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

Vladimir Tretyak

Institute for Nuclear Research, Kyiv, Ukraine

Laboratori Nazionali del Gran Sasso, Italy, 17 March 2015

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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.);

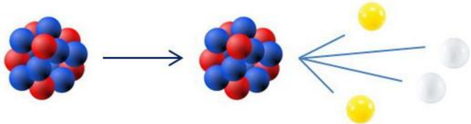
Which particles are emitted by sources of radiation: how many particles and of which type, their energies, directions and times of emission.

Aim of the DECAY0 event generator is to generate – by Monte Carlo method – initial kinematics of particles emitted in:

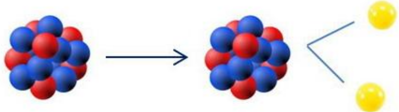
1) 2β decays of atomic nuclei ($2\beta^-$, $2\beta^+$, $\varepsilon\beta^+$, 2ε)
2) α, β decays of nuclides dangerous to imitate 2β processes
3) α, β decays of nuclides in calibration sources

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 $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$

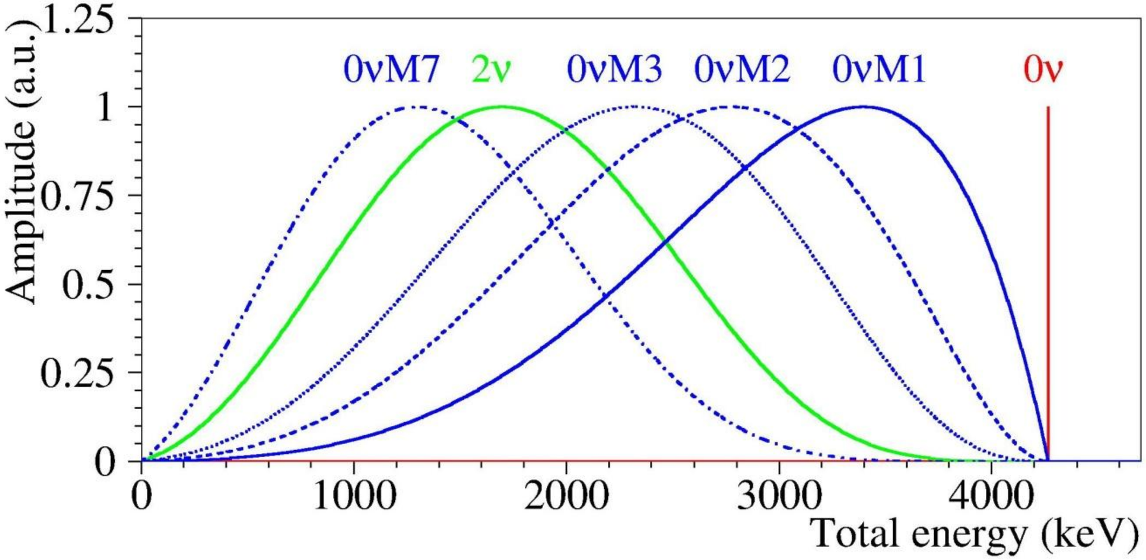


$2\beta2\nu$ - fully allowed in SM (however, very rare, $T_{1/2} \cong 10^{18} - 10^{24}$ y for already observed decays)

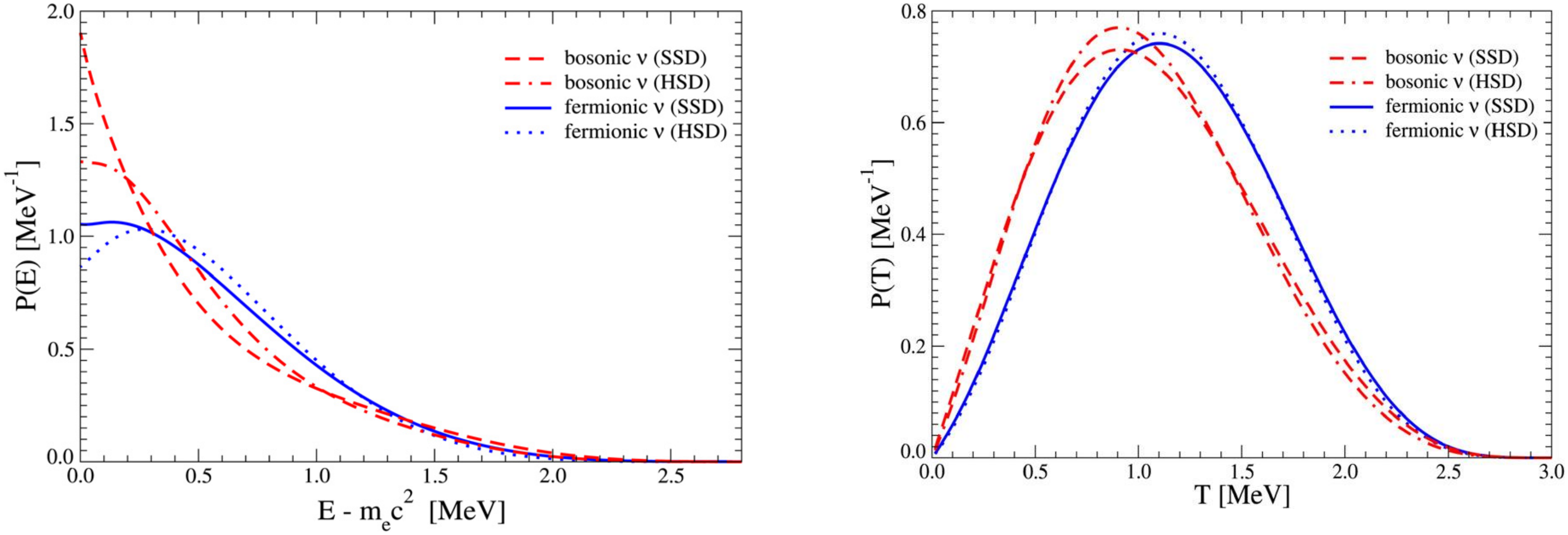
$2\beta0\nu$ - forbidden in SM (because of $\Delta L=2$, not observed yet (but HVKK claim for ^{76}Ge), $T_{1/2} > 10^{23} - 10^{25}$ y for the best experiments; predicted by many theories)

Also: $2\beta^{+}$ decay (emission of positrons instead of electrons),
$\varepsilon\beta^{+}$ (electron capture + emission of β^{+}), 2ε process,
$2\beta0\nu M$ (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



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]

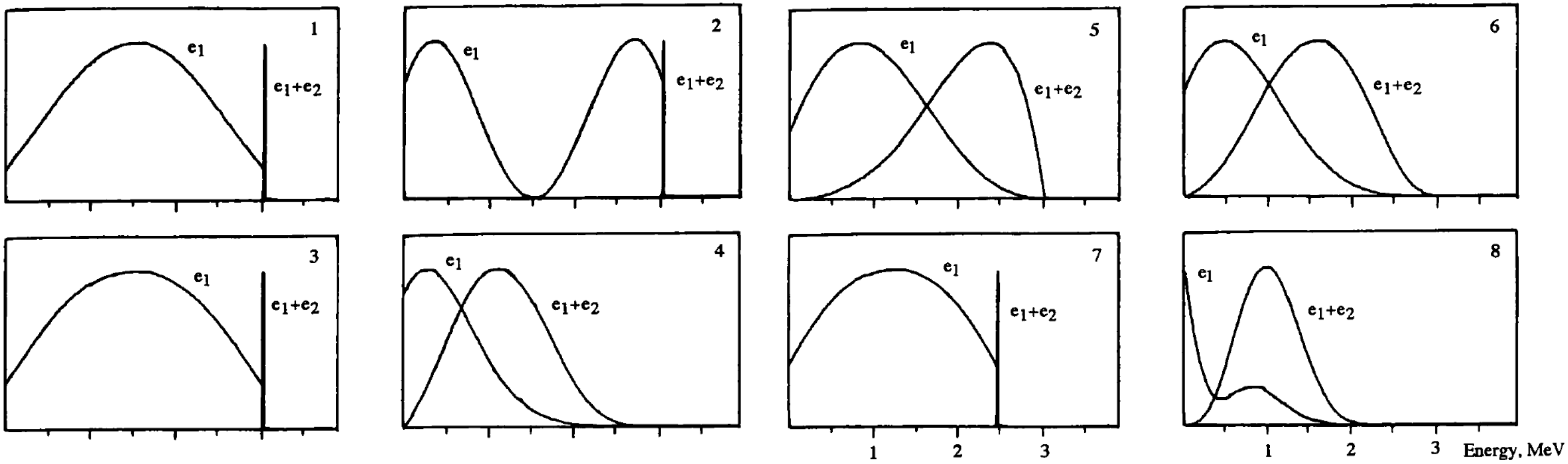


Figure 4. Theoretical distributions for the energy of a single electron (e_1) and for the sum of electron energies ($e_1 + e_2$) for ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $E(2^+)$ = 540 keV) for different modes and mechanisms of 2β decay: (1) $0\nu2\beta$ decay with neutrino mass, 0^+–0^+ transition, $2n$ 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

