\pi} = 4^+$ classified as 4 FNU

Was searched for since 1940, first observed in 1970, first measurement of β shape in 1988 with CdTe detector

One of the last experiments: P. Belli et al., PRC 76 (2007) 064603
CdWO$_4$ scintillator 434 g, LNGS (3600 m w.e.), 2758 h



Experimental spectrum (S/B ratio = 1/50) and its fit by:

$$f(E) = \int_0^{Q_\beta} \rho(E') R(E, E') dE' \qquad \rho(E) = wpF(E, Z)(Q_\beta - E)^2 \cdot C(w)$$

$$C(w) = p^6 + 7a_1 p^4 q^2 + 7a_2 p^2 q^4 + a_3 q^6 \qquad R(E, E') = \frac{1}{\sqrt{2\pi}\sigma(E')} \exp\left(-\frac{(E - E')^2}{2\sigma^2(E')}\right)$$

Kurie plots not accounting and accounting for correction factor C(w)

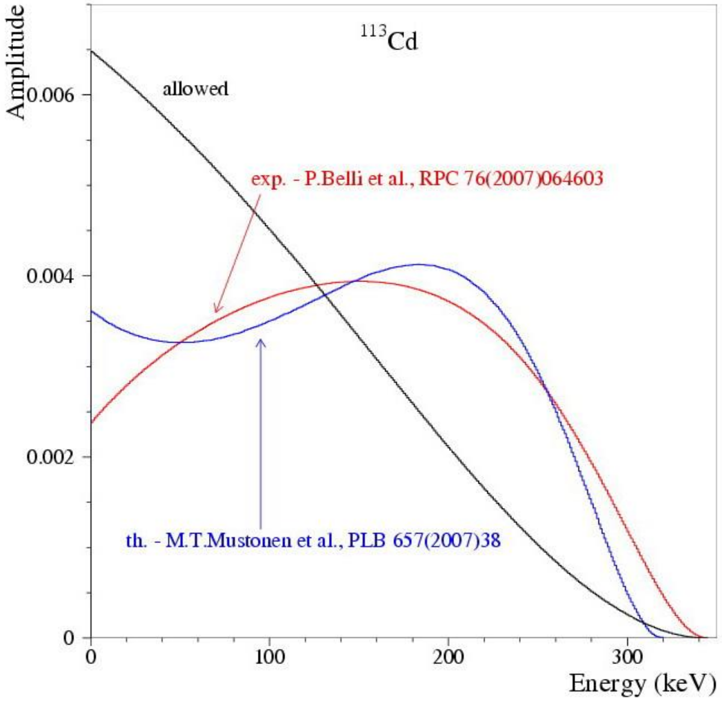
Big statistics, purity of crystal lead to determination of $T_{1/2}$ with small uncertainty:
$T_{1/2}$=(8.04±0.05)e15 y

Experimental spectrum is excellently described as 3 FU ($\Delta J^{\Delta\pi} = 4^-$):
$C(E) = P^6+c_1P^4Q^2+c_2P^2Q^4+c_3Q^6$ with $c_1 = 7.112$, $c_2 = 10.493$, $c_3 = 3.034$
(small puzzle: shape for $\Delta J^{\Delta\pi} = 4^+$ is described perfectly by shape for $\Delta J^{\Delta\pi} = 4^-$)

Recent theoretical description as 4 FNU:
M.T. Mustonen et al., PRC 73 (2006) 054301 + 76 (2007) 019901(E); PLB 657 (2007) 38 (shape different from the experimental one)

