DECAY0:
event generator for initial kinematics of events in α, β and 2β decays of atomic nuclei

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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 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.)

  What 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:

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

2β decay

$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$
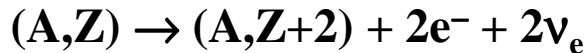
Two-neutrino double beta decay – allowed in the Standard Model process.
However, extremely rare: $T_{1/2} \sim 10^{18} - 10^{24}$ yr.
Near 50 years from prediction (1935) to direct experimental observation in laboratory (1987): twice bigger time than that needed to register neutrino (1930-1956).

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

Neutrinoless double beta decay – violates L on two units and is forbidden in the SM.
Predicted by many SM extensions. Subject of intensive experimental searches to-date.

(A,Z)	$\rightarrow (A,Z–2) + 2e^+$	$(+ 2\nu_e)$	**Processes with emission**
$e^- + (A,Z)$	$\rightarrow (A,Z–2) + e^+$	$(+ 2\nu_e)$	**of positrons and/or**
$e^-_1 + e^-_2 + (A,Z)$	$\rightarrow (A,Z–2)$	$(+ 2\nu_e)$	**electron capture**

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

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The sampling of energies and angles of e^- or e^+ is based on 3-dimensional distributions $\rho_{12\theta}(t_1,t_2,\cos\theta)$. The distributions are different for different modes 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$^\pm$ 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$^\pm$ decay with right-handed currents (λ term), 0$^+$ - 0$^+$ transition, 2n mechanism

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

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

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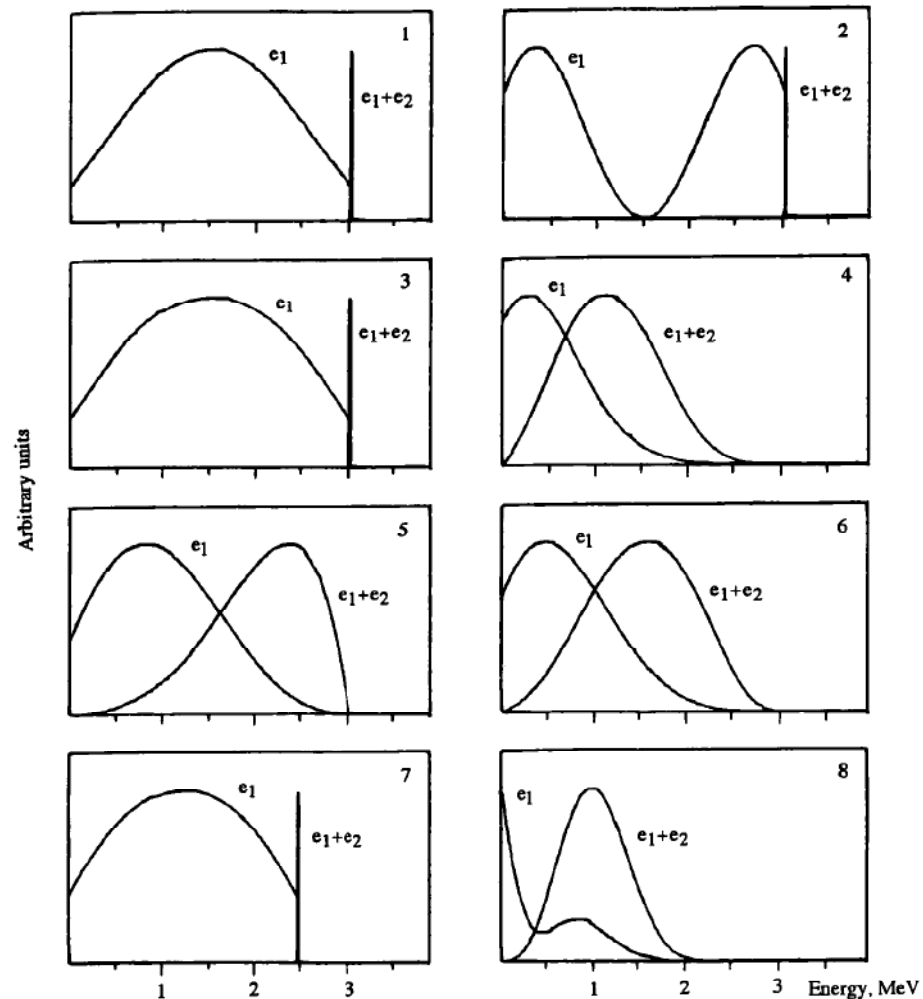
and so on

