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

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First of all,
I want to thank you for invitation to the Oxford University and for the honor to give a seminar here!

To predict response function of a detector for some events with general simulation tools such as GEANT, EGS, MCNP or some other programs, one has to explain these programs:

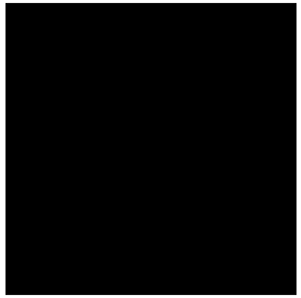
What is a geometry of experiment (position of detector, its size and material, positions of sources of radiation, shieldings, existence of magnetic and electric fields, etc.)

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

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: $T_{1/2} \sim 10^{18} - 10^{21}$ yr.
Near 50 years from prediction to direct experimental observation in laboratory (twice bigger time span than that needed to register neutrino).

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

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) ⇒ different energy and angular distributions of emitted $\beta^\pm$ particles

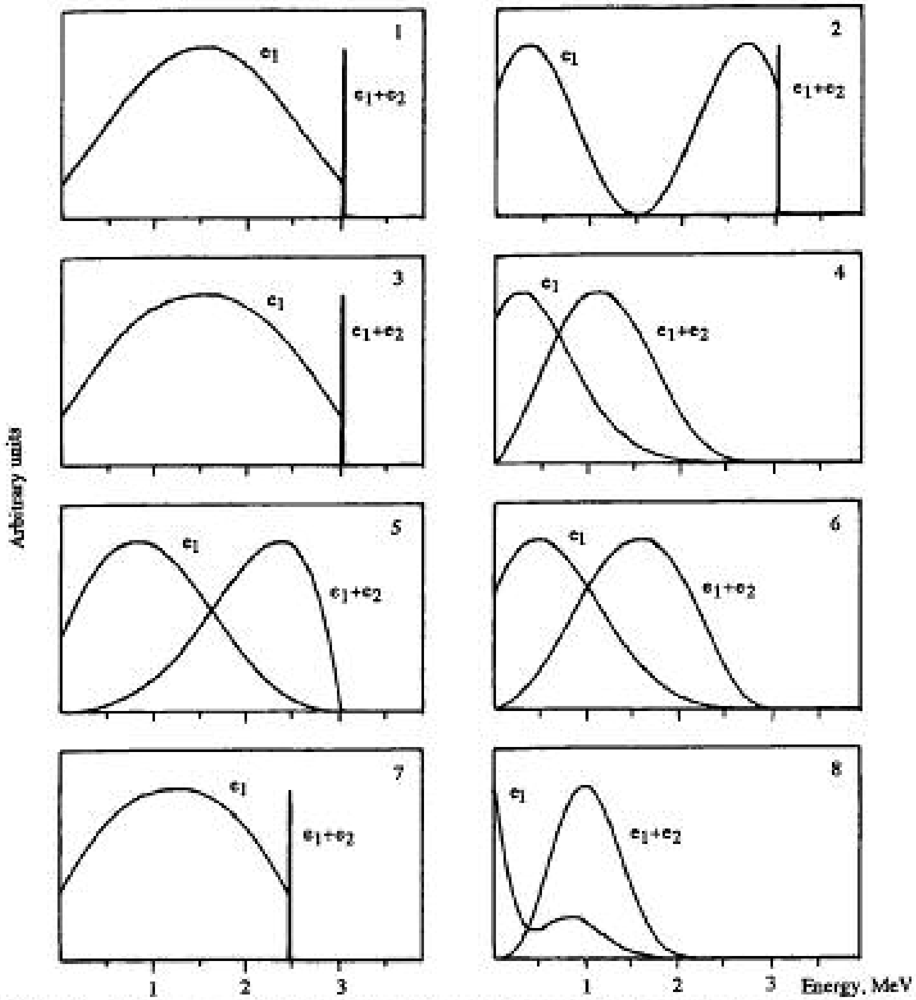


Figure 4. Theoretical distributions for the energy of a single electron (e_1) and for the sum of electron energies ($e_1 + e_2$) for ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $E(2^+)$ = 540 keV) for different modes and mechanisms of 2β decay: (1) $0\nu2\beta$ decay with neutrino mass, 0^+–0^+ transition,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

