DECAY0 event generator for initial kinematics of particles in α, β and 2β decays

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1. Introduction

There are number of general simulation tools – such as GEANT3, GEANT4, EGS, MCNP or other programs – which allow to calculate response function of a detector for radioactive decays which occur somewhere near or inside a detector. To obtain result of simulation, one has to explain to these programs:

What is a geometry of experiment (position of detector, its size and material, positions of sources of radiation, shieldings, existence of magnetic and electric fields, etc.);

Which particles are emitted by sources of radiation: how many particles and of which type, their energies, directions and times of emission.

Aim of the DECAY0 event generator is to generate – by Monte Carlo method – initial kinematics of particles emitted in:
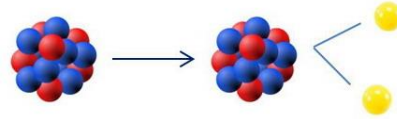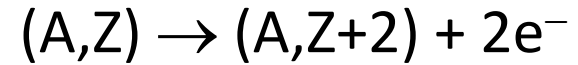1) 2β decays of atomic nuclei ($2\beta^-$, $2\beta^+$, $\varepsilon\beta^+$, 2ε)
2) α, β decays of nuclides dangerous to imitate 2β processes
3) α, β decays of nuclides in calibration sources

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2. Generation of 2β decays

Two neutrino (2ν) double beta decay $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$
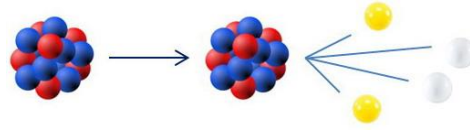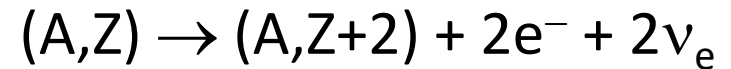
Neutrinoless (0ν) double beta decay $(A,Z) \rightarrow (A,Z+2) + 2e^-$

2β2ν - fully allowed in SM; however, very rare,
   $T_{1/2} \cong 10^{18} - 10^{24}$ y for already observed decays

2β0ν - forbidden in SM (because of $\Delta L=2$); not observed yet,
 $T_{1/2} > 10^{24} - 10^{26}$ y for the best experiments,
   predicted by many theories

Also: 2β^+ decay (emission of positrons instead of electrons),
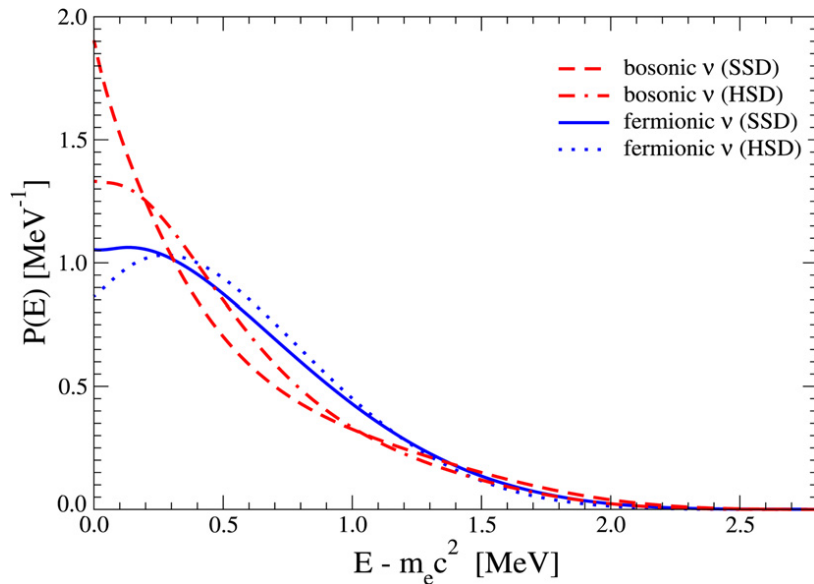 $\epsilon\beta^+$ (electron capture + emission of β^+), 2ϵ capture,
   2β0νM (emission of different Majorons)

Different modes (2ν, 0ν, Majorons, …) and mechanisms (2n, N*, ν mass, right-handed currents), decay to 0^+ or 2^+ level $\Rightarrow$ different energy and angular distributions of emitted $\beta^\pm$ particles

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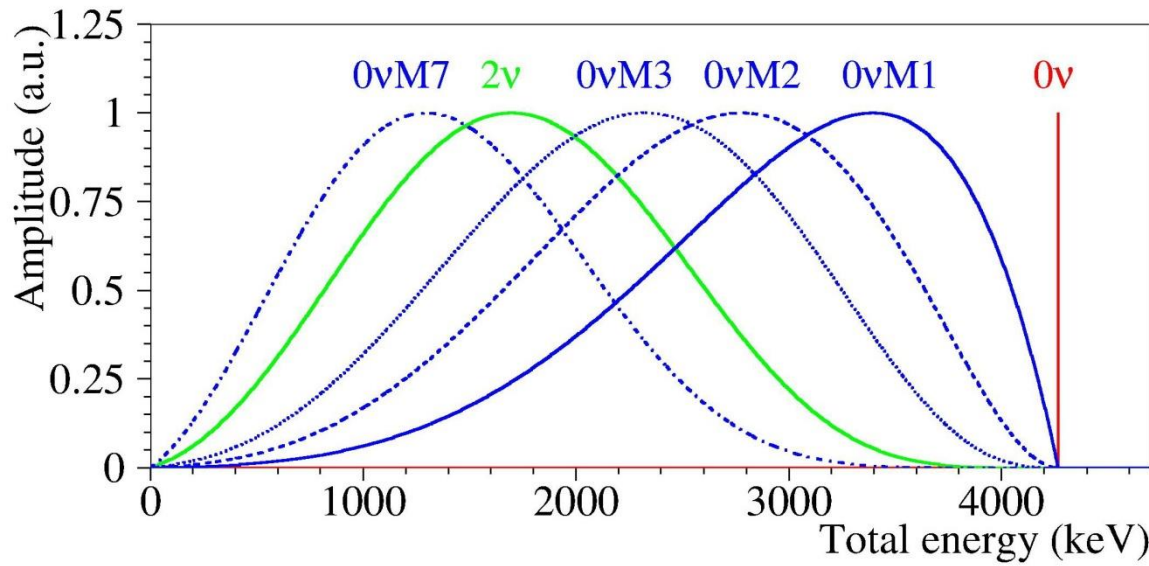
Energy distributions in different modes of 2β decay (sum of e⁻ energies, ^{48}Ca)
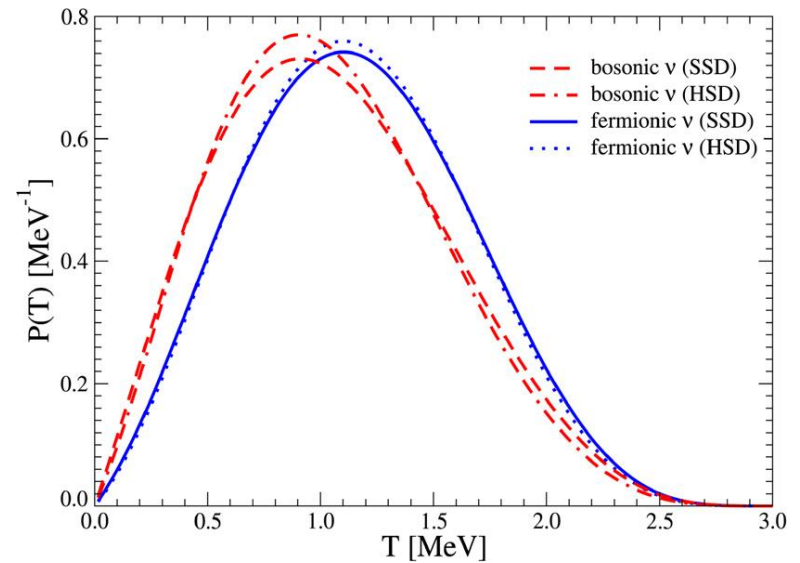
Energy distributions (single e⁻ and sum of e⁻ energies, ^{100}Mo) for 2β2ν decay with bosonic ν's [A.S. Barabash et al., NPB 783 (2007) 90]
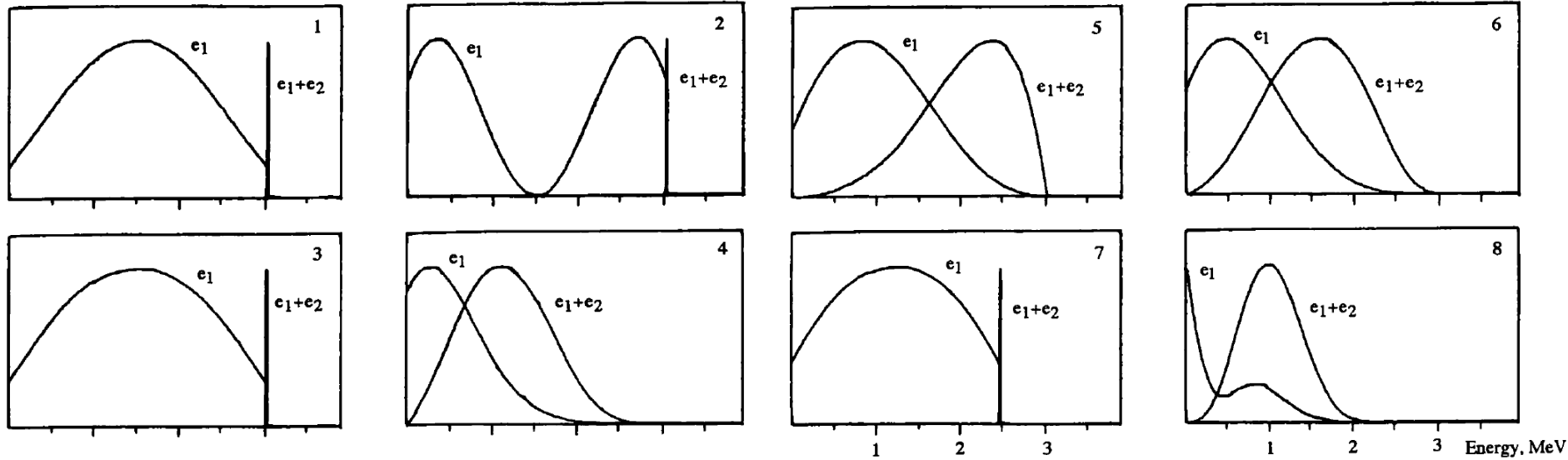
Figure 4. Theoretical distributions for the energy of a single electron (e_1) and for the sum of electron energies ($e_1 + e_2$) for ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $E(2^+)$ = 540 keV) for different modes and mechanisms of 2β decay: (1) $0\nu2\beta$ decay with neutrino mass, $0^+–0^+$ transition, $2n$ mechanism; (2) $0\nu2\beta$ decay with right-handed currents, $0^+–0^+$ transition, $2n$ mechanism; (3) $0\nu2\beta$ decay with right-handed currents, $0^+–0^+$ transition, N^* mechanism; (4) $2\nu2\beta$ decay, $0^+–0^+$ transition, $2n$ mechanism; (5) $0\nu2\beta$ decay with Majoron emission, $0^+–0^+$ transition, $2n$ mechanism; (6) $0\nu2\beta$ decay with double Majoron emission, $0^+–0^+$ transition, $2n$ mechanism; (7) $0\nu2\beta$ decay with right-handed currents, $0^+–2^+$ transition, $2n$ mechanism; (8) $2\nu2\beta$ decay, $0^+–2^+$ transition, $2n$ mechanism and N^* mechanism.