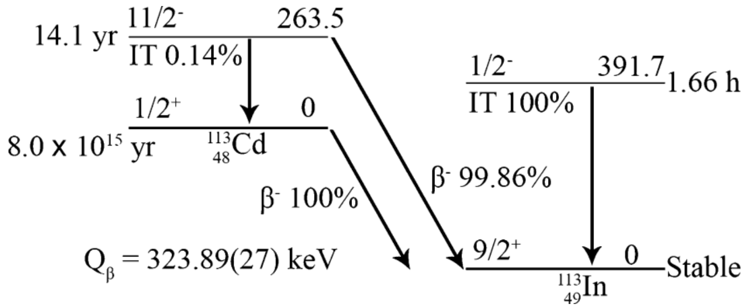
But: dependence of shape on g_A value:
M. Haaranen et al., PRC 93 (2016) 034308
for $g_A = 0.9$ theor. shape is close to the exp. one

Last experimental work:
J.V. Dawson et al., NPA 818 (2009) 264
16 CdZnTe detectors, LNGS, 6.58 kg×d
Confirmed $T_{1/2}$ and shape of spectrum, but gave different Q_β value
(322 keV instead of 345 keV in Belli’2007)
(another small puzzle …)



New measurements are in progress at LSM with CdWO$_4$ scintillating bolometer (433 g), EDELWEISS set-up, 17 mK;
threshold: ~4(15) keV for heat(light); FWHM at 356 keV: 3.7(54) keV for heat(light)

Investigations in progress: ^{113m}Cd



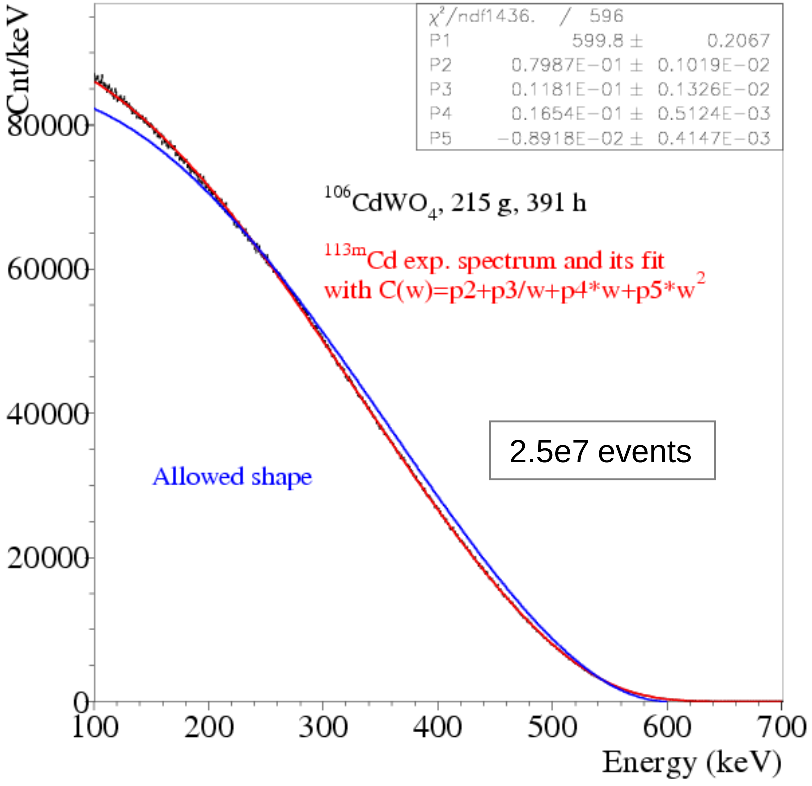
$11/2^- \rightarrow 9/2^+$ $\Delta J^{\Delta\pi} = 1^-$ classified as 1 FNU

shape was not measured previously

$^{106}CdWO_4$ scintillator 215 g, LNGS (3600 m w.e.), 391 h

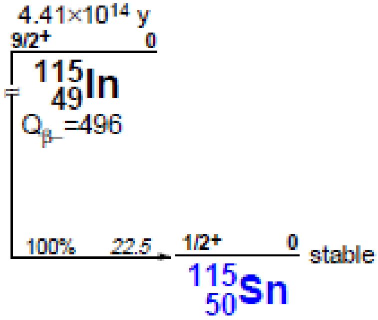
Quite high activity of ^{113m}Cd: 83 Bq/kg (probably before enrichment this Cd was used in reactor shielding)

