Modeling Liquid Noble Gas Scintillation Detectors

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Abstract

SoftWare for Optimization of Radiation Detectors, SWORD[1] is a framework and graphical user interface (GUI) for simulating radiation detectors by using existing Monte Carlo radiation transport code. SWORD can use either the GEANT 4 toolkit from CERN[2] (version 8.1 is included with SWORD version 4.0) or the MCNPX[3] code as its simulation engine. SWORD was used with the GEANT 4 engine to simulate a liquid krypton detector for photon and neutron beams as a function of energy. The generated HepRep file was rendered in WIRED4, a plugin to the JAS3 Analysis System, and filtered to show the particle trajectories of interest. A mapping of the energy density deposited by gamma rays within the detector will be created to improve understanding of scintillation light production and propagation within the detector, which will help in improving the measured energy resolution of gamma rays.

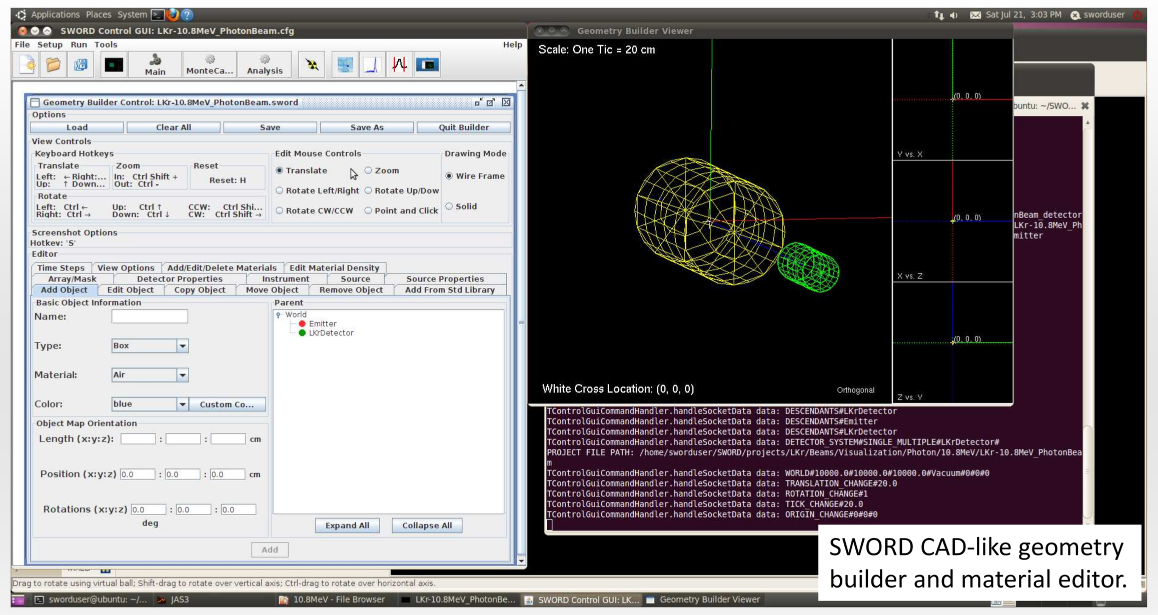
SWORD

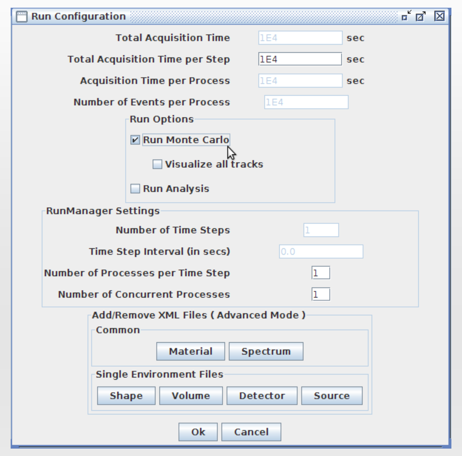
SWORD is intended for system designers, sponsors and operators that want to easily simulate and evaluate radiation detection systems without having to construct the actual hardware system. Radiation detection instruments are constructed using a CAD-like graphical interface to assign a material, detection and/or emission properties to objects. Objects can be positioned, grouped, arrayed or nested to produce compound objects, and materials can have customized elemental compositions and densities. SWORD also includes several "standard" objects, sources and detector designs that can be used and customized by the user.