2β decay in the DECAY0

- **21 isotope – 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**
- **14 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

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

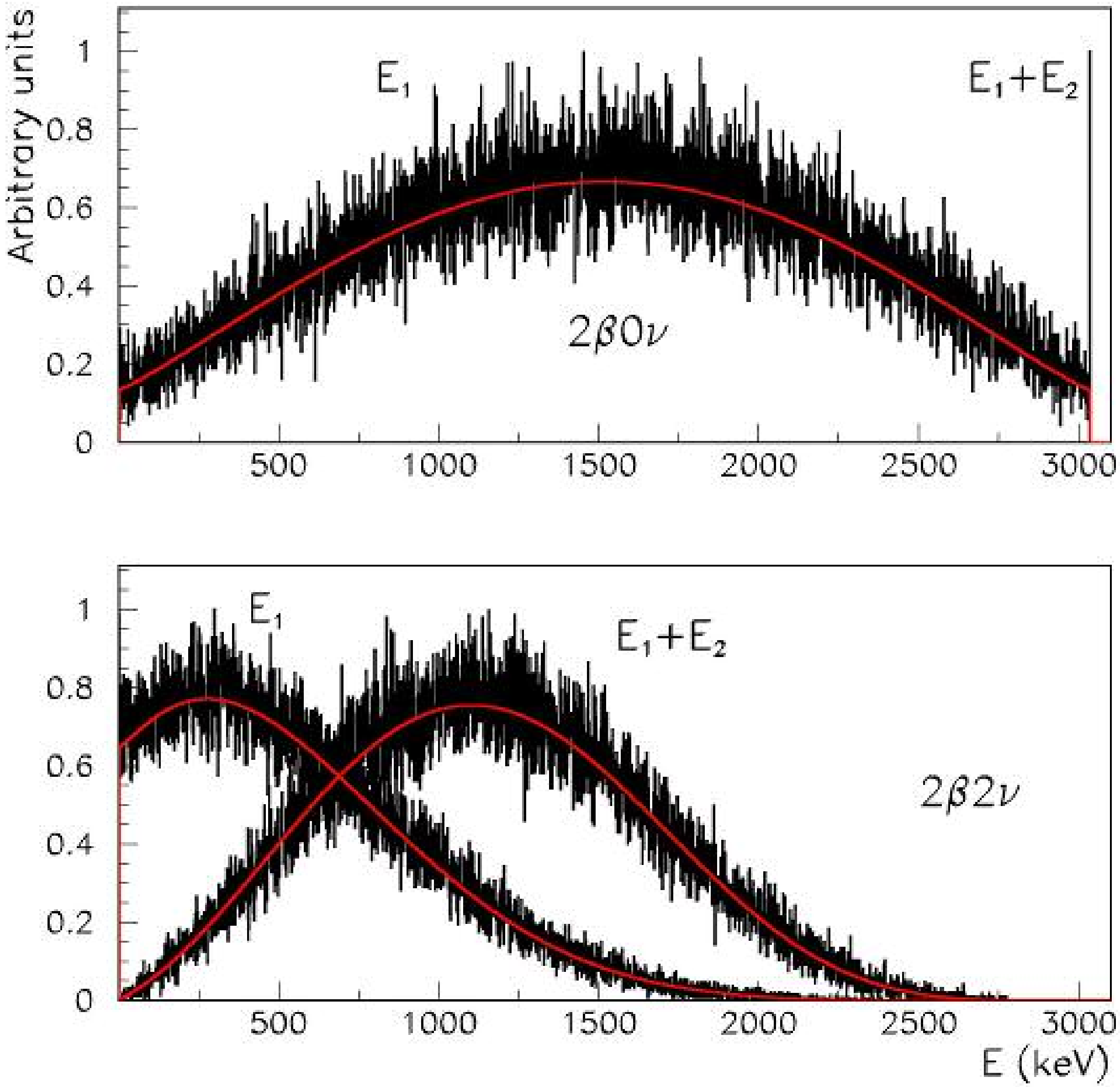
2β decay: decay modes, transitions, mechanisms (2n and N^*)

