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Nuclear Physics B (Proc. Suppl.) 125 (2003) 75–79

NUCLEAR PHYSICS B
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GATE (Geant4 Application for Tomographic Emission): a PET/SPECT general-purpose simulation platform

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We present the development of GATE, the Geant4 Application for Tomographic Emission, as a new general purpose simulation platform for PET and SPECT applications. Built on top of the Geant4 simulation toolkit, it provides multiple new features with the objective to ease the use of Geant4 in the field of nuclear medicine. The handling of time, with the description of time-dependent phenomena such as movement of geometry elements or source decay kinetics, is a key and original feature of the platform. Scripting via a command language substitutes to C++ coding. This allows to set up simulations, from the description of the geometry to the modelling of the electronics. The high modularity of the design of GATE has allowed a fast and efficient development of its various components.

1. INTRODUCTION

Since a couple of decades, accurate Monte Carlo simulations have been widely used in parallel to analytical computations or experimental studies for a large range of positron emission tomography (PET) and single photon emission computed tomography (SPECT) applications such as scanner design, image reconstruction, scatter correction, or protocol optimisation [1].

GATE, the Geant4 Application for Tomographic Emission, combines the advantages of the general- purpose Geant4 simulation code [2] and of specific software tool implementations dedicated to emission tomography. Indeed, GATE takes advantage of the well-validated physics models, of the geometry description, and of the visualisation and 3D rendering tools offered by Geant4. Furthermore, GATE integrates specific components to facilitate its use in the PET/SPECT domain.

The software consists in several hundreds of C++ classes. They compose an object-oriented, modular set of components for PET and SPECT. Users may develop new modules fit to their requirements, and thus contribute to the extension of GATE capabilities.

One distinctive and original feature of GATE is the modelling of time-dependent processes: the changes with time in the geometry are kept synchronized with the evolution of the source activities and spatial distributions [3]. Moreover, GATE includes a coherent management of parallel multiple sources with independent time-profiles and locations.

A wide application range of GATE is provided by the creation of a dedicated scripting mechanism for modelling the scanner and attenuation geometries, for specifying complex source distributions, and for setting up detector models and

*This work was supported by the Swiss National Foundation for Research under Grant No. 21-63870.00 and by the Agassiz foundation.

doi:10.1016/S0920-5632(03)02224-2

output options. Moreover, an interface with the ROOT data analysis package [4] allows real-time visualization of all recorded information.

2. THE PLATFORM STRUCTURE

GATE encapsulates the Geant4 libraries into a set of layers written in C++. A core layer, close to the Geant4 kernel, comprises the base-classes that define the mechanisms embedded in GATE to manage time, geometry, sources and read-out. This includes building, positioning, replicating, and moving volume objects, as well as handling of decay kinetics of multiple sources. While some base-classes are derived from Geant4 classes, most of them define new class hierarchies and class collaborations.

An application layer implements concrete classes derived from base-classes of the core layer, *e.g.* to build specific volume shapes (boxes, spheres), or operations on these volume shapes (translation, rotation) and/or on read-out (models of energy resolution, event-wise encoders of output data). Users may extend the GATE functionalities by developing new classes within the application layer.

The scripting language of Geant4 is extended for each base- or application-class to allow interactive creation and control of objects. Provided that all necessary resources are already available in the application layer, the use of GATE does not require C++ programming at all: full set-up and control of the simulation is performed using interactive scripting or execution of macros.

3. MANAGEMENT OF TIME AND SOURCES

One of the most innovative features of GATE is the handling of time dependent phenomena, such as geometries with moving objects or sources with time-dependent activities. The capability of synchronising all time-dependent components allows a coherent description of the acquisition process. A detailed description of the time management in GATE is given in [3].

The movements of the geometry elements are dynamically created and their parameters are set via scripting. Several different types of movements are already implemented and can be attached to the objects one after the other to mimic complex real detector, phantom or patient movements.

The Geant4 General Source Particle Module (GSPM) was customised to handle multiple sources with different radioisotopes, activities and positions. A specific development is integrated in GATE to generate radioactive decay times following a chronological time flow. For each event, the source manager chooses randomly which source is going to decay from the current activities of all sources. The simulation of a chronological time flow allows the modelling of time-dependent detection processes (*e.g.* count rates, pile-up, dead time), either within GATE or after simulation using post-simulation analysis.