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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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2β decay in the DECAY0

- **32 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**
- **16 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

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

Also: ^{84}Sr, ^{96,104}Ru, ^{112,122,124}Sn, ^{136,138,142}Ce, ^{180,186}W

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

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

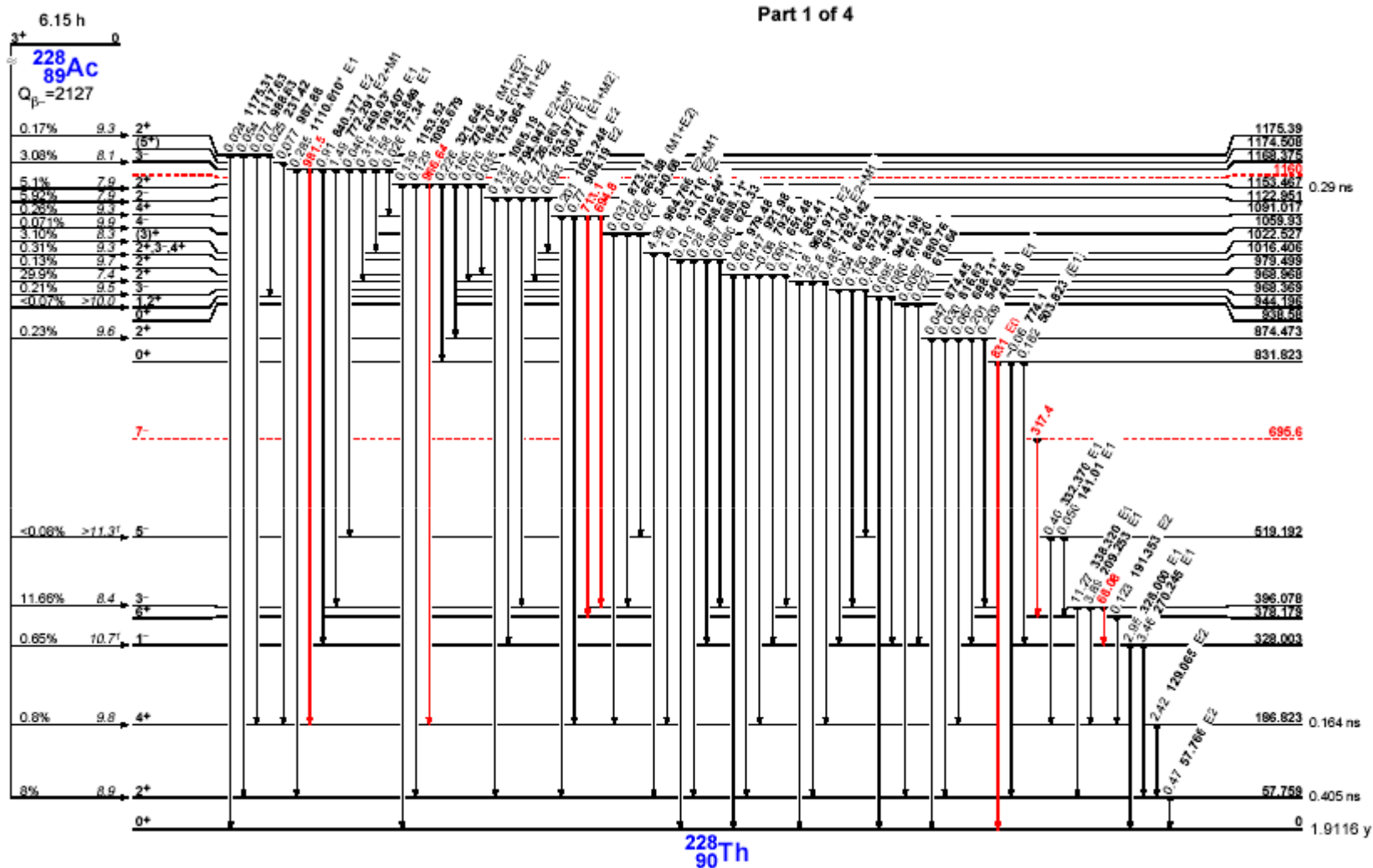|			
$0\nu2\beta(m_\nu)$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta(rhc)$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta(rhc)$	$0^+ \rightarrow 0^+, 2^+$	N*	
$2\nu2\beta$	$0^+ \rightarrow 0^+$	2n	
$0\nu2\beta M1$	$0^+ \rightarrow 0^+$	2n	Majoron with SI=1 [a]
$0\nu2\beta M2$	$0^+ \rightarrow 0^+$	2n	Majoron with SI=2 [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
$0\nu2\beta(rhc)$	$0^+ \rightarrow 2^+$	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	