From: V.I. Tretyak and Yu.G. Zdesenko, "Tables of double beta decay data", At. Data Nucl. Data Tables 61 (1995) 43

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The sampling of energies and angles of e⁻ or e⁺ is based on 3-d distributions $\rho_{12\theta}(t_1, t_2, \cos\theta)$, different for different modes and mechanisms of 2β decay.

Some formulas ($e_i = t_i + 1$, $p_i^2 = t_i(t_i + 2)$, $\beta_i = p_i/e_i$, $F(t_i, Z)$ – Fermi function):

0ν2β± decay with neutrino mass, 0⁺ - 0⁺ transition, 2n mechanism

$$\rho_{12\theta}(t_1, t_2, \cos\theta) = e_1 p_1 F(t_1, Z) e_2 p_2 F(t_2, Z) \delta(t_0 - t_1 - t_2)(1 - \beta_1 \beta_2 \cos\theta)$$

0ν2β± decay with right-handed currents (λ term), 0⁺ - 0⁺, 2n

$$\rho_{12\theta}(t_1, t_2, \cos\theta) = e_1 p_1 F(t_1, Z) e_2 p_2 F(t_2, Z)(t_1 - t_2)^2 \delta(t_0 - t_1 - t_2)(1 + \beta_1 \beta_2 \cos\theta)$$

2ν2β± decay, 0⁺ - 0⁺ transition, 2n mechanism

$$\rho_{12\theta}(t_1, t_2, \cos\theta) = e_1 p_1 F(t_1, Z) e_2 p_2 F(t_2, Z)(t_0 - t_1 - t_2)^5 (1 - \beta_1 \beta_2 \cos\theta)$$

0ν2β± decay with different Majorons (GR, double, bulk, vector, etc.), 0⁺ - 0⁺ transition, 2n mechanism (k=1,2,3,7)

$$\rho_{12\theta}(t_1, t_2, \cos\theta) = e_1 p_1 F(t_1, Z) e_2 p_2 F(t_2, Z)(t_0 - t_1 - t_2)^k (1 - \beta_1 \beta_2 \cos\theta)$$

and others

$$F(t, Z) = const \cdot p^{2s-2} exp(\pi\eta) \mid \Gamma(s + i\eta) \mid^2 \qquad s = \sqrt{1 - (\alpha Z)^2}, \; \eta = \alpha Z e/p, \; \alpha = 1/137.036$$

No Primakoff-Rosen approximation $F(t_i, Z) \sim e/p$

2β decay in DECAY0

- ◆ 47 isotopes – the most interesting from the whole list of 69
- ◆ $2\beta^-$, 2ε, $\varepsilon\beta^+$, $2\beta^+$ processes
- ◆ transitions to ground state and few excited 2^+ and 0^+ levels of daughter nucleus
- ◆ 20 modes of decay (2ν; 0ν with ν mass and r.-h. currents; different Majorons; 2n and N^* mechanisms)

2β decay: isotopes, 2β processes, levels of daughter nucleus

^{48}Ca $\to$ ^{48}Ti	$2\beta^-$	g.s.	2^+_1	2^+_2		
^{58}Ni $\to$ ^{58}Fe	2ε, $\varepsilon\beta^+$	g.s.	2^+_1	2^+_2		
^{64}Zn $\to$ ^{64}Ni	2ε, $\varepsilon\beta^+$	g.s.				
^{70}Zn $\to$ ^{70}Ge	$2\beta^-$	g.s.				
^{76}Ge $\to$ ^{76}Se	$2\beta^-$	g.s.	2^+_1	0^+_1	2^+_2	
^{74}Se $\to$ ^{74}Ge	2ε, $\varepsilon\beta^+$	g.s.	2^+_1	2^+_2		
^{82}Se $\to$ ^{82}Kr	$2\beta^-$	g.s.	2^+_1	2^+_2		
^{94}Zr $\to$ ^{94}Mo	$2\beta^-$	g.s.	2^+_1			
^{96}Zr $\to$ ^{96}Mo	$2\beta^-$	g.s.	2^+_1	0^+_1	2^+_2	2^+_3
^{92}Mo $\to$ ^{92}Zr	2ε, $\varepsilon\beta^+$	g.s.	2^+_1	0^+_1		
^{100}Mo $\to$ ^{100}Ru	$2\beta^-$	g.s.	2^+_1	0^+_1	2^+_2	0^+_2
^{106}Cd $\to$ ^{106}Pd	2ε, $\varepsilon\beta^+$, $2\beta^+$	g.s.	2^+_1	2^+_2	0^+_1	2^+_3	0^+_2
^{108}Cd $\to$ ^{108}Pd	2ε	g.s.				
^{114}Cd $\to$ ^{114}Sn	$2\beta^-$	g.s.				
^{116}Cd $\to$ ^{116}Sn	$2\beta^-$	g.s.	2^+_1	0^+_1	0^+_2	2^+_2	2^+_3
^{120}Te $\to$ ^{120}Sn	2ε, $\varepsilon\beta^+$	g.s.	2^+_1			
^{128}Te $\to$ ^{128}Xe	$2\beta^-$	g.s.	2^+_1			
^{130}Te $\to$ ^{130}Xe	$2\beta^-$	g.s.	2^+_1	2^+_2	0^+_1	
^{136}Xe $\to$ ^{136}Ba	$2\beta^-$	g.s.	2^+_1	2^+_2	0^+_1	
^{148}Nd $\to$ ^{148}Sm	$2\beta^-$	g.s.	2^+_1	2^+_2		
^{150}Nd $\to$ ^{150}Sm	$2\beta^-$	g.s.	2^+_1	0^+_1	2^+_2	2^+_3	0^+_2

Also: ^{40,46}Ca, ^{84}Sr, ^{96,104}Ru, ^{112,122,124}Sn, ^{136,138,142}Ce, ^{156,158}Dy, ^{180,186}W, ^{184,192,}Os, ^{190,198}Pt, ..11

For 2β decay to excited level – subsequent de-excitation process

2β decay: decay modes, transitions, mechanisms (2n and N^*)

|			
$0\nu2\beta(m_\nu)$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta(rhc-\lambda)$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta(rhc-\lambda)$	$0^+ \rightarrow 0^+, 2^+$	N*	
$2\nu2\beta$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta$M1	$0^+ \rightarrow 0^+$	2n	Majoron with SI=1 [a]
$0\nu2\beta$M2	$0^+ \rightarrow 0^+$	2n	Majoron with SI=2 [b]
$0\nu2\beta$M3	$0^+ \rightarrow 0^+$	2n	Majoron with SI=3 [c]
$0\nu2\beta$M7	$0^+ \rightarrow 0^+$	2n	Majoron with SI=7
$0\nu2\beta(rhc-\lambda)$	$0^+ \rightarrow 2^+$	2n	
$2\nu2\beta$	$0^+ \rightarrow 2^+$	2n, N^*	
$0\nu K\beta^+$	$0^+ \rightarrow 0^+, 2^+$		
$2\nu K\beta^+$	$0^+ \rightarrow 0^+, 2^+$		
$0\nu2K$	$0^+ \rightarrow 0^+, 2^+$		
$2\nu2K$	$0^+ \rightarrow 0^+, 2^+$		
$2\nu2\beta$	$0^+ \rightarrow 0^+$	with bosonic neutrinos	
$2\nu2\beta$	$0^+ \rightarrow 2^+$	with bosonic neutrinos	
$0\nu2\beta(rhc-\eta)$	$0^+ \rightarrow 0^+$	2n	