$0\nu2\beta(m_\nu)$	$0^+ \to 0^+$	2n	
$0\nu2\beta$(rhc)	$0^+ \to 0^+$	2n	
$0\nu2\beta$(rhc)	$0^+ \to 0^+, 2^+$	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
$0\nu2\beta$(rhc)	$0^+ \to 2^+$	2n	
$2\nu2\beta$	$0^+ \to 2^+$	2n, N^*	
$0\nu K\beta+$	$0^+ \to 0^+, 2^+$		
$2\nu K\beta+$	$0^+ \to 0^+, 2^+$		
$0\nu2K$	$0^+ \to 0^+, 2^+$		
$2\nu2K$	$0^+ \to 0^+, 2^+$		

[a] old Majoron of Gelmini-Roncadelli

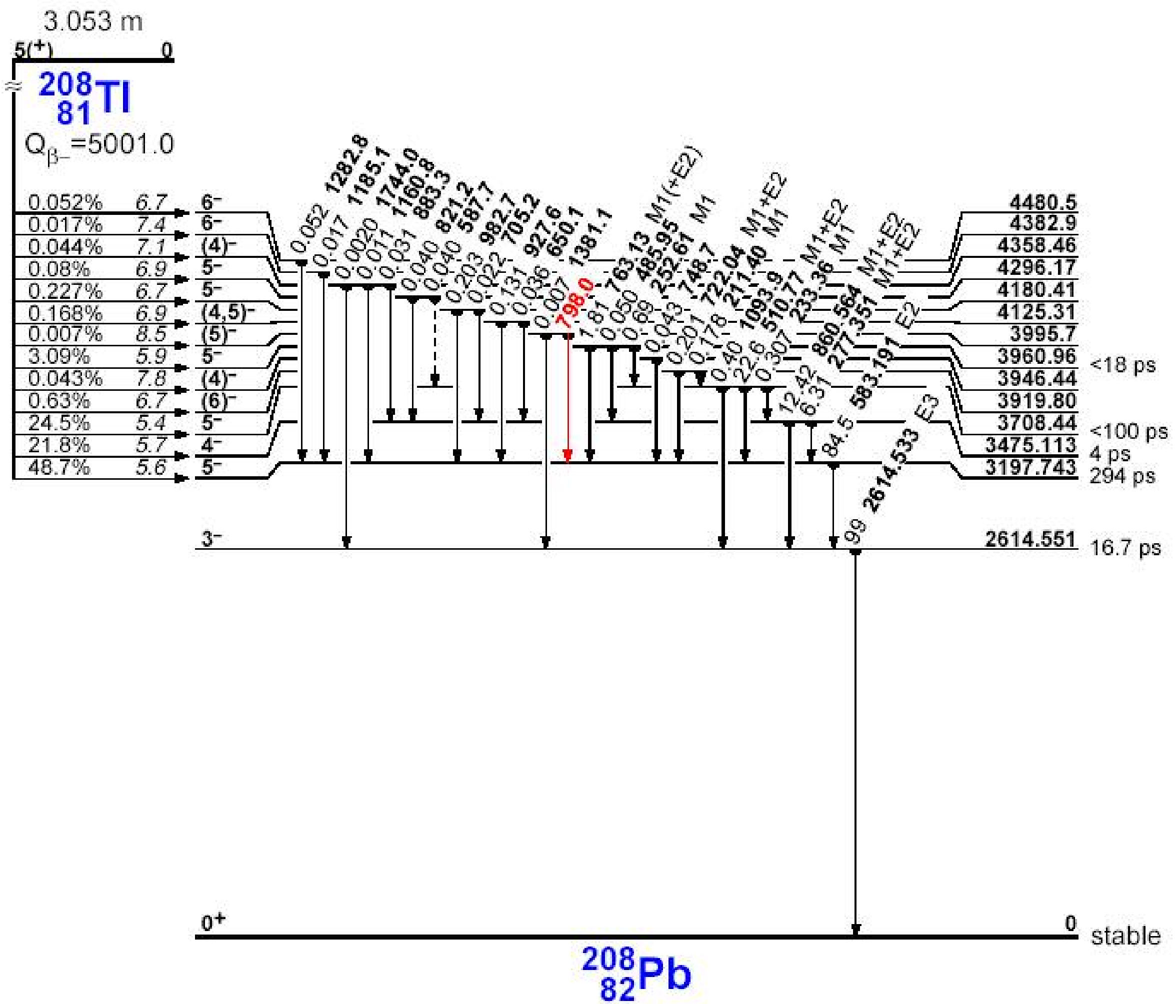
[b] bulk Majoron of Mohapatra

[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



Example:
Scheme of ^{208}Tl decay

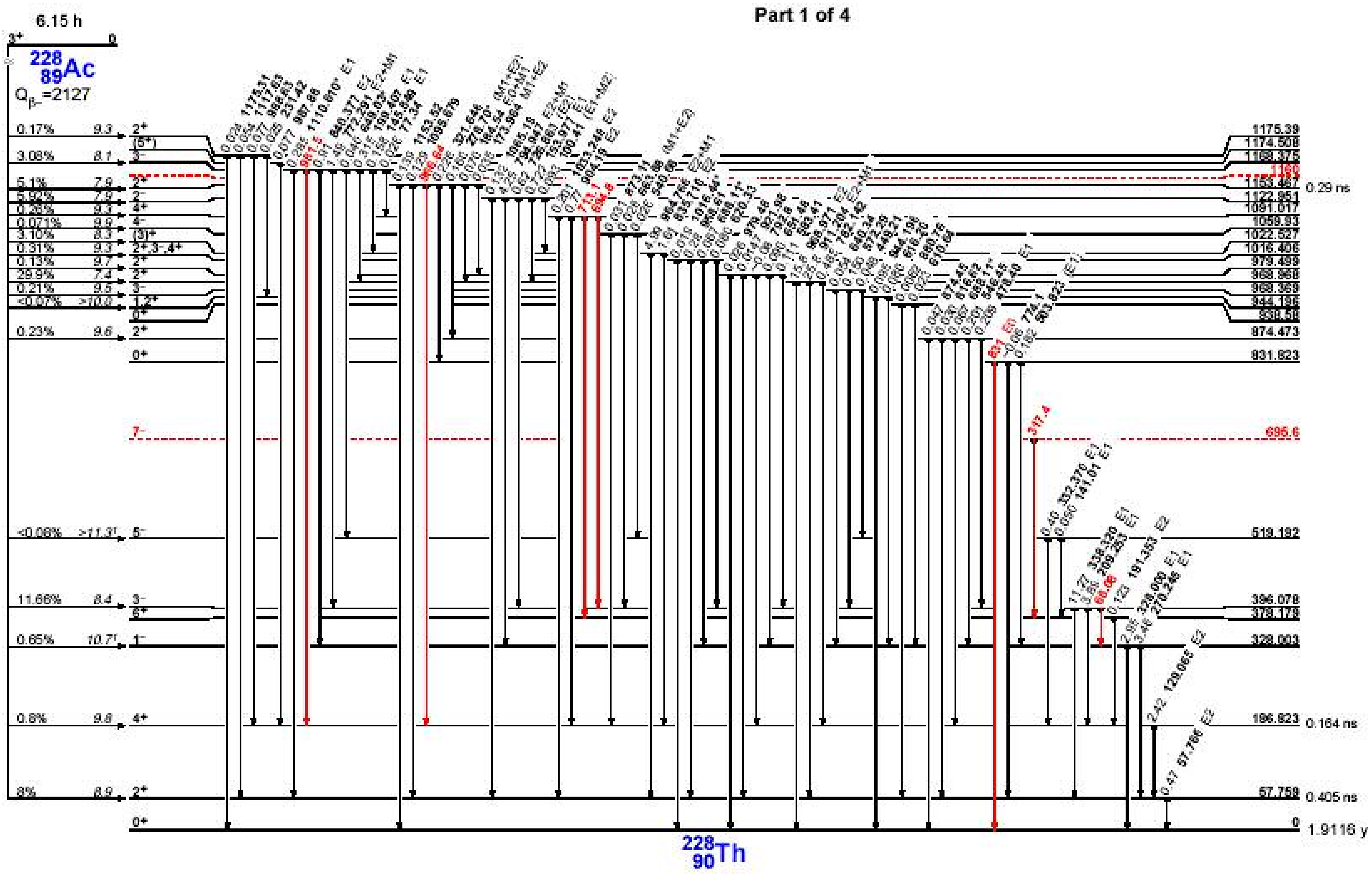
- emission of β particle; shape of energy spectrum will depend on change in nuclear spin and parity;