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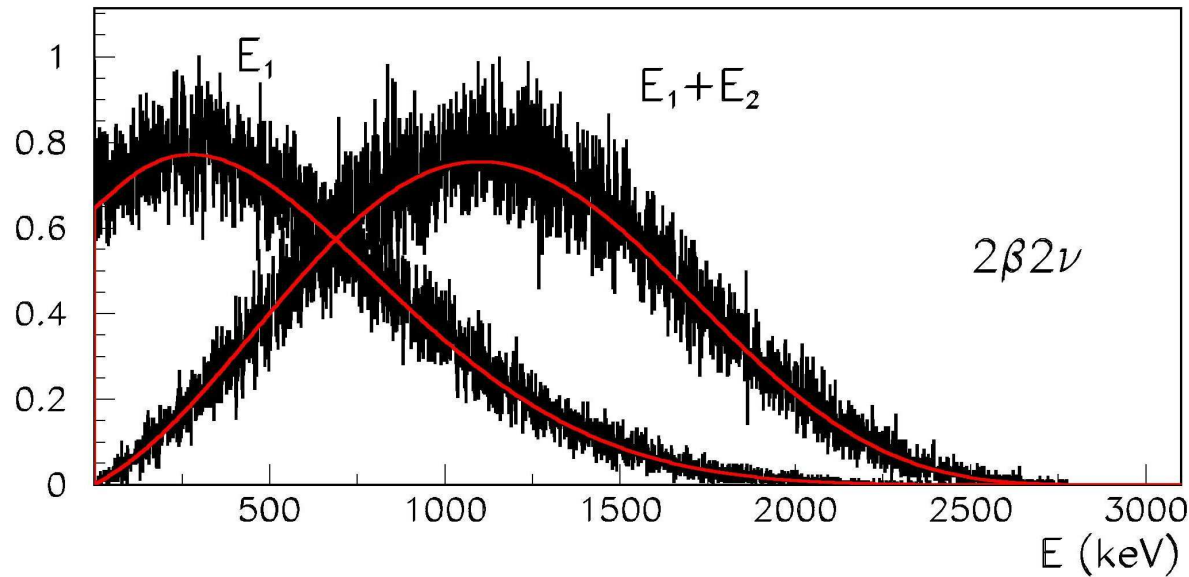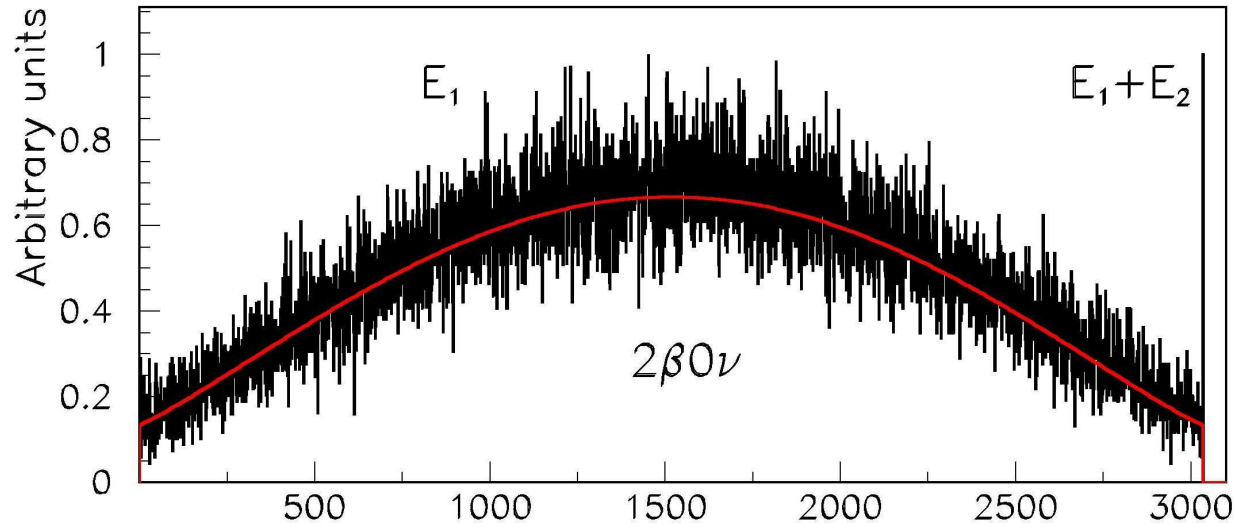
Generated by DECAY0 initial energy spectra of electrons emitted in 2β (two neutrino and neutrinoless) decays of ^{100}Mo ($Q_{2\beta}$=3034 keV): E_1 – single electron spectrum, E_1+E_2 – sum of the electrons energies. Generated distributions are shown together with theoretical curves.