[a] old Majoron of Gelmini-Roncadelli
[b] bulk Majoron of Mohapatra
[c] double Majoron, vector Majoron, charged Majoron
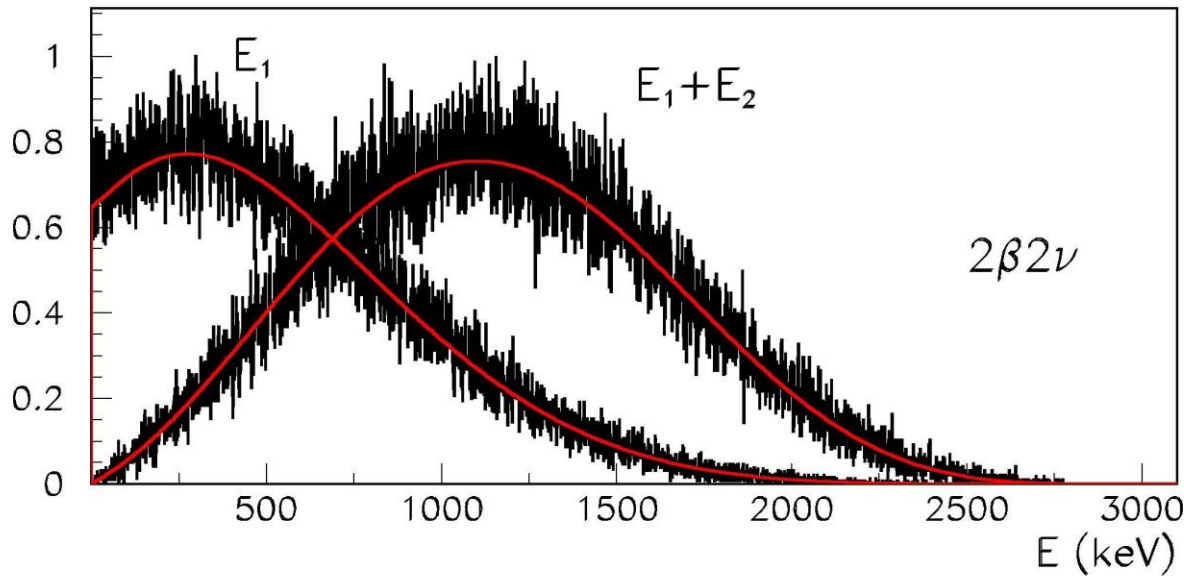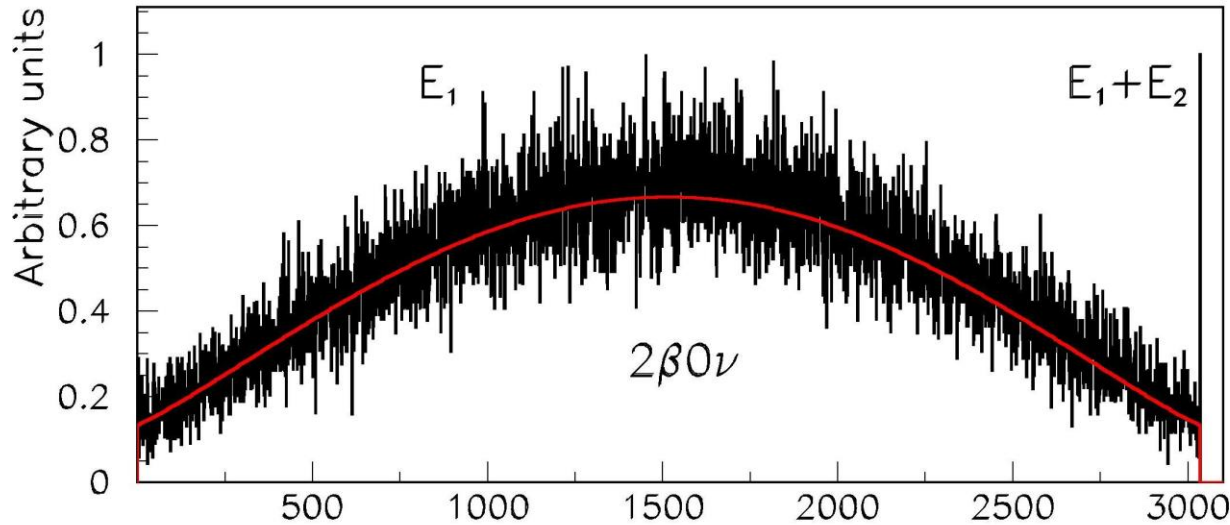
Generated by DECAY0 initial energy spectra of electrons emitted in 2β (two neutrino and neutrinoless) decays of ^{100}Mo ($Q_{2\beta}$=3034 keV): E_1 – single electron spectrum, E_1+E_2 – sum of the electrons energies. Generated distributions are shown together with theoretical curves.

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3. Single β and α decays
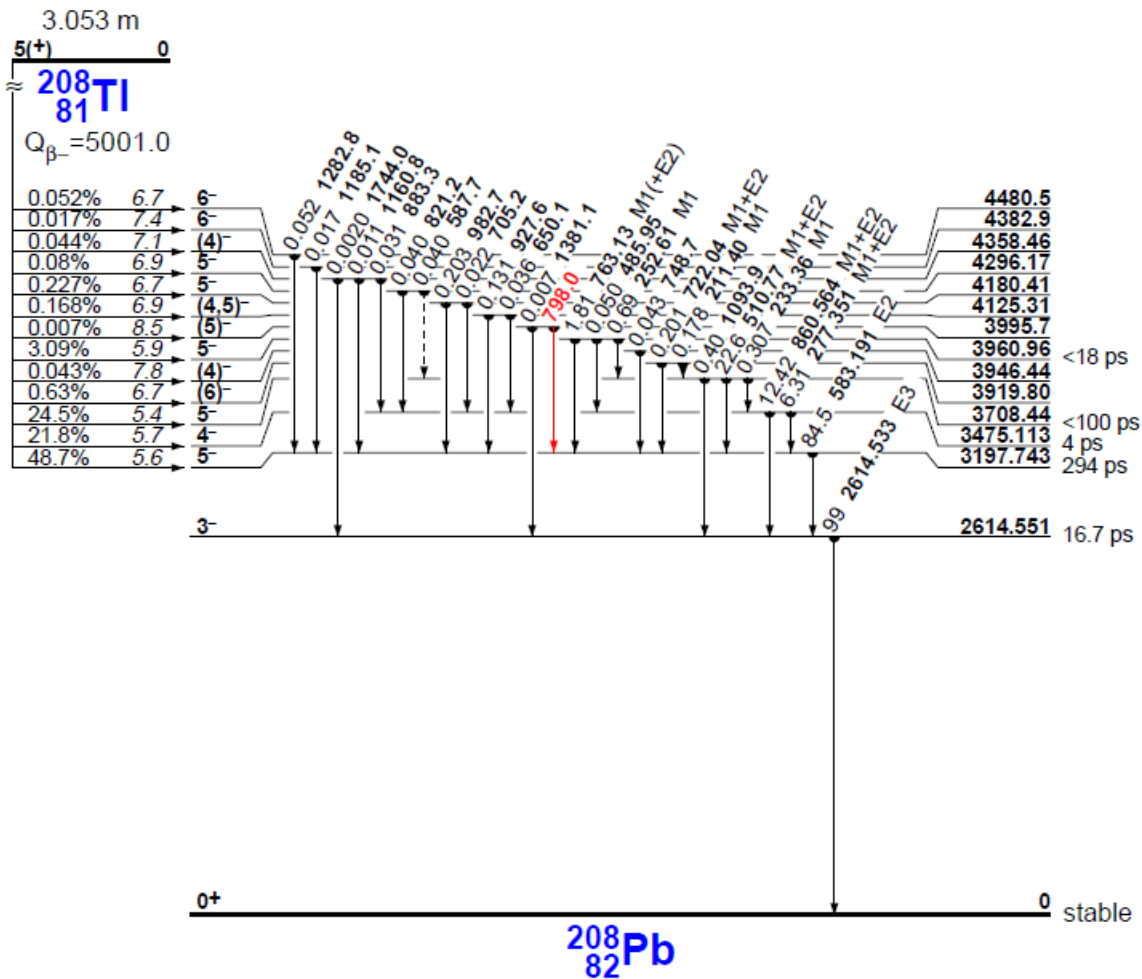
Example: scheme of ^{208}Tl decay

- emission of β particle: energy spectrum depends on change in spin and parity;
- 13 levels of ^{208}Pb are populated with different probabilities;
- populated level de-excites with emission of γ, conversion e^- or pair e^+e^-;
- lower levels are populated with different probabilities;
- process continues till the ground state will be reached

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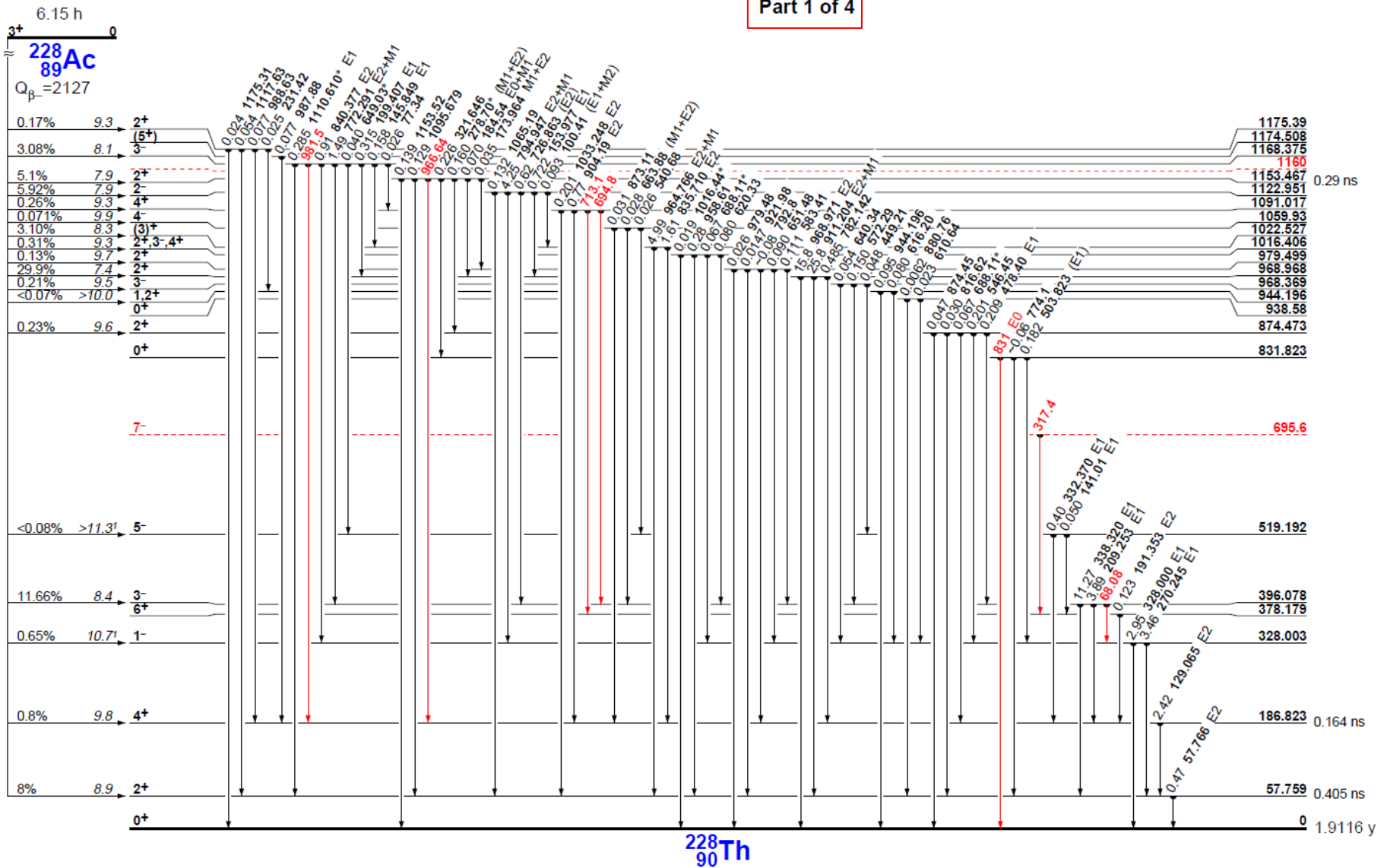
Sometimes schemes of decay are quite complex:
part 1 of 4 for ^{228}Ac $\rightarrow$ ^{228}Th β decay

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α and single β decays

♦ 63 isotopes:
  dangerous nuclides and calibration sources;
♦ careful description of decay schemes:
  up to 48 excited levels and up to 166 different transitions;
♦ for each transition, 3 concurrent processes are considered:
  emission of γ quantum, conversion electron or e^+e^- pair.