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):

$0\nu2\beta^\pm$ decay with neutrino mass, 0^+ - 0^+ transition, 2n mechanism

$$\rho_{12\theta}(t_1,t_2,cos\theta) = e_1p_1F(t_1,Z)e_2p_2F(t_2,Z)\delta(t_0-t_1-t_2)(1-\beta_1\beta_2cos\theta)$$

$0\nu2\beta^\pm$ decay with right-handed currents (λ term), 0^+ - 0^+, 2n

$$\rho_{12\theta}(t_1,t_2,cos\theta) = e_1p_1F(t_1,Z)e_2p_2F(t_2,Z)(t_1-t_2)^2\delta(t_0-t_1-t_2)(1+\beta_1\beta_2cos\theta)$$

$2\nu2\beta^\pm$ decay, 0^+ - 0^+ transition, 2n mechanism

$$\rho_{12\theta}(t_1,t_2,cos\theta) = e_1p_1F(t_1,Z)e_2p_2F(t_2,Z)(t_0-t_1-t_2)^5(1-\beta_1\beta_2cos\theta)$$

$0\nu2\beta^\pm$ decay with different Majorons (GR, double, bulk, vector, etc.), 0^+ - 0^+ transition, 2n mechanism (k=1,2,3,7)

$$\rho_{12\theta}(t_1,t_2,cos\theta) = e_1p_1F(t_1,Z)e_2p_2F(t_2,Z)(t_0-t_1-t_2)^k(1-\beta_1\beta_2cos\theta)$$

and others

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

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

2β decay in DECAY0

- 40 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
- 17 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

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

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

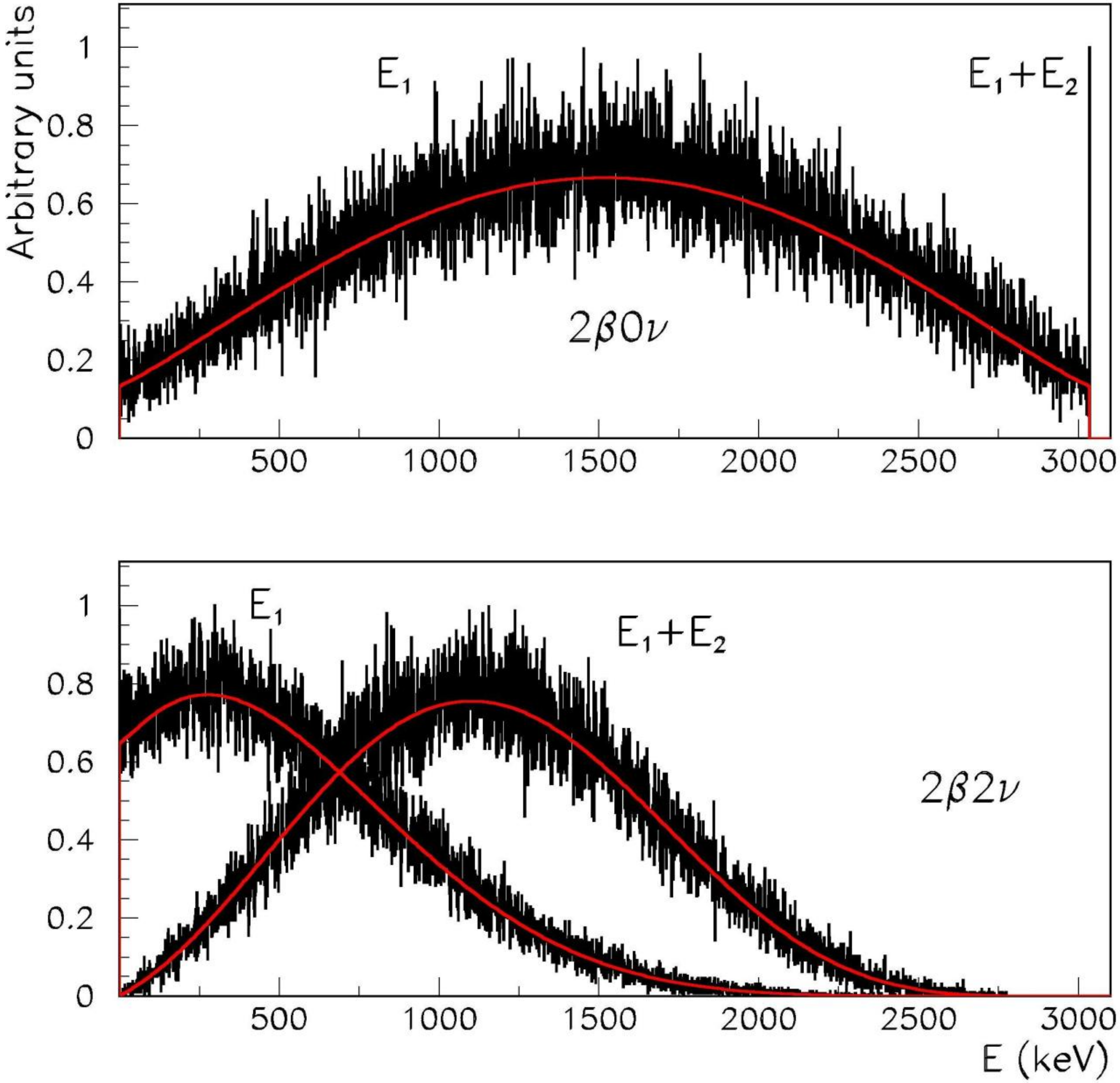
2β decay: decay modes, transitions, mechanisms (2n and N^*)