Preliminary results:



Experimental spectrum deviates from the allowed shape

Not very recent investigations: ^{115}In δ=95.71%



$9/2^+ \rightarrow 1/2^+$ $\Delta J^{\Delta\pi} = 4^+$ classified as 4 FNU

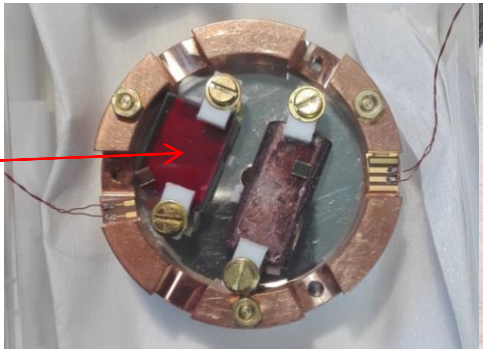
Contrary to ^{113}Cd, the spectrum shape was measured only in one work, L. Pfeiffer et al., PRC 19 (1979) 1035:

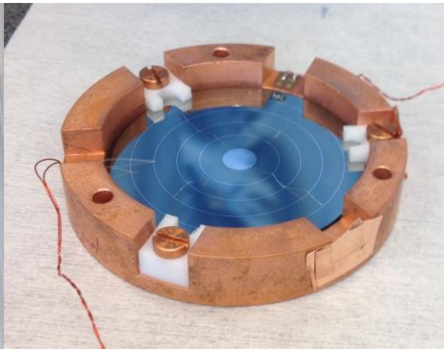
Liquid scintillator (LS) loaded by In at 51.2 g/l, measurements at the sea level.
What could be improved:
(1) Background, in particular n capture by ^{115}In (^{116}In is β^- unstable, Q=3275 keV)
(2) Strong quenching of low-energy electrons in LS (was not discussed)
(3) Resolution "is not known and is not readily measurable"
(4) Q was obtained as 492.7(13.6) keV and 470.6(5.2) keV; today value is 499(4)
(5) $T_{1/2}$=(4.41±0.24)e14 y (since 1979 – in all tables), but in some disagreement with previous results (e.g. G.B. Beard et al., PR 122 (1961) 1576: $T_{1/2}$=(6.9±1.5)e14 y)
(6) Energy threshold – around 50 keV
(7) Shape is described as polynomial in E
Remeasuring in low background conditions would be very interesting!

Recent theoretical description as 4 FNU:
M.T. Mustonen et al., PRC 73 (2006) 054301 + PRC 76 (2007) 019901(E)
M.T. Mustonen et al., PLB 657 (2007) 38
M. Haaranen et al., PRC 93 (2016) 034308; 95 (2017) 024327 (in dep. on g_A)
J. Kostensalo et al., PRC 95 (2017) 044313 (in dependence on g_A)

Nice news:

possibility to measure ^{115}In β decay with new crystal scintillator – LiInSe$_2$ (MIT, Lindley Winslow)