Nuclides from U/Th chains + Cosmogenic isotopes + Calibration sources:

Ac228	Co60	K40	Sr90	Zr96+Nb96
Ar39	Cs136	K42	Ta182	Recently added:
Ar42	Cs137+Ba137m	Mn54	Te133	Am241
As79+Se79m	Eu147	Na22	Te133m	Kr81
Bi207+Pb207m	Eu152	P32	Te134	Kr85
Bi208	Eu154	Pa234m	Tl207	Pb210
Bi210	Gd146	Pb211	Tl208	Ra228
Bi212+Po212	Hf182	Pb212	Xe133	Rb87
Bi214+Po214	I126	Pb214	Xe135	Sb125
C14	I133	Rh106	Y88	Th234
Ca48+Sc48	I134	Sb126	Y90	Xe129m
Cd113	I135	Sb133	Zn65	Xe131m …

Description of decays and de-excitation processes:
in accordance with Nuclear Data Sheets and Table of Isotopes, 1998;

For each transition, three concurrent processes are taken into account:
emission of γ quantum, conversion electron or e^+e^- pair;
coefficients of conversions – experimental values or theoretical from BrICC.

Allowed and forbidden β decays:

classified in dependence on change in spin and parity of mother and daughter nuclei

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

$0^+ \; 1^+$ — allowed

$0^- \; 1^- \; 2^+ \; 3^- \; 4^+ \; \dots \quad \Delta\pi = (-1)^{\Delta J}$ — forb. non-unique; forbidenness $= \Delta J$

$2^- \; 3^+ \; 4^- \; \dots \qquad \Delta\pi = (-1)^{\Delta J - 1}$ — forb. unique; forbidenness $= \Delta J - 1$

Energy spectrum of emitted β particles depends on $\Delta J^{\Delta\pi}$.

Shape of β spectrum in general is described as:

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

$\rho_{allowed}(E) = F(Z_d,E)WP(Q_\beta - E)^2$ — allowed spectrum

W (P) – total energy (momentum) of β particle

$F(Z_d,E)$ – Fermi function

C – (empirical) correction factor   W – in $m_e c^2$ units; P,Q – in $m_e c$ 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 $\dots \lambda_2, \lambda_4, \dots,$

where λ_i – Coulomb functions calculated in H. Behrens, J. Janecke, Numerical Tables for Beta-Decay and Electron Capture, 1969

Theoretical calculations of coefficients a_i, b_i, c_i:
mixture of products of phase space factors with different nuclear matrix elements (a lot of theoretical efforts, but very often without reliable results) .
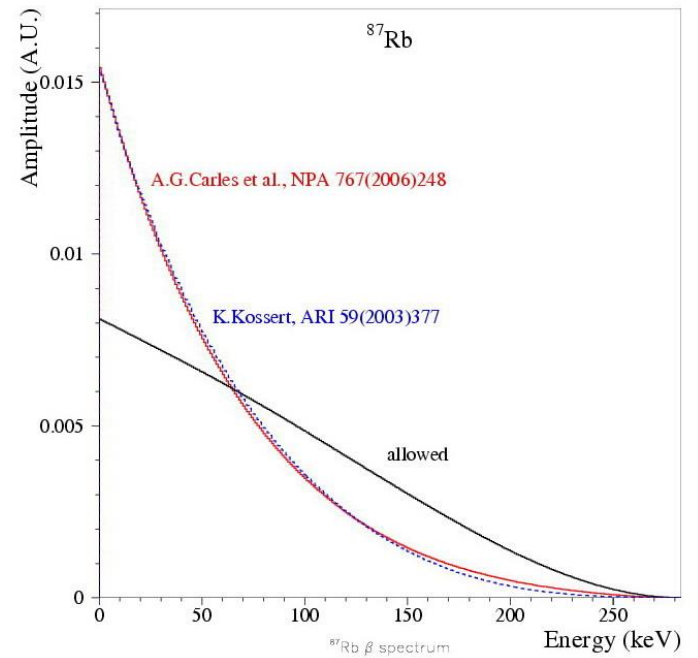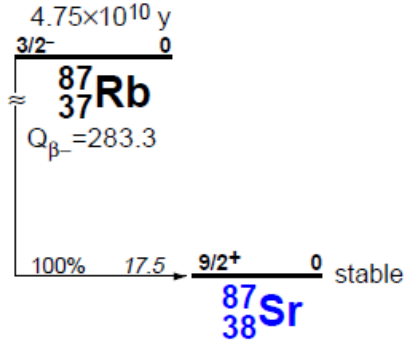
Best of all is to use shape measured experimentally (the problem is that results could be different in different experiments …).

Compilations of experimental 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;
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.
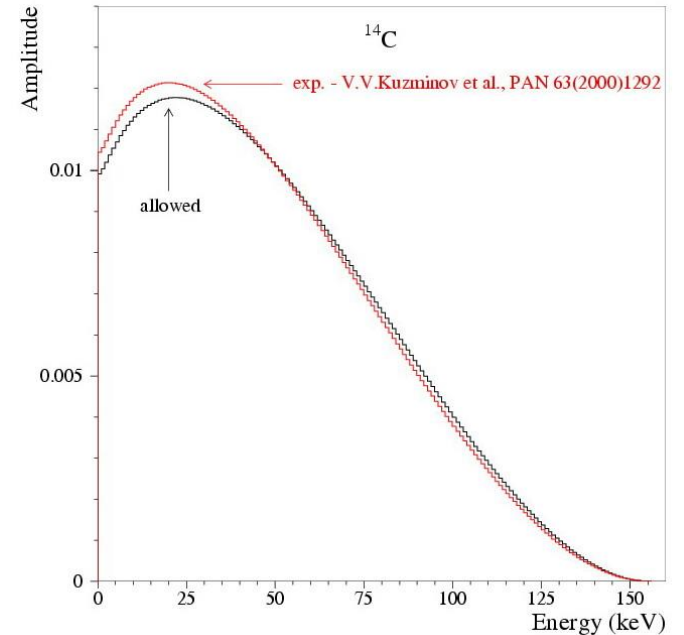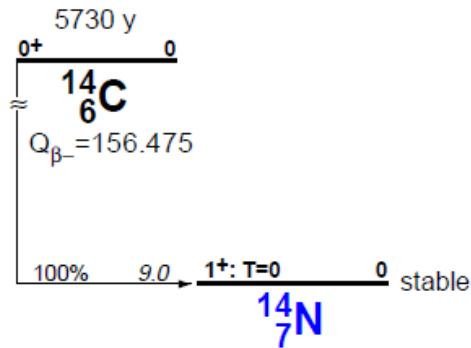
^{87}Rb

$3/2^- \rightarrow 9/2^+$ $\Delta J^{\Delta\pi} = 3^-$ (3 FNU)

4.75×10^{10} y

$3/2^-$ 0

$^{87}_{37}$Rb

$Q_{\beta^-} = 283.3$

100%   17.5 $9/2^+$ 0   stable

$^{87}_{38}$Sr

^{87}Rb

A.G.Carles et al., NPA 767(2006)248

K.Kossert, ARI 59(2003)377

allowed

^{87}Rb β spectrum

Energy (keV)

Amplitude (A.U.)

^{14}C

$0^+ \rightarrow 1^+$ $\Delta J^{\Delta\pi} = 1^+$ (allowed, but …)

5730 y

0^+ 0

$^{14}_{6}$C

$Q_{\beta^-} = 156.475$

100%   9.0 1^+: T=0   0   stable

$^{14}_{7}$N

^{14}C

exp. - V.V.Kuzminov et al., PAN 63(2000)1292

allowed

Amplitude

Energy (keV)

^{40}K

10.7% EC, 89.3% β decay
$$4^- \rightarrow 0^+ \quad \Delta J^{\Delta\pi} = 4^- \quad (3\ FU)$$
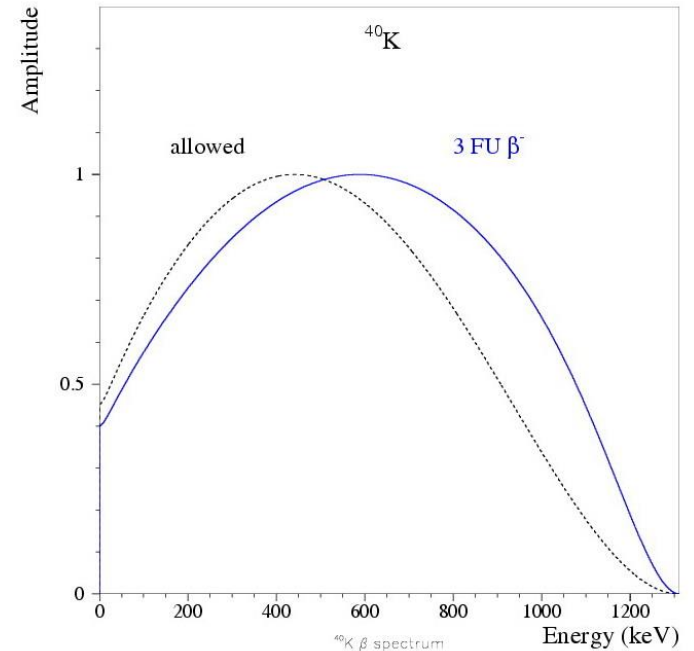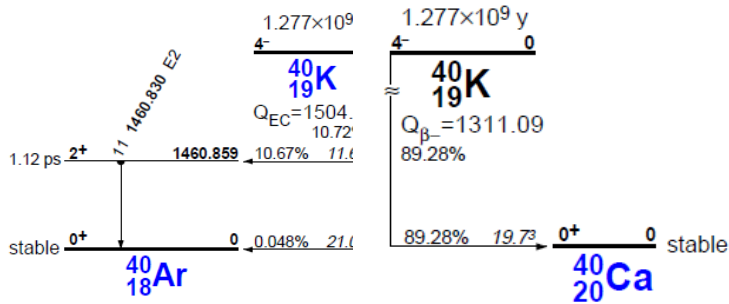
^{90}Sr and ^{90}Y