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

[a] old Majoron of Gelmini-Roncadelli

[b] bulk Majoron of Mohapatra

[c] double Majoron, vector Majoron, charged Majoron



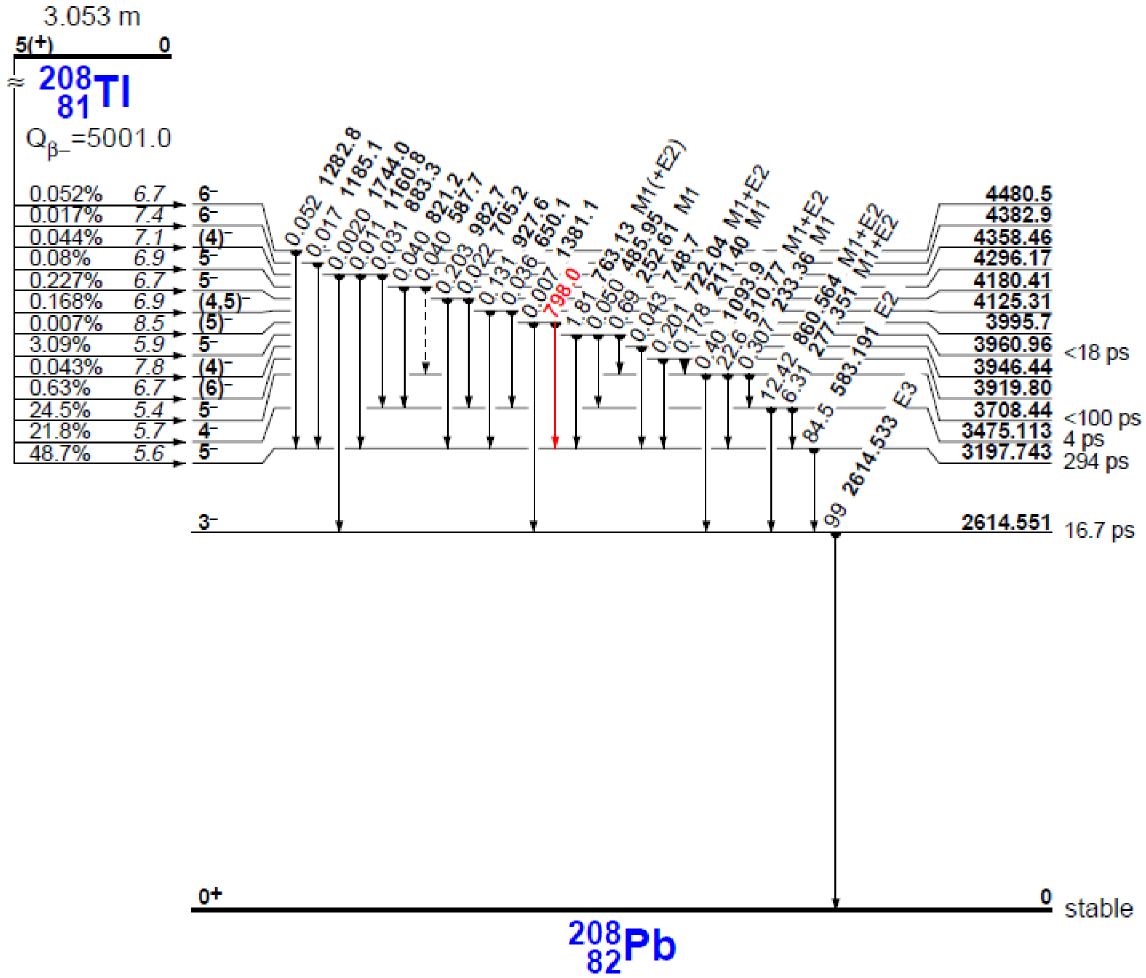
Generated by DECAY0 initial energy spectra of electrons emitted in 2β (two neutrino and neutrinoless) decays of ^{100}Mo ($Q_{2\beta}$=3034 keV):

E_1 – single electron spectrum,

E_1+E_2 – sum of the electrons energies.

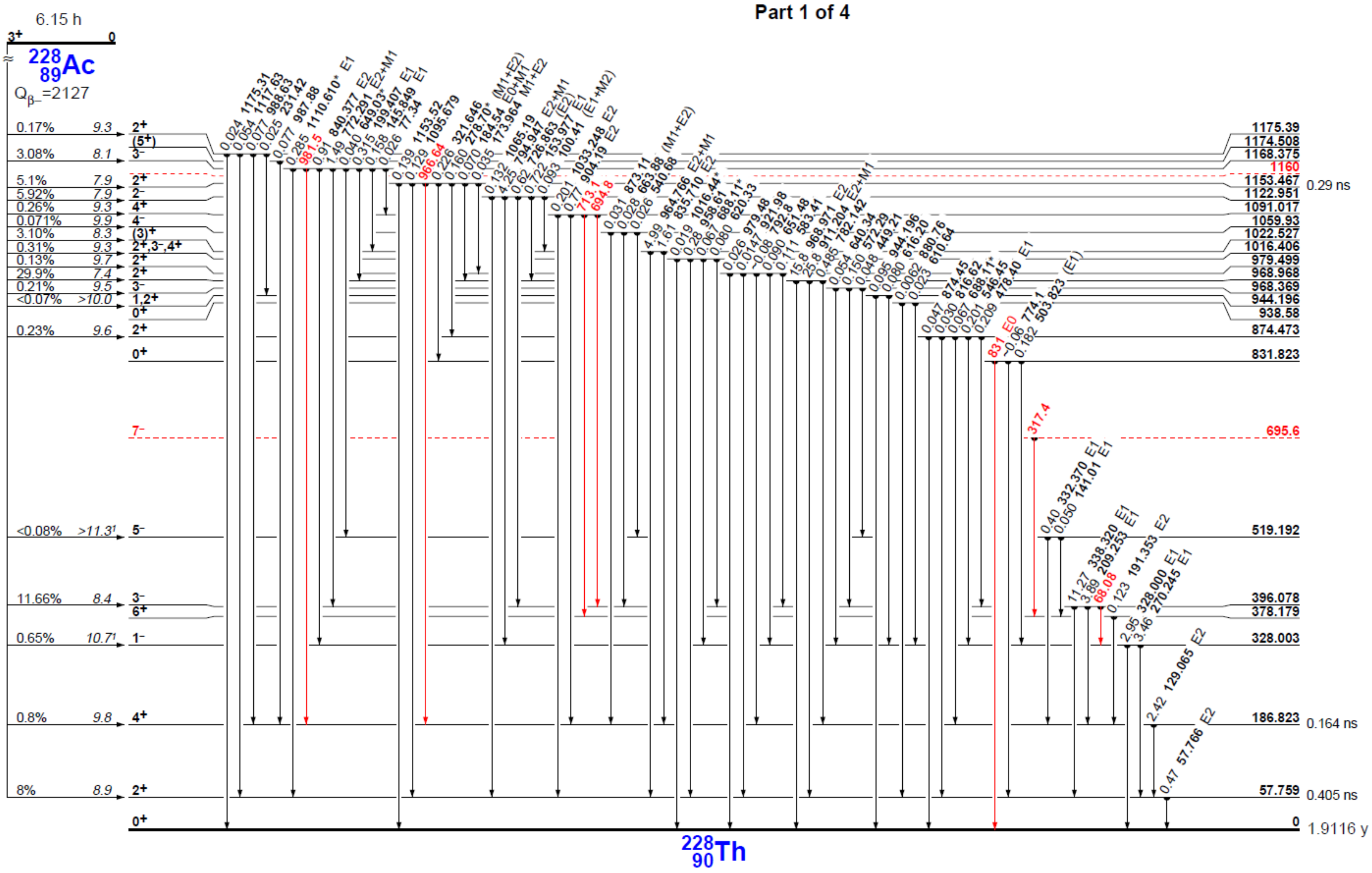
Generated distributions are shown together with theoretical curves.

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



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

α and single β decays

- 59 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
Ar39
Ar42
As79+Se79m
Bi207+Pb207m
Bi208
Bi210
Bi212+Po212
Bi214+Po214
C14
Ca48+Sc48
Cd113

Co60
Cs136
Cs137+Ba137m
Eu147
Eu152
Eu154
Gd146
Hf182
I126
I133
I134
I135

K40
K42
Mn54
Na22
P32
Pa234m
Pb211
Pb212
Pb214
Rh106
Sb126
Sb133

Sr90
Ta182
Te133
Te133m
Te134
Tl207
Tl208
Xe133
Xe135
Y88
Y90
Zn65

Zr96+Nb96

Recently added:

Am241
Kr81
Kr85
Pb210
Ra228
Rb87
Sb125
Th234
Xe129m
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^+ … $\Delta\pi = (-1)^{\Delta J}$ – forb. non-unique; forbidenness = ΔJ

2^- 3^+ 4^- … $\Delta\pi = (-1)^{\Delta J-1}$ – 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:

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

$\rho_{\mathrm{allowed}}(E) = F(Z_d,E)WP(Q_\beta - E)^2$ – 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 … $\lambda_2, \lambda_4, \ldots$,

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) .

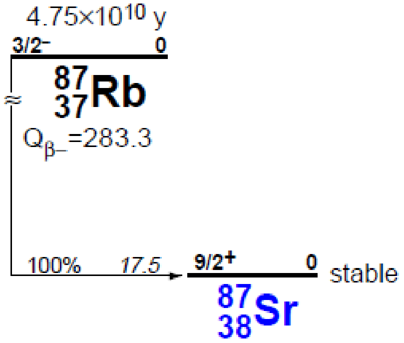
Best of all is to use shape measured experimentally (the problem is that results could be different in different experiments …).