- 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 ground states will be reached



Sometimes schemes of decay are quite complex:

Part 1 of 4 for ^{228}Ac → ^{228}Th β decay

α and β decay

- **44 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

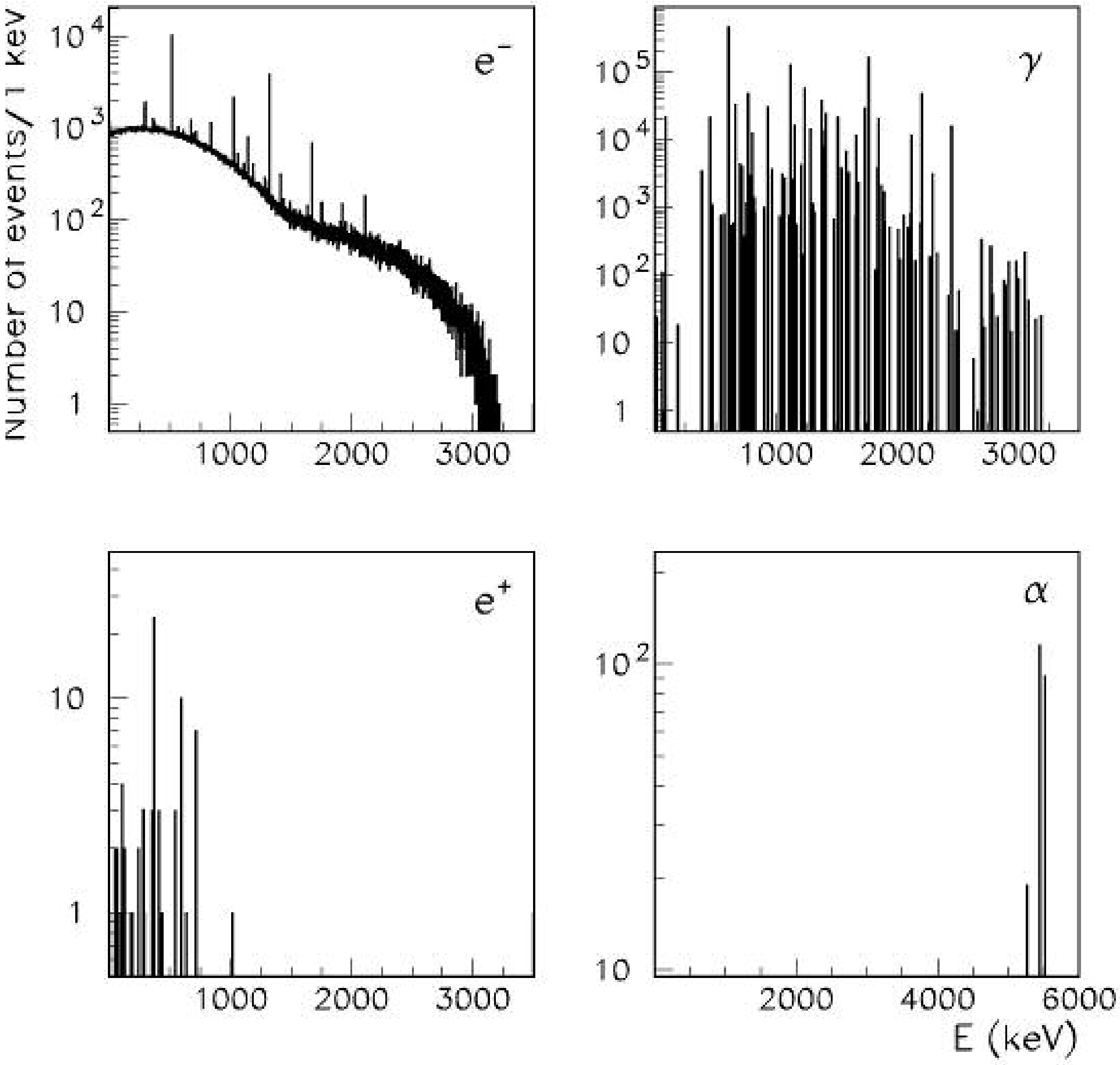
Ac228	Co60	K40	Sr90	Zr96+Nb96
Ar39	Cs136	K42	Ta182	
Ar42	Cs137+Ba137m	Mn54	Te133	
As79+Se79m	Eu147	Na22	Te133m	
Bi207+Pb207m	Eu152	P32	Te134	
Bi208	Eu154	Pa234m	Tl207	
Bi210	Gd146	Pb211	Tl208	
Bi212+Po212	Hf182	Pb212	Xe133	
Bi214+Po214	I126	Pb214	Xe135	
C14	I133	Rh106	Y88	
Ca48+Sc48	I134	Sb126	Y90	
Cd113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