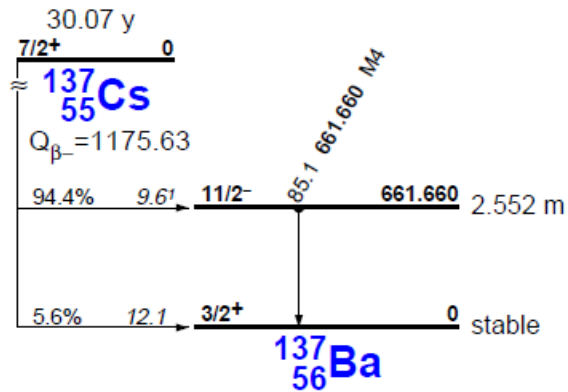## Both are (practically) pure β decayers
$$\Delta J^{\Delta\pi} = 2^- \quad (1\ FU)$$
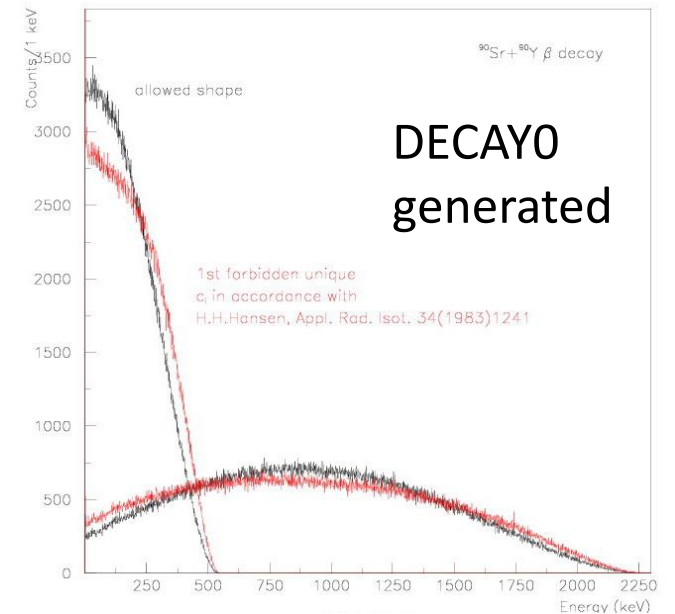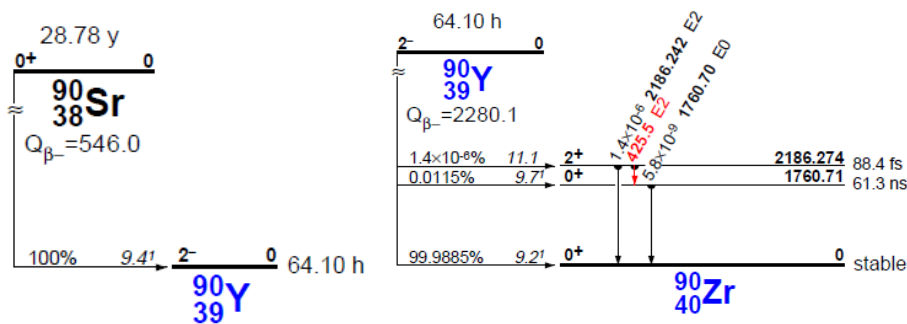
DECAY0 generated
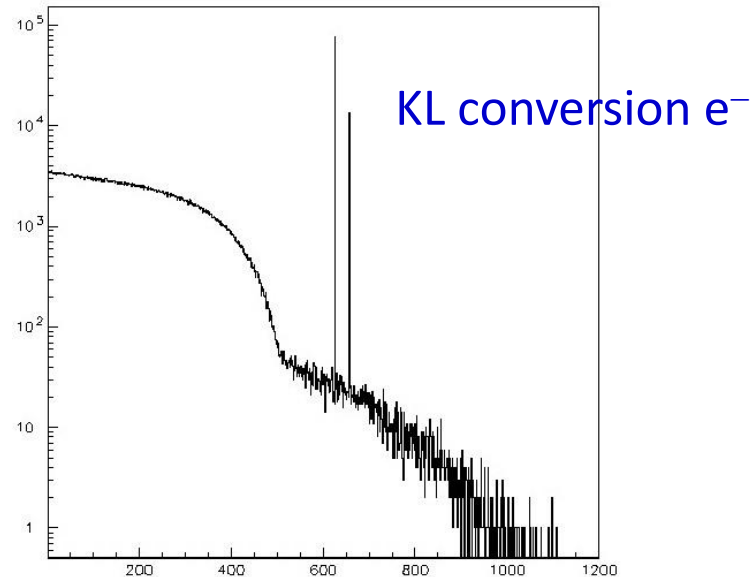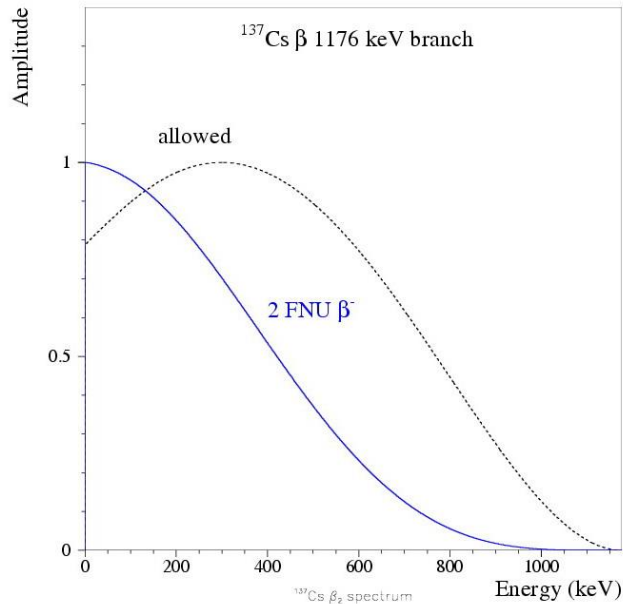
^{137}Cs

(1) 94.4% $7/2^+ \rightarrow 11/2^-$ $\Delta J^{\Delta\pi} = 2^-$ (1 FU)
(2) 5.6% $7/2^+ \rightarrow 3/2^+$ $\Delta J^{\Delta\pi} = 2^+$ (2 FNU)

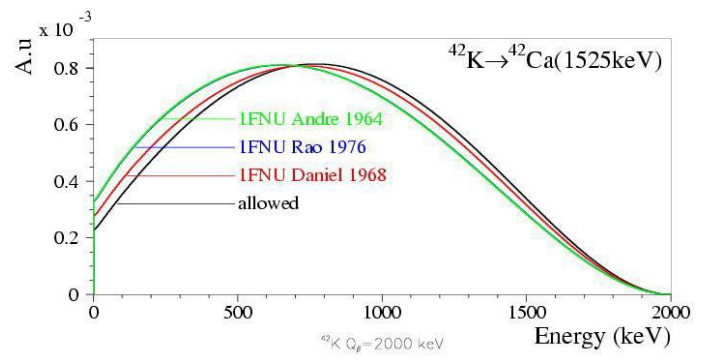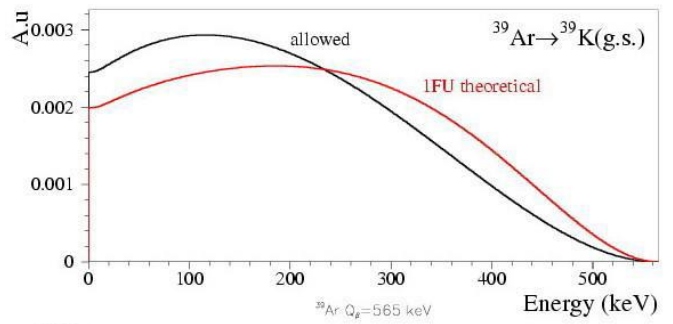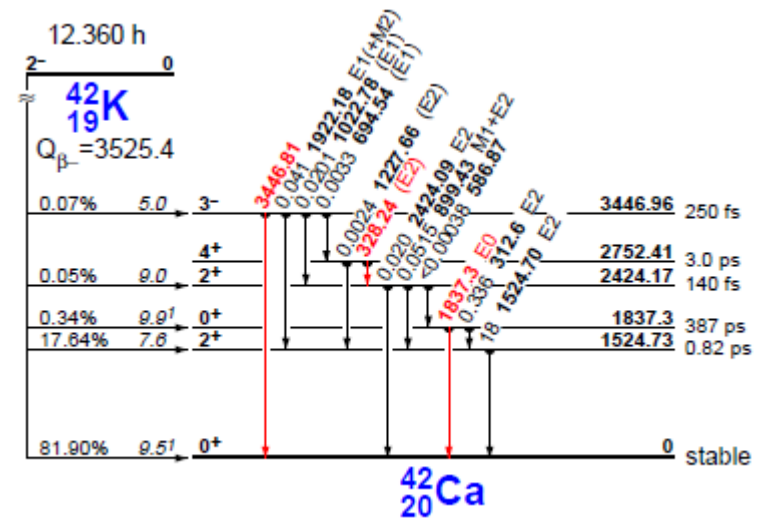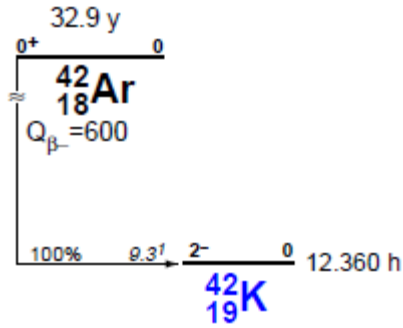"Real" spectrum of electrons emitted by ^{137}Cs (generated with DECAY0)
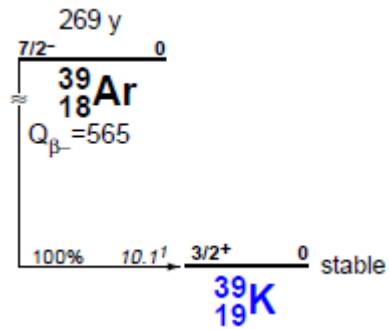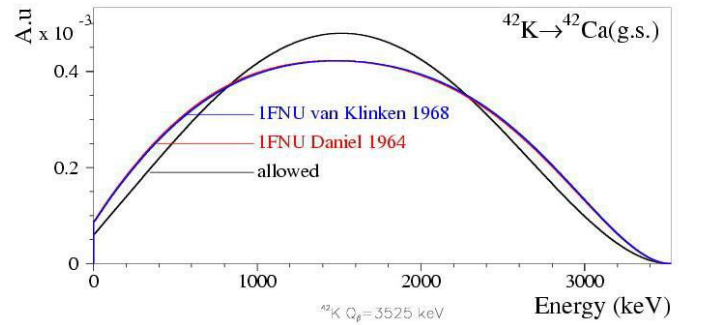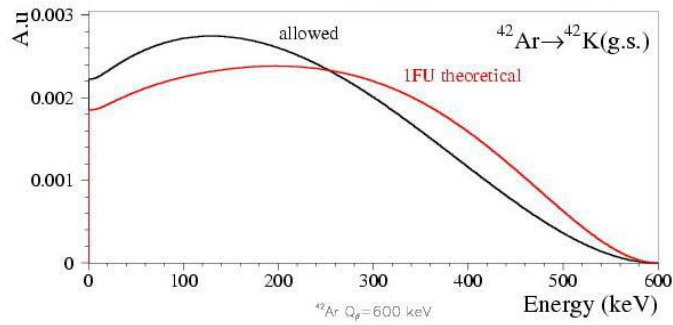