One example involving multiple sources is given in Figs. 1, 2 and 3 to illustrate the possibilities of GATE. In this example, a central line source (1 mm diameter, 1 cm length) filled with 1 MBq of ^{15}O was immersed into a water-filled cylindrical phantom (10 cm diameter, 5 cm length). The simulated scanner comprised arrays of 8×8 crystals (2×2×10 mm^3) of $Lu_{0.7}Y_{0.3}AP$ arranged in a 172 mm diameter ring of 30 modules. To model

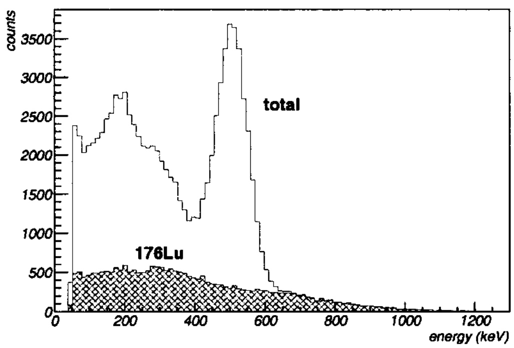

Figure 1. Energy response spectrum: the ^{176}Lu natural radioactivity spectrum (filled histogram) overlaps the photoelectric peak of the annihilation photons from the ^{15}O source.

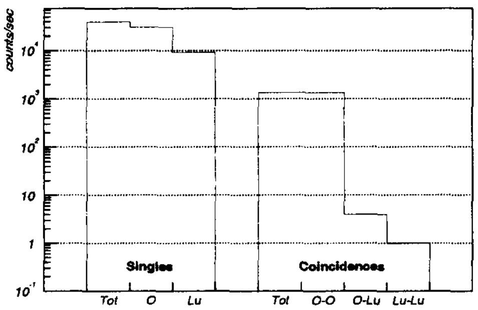

Figure 2. Summary of the counts of detected single gamma rays and coincidences as a function of the source origin.

the natural radioactivity of Lutetium-based scintillators due to ^{176}Lu, an activity of 22.3 kBq was uniformly distributed in the scanner crystal volume. The model included an energy threshold set at 400 keV, and an intrinsic energy resolution of 19% at 511 keV was set.

As a result, a significant background contribution to the energy spectrum is due to the detection of gamma rays from ^{176}Lu decays (Fig. 1). This contribution from ^{176}Lu is however reduced by two orders of magnitude if a coincidence of two signals above thresholds is required within a short time window. Fig. 2 shows a summary of the counts of detected single gamma rays and coincidences as a function of the source origin for a coincidence time window of 10 ns.

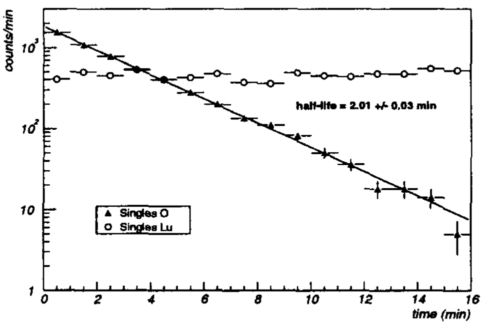

Figure 3. Counts of detected single gamma rays as a function of time for a ^{15}O source in presence of the ^{176}Lu natural radioactivity of the crystal materials.

In Fig. 3, the activities of ^{15}O and ^{176}Lu were reduced by a factor 10^3, down to 1 kBq and 22.3 Bq, respectively. Owing to its long half-life, the relative contribution of ^{176}Lu becomes more important as the ^{15}O activity decreases with time. An exponential fit to the ^{15}O counts gave a decay half-life of 2.01±0.03 min, consistent with the half-life of ^{15}O used for the simulation (2.02 min), while the ^{176}Lu contribution is constant with time.

4. GEOMETRY SCRIPTING

The construction of the geometry is one of the most time-consuming tasks during a standard Geant4 simulation set-up. Moreover, it is prone to errors, due to the long and repetitive work of C++ coding. Some tools are available for building the Geant4 geometry without C++ coding using automated code generation [5]. However, this approach does not permit the modification of the geometry during simulations.

As an illustration of the scripted approach used by GATE, the following sample of commands shows the construction of an 8×8 array of LuYAP crystals (2×2×10 mm^3) with a 2.25 mm pitch:

```
# C R Y S T A L
/gate/module/daughters/name crystal
/gate/module/daughters/insert box
/gate/crystal/geometry/setXLength 10.  mm
/gate/crystal/geometry/setYLength 2.  mm
/gate/crystal/geometry/setZLength 2.  mm
/gate/crystal/setMaterial LuYAP
# R E P E A T   C R Y S T A L
/gate/crystal/repeaters/name array
/gate/crystal/repeaters/insert cubicArray
/gate/crystal/array/setRepeatNumberX 8
/gate/crystal/array/setRepeatNumberY 8
/gate/crystal/array/setRepeatNumberZ 1
/gate/crystal/array/setRepeatVector 0.  2.25 2.25 mm
```

This illustrates the basic mechanisms used for the construction of complex geometries. First, new volume shapes are created, and their parameters (dimensions, material, position) are set. Then, these shapes may be replicated following regular patterns such as arrays or rings. The complete scanner shown on Fig. 4 was built using the same mechanisms.

