AN EVENT GENERATOR FOR BETA DECAY STUDIES BASED ON THE STATISTICAL NUCLEAR MODEL

María Dolores Jordán Martín
Instituto de Física Corpuscular
(CSIC-Univ. de Valencia)

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- Delayed neutron emission
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Introduction

- Complex experiments: design, optimization and performance characterization of experimental set-ups $\Rightarrow$ simulations
  - An event generator as realistic as possible
  - Good knowledge of decaying sources (decay type, γ-ray emission, possible emission of other particles,...)
- Geant4 simulation toolkit $\Rightarrow$ G4RadioactiveDecay is based on known nuclear level schemes from databases (high resolution measurements)
  - Not always complete (spin and parities)
  - Possibly affected from Pandemonium effect (A. Algora talk)

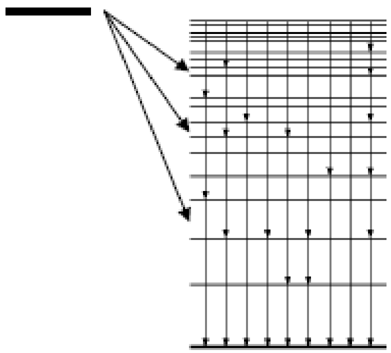
Objective

- An event generator for realistic simulation of complex beta decay experimental set-ups (more flexible than Geant4 “G4RadioactiveDecay”)
- Primary processes

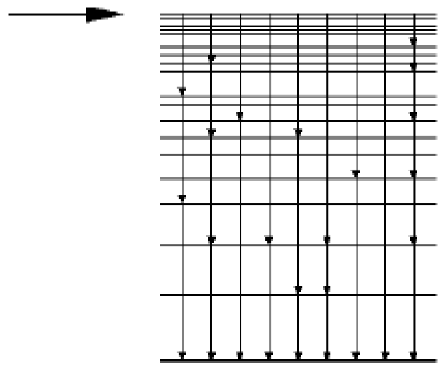
  β^--decay

  β^+/EC-decay

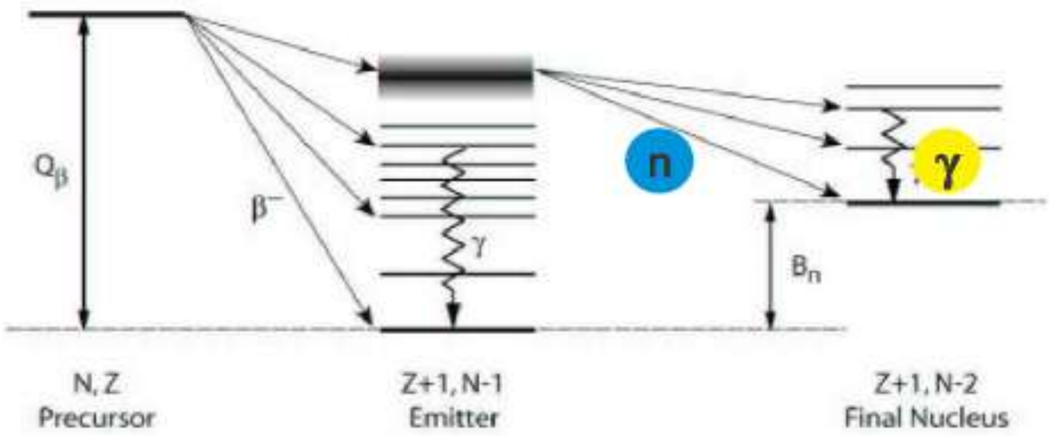
  βn-decay



Isomeric decay

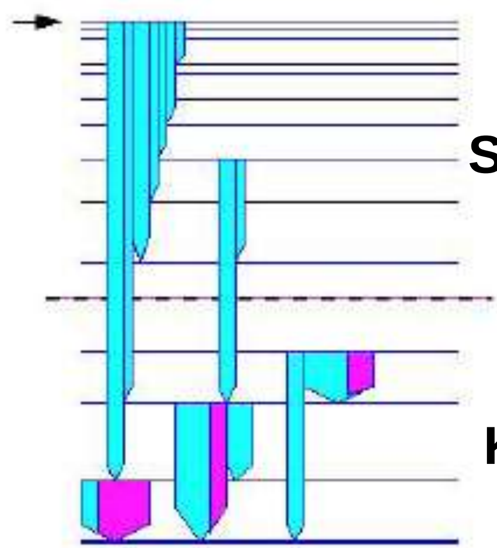


- Secondary processes
  - β-delayed neutron emission



Basis for generator

- Level scheme construction:
  - at low energies: known level scheme
  - At high energies (above the E_{cut}): statistical model