KL conversion e$^-$

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^{39}Ar, ^{42}Ar and ^{42}K

^{39}Ar, ^{42}Ar: $\Delta J^{\Delta\pi} = 2^-$ (1 FU)
^{42}K(81.90%): $\Delta J^{\Delta\pi} = 2^-$ (1 FU)
^{42}K(17.64%): $\Delta J^{\Delta\pi} = 0^-$ (1 FNU)

269 y
7/2⁻   0

$^{39}_{18}$Ar
Q_{β^-}=565

100%   10.1¹   3/2⁺   0   stable
$^{39}_{19}$K

32.9 y
0⁺   0

$^{42}_{18}$Ar
Q_{β^-}=600

100%   9.3¹   2⁻   0 12.360 h
$^{42}_{19}$K

12.360 h
2⁻   0

$^{42}_{19}$K
Q_{β^-}=3525.4

0.07%   5.0   3⁻   3446.96 250 fs
                4⁺   2752.41 3.0 ps
0.05%   9.0   2⁺   2424.17 140 fs
0.34%   9.9¹ 0⁺   1837.3   387 ps
17.64% 7.6   2⁺   1524.73 0.82 ps

81.90% 9.5¹ 0⁺   0 stable

$^{42}_{20}$Ca

Shapes in red
are used in the
DECAY0

allowed
1FU theoretical
^{39}Ar→^{39}K(g.s.)
Energy (keV)
^{39}Ar Q_β=565 keV

allowed
1FU theoretical
^{42}Ar→^{42}K(g.s.)
Energy (keV)
^{42}Ar Q_β=600 keV

^{42}K→^{42}Ca(1525keV)
1FNU Andre 1964
1FNU Rao 1976
1FNU Daniel 1968
allowed
Energy (keV)
^{42}K Q_β=2000 keV

^{42}K→^{42}Ca(g.s.)
1FNU van Klinken 1968
1FNU Daniel 1964
allowed
Energy (keV)
^{42}K Q_β=3525 keV

25
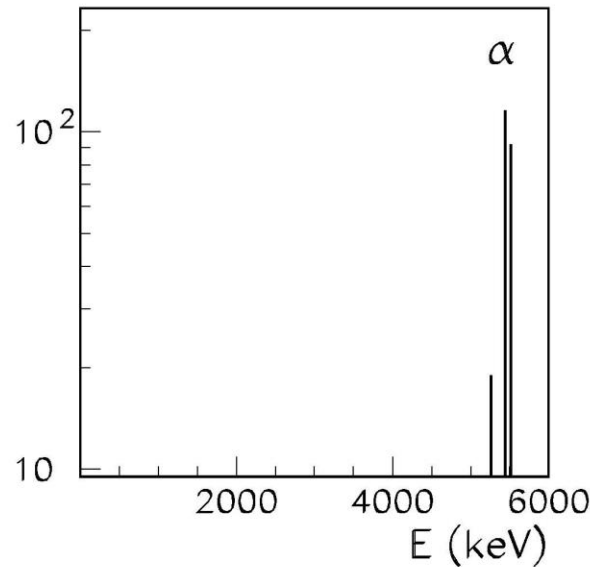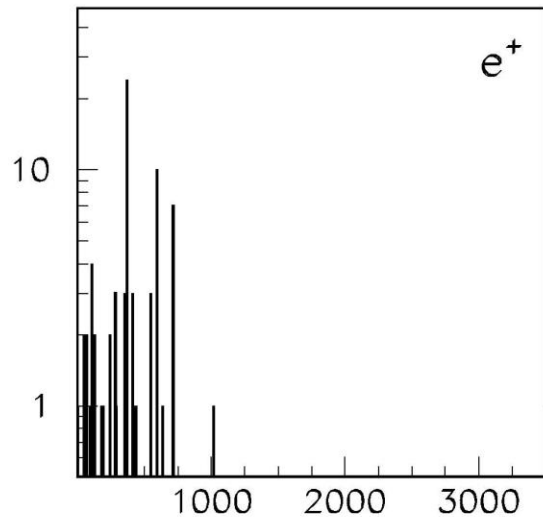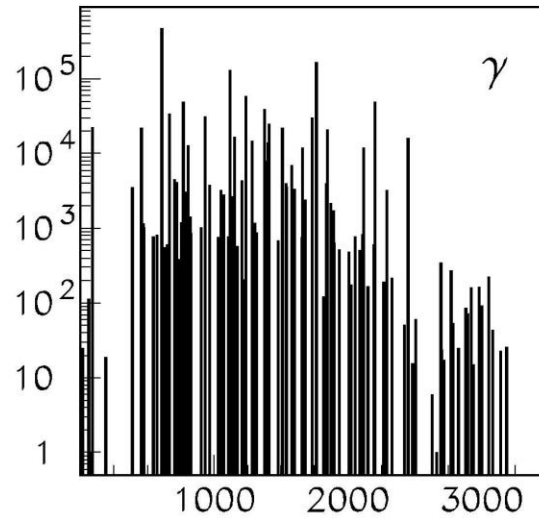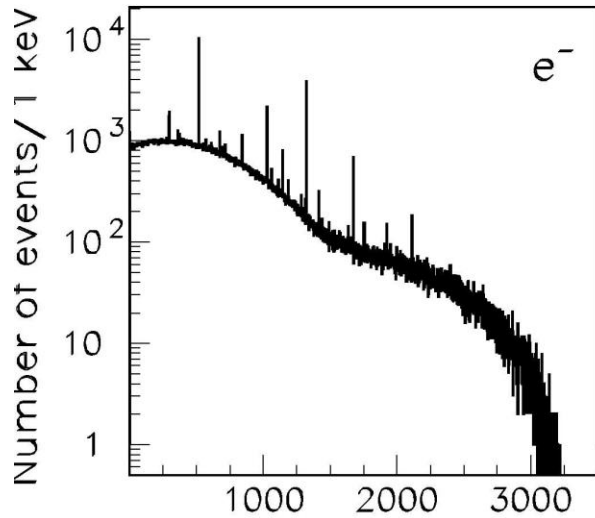
Generated by DECAY0 initial energy spectra of electrons, γ quanta, positrons and α particles in ^{214}Bi decay.

One can see discrete lines of conversion electrons on continuous spectrum of beta particles

4. Artificial events

♦ Emission of 38 particles from the GEANT3 list with needed direction and energies

Gamma	1	Kaon 0 short	16	Antiomega +	32
Positron	2	Eta	17	Deuteron	45
Electron	3	Lambda	18	Tritium	46
Neutrino	4	Sigma +	19	Alpha	47
Muon +	5	Sigma 0	20	Geantino	48
Muon -	6	Sigma -	21	He3	49
Pion 0	7	Xi 0	22	Cerenkov	50
Pion +	8	Xi -	23		
Pion -	9	Omega	24		
Kaon 0 long	10	Antineutron	25		
Kaon +	11	Antilambda	26		
Kaon -	12	Antisigma -	27		
Neutron	13	Antisigma 0	28		
Proton	14	Antisigma +	29		
Antiproton	15	Antixi 0	30		
		Antixi +	31		

♦ Artificial e^+e^- pairs, and α and β decays with needed Q and Z values

♦ Compton and Moller scattering

♦ Possibility to construct events consisted of few (up to 10) parts: e.g. α or β decay with emission of 1, 2, … γ's, etc.

5. DECAY0 output

User asks DECAY0 to generate 2β, or α or β, or artificial events, and how many, in dialog:

```
DECAY0: Generation of events of decay of natural radioactive
        isotopes and various modes of double beta decay

DECAY units: energy    - MeV
             momentum  - MeV/c
             time      - sec
             angle     - degree

Which type of events do you want to generate:
     1. double beta processes
     2. internal or external background or calibration sources
? 1

Double beta nuclides:
     Ca40     Ca46     Ca48
     Ni58
     Zn64     Zn70
     Ge76
     Se74     Se82
     Sr84
     Zr94     Zr96
     Mo92     Mo100
     Ru96     Ru104
     Cd106    Cd108    Cd114    Cd116
     Sn112    Sn122    Sn124
     Te120    Te128    Te130
     Xe136
     Ce136    Ce138    Ce142
     Nd148    Nd150
     Dy156    Dy158
     W180     W186
     Os184    Os192
     Pt190    Pt198
     Bi214+At214
     Pb214+Po214
     Po218+Rn218+Po214
     Rn222+Ra222+Rn218+Po214
? ge76

76-Se level:    0. 0+ (gs)    {0 MeV}
                1. 2+ (1)   {0.559 MeV}
                2. 0+ (1)   {1.122 MeV}
                3. 2+ (2)   {1.216 MeV}
? 0
```

```
mode of bb-decay:
     1. 0nubb(mn)          0+ -> 0+      {2n}
     2. 0nubb(rhc-lambda)  0+ -> 0+      {2n}
     3. 0nubb(rhc-lambda)  0+ -> 0+, 2+ {N*}
     4. 2nubb              0+ -> 0+      {2n}
     5. 0nubbM1            0+ -> 0+      {2n}
     6. 0nubbM2            0+ -> 0+      {2n}
     7. 0nubbM3            0+ -> 0+      {2n}
     8. 0nubbM7            0+ -> 0+      {2n}
     9. 0nubb(rhc-lambda)  0+ -> 2+      {2n}
    10. 2nubb              0+ -> 2+      {2n}, {N*}
    11. 0nuKb+                  0+ -> 0+, 2+
    12. 2nuKb+                  0+ -> 0+, 2+
    13. 0nu2K                   0+ -> 0+, 2+
    14. 2nu2K                   0+ -> 0+, 2+
    15. 2nubb                   0+ -> 0+ with bosonic neutrinos
    16. 2nubb                   0+ -> 2+ with bosonic neutrinos
    17. 0nubb(rhc-eta)     0+ -> 0+ simplified expression
    18. 0nubb(rhc-eta)     0+ -> 0+ with specific NMEs
        5-8: Majoron(s) with spectral index SI:
             SI=1 - old M of Gelmini-Roncadelli
             SI=2 - bulk M of Mohapatra
             SI=3 - double M, vector M, charged M
             SI=7
? 4
do you want to restrict energy range for generated particles?

number of events to generate     : 1000
number of first event [1]        :
to write generated events in file ? y
name of file                     : ge76.txt

wait, please: calculation of theoretical spectrum
starting the generation
RANLUX DEFAULT INITIALIZATION:   314159265
RANLUX DEFAULT LUXURY LEVEL =   3      p = 223
final random integer =      12345
toallevents=      1.000000
```

There is a possibility to use DECAY0 also as a subroutine in bigger program.