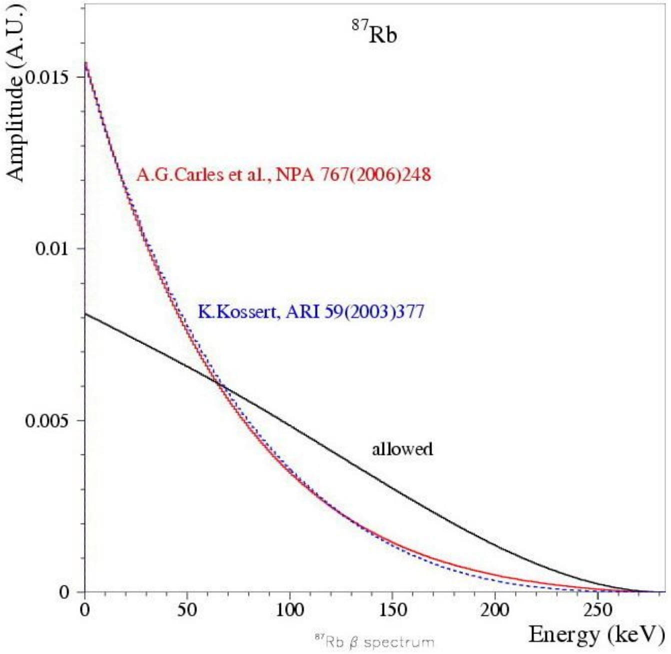
Compilations of experimental a_i, b_i, c_i:

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).

^{87}Rb

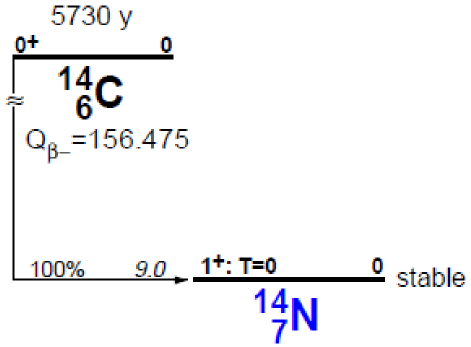
$3/2^- \rightarrow 9/2^+ \quad \Delta J^{\Delta\pi} = 3^-$ (3 FNU)

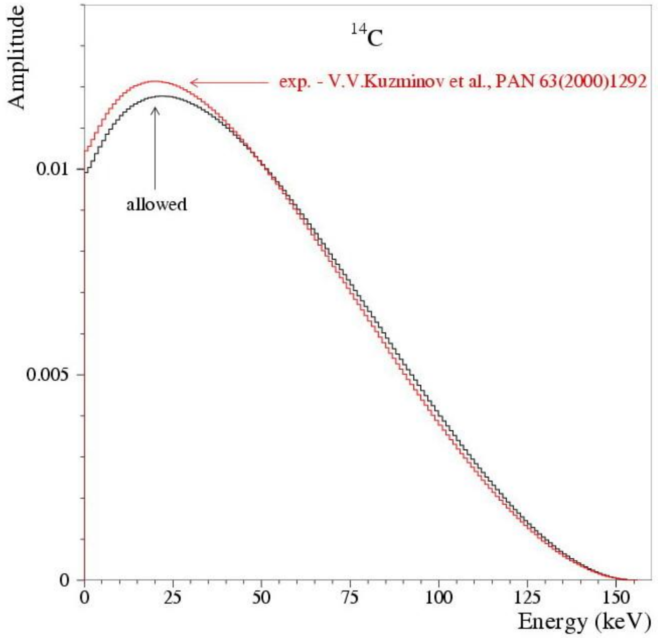




^{14}C

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

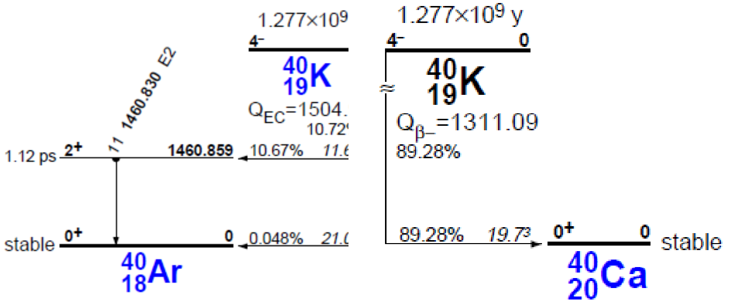


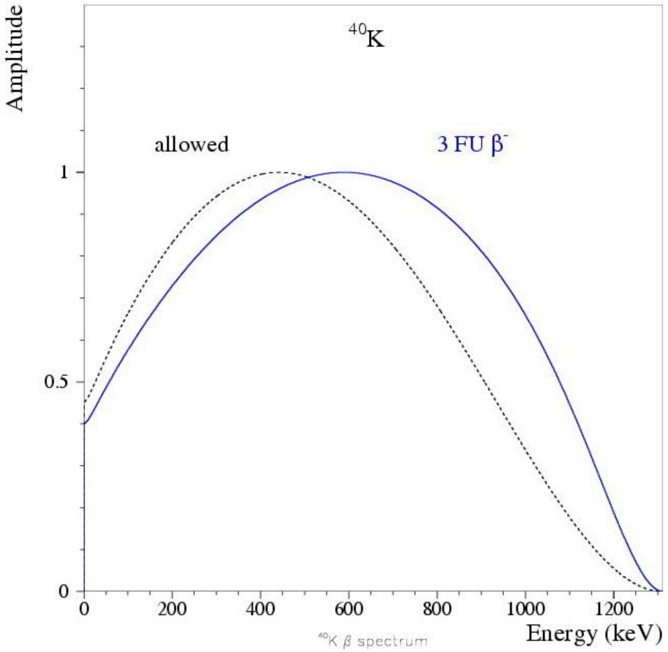


^{40}K

10.7% EC, 89.3% β decay

$4^- \rightarrow 0^+ \quad \Delta J^{\Delta\pi} = 4^- \quad$ (3 FU)

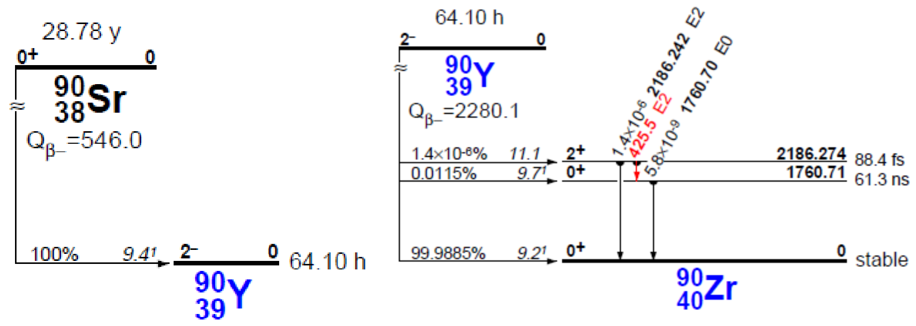


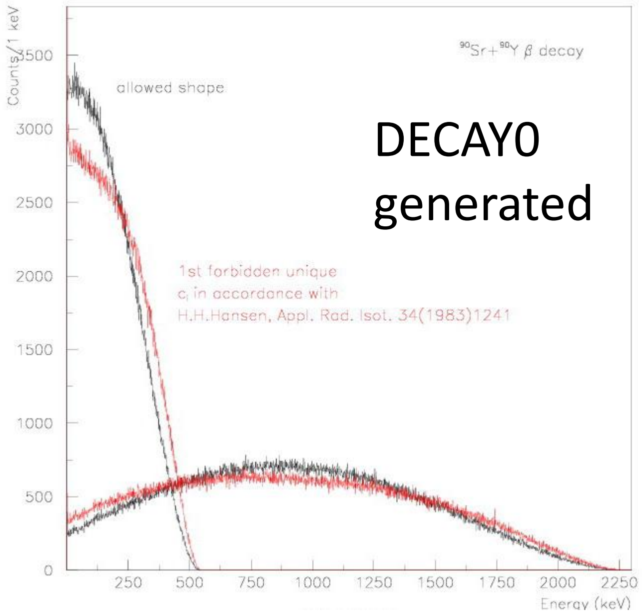


^{90}Sr and ^{90}Y

Both are (practically) pure β decayers

$\Delta J^{\Delta\pi} = 2^- \quad$ (1 FU)