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 GEANT 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 ~13,500 lines

Example of file generated by the DECAY0 ($2\beta2\nu$ 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
```

Current applications of the DECAY0:

LPD KINR (many years)

NEMO (since ~1992) & SuperNEMO

DAMA

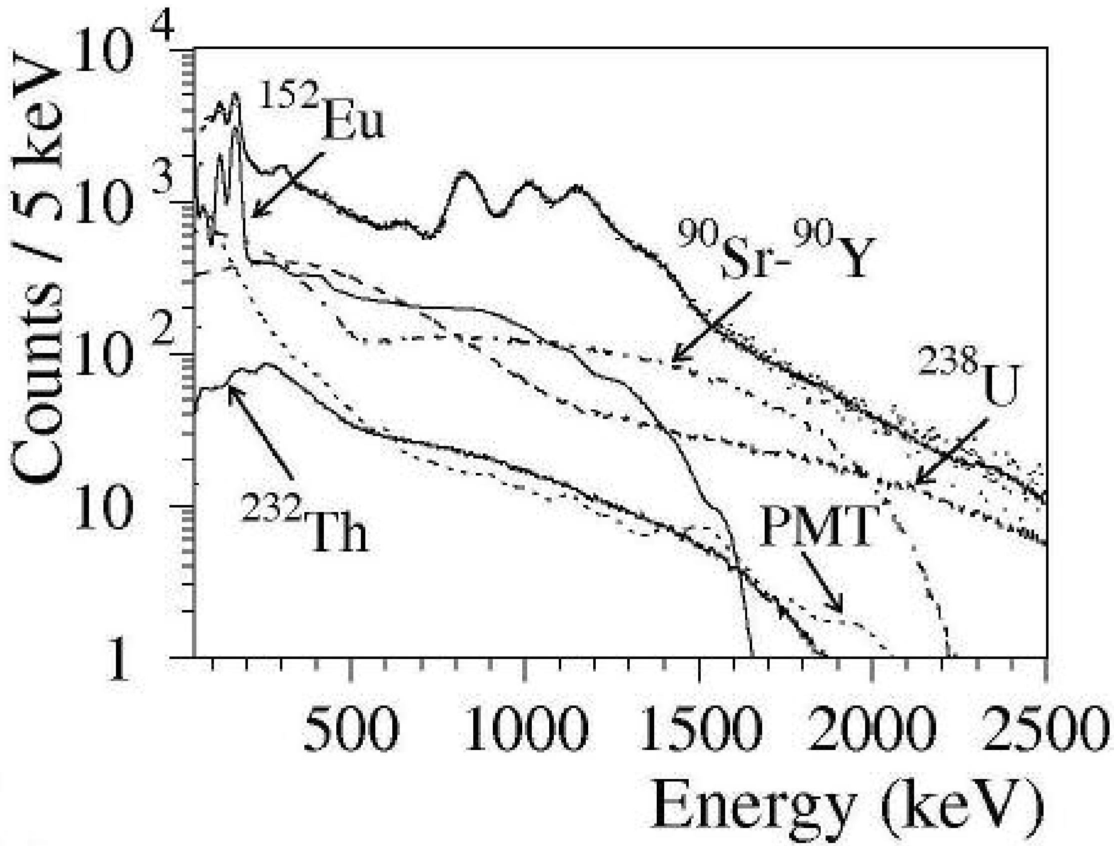
COBRA

GERDA (for 2β decay)

Example 1: KINR + DAMA

CaF_2 scintillator 370 g, 7426 h of measurements in the DAMA low-background R&D set-up at LNGS [NPA, in press]

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 [PRL 95(2005)182302]

$2\beta2\nu$ 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