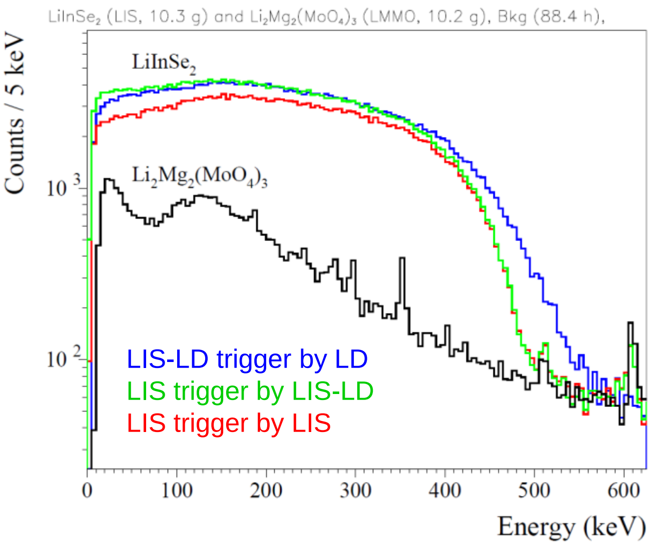


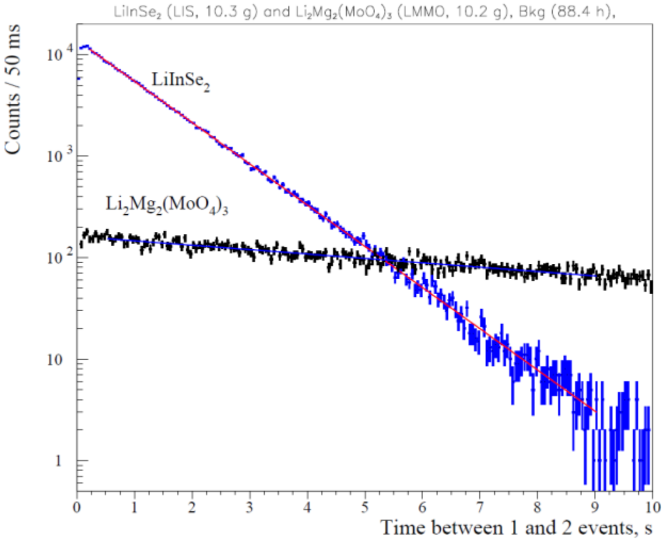
Ge LD with Neganov-Luke amplification

CSNSM-MIT-KINR experiment in France:

- **LiInSe$_2$ (8×15×19 mm, 10.3 g) scintillating bolometer, high light yield (~14 keV/MeV)**
- **Neganov-Luke Ge light detector**
- **Calibration by environmental γ's (heat) and by ^{55}Fe X-ray (light); threshold: ~3(5) keV for heat(light); FWHM at 609 keV: 11(121) keV for heat(light)**
- **Goal: threshold well below ~50 keV**

Very preliminary (t=88 h): $T_{1/2}$ = 5.58(2)×10^{14} y

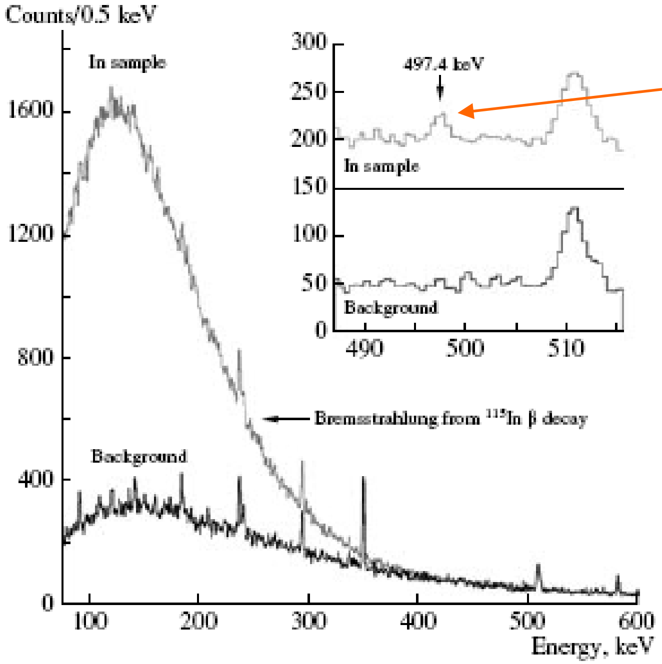




Problem of pile-ups

Recent discovery: ^{115}In → ^{115}Sn*

First observation of β decay of ^{115}In to the first excited level (E_{exc}= 497.334(22) keV) of ^{115}Sn: C.M. Cattadori et al., NPA 748 (2005) 333 + Phys. At. Nucl. 70 (2007) 127: LNGS, ~1 kg In, 4 HPGe 225 cm^3 each, 2762 h In + 1601 h bkg