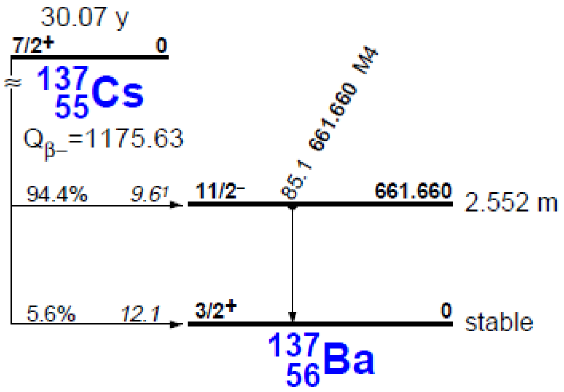


DECAY0 generated

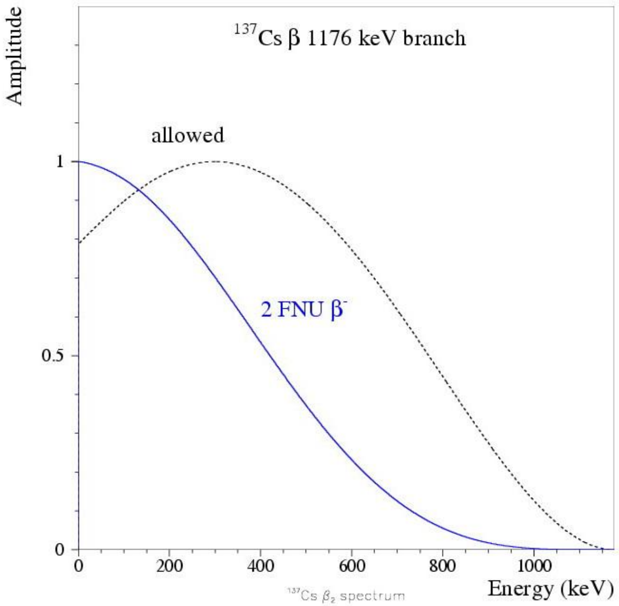
^{137}Cs

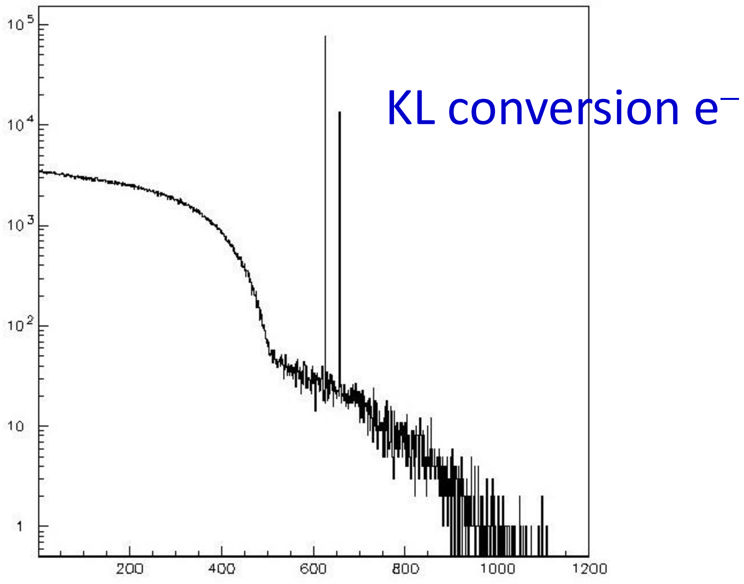
(1) 94.4% $7/2^+ \rightarrow 11/2^-$ $\Delta J^{\Delta\pi} = 2^-$ (1 FU)

(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)





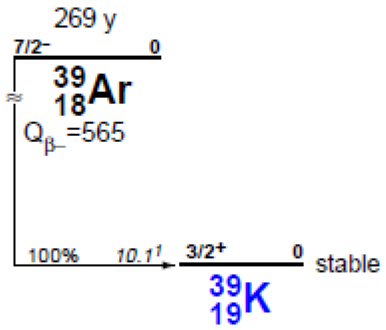
KL conversion e^-

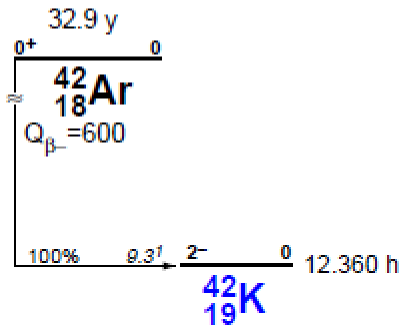
^{39}Ar, ^{42}Ar and ^{42}K

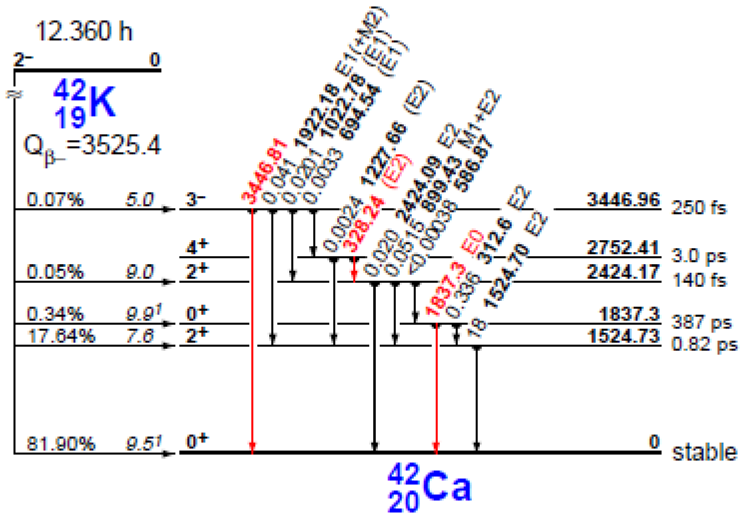
^{39}Ar, ^{42}Ar: $\Delta J^{\Delta\pi} = 2^-$ (1 FU)

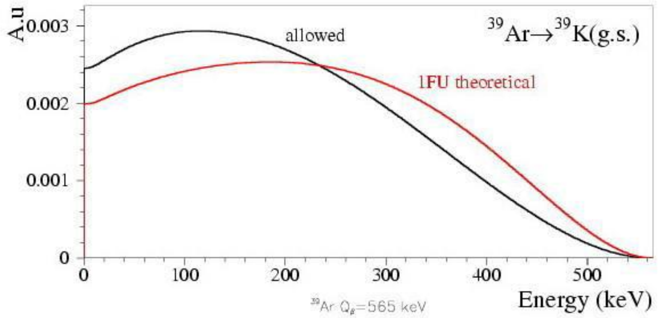
^{42}K(81.90%): $\Delta J^{\Delta\pi} = 2^-$ (1 FU)

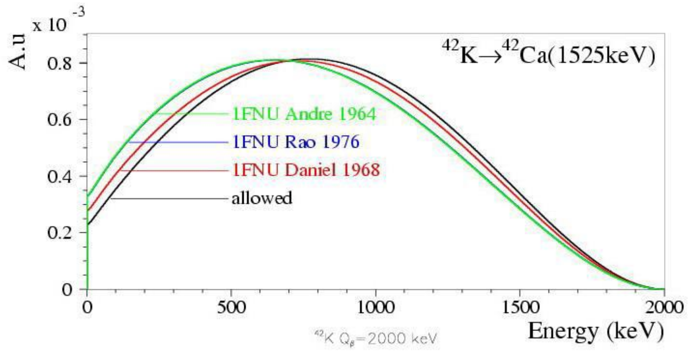
^{42}K(17.64%): $\Delta J^{\Delta\pi} = 0^-$ (1 FNU)