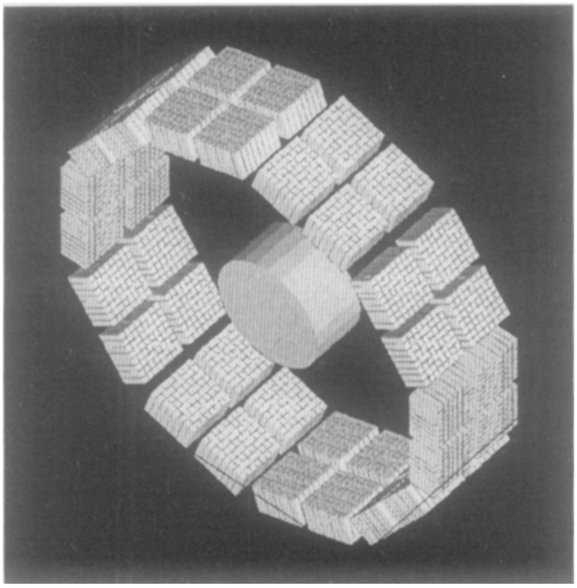

Figure 4. Example of a 2-ring PET detector geometry created applying "repeaters" with different patterns to a limited set of basic volumes.

Visual feedback is a key tool in both the development and the analysis of simulation studies. GATE makes use of all the visualisation tools offered by Geant4. Coupled together with the scripted geometry creation, interactive visualisation allows the user to see "on-the-fly" the introduction of new volumes and the effect of the changes in their parameters and positions.

5. EVENT ANALYSIS AND DATA OUTPUT

Data output for post-simulation analysis is not part of the Geant4 toolkit, even if hooks are foreseen for this purpose. GATE takes advantage of the common characteristics of PET and SPECT to offer data analysis, detector modelling and data output features specifically suited for these applications.

During simulations, the events are processed in order to extract relevant information: gamma histories are entirely followed and analysed *e.g.* to determine which source originated the event, to count the number of scatter interactions, etc.

Geant4 simulation histories yield very "low-level" information such as the energy deposited during each interaction. The use of these interaction histories in order to mimic realistic output data is realised with a dedicated module. The latter models the detector and its electronics responses as a user- defined, linear signal processing chain. Various components are available (position and energy resolutions, electronics thresholds) and can be inserted via scripted commands. Fig. 5 shows an example of such a readout chain.

Furthermore, several output options are provided to the user: both the "low-level" information and the output of the detector modelling can be stored in parallel into multiple output files with different formats (*e.g.* ASCII, ROOT [4], Interfile...).

Finally, GATE is interfaced with the ROOT data analysis package [4] to allow real-time visualization of all recorded information during sim-

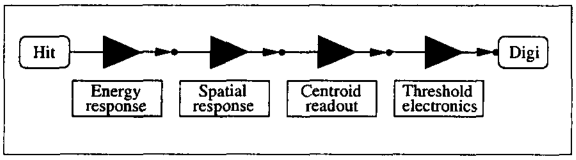

Figure 5. Example of the application of a chain of signal processing modules to model the detector readout.

ulations. The user can select via scripting any number and type of information to be plotted.

6. CONCLUSIONS

The implementation of a new simulation tool using Geant4 has been described: GATE has been specifically designed for PET and SPECT applications. The handling of time at many levels of the simulation, from the movement of geometry elements to source decay kinetics, is a key and original feature of this platform. The ease of using this platform to define various experimental set-up configurations is a result of the interactive scripting mechanism implemented in GATE. The analysis and readout modules provide the user with a versatile mechanism for the extraction and for the treatment of relevant information from the simulation. All these features make GATE a very promising tool for a wide set of applications in PET and SPECT.

Further development and validation of GATE is presently carried on within the OpenGATE collaboration [6], with the objective to provide the academic community with a free, general-purpose Geant4-based simulation platform for emission tomography. This quickly-growing collaboration makes the development and validation of GATE benefit from the specific experience of each member of the collaboration. The "gridification" of GATE is currently under development and a public release of the software should hopefully be announced during summer 2003.

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