Result is written in text file (easy to read by any program: GEANT, EGS, MCNP, … or your own code). In beginning of file, explanation of data is given (units, 3 components of momentum, times, etc.).

Example of file generated by the DECAY0 (2β0ν decay of ^{76}Ge):

```
DECAY0 generated file: ge76.txt
 date and hour       :    13.10.2004    13:49:54
 initial random number :         0

 event type: Ge76
            0nubb(mn) 0+ -> 0+      {2n}
            level, Elevel (MeV) =  0+        .00000      MeV

Format of data:
 for each event     - event's number,
                      time of event's start,
                      number of emitted particles;
 for each particle - GEANT number of particle,
                      x,y,z components of momentum,
                      time shift from previous time


Time - in sec, momentum - in MeV/c

First event and full number of events:
           1            5


     1  .000000         2
 3  -.158519      -1.21733       .495074       .000000
 3   .435222       .577828      -1.38279       .000000
     2  .000000         2
 3  -.276698      -.817737      1.30184        .000000
 3   1.14743       .493095      -.434010       .000000
     3  .000000         2
 3   1.23563      -.871679       .467743       .000000
 3  -.536833E-01   1.26254       .309205       .000000
     4  .000000         2
 3   .343333      -1.19969      -.921614       .000000
 3  -.212937       .659766      1.13869        .000000
     5  .000000         2
 3   1.00859       .103761E-02   .409639       .000000
 3  -.182828      1.14362       -1.36064       .000000
```

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Example of file generated by the DECAY0 (decay of ^{208}Tl):

```
DECAY0 generated file: tl208.txt
 date and hour          :     13.10.2004     13:50:30
 initial random number :              0

 event type: Tl208

Format of data:
 for each event     - event's number,
                       time of event's start,
                       number of emitted particles;
 for each particle - GEANT number of particle,
                       x,y,z components of momentum,
                       time shift from previous time

Time - in sec, momentum - in MeV/c

First event and full number of events:
            1              3


      1   427.288         3
 3   .691615E-01   .220986        .482348       .000000
 1    .270020      -.331719       .396157       .102899E-09
 1   -1.65769       .593713       -1.93334      .773901E-11
      2   306.972         4
 3   .778422       .793706        .163059E-01   .000000
 1   -.955445E-01  -.277438       -.418355      .000000
 1   .811938E-01   -.494772       -.297485      .496265E-09
 1    1.72770       1.32310        1.45007       .189274E-10
      3   92.4015         5
 3   .380951       .124934        -.753557E-01  .000000
 3   -.361833      -.259030        .175668       .129095E-11
 1   .320849E-01   .585443E-01    .573334E-01   .000000
 1   -.234804       .477869       -.237481      .352442E-10
 1   -.686406      -.790540E-01   -2.52207       .868726E-11
```

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6. Examples of application

DECAY0 code was written more than 30 years ago (start in 1985) – in times, when GEANT4 and its internal event generator for α and β decays did not exist. But it still is used – with updates – by number of groups, which work mainly in field of searches for rare decays.

DECAY0 is written in FORTRAN and currently consists of ~18,900 lines.

DECAY0 is used:
LPD KINR (many years)
NEMO-2,3 (since ~1992) + SuperNEMO (with historical name GENBB)
GERDA/Majorana (for 2β decay)

SNO+	AMoRE	NEXT
LUMINEU	CUPID-Mo	
DAMA exp.	COBRA	TGV
DEAP	LUX-ZEPLIN	PandaX (II, III, 4T)
THEIA	TREX-DM	XENON

Example 1: DAMA + KINR (first observation of α decay of ^{151}Eu)

CaF_2 scintillator 370 g, 7426 h of measurements in the DAMA low-background R&D set-up at LNGS [P. Belli et al., NPA 789 (2007) 15].

Experimental data are fitted by simulated the most important components of γ/β spectrum (^{152}Eu, ^{90}Sr-^{90}Y, ^{232}Th, ^{238}U + external gammas from PMT.
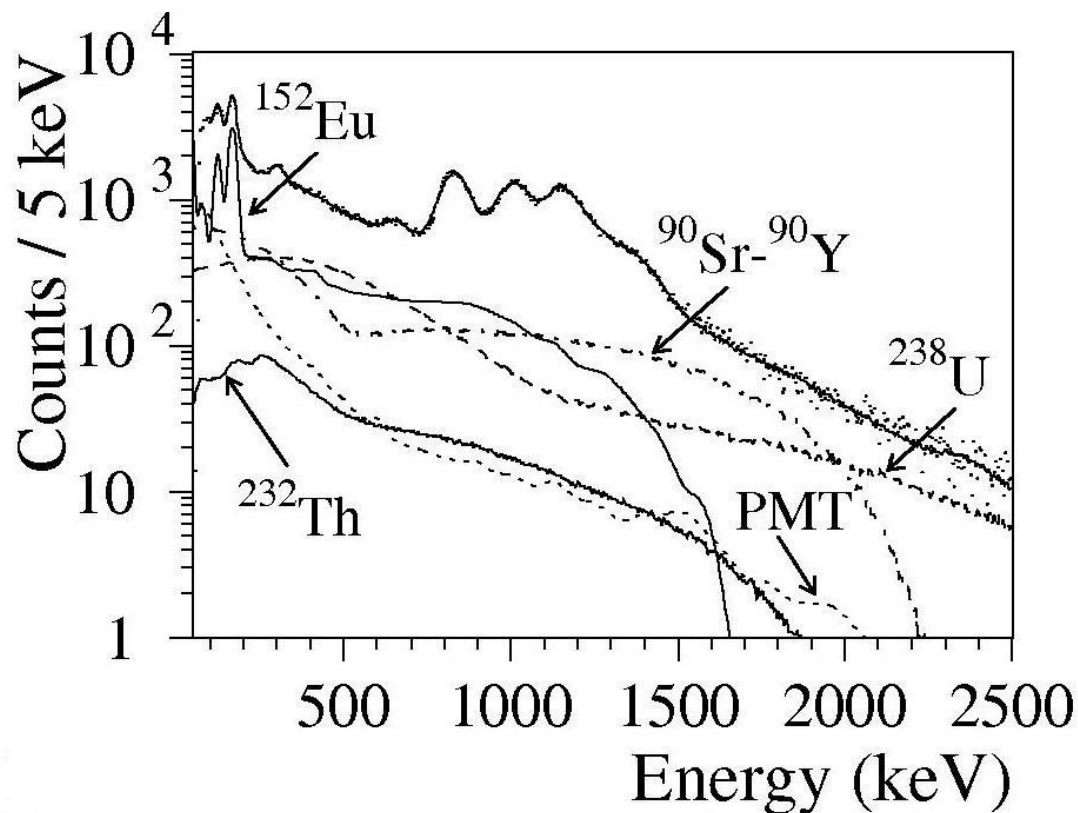
Example 2: NEMO-3 (investigation of 2β decay of ^{100}Mo)

~7 kg of ^{100}Mo, 389 d of data taking in the Modane Underground Laboratory [R. Arnold et al., PRL 95 (2005) 182302]