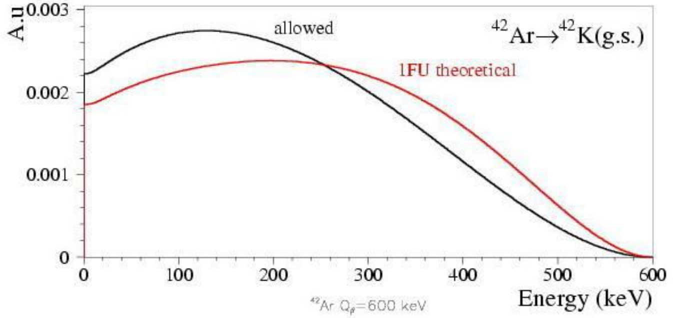


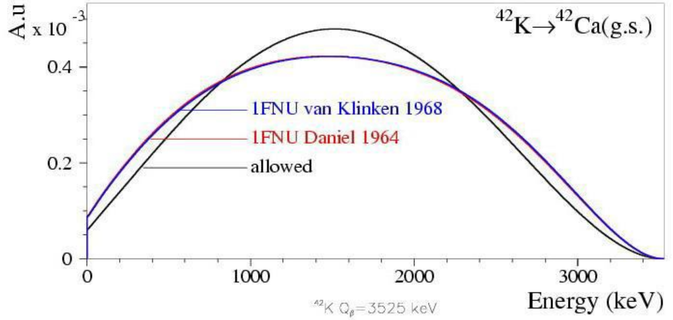


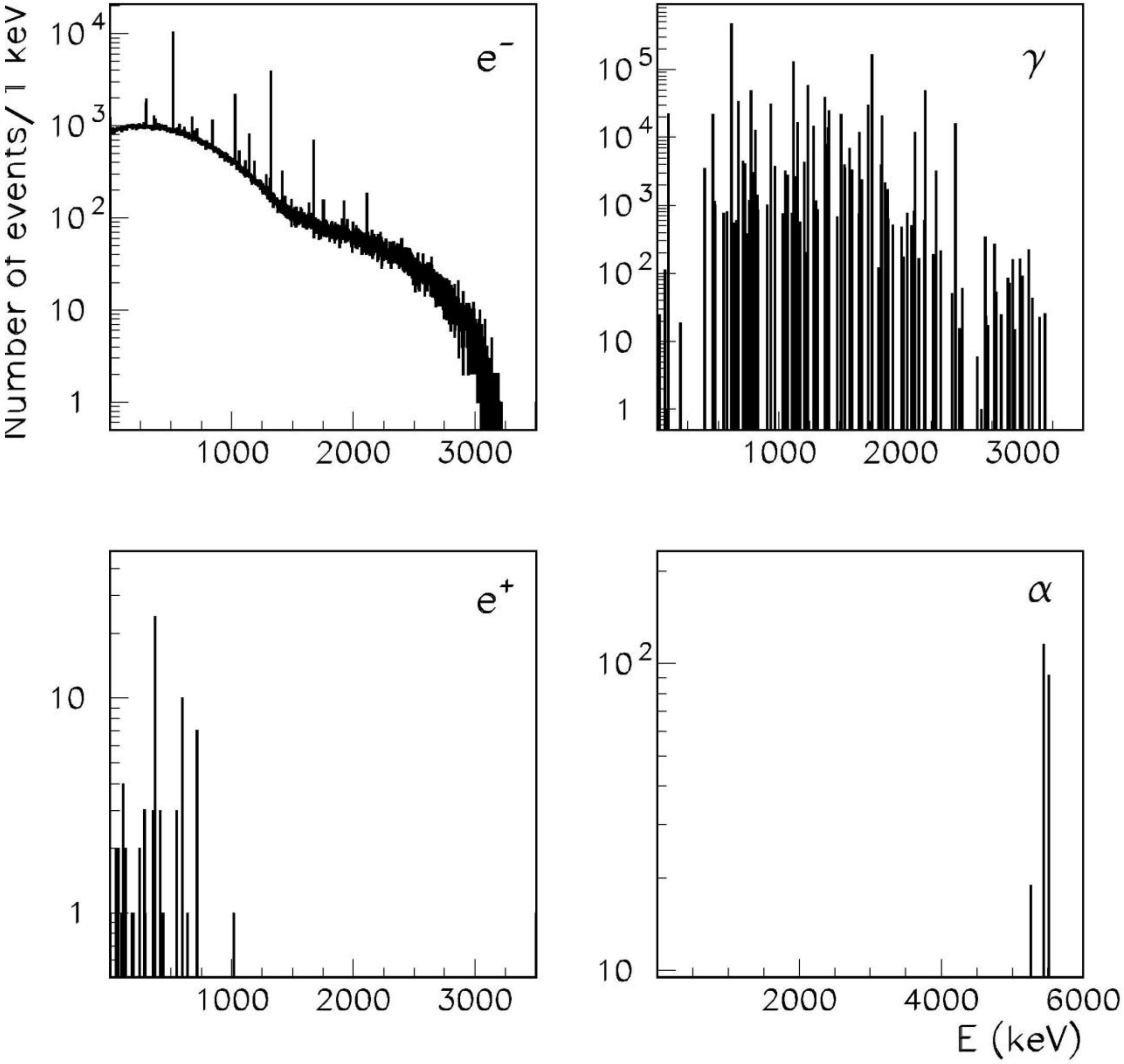




Shapes in red are used in the DECAY0





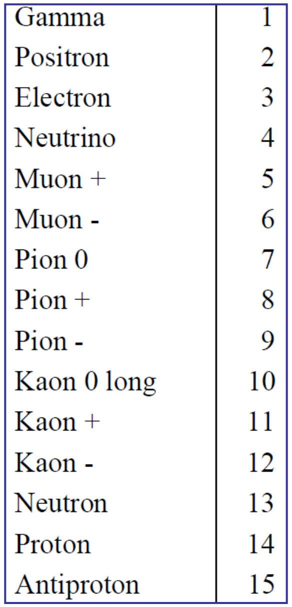


Generated by DECAY0 initial energy spectra of electrons, γ quanta, positrons and α particles in ^{214}Bi decay.

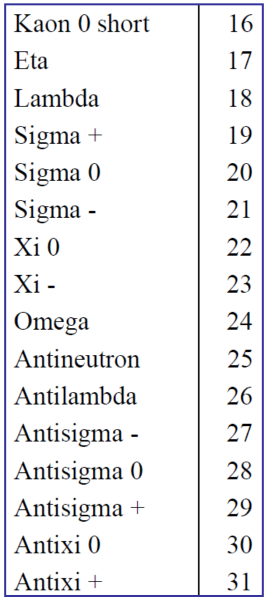
One can see discrete lines of conversion electrons on continuous spectrum of beta particles

4. Artificial events

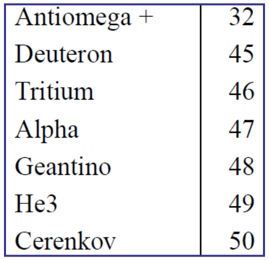
- Emission of 38 particles from the GEANT3 list with needed direction and energies



Gamma	1
Positron	2
Electron	3
Neutrino	4
Muon +	5
Muon -	6
Pion 0	7
Pion +	8
Pion -	9
Kaon 0 long	10
Kaon +	11
Kaon -	12
Neutron	13
Proton	14
Antiproton	15



Kaon 0 short	16
Eta	17
Lambda	18
Sigma +	19
Sigma 0	20
Sigma -	21
Xi 0	22
Xi -	23
Omega	24
Antineutron	25
Antilambda	26
Antisigma -	27
Antisigma 0	28
Antisigma +	29
Antixi 0	30
Antixi +	31