α and β decays in the DECAY0

- emission of β particle; shape of energy spectrum will depend on change in nuclear 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 β decay

◆ **58 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)**

α and β decays: isotopes

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

Ac228	Co60	K40	Sr90	Zr96+Nb96
Ar39	Cs136	K42	Ta182	
Ar42	Cs137+Ba137m	Mn54	Te133	**Recently added:**
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
   (up to 48 excited levels and up to 166 different transitions)

For each transition, three concurrent processes are taken into account:
   emission of γ quantum, conversion electron or e^+e^- pair
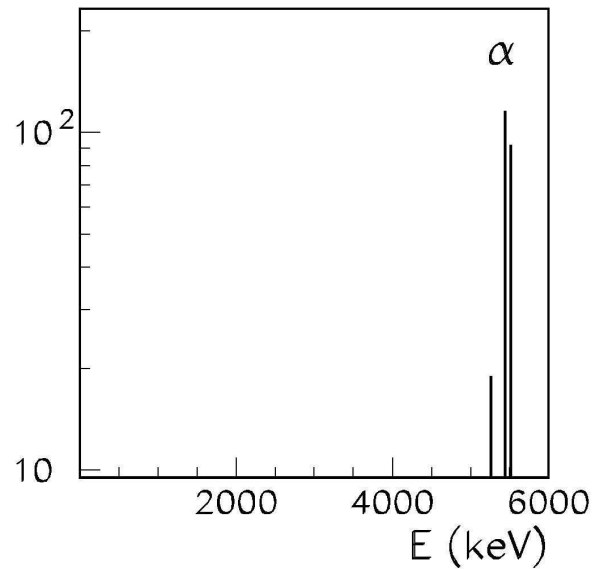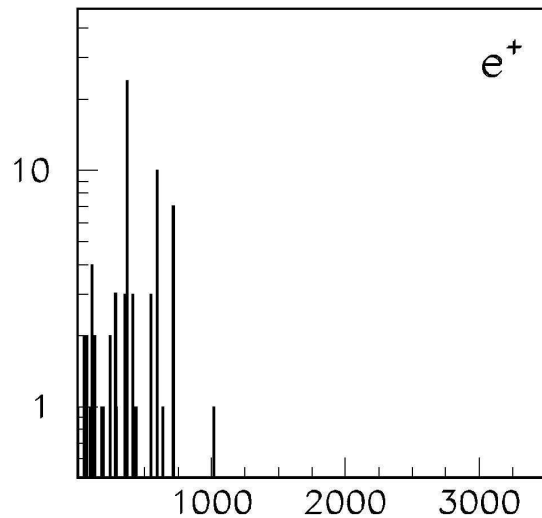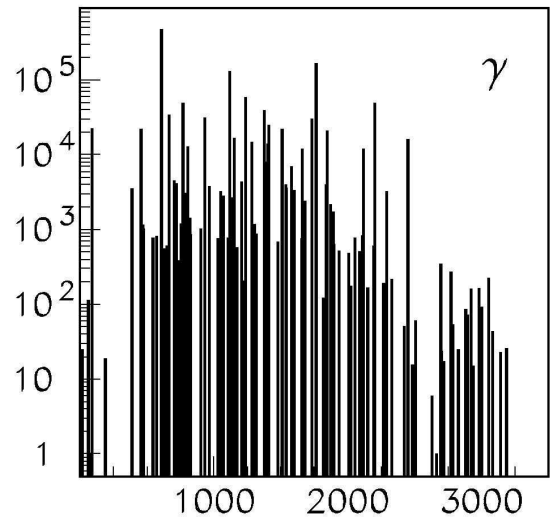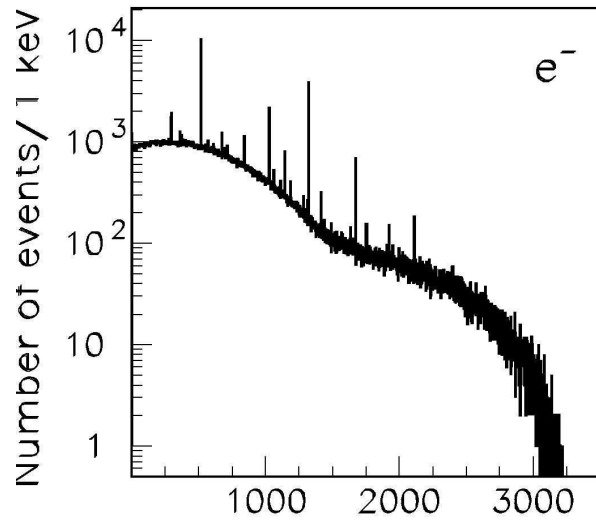
Generated by DECAY0 initial energy spectra of electrons, γ quanta, positrons and α particles in ^{214}Bi decay.