- β-strength distribution
- Approximations/simplifications:
  - β-spectral shape: allowed transitions
  - Electrons (EC or CE) only from K-shell
  - Above S_n, no γ/n competition ⇒ n emitted
  - Fluctuations in the statistical model are omitted

Low lying level scheme

- Information from ENSDF database
- Data not always complete: spin, parities, internal conversion coefficients,... of several levels are not given
- Level schemes considered complete up to E_{cut}.
- RIPL-2 library was complemented by T. Belgya with data missing in ENSDF for 3117 nuclides.
- http://www-nds.iaea.org/RIPL-3/levels/

Implementation of the statistical model (I)

- Nuclear level density:
  - Back shifted Fermi Gas formula
  - Constant Temperature
  - Gilbert-Cameron (CT + BSFG)

$$\rho(J,E_x) = \rho(J)\,\rho(E_x)$$

$$\rho(J) = \frac{2J+1}{2\sigma^2}\exp\left(-\frac{J(J+1)}{2\sigma^2}\right)$$

$$\rho(E_x) = \frac{1}{12\sqrt{2}\,\sigma\,a^{1/4}(E_x-\Delta)^{5/4}}\,e^{2\sqrt{a(E_x-\Delta)}}$$

$$\sigma^2 = 0.0145\,A^{5/3}\,t \quad , \quad t = \frac{1+\sqrt{1+4a(E_x-\Delta)}}{2a}$$

<d> ≈ ρ^{-1}

BSFG formula (a,Δ)

Implementation of the statistical model (II)

- γ-strengths: average radiation width from levels of spin-parity J^π at excitation energy E_x into levels within a certain interval

$$\langle \Gamma_\gamma \rangle = \frac{1}{\rho(E_x, J^\pi)} \sum \text{[illegible]}$$

  - L: multipolarity
  - X: transition character (E: electric, M: magnetic)
  - f_{XL}: strength functions

Average branching ratios: $b_{if} \propto \langle \Gamma_\gamma \rangle_{if}$

Implementation of the statistical model (III)

- Giant resonances functions (E_0, Γ_0 and σ_0):

Generalized lorentzian

$$f_{E1}(E_\gamma) = 8.674\times10^{-8}\,\sigma_0\Gamma_0\left[\frac{E_\gamma\Gamma(E_\gamma)}{\left(E_\gamma^2-E_0^2\right)^2+E_\gamma^2\Gamma(E_\gamma)^2}+\frac{0.7\,\Gamma_0 4\pi^2T^2}{E_0^5}\right]$$

$$\Gamma(E_\gamma) = \Gamma_0\frac{E_\gamma^2+4\pi^2T^2}{E_0^2} \qquad T=\sqrt{\frac{S_n-E_\gamma}{a}}$$

Standard Lorentzian

$$f_{M1}(E_\gamma) = 8.674\times10^{-8}\,\frac{\sigma_0 E_\gamma\Gamma_0^2}{\left(E_\gamma^2-E_0^2\right)^2+E_\gamma^2\Gamma_0^2}$$

$$f_{E2}(E_\gamma) = 5.22\times10^{-8}\,\frac{\sigma_0 E_\gamma^{-1}\Gamma_0^2}{\left(E_\gamma^2-E_0^2\right)^2+E_\gamma^2\Gamma_0^2}$$