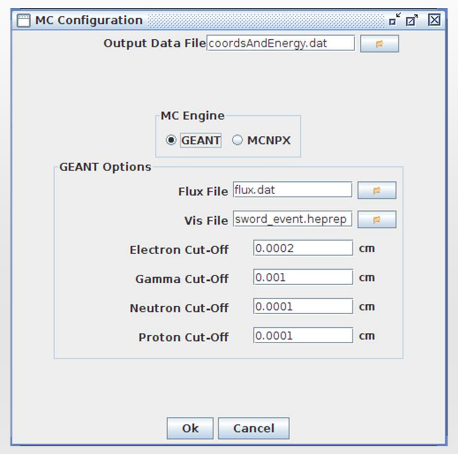
As a graphical front-end, SWORD can interface independently of the chosen Monte Carlo engine. SWORD gives the option using one of the two simulation engines: GEANT 4 from CERN (version 8.1 included with the SWORD distribution) and MCNPX. The SWORD workflow consists of four steps:

- Design the scenario: geometric elements, material properties, radioactive emission, and detector properties. SWORD includes a CAD-like interface for building geometries.
- Configure the run: simulation duration, select analysis processes to be run, and what outputs to be produced.
- Run the simulation. This is normally done within the SWORD interface but a "batch" mode without graphical interface is available as well.
- Examine the results. Interactive viewers for spectra and images are provided by SWORD. Spectra and images are output as ASCII text files that can also be read by a variety of other tools such as spreadsheets.

User Interface

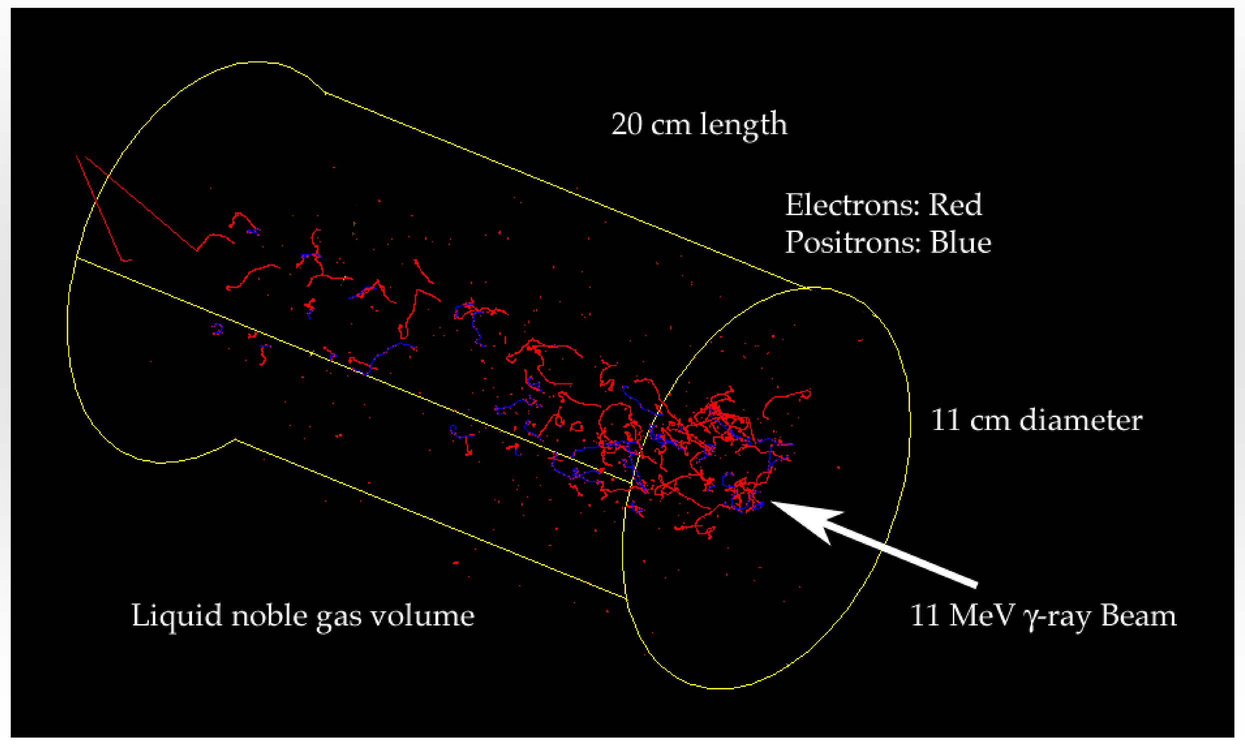

SWORD CAD-like geometry builder and material editor.