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

special events

◆ **emission of 38 particles from the GEANT3 list with needed direction and energies**

◆ **artificial e^+e^- pairs, and α and β decays with needed Q and Z values**

◆ **Compton and Moller scattering**

The DECAY0 code is written in FORTRAN and currently consists of ~16,000 lines

Example of file generated by the DECAY0 (2β2ν decay of ⁷⁶Ge):

```
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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Current applications of the DECAY0:

**LPD KINR (many years)**

NEMO2&3 (since ~1992) + SuperNEMO

DAMA

COBRA

GERDA/Majorana (for 2β decay)

Some others (KIMS, Indian 2β people, EXO, SNO+, …)

Example 1: KINR + DAMA

CaF$_2$ scintillator 370 g, 7426 h of measurements in the DAMA low-background R&D set-up at LNGS [P.Belli et al., Nucl. Phys. A 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
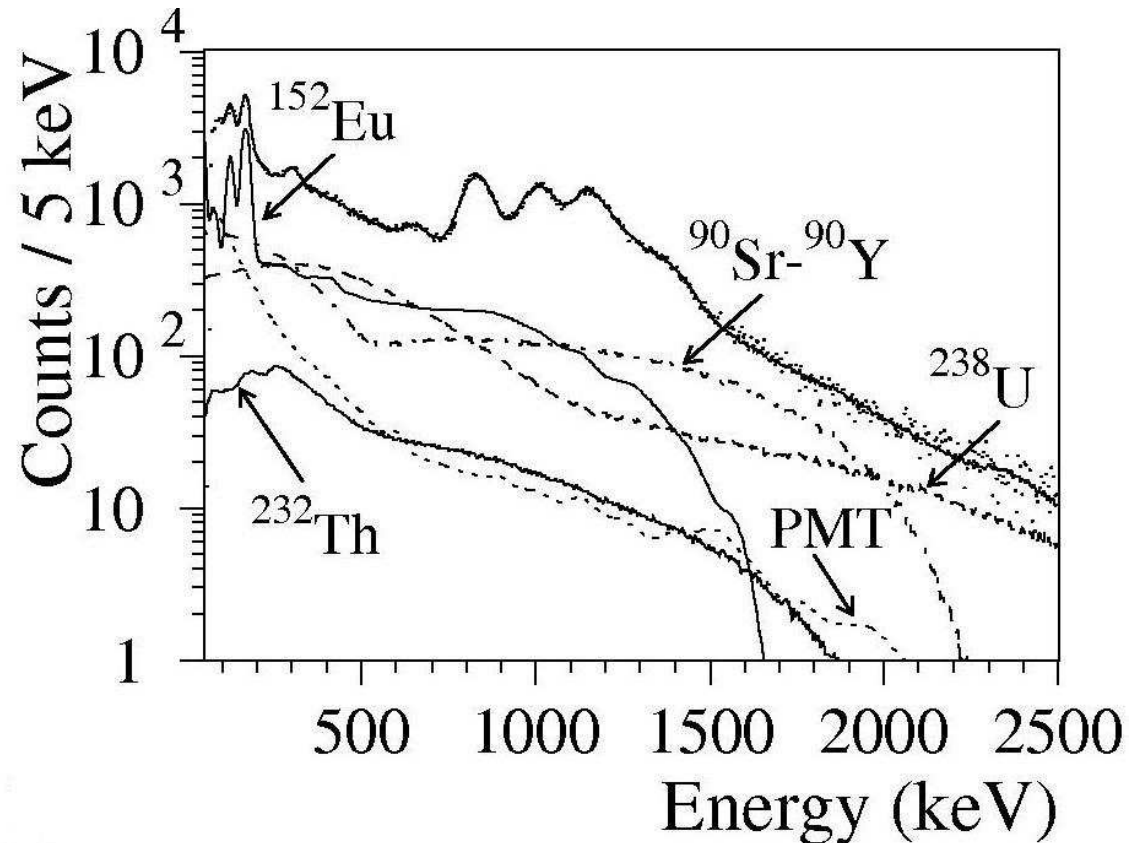
Example 2: NEMO experiment

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

2β2ν decay of ^{100}Mo – experimental data are compared with simulated distributions for:
(a) sum of electron energies;
(b) angular distribution between electrons:
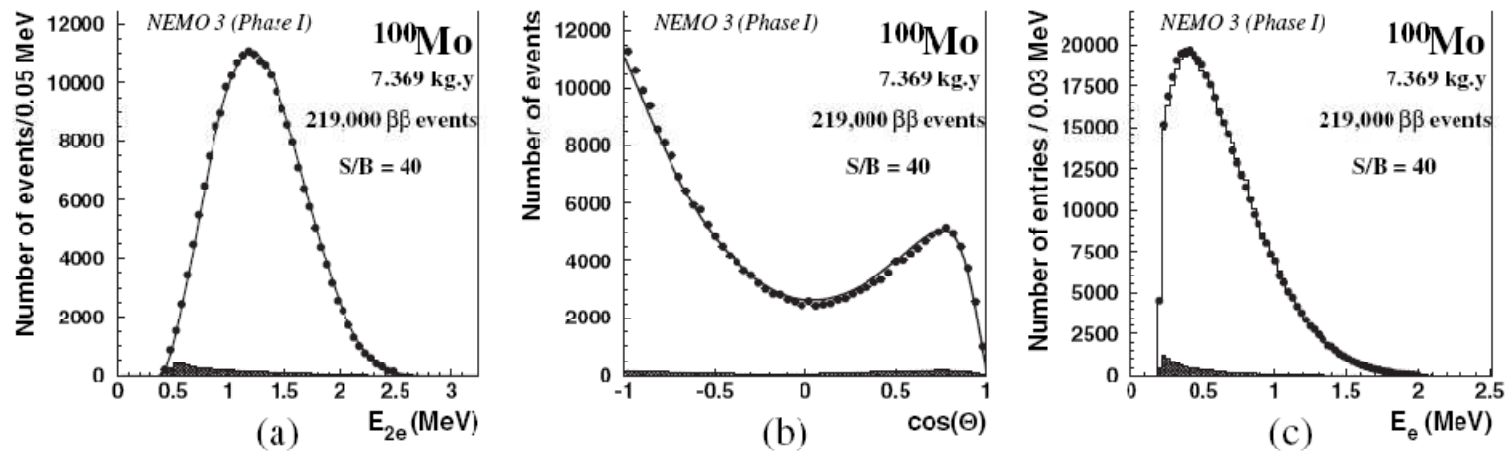**(c) energy spectrum of single electrons**

FIG. 2. (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two electrons, and (c) single energy spectrum of the electrons, after background subtraction from ^{100}Mo with 7.369 kg · yr exposure. The solid line corresponds to the expected spectrum from $\beta\beta2\nu$ simulations and the shaded histogram is the subtracted background computed by Monte Carlo simulations. The signal contains 219000 $\beta\beta$ events and the signal-to-background ratio is 40.

Conclusion:

DECAY0 event generator is to-date the most developed event generator for simulations of different 2β decay processes. Generation of single β and α decays of atomic nuclei also is possible (however, it is possible in GEANT4 too with its own event generator).

DECAY0 is successfully used in several big experiments devoted to searches for rare nuclear α, β and 2β decays (NEMO, DAMA, KINR, COBRA, GERDA/Majorana and others).

Thank you for attention!