Delayed neutron emission

- Neutron width:
  - The nuclear surface is equivalent to a change of potential ⇒ for emission of l-orbital neutron:

$$\langle \Gamma_n^l \rangle = \frac{1}{2\pi\rho(J,\pi,E_x)} T_n^l(E_n)$$

Square well potential

  - T_n^l: neutron transmission coefficients

$$T_n^l(E_n) = \frac{4 x v_l X}{X^2 + (2 x X + x^2) v_l'}$$

$$x = \frac{\sqrt{2\mu_n E_n}}{\hbar} \qquad X = \frac{\sqrt{2\mu_n (E_n + V_0)}}{\hbar}$$

l	v_l	v_l'
0	1	1
1	$\frac{x^2}{1+x^2}$	$\frac{1}{x^2} + \left(1 - \frac{1}{x^2}\right)^2$
2	$\frac{x^4}{9+3x^2+x^4}$	$\left(1 - \frac{6}{x^2}\right)^2 + \left(\frac{6}{x^3} - \frac{3}{x^2}\right)^2$
3	$\frac{x^6}{225+45x^2+6x^4+x^6}$	$\left(1 - \frac{21}{x^2} + \frac{45}{x^4}\right)^2 + \left(\frac{45}{x^3} - \frac{6}{x}\right)^2$

inputs

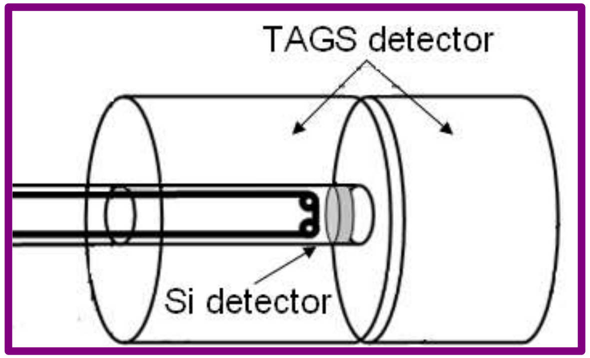
- Parent nucleus/level variables (A, Z, $T_{1/2}$, J^{π})
- Type of decay (β^-, β^+/EC, Isomeric Decay, βn)
- β-decay
  - Q-value
  - β-intensity distribution
  - known part of the level scheme: E_{lev}, J^{π}, E_{γ}, I_{γ} and α
  - unknown part of level scheme: parameters of the statistical model
  - neutron separation energy of the daughter nucleus (S_n) } βn
  - level scheme of the final nucleus (assumed always known) } βn
- Isomeric decay ⇒ De-excitation level scheme (assumed to be known)