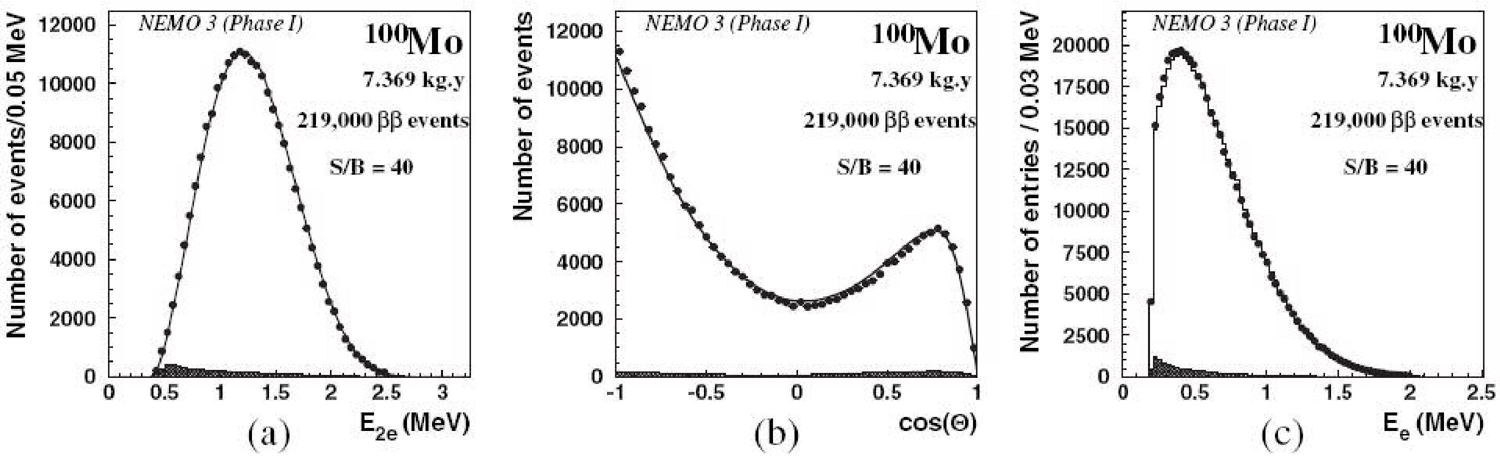


FIG. 2. (a) Energy sum spectrum of the two electrons, (b) angular distribution of the two electrons, and (c) single energy spectrum of the electrons, after background subtraction from ^{100}Mo with 7.369 kg · yr exposure. The solid line corresponds to the expected spectrum from $\beta\beta2\nu$ simulations and the shaded histogram is the subtracted background computed by Monte Carlo simulations. The signal contains 219 000 $\beta\beta$ events and the signal-to-background ratio is 40.

Conclusion:

DECAY0 event generator is to-date probably the most developed event generator in low-energy nuclear physics. It 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!