Simulation run configuration window


Monte Carlo configuration window

The SWORD simulation begins by building the simulation world in the geometry builder, which is a CAD-like interface. From here, primitive shapes like boxes, cylinders and spheres can be constructed that are made out of custom materials and can have detector or radiation emission properties. The next step is to configure the run options, which includes how long to run the simulation and what outputs the simulation should produce. Some MC radiation transport code options for either GEANT or MNCPX can be configured as well. Finally, the user can select whether or not to perform an analysis on the MC output such as generating an energy spectrum.

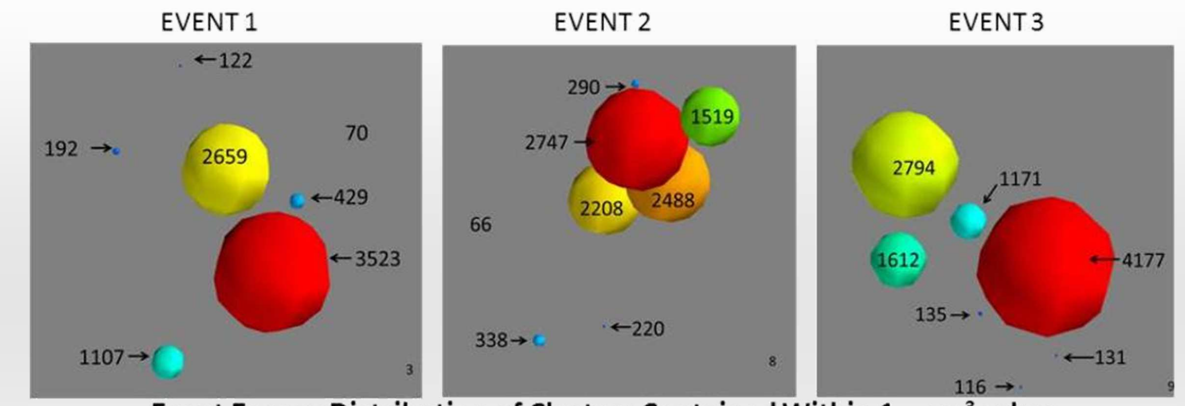
SWORD–Detector Particle Tracks



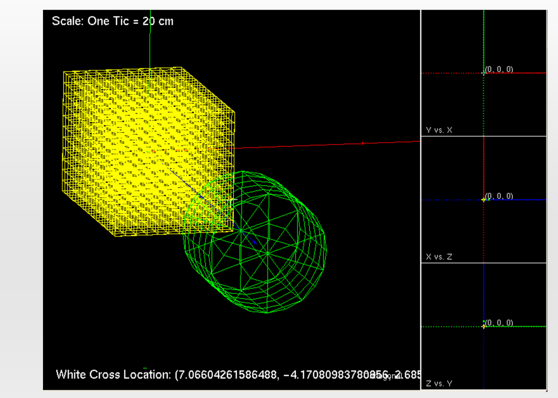
To simulate a vacuum chamber similar to a future detector design, the simulation world was set to be a vacuum. A simple model of a liquid noble gas (LNG) detector was constructed using a cylinder of liquid krypton 20 cm long and 11 cm in diameter, and a cylindrical beam source was placed 25 cm away from the front face of LNG detector on the same axis, directed straight towards the face. The source was set to generate 2.22 MeV, 6.1 MeV or 10.8 MeV photons randomly distributed on the source cylinder's face at a rate of one per second.

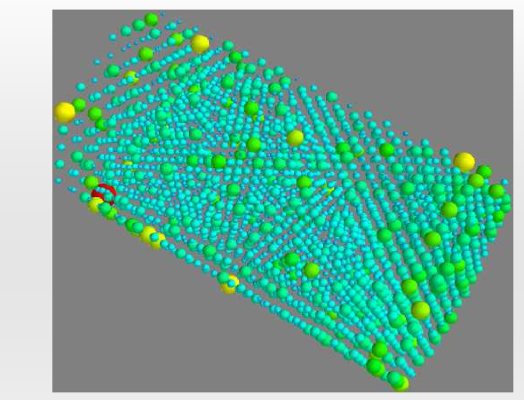
The simulation was set to run for 100 seconds, producing GEANT4 Monte Carlo (MC) simulation results, visualization tracks of the particle trajectories and detector energy spectra. Using WIRED 4 "cuts", the HepRep visualization tracks were filtered to show only nonzero charges—negative charges shown in red and positive charges shown in blue—thus removing the photon tracks.