Integration in Geant4

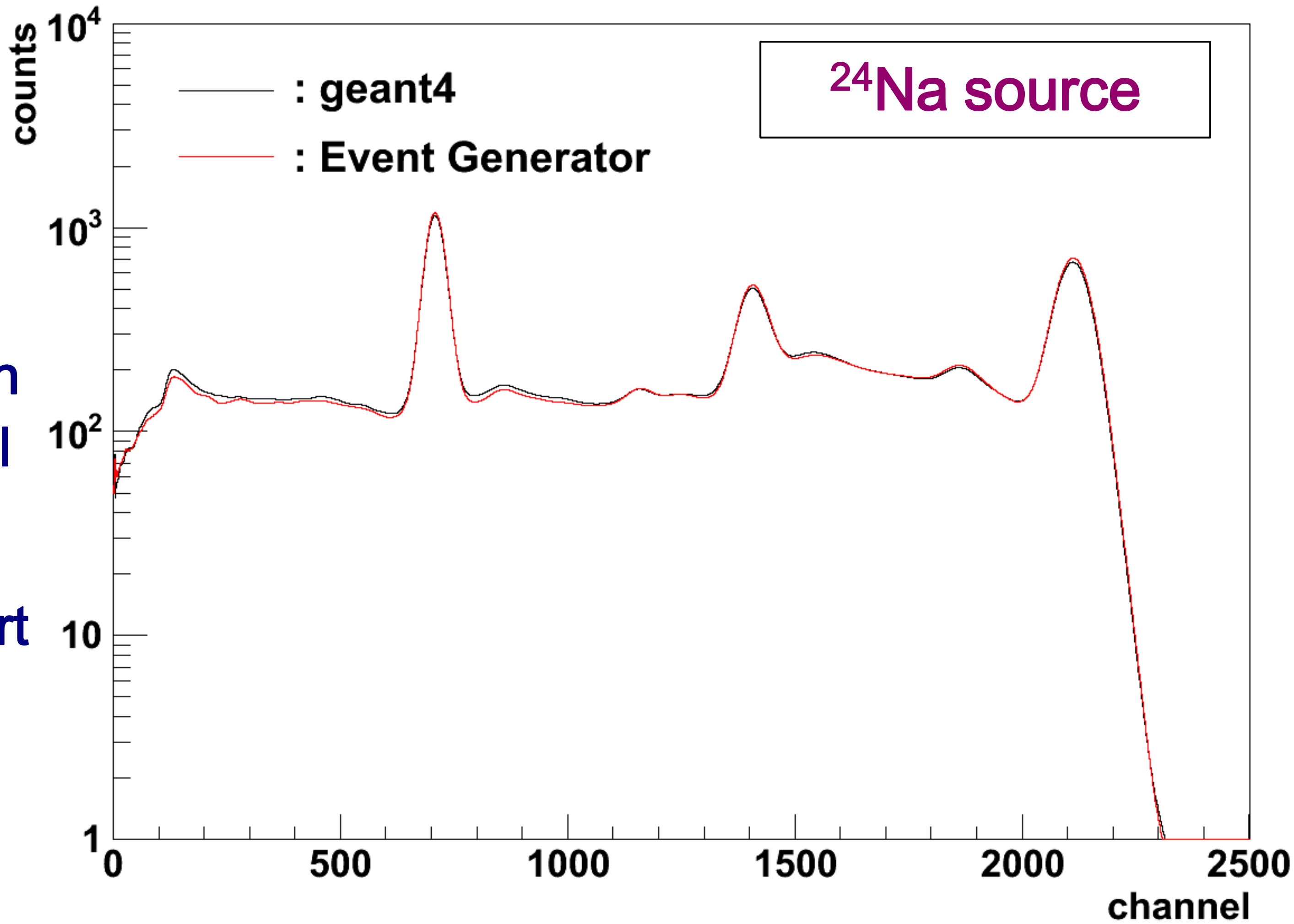
- Main program:
  - DecayGeneratorAction.cc
- External data files:
  - DecayGeneratorInput.dat
  - KnownLevelScheme.dat
  - BetaIntensity.dat (theoretical calculation for example)
  - DelayedNeutronLevelScheme.dat
  - BSFGparameters.dat (RIPL-2, RIPL-3) If the level density parameters for a given (Z,A) are not in the dat file a global parametrization is used (A.J. Koning et al., Nucl. Phys. A 810 (2008) 13)

Tests performed

- Simulation of a TAGS + Si detectors (experiment performed in Jyväskylä in 2007)



- Test using well known sources (knowm level scheme part)
- Test for unknown part of the level scheme (statistical model) using TAGS data



NEDENSAA NuPNET project

- NEDENSAA: NEutron Dectectors developments for Nuclear Structure, Astrophysics and Applications
- Collaboration of several European countries.
- Project interested in spectroscopy of exotic neutron-rich nuclei
- Optimization of the combination of different geometries: high resolution spectroscopy (Ge detectors) + neutron detectors or/and medium resolution, high efficiency ($LaBr_3$ detectors)
- Use of the event generator for the performance of the tests combining the different kind of detectors.

Status and future plans

- **Status:**
  - Adapted to the last version of Geant4 (geant4.6.0) and ready to be used.

- **Future plans:**
  - To make it more user friendly and simplifying imputs
  - To include the emission of other secondary particles: p and α
  - To include the decaying nuclei spatial implantation distribution
  - To include backgrounds:
    - Implantation breamsstrahlung
    - Beam-line related background
    - Ambient background

Summary

- We have developed a “realistic” event generator for design, optimization and performance characterization of β-decay experiments
- The statistical model of the nucleus has been used for population and decay of the nucleus at high excitation energies, above E_{cut}.
- The event generator has been integrated in the Geant4 framework and it has been tested.
- The event generator will be used, within the NEDENSAA (NuPNET) framework, for testing new combinations of detectors.

Thank you for your attention!

Thanks to the collaborators:
J.L. Taín & A. Algora