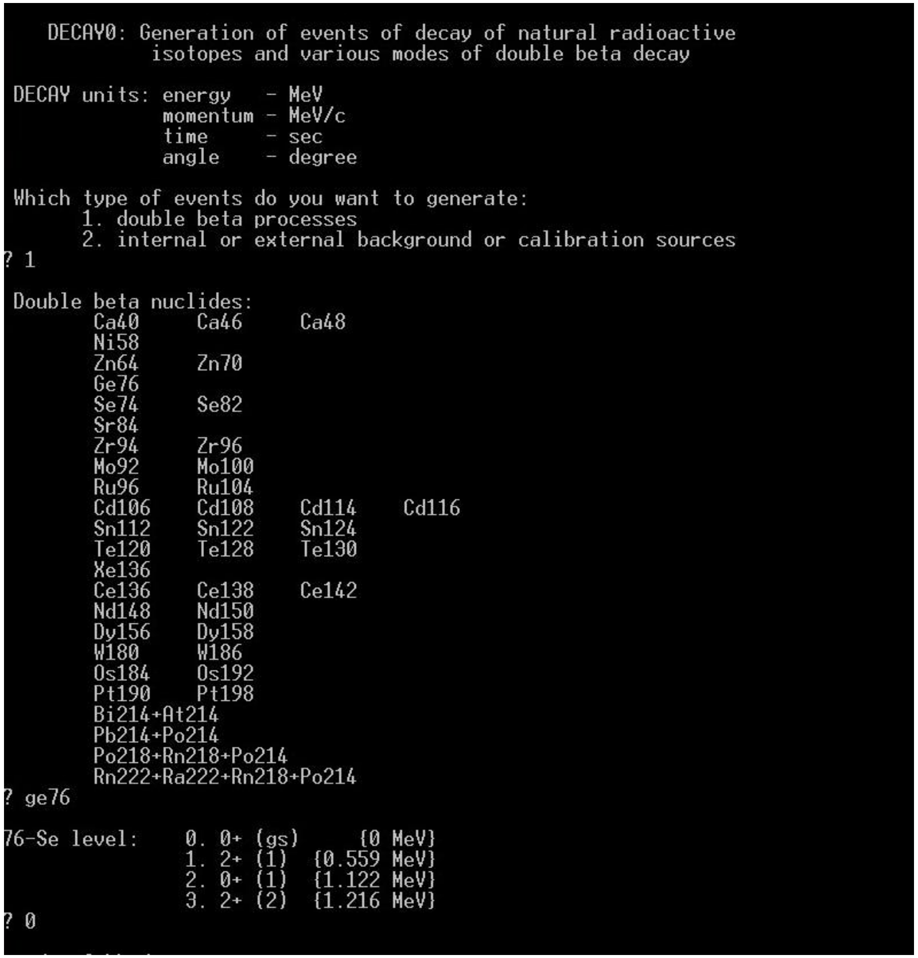


Antiomega +	32
Deuteron	45
Tritium	46
Alpha	47
Geantino	48
He3	49
Cerenkov	50

- 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 ($2\beta0\nu$ 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
```

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
```

6. Examples of application

DECAY0 code was written more than 20 years ago – 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 ~17,500 lines.

DECAY0 is used:

LPD KINR (many years)

NEMO-2,3 (since ~1992) + SuperNEMO (with historical name GENBB)

DAMA

COBRA

SNO+

AMoRE

NEXT

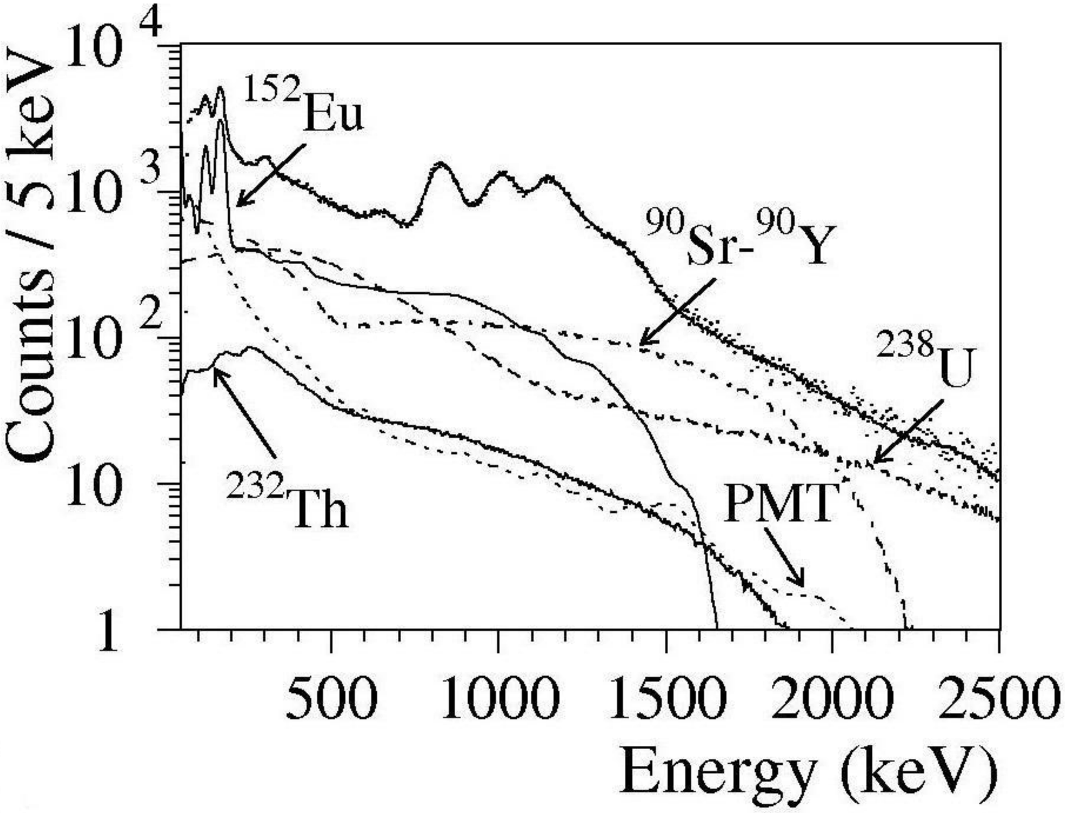
GERDA/Majorana (for 2β decay)

…

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].

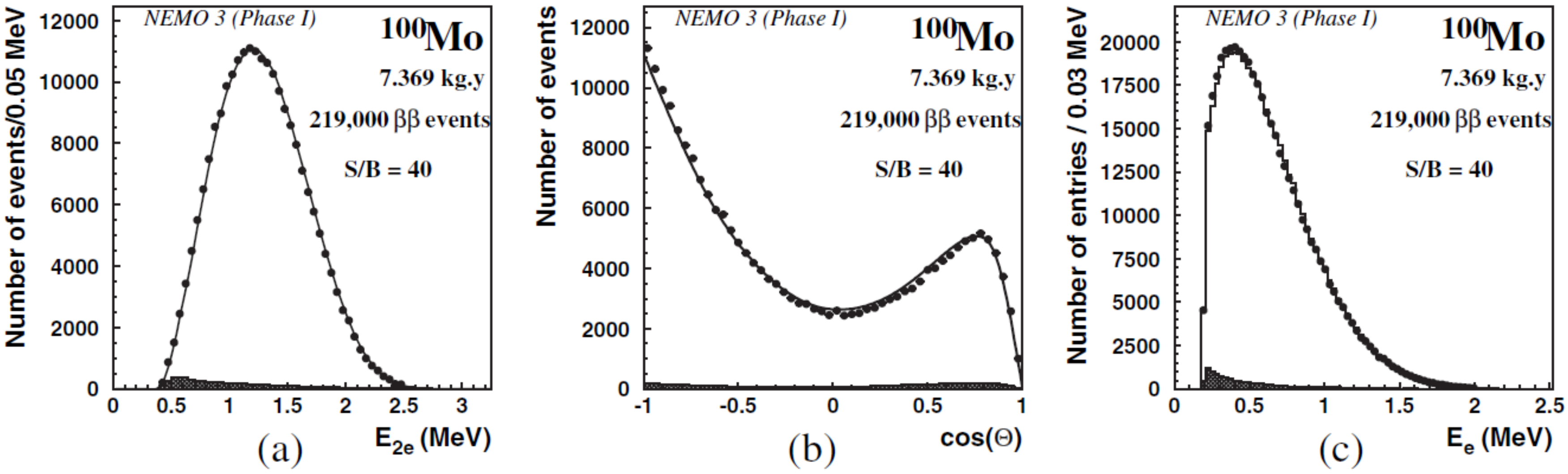
Experimental data are fitted by simulated the most important components of γ/β spectrum (^{152}Eu, ^{90}Sr-^{90}Y, ^{232}Th, ^{238}U + external gammas from PMT.