Measured energy of the de-excitation peak = 497.48(21) keV, S=90±22 counts (4σ observation), $T_{1/2}$=(3.7±1.0)e20 y

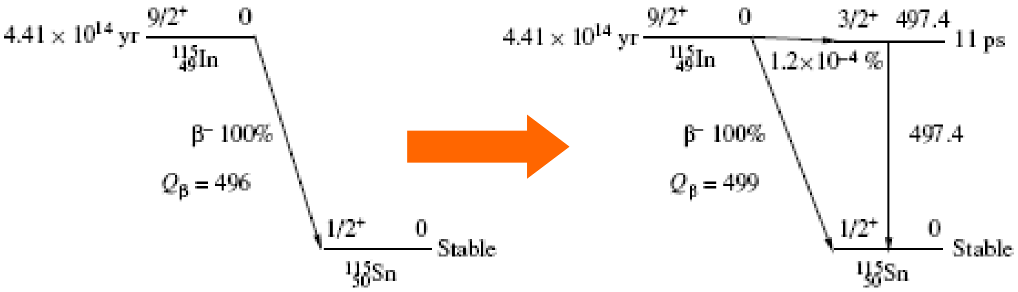


Fig. 2. Old (*a*) and new (*b*) schemes of ^{115}In → ^{115}Sn β decay (energy in keV).

Confirmation of observation of ^{115}In → ^{115}Sn* decay

HADES underground laboratory (500 m w.e.), 2566 g of In, 3 Ge detectors:
$T_{1/2}$=(4.1±0.6)e20 y (E. Wieslander et al., PRL 103(2009)122501)
$T_{1/2}$=(4.3±0.5)e20 y (E. Andreotti et al., PRC 84(2011)044605)

Situation in 2005:

ΔM_a = 499±4 keV (G. Audi et al., 729 (2003) 337)

E_{exc} = 497.334(22) keV (J. Blachot, NDS 104 (2005) 967)

$Q_\beta^* = \Delta M_a - E_{exc}$ = 1.7±4 keV – possibly the lowest known measured Q_β value

Precise measurements of difference ΔM_a of ^{115}In–^{115}Sn masses

ΔM_a = 497.489±0.010 keV (B.J. Mount et al., PRL 103(2009)122502)

Thus, Q_β^* = (497.489±0.010)–(497.334±0.022) = 155±24 eV

Really the lowest Q value of a known β decay (^{163}Ho – 2.555 keV, ^{187}Re – 2.469 keV) and highest (partial) $T_{1/2}$

Paradoxical situation: masses of the nuclei (~100 GeV) are known with precision 10 eV while E_{exc} (~500 keV) – with precision 22 eV (needs to be remeasured). Recent remeasurements of E_{exc}:

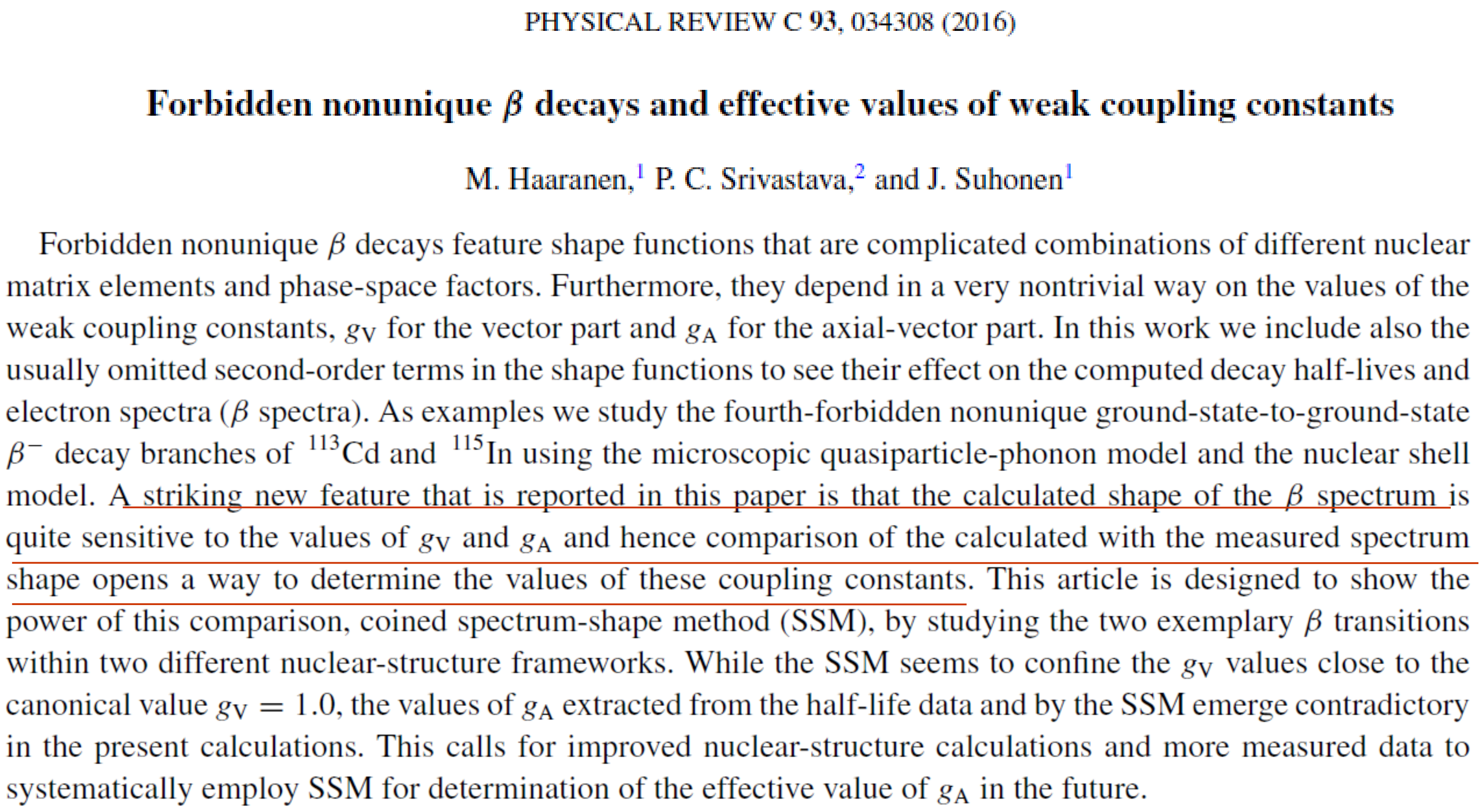
W. Urban et al., PRC 94 (2016) 011302: 497.316(7) keV → Q_β^* = 173±12 eV

V.A. Zheltonozhsky et al., to be published: 497.341(3) keV → Q_β^* = 148±10 eV

Influence of different chemical environment on $T_{1/2}$ (In, $InCl_3$, etc.). If to use dependence $T_{1/2} \sim 1/Q^5$ and change Q on 1 eV only, we will obtain $(155/154)^5 = 1.03$ – 3% change in $T_{1/2}$. Difficult but maybe possible to see (current accuracy – 12%).

Deviations from theoretical spectrum due to non-zero ν mass? Theoretical spectrum ($\Delta J^{\Delta\pi} = 3^+$ – classified as 2 FU) was calculated in R. Dvornicky, F. Simkovic, AIP Conf. Proc. 1417(2011)33. Very difficult experimentally.