SWORD–Detector Energy Density Calculations



Event Energy Distribution of Clusters Contained Within 1 – cm³ cubes Energy in keV

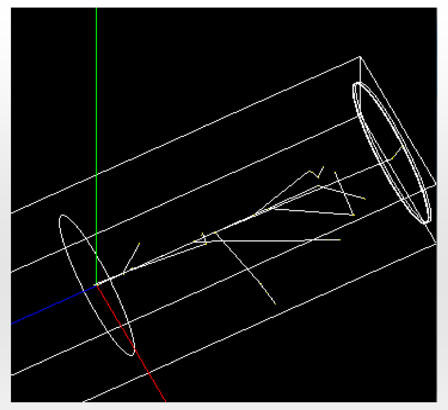

LNG detector array with 10.8 MeV γ-beam source


LNG detector array with 10.8 MeV γ-beam source

When determining the energy densities inside the detector, an array of 11 by 11 by 20 1 cubic centimeter LNG detectors were used as a model of the cylindrical LNG detector. A single event was simulated per run, and the GEANT4 output was parsed using a Perl script that output the energy deposited in each small detector volume, or voxel, for each "hit" in that voxel. A Python script then opened the Perl script output files to plot the result in a 3D Mayavi plot. A 10,000-event simulation was also run with 10.8 MeV photons to find and plot the average energy deposited in each voxel per hit.

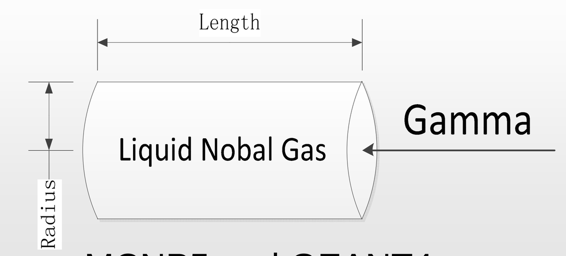
Monte Carlo Simulation Codes

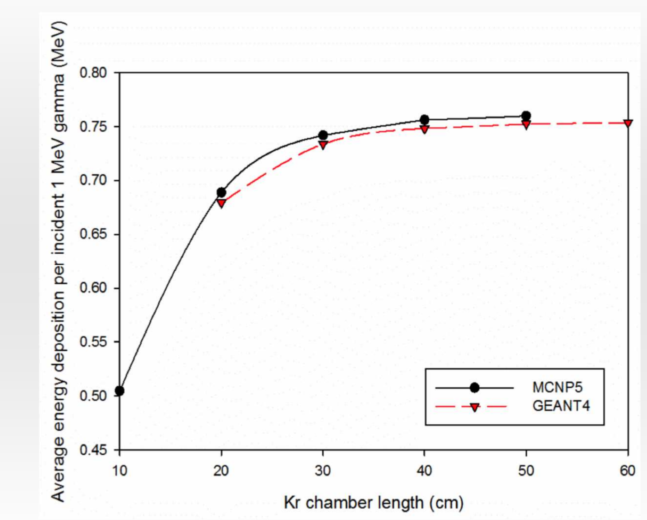
- Cylindrical detector volume is considered in the Monte Carlo simulation.
- For verification of the model, MCNP5 and Geant4 are compared
- MCNPX: Developed by Los Alamos National Laboratory and stands for Monte Carlo N-Particle[3].
- GEANT4: A toolkit developed by European Organization for Nuclear Research for the simulation of the passage of particles through matter[4]:
  - GEANT4 provides a complete set of tools for all areas of detector simulation: geometry, tracking, detector response, run, event and track management, visualization and user interface.
  - To accurately model the low energy processes in GEANT4, the experimental data based Livermore low energy electromagnetic process is used.
  - The cutoff energies are set to 250 eV for both gamma and electron.