Example 2: NEMO-3 (investigation of 2β decay of ^{100}Mo)

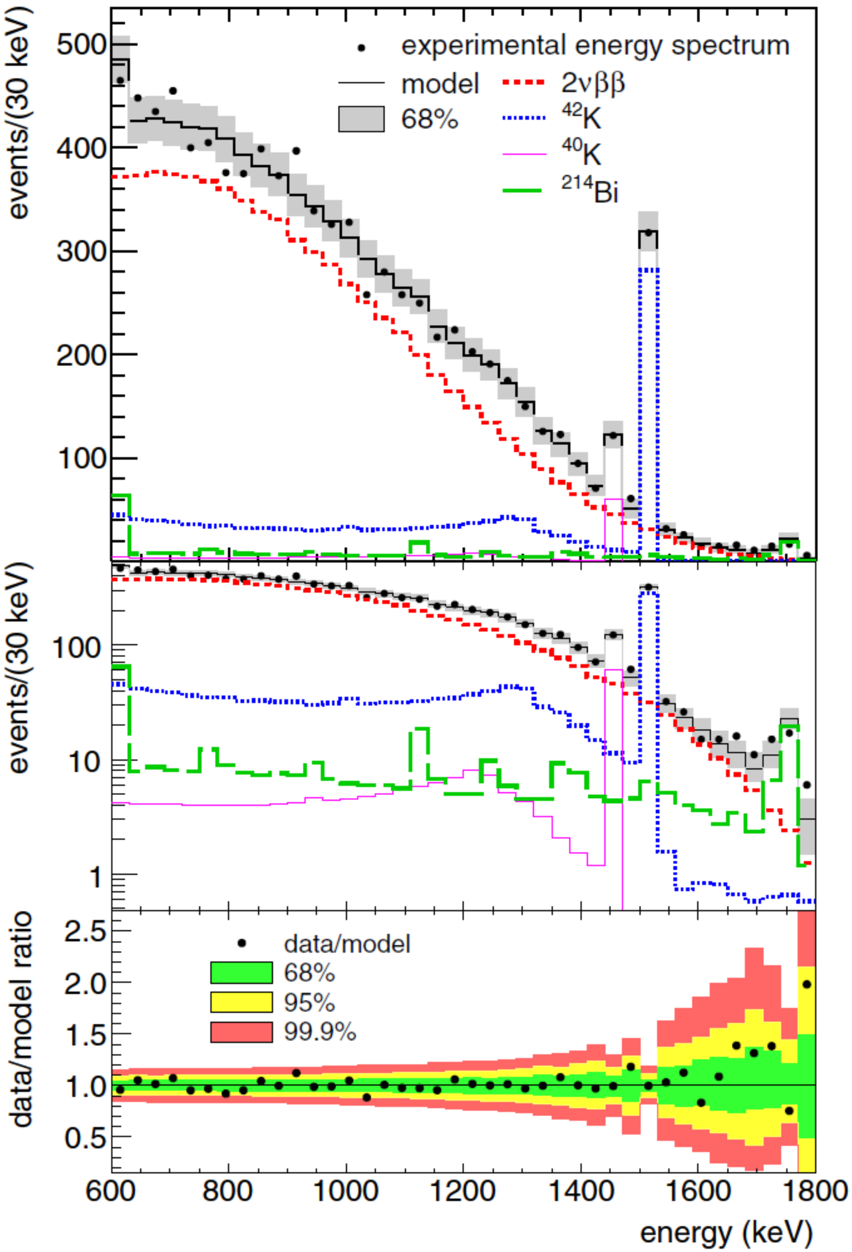
~7 kg of ^{100}Mo, 389 d of data taking in the Modane Underground Laboratory [R. Arnold et al., PRL 95 (2005) 182302]

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

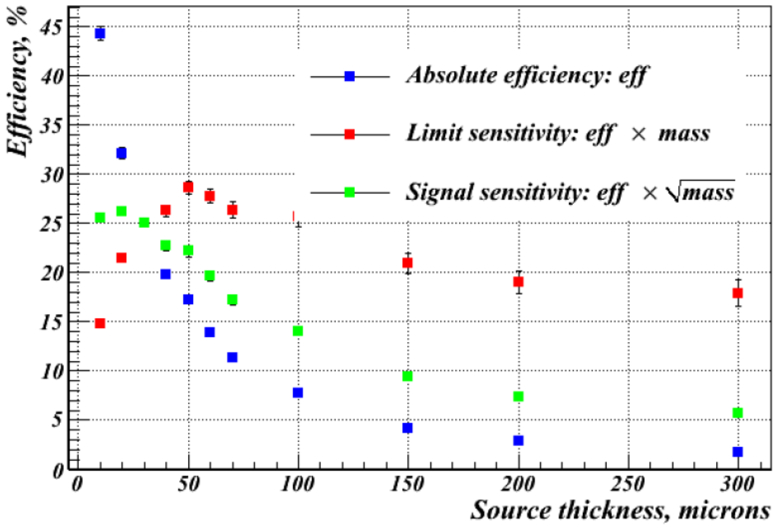


Example 3: GERDA (investigation of 2β decay of ^{76}Ge)

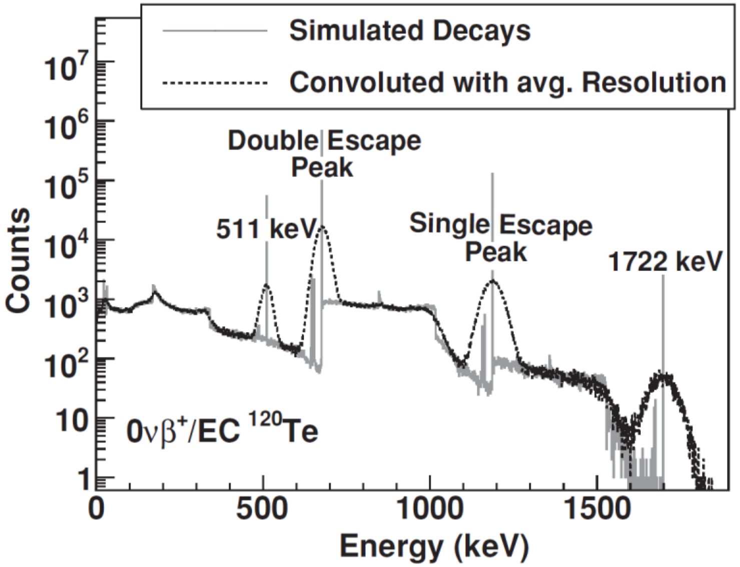
Phase I, 6 HPGe enriched in ^{76}Ge to 86%, 14.63 kg, 126 d of data taking in the Laboratori Nazionali del Gran Sasso [M. Agostini et al., JPG 40 (2013) 035110]



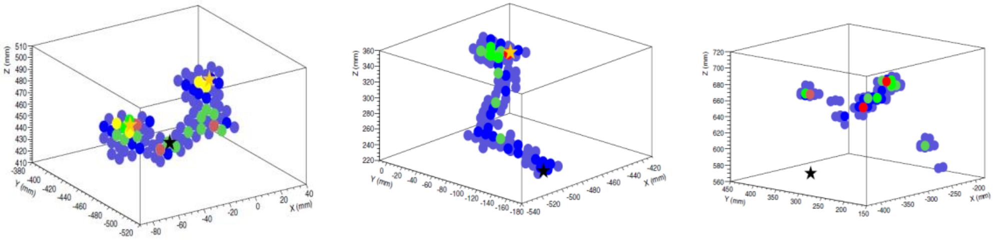
Examples of simulations with DECAY0 but without direct comparison with experimental data:



TGV – JINST 06 (2011) C01057



COBRA – PRC 80 (2009) 025502

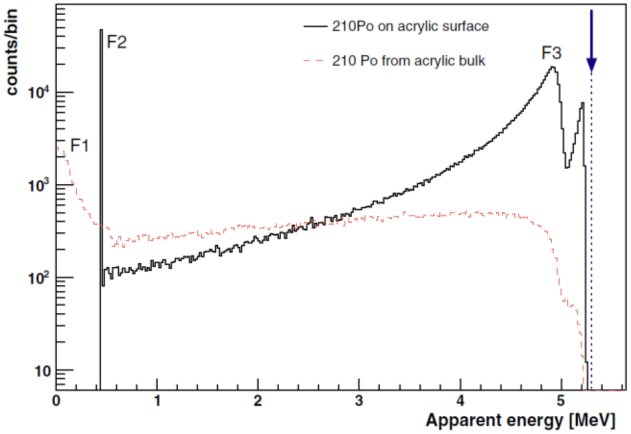


^{136}Xe $2\beta0\nu$

^{214}Bi

^{208}Tl

NEXT – JPG 40 (2013) 125203



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7. Conclusions

Written more than 20 years ago, DECAY0 is to-date the most developed event generator for simulation of different 2β decay processes (40 2β nuclides, 17 2β modes, decays to g.s. and excited levels).

Generation of single β and α decays of atomic nuclei also is possible for 59 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 ~17,500 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, NEXT, GERDA/Majorana and others).

Thank you for attention!