Forbidden non-unique β decays and g_A and g_V values



PHYSICAL REVIEW C 93, 034308 (2016)

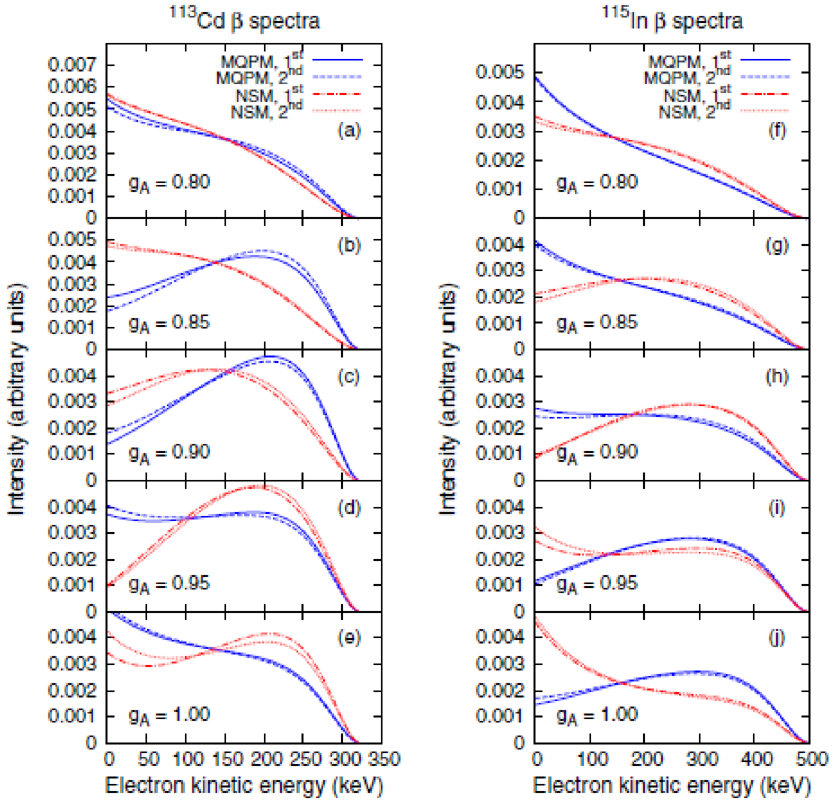
Forbidden nonunique β decays and effective values of weak coupling constants

M. Haaranen,[1] P. C. Srivastava,[2] and J. Suhonen[1]

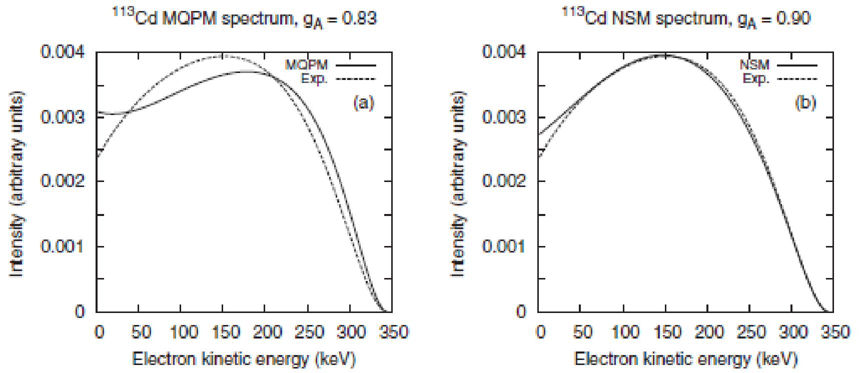
Forbidden nonunique β decays feature shape functions that are complicated combinations of different nuclear matrix elements and phase-space factors. Furthermore, they depend in a very nontrivial way on the values of the weak coupling constants, g_V for the vector part and g_A for the axial-vector part. In this work we include also the usually omitted second-order terms in the shape functions to see their effect on the computed decay half-lives and electron spectra (β spectra). As examples we study the fourth-forbidden nonunique ground-state-to-ground-state β^- decay branches of ^{113}Cd and ^{115}In using the microscopic quasiparticle-phonon model and the nuclear shell model. A striking new feature that is reported in this paper is that the calculated shape of the β spectrum is quite sensitive to the values of g_V and g_A and hence comparison of the calculated with the measured spectrum shape opens a way to determine the values of these coupling constants. This article is designed to show the power of this comparison, coined spectrum-shape method (SSM), by studying the two exemplary β transitions within two different nuclear-structure frameworks. While the SSM seems to confine the g_V values close to the canonical value $g_V = 1.0$, the values of g_A extracted from the half-life data and by the SSM emerge contradictory in the present calculations. This calls for improved nuclear-structure calculations and more measured data to systematically employ SSM for determination of the effective value of g_A in the future.