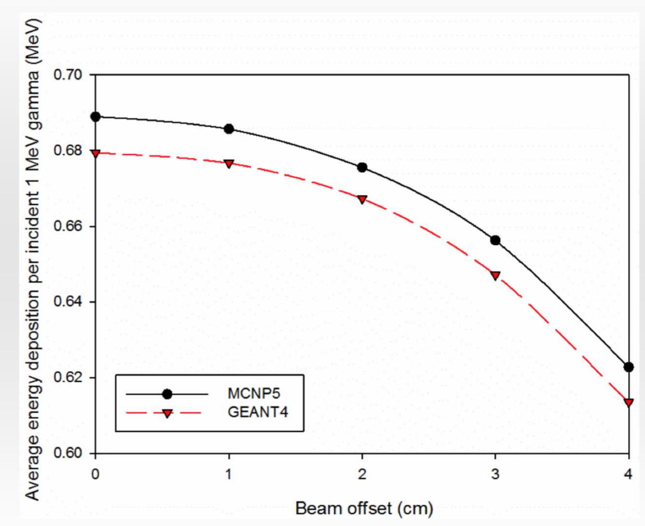

Trajectories of 7 incident 1 MeV gammas and their secondaries. White lines denote neutral particles (photons).

Average Energy Deposition per Incident Gamma vs. Kr Chamber Length /Gamma Beam Offset

- Pure liquid Kr
- Kr chamber radius: 5 cm
- Incident gamma: 1 MeV
- Source: beam- cylindrical
- Events: 1 M incident gamma
- Good agreement achieved between MCNP5 and GEANT4
- GEANT4 used 2.413 g·cm^{-3} as the liquid Kr density while MCNP5 used 2.45 g·cm^{-3} as the density which may accounts for the small difference.
- GEANT4 calculation shows that about 90% deposited energy are deposited by electrons through ionization, Bremsstrahlung and scintillation processes.
- The other 10% deposited energy are deposited by photons through photoelectric effect, Compton scattering and Rayleigh scattering.

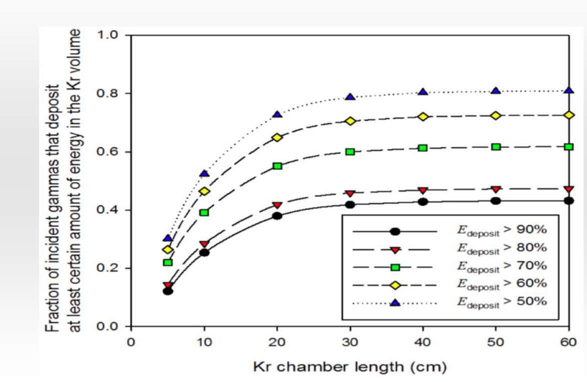


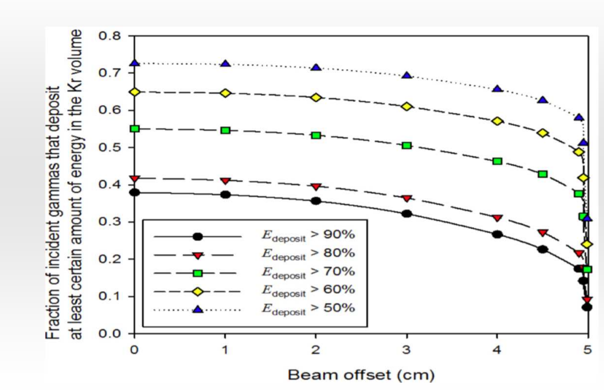




Fraction Energy Deposition for 1 MeV Gammas in the LKr Chamber

- Figures show GEANT4 calculation results (Pure liquid Kr)
- Compared to MCNP5 results of $E_{deposit}$ > 0.995 MeV, all absolute difference is lower than 0.01, except for the case of 4.99 cm offset, where GEANT4 calculated fraction is 0.0672, but MCNP5 result is 0.1573
- In general, the two Monte Carlo methods agree well with each other.





Acknowledgments

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References

1. Oak Ridge National Laboratory (2012, Apr.). RSICC CODE PACKAGE CCC-767 [Online]. Available: http://www-rsicc.ornl.gov/codes/ccc/ccc7/ccc-767.html.
2. GEANT4 - a simulation toolkit, S. Agostinelli *et al.*, Nucl. Instrum. Meth. A **506**, 250 (2003).
3. MCNPX, LANL, LA-UR-11-1502, March, 2011.
4. D. S. Koltick et al., *AIP Conf. Proc.* 1099 (2009) 685.
5. M. G. Hosack, S. M. Hassan, A. Hassenein, D. S. Koltick, IEEE Transactions on Nuclear Science, submitted (2012)
6. S. M. Hassan, Ahmed Hassanein, David S. Koltick, Nader Satvat, Xue Yang, IEEE Transactions on Nuclear Science, submitted (2012)

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