2β2ν decay of ^{100}Mo – experimental data (219,000 events, S/B=40) are compared with simulated distributions for:
(a) sum of electron energies;
(b) angular distribution between electrons:
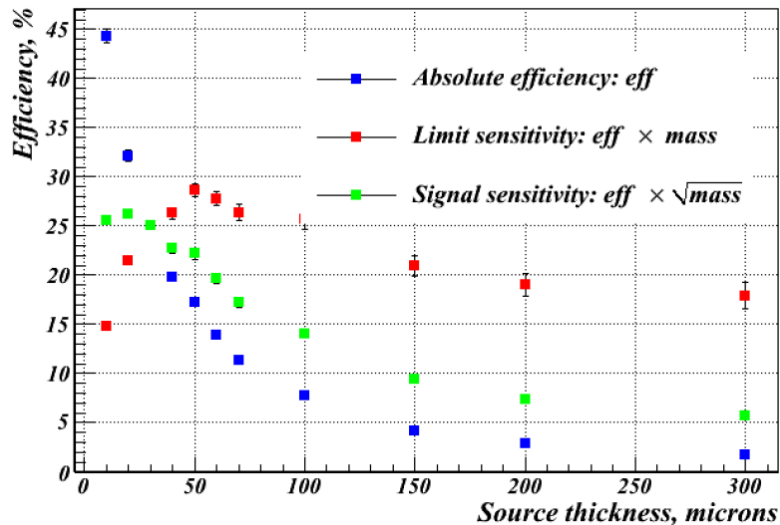(c) energy spectrum of single electrons
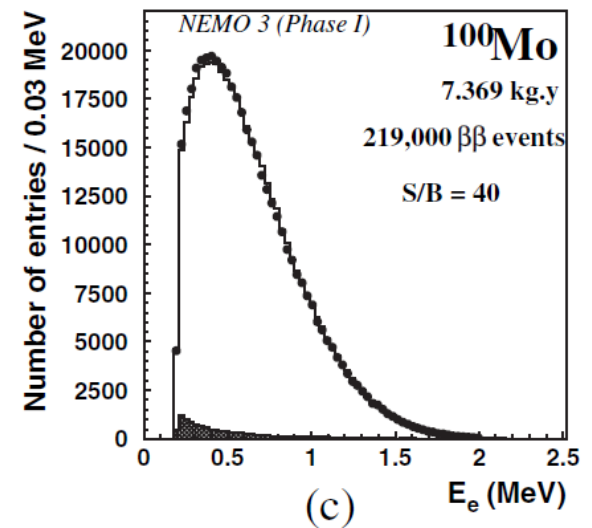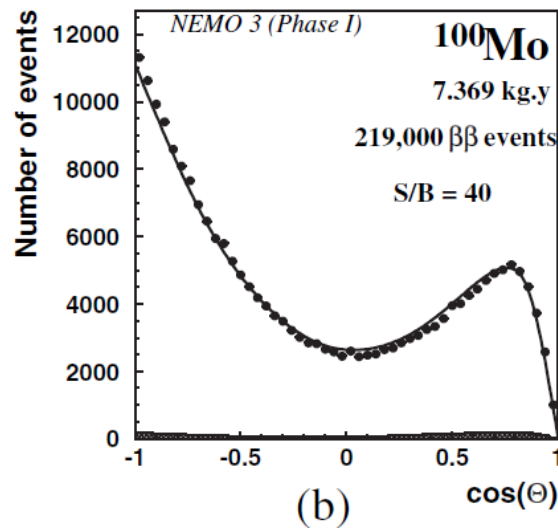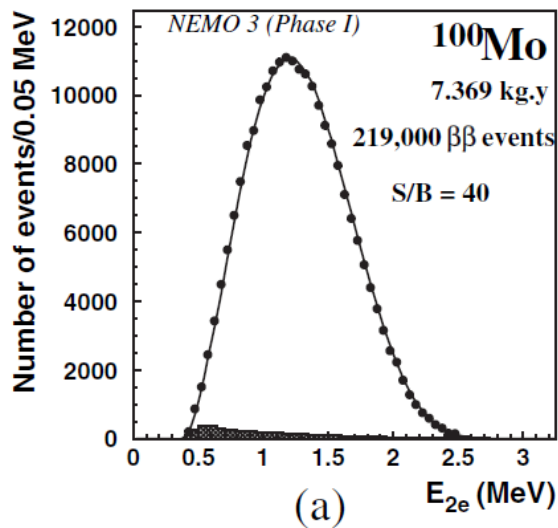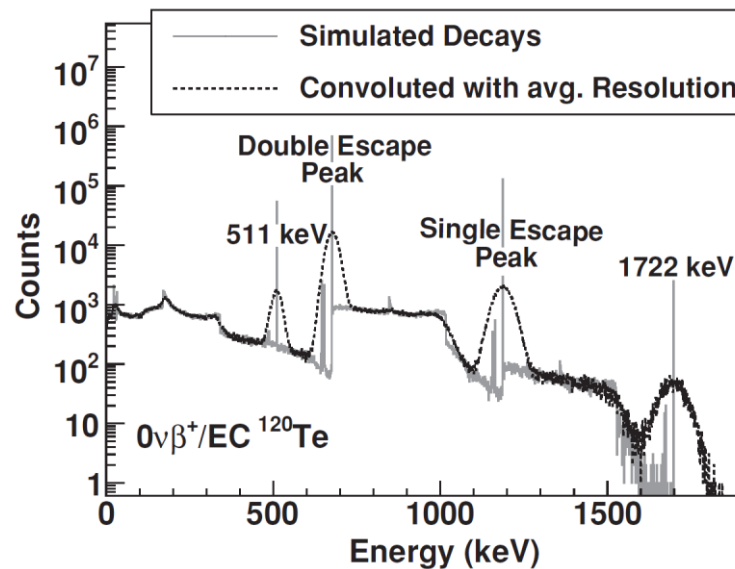
Example 3: GERDA (investigation of 2β decay of ^{76}Ge)

Phase I, 6 HPGe enriched
in ^{76}Ge to 86%, 14.63 kg,
126 d of data taking in the
Laboratori Nazionali del Gran Sasso
[M. Agostini et al., JPG 40
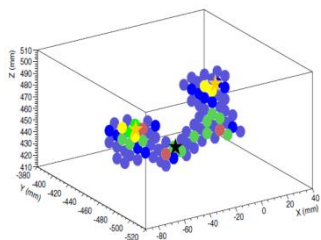(2013) 035110]
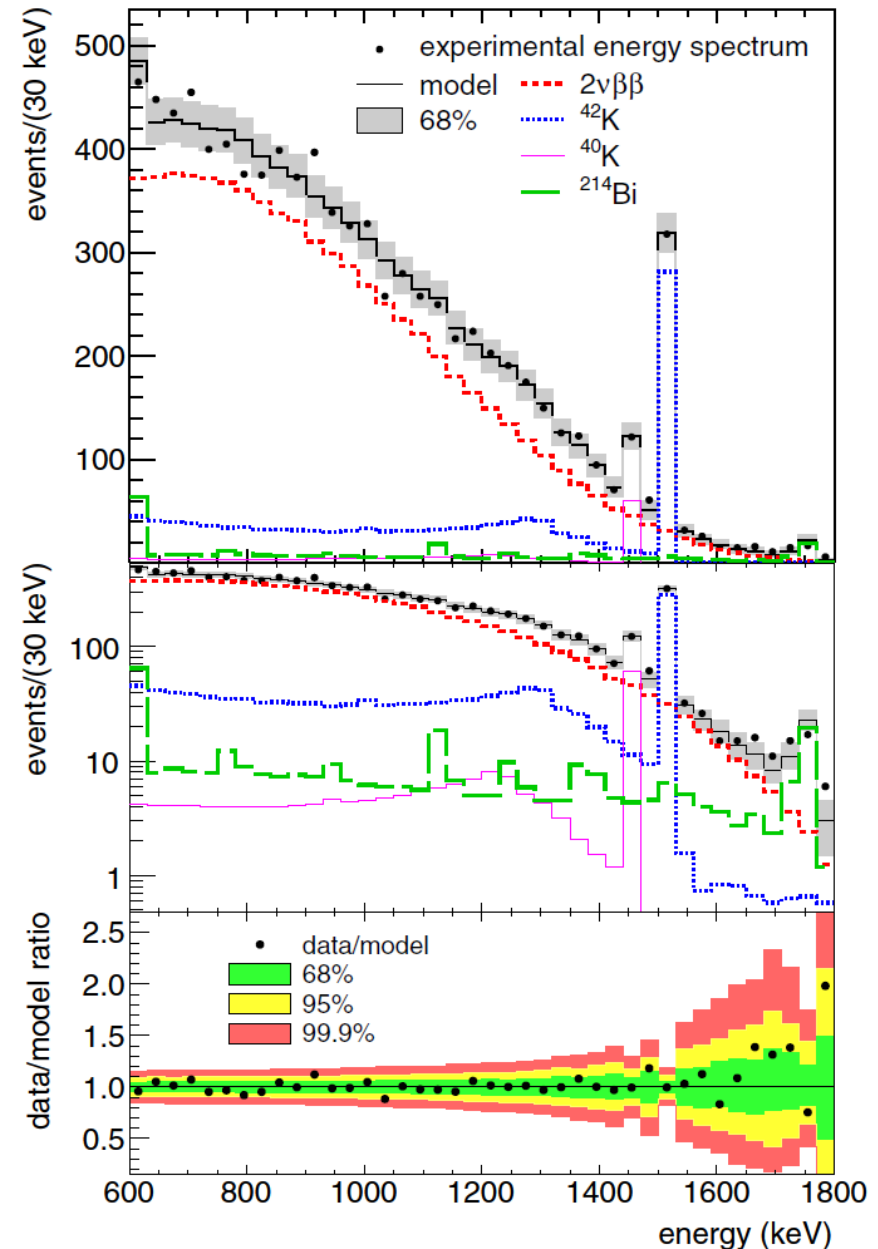
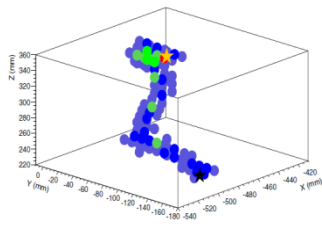# Examples of simulations with DECAY0 but without direct comparison with experimental data:
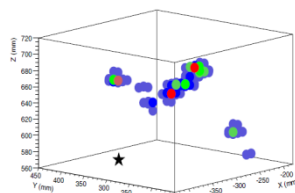

TGV – JINST 06 (2011) C01057

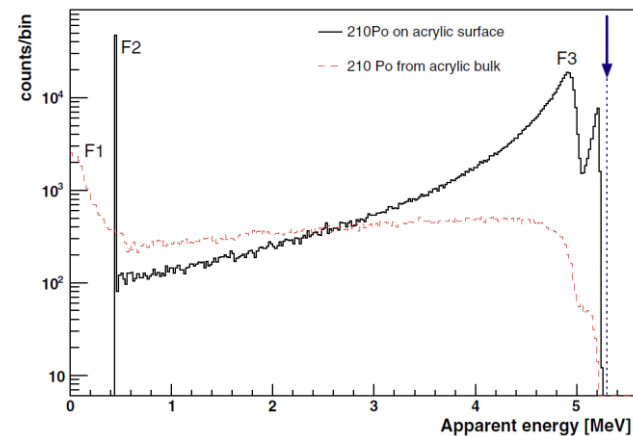COBRA – PRC 80 (2009) 025502

^{136}Xe 2β0ν ^{214}Bi ^{208}Tl

NEXT – JPG 40 (2013) 125203

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7. Conclusions

Written more than 30 years ago, DECAY0 is to-date the most developed event generator for simulation of different 2β decay processes (47 2β nuclides, 20 2β modes, decays to g.s. and excited levels).

Generation of single β and α decays of atomic nuclei also is possible for 63 nuclides dangerous for imitating 2β decay or calibration sources (however, now it is possible also in GEANT4 with its own internal event generator).

The code consists currently of ~18,900 FORTRAN lines and is available for other groups, in case of their interest.

DECAY0 was and still is used in several big experiments devoted to searches for rare nuclear α, β and 2β decays (KINR, NEMO, DAMA, COBRA, AMoRE, CUPID-Mo, NEXT, GERDA/Majorana, SNO+ and others).

Thank you for attention!