Rate of 2β decay is ~g_A^4. For bare nucleon g_A=1.25, for infinite nuclear matter g_A=1. This already gives uncertainty of $(1.25)^4$=2.44 !
However, g_A could be quenched down to ~0.4, and 0.4^4=0.025 – thus we have ~2 orders of magnitude uncertainty in $T_{1/2}$ for 2β decays !

For non-unique forbidden beta decays, shape of energy spectrum depends on sum of different nuclear matrix elements (NMEs) with different phase space factors which include also g_A and g_V constants. Comparing theoretical shape with experimental, it is possible to find their values.

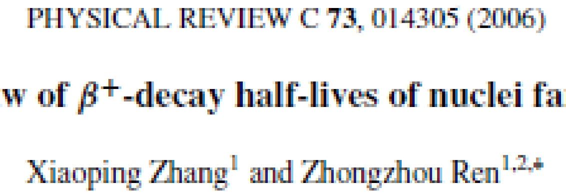


The authors used our experimental spectrum [P. Belli et al., PRC 76 (2007) 064603 to find g_A value (depends also on theory (MQPM, NSM, …)



See also:
M. Haaranen et al., PRC 95 (2017) 024327
J. Kostensalo et al., PRC 95 (2017) 044313

Semiempirical formulae for β $T_{1/2}$



PHYSICAL REVIEW C **73**, 014305 (2006)

New exponential law of β^+-decay half-lives of nuclei far from β-stable line

Xiaoping Zhang[1] and Zhongzhou Ren[1,2,*]

$$\log_{10} T_{1/2} = (c_1 Z + c_2) N + c_3 Z + c_4,$$

c_i are given for 1st and 2nd forb. β^+ decays

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Simple Formula of β^+-Decay Half-Lives of Nuclei Far From β-Stable Line*

ZHANG Xiao-Ping,[1] REN Zhong-Zhou,[1,2,†] and ZHI Qi-Jun[1]

the same formula; c_i are given for allowed,1st and 2nd forbidden β^+ decays

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Systematics of β^--decay half-lives of nuclei far from the β-stable line

Xiaoping Zhang[1], Zhongzhou Ren[1,2], Qijun Zhi[1] and Qiang Zheng[1]

the same formula; c_i are for β^- decays

Conclusions

There was a little interest in investigations of rare β decays since ~1970's – no $T_{1/2}$ were measured with higher precision, no shapes of β spectra.

During last time, development of experimental technique lead to improvement in sensitivity, and new decays were observed with extreme characteristics (β with lowest Q of 155 eV for $^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}^*$).

Interest to β shapes also is growing, in particular for nuclides which create background in rare events' searches.

Many theoretical works also appeared last time. New approach to measure g_A/g_V ratio through non-unique forbidden beta decays (^{113}Cd, ^{115}In) is proposed.

It could be concluded that investigations of rare β decays start to revive now, and we could expect new interesting theoretical works and experimental measurements.

Thank you for attention!