HOU Reconstruction & Simulation (HOURS): An update on event generation & simulation tools

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- HOURS overview
- Detector description and Simulation
- Muon± capture/decay
- Event generation and simulation for the sparse ORCA detector
- Light produced by $\nu_\mu$ and $\bar{\nu}_\mu$ fully contained CC events
- Event generation and simulation for the sparse ORCA detector
- Conclusions
Developed by HOU physics laboratory team
- Event generation (A. Tsirigotis, D. Lenis)
- Detector description and Simulation (A. Tsirigotis)
- Optical noise, PMT response and electronics simulation (A. Tsirigotis, G. Bourlis)
- DOM charge reconstruction/Pulse arrival time corrections (G. Bourlis)
- Prefit and filtering algorithms (A. Tsirigotis)
- Event reconstruction (A. Tsirigotis, D. Lenis)
  - Event direction estimation
  - Energy reconstruction
- Analysis Tools (A. Tsirigotis, S. Tzamarias, A. Leisos)

Users
- HOU physics laboratory team, ...

Documentation/availability
- Documentation will be soon available (preparing user guide)
- Package available in Lyon at:
  - /sps/km3net/users/tsirigot/HOURS (see README files for details)
    - Detector description and simulation
    - Optical noise and PMT response simulation
  - /sps/km3net/users/tsirigot/genie (see README files for details)
    - GENIE based event generator

Simulation data format
- ANTARES evt format
Detector description & Simulation

- Any detector geometry can be described in a very effective way (GDML input)
- All the relevant physics processes are included in the simulation

Full GEANT4 simulation

Fast Simulation

SLOW

2 to several thousand times faster than full Simulation (depended on muon energy and DOM density)

Parametrizations for:

- EM showers (from e-, e+, γ)
- HA showers (from long lived hadrons)
- Low energy electrons (from ionization)
- Direct Cherenkov photons (from muon)

Each parametrization describes the number and time profile of photons arriving on a PMT in bins of:
Shower energy (E) (EM and HA showers)
PMT position (D,θ) relative to shower vertex/muon position,
PMT orientation (θ_{pmt},φ_{pmt})

Shower vertex/muon position

Shower/muon direction

θ

D

pmt axis

θ_{pmt}

φ_{pmt}
Detector description & Simulation - physics processes

**All non-stable**
- Decay

**All charged**
- Cherenkov
- Ionization
- Multiple Scattering

**Optical photon**
- Absorption
- Mie & Rayleigh scattering

**Gamma**
- Gamma Conversion
- Compton Scattering
- Photo Electric Effect
- Fast simulation process (EM)

**Electron/Positron**
- Bremsstrahlung
- Fast simulation process (EM)

**Positron**
- Annihilation

**Muon-/Muon+**
-Muon Ionization
- Bremsstrahlung
- Pair Production
- Muon Nuclear Interaction

**Muon-**
-Capture At Rest (NEW)

**Hadron**
-Hadronic Elastic scattering processes
-Hadronic Inelastic scattering processes

**Pion-/Kaon-**
-Capture At Rest (NEW)

**Pion±/Kaon±/KaonZeroLong/Proton±/Neutron±**
-Fast simulation process (HA)

**Proton-**
-Annihilation
Muon-$^-$ captured by atoms

Muon-$^-$ decay in K-shell ($\sim$90%)

Muon-$^-$ captured by nucleus ($\sim$10%)

Muonic atom with the muon at 1s state

Total energy deposition by secondaries
(e + low energy $\gamma$
(y + low energy e)

Muon$^+$ decay

Total energy deposition by secondaries
(positron)
Muon± capture/decay

Emission time of secondaries (with respect to the time the muon stops)

- Muon- decay in K-shell
- Muon- captured by nucleus
- Muon+ decay

• Decay/capture times not very different
• Muon- decay in orbit (high energy secondaries) is 10 times more frequent than capture (low energy secondaries)

In principle in ~10% of the $\nu_\mu$ CC events you can identify a Muon- by looking at the produced light at the track end

![Graphs showing decay and capture times](image.png)
Neutrino event generator based on Genie v2.7.1

Complete composition of sea water and crust taken into account (also in simulation)

Sea water composition

| Abundance | Abundance Na = 0.5360 mole/kg; |
| Abundance | Abundance Mg = 0.0604 mole/kg; |
| Abundance | Abundance Ca = 0.0118 mole/kg; |
| Abundance | Abundance K = 0.0117 mole/kg; |
| Abundance | Abundance Cl = 0.6240 mole/kg; |
| Abundance | Abundance SO4 = 0.0322 mole/kg; |
| Abundance | Abundance HCO3 = 0.0027 mole/kg; |

Bartol flux (solar minimum) for

\( \nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu \)

\( E^{-2} \) flux for \( \nu_\tau, \overline{\nu}_\tau \)

Particles that cannot by default handled by GEANT4 are forced to decay in Genie
Sparse ORCA detector configuration

50 Strings, ~20m spaced
20 DOMs per string, 6m spaced
1.75 Mt instrumented volume

1000 DOMs

~1 CPU sec/event for full GEANT4 simulation
Low energy neutrino generation run – Sparse ORCA detector

- 1-100 GeV Bartol flux (solar minimum) for $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$

- 1-100 GeV $E^{-2}$ flux for $\nu_\tau$, $\bar{\nu}_\tau$

- Only the fully-contained CC $\nu_\mu$, $\bar{\nu}_\mu$ events in the detector instrumented volume are processed for this study

Files available in /sps/km3net/users/tsirigot/ORCARunDense/bartol_genie_gene/run10 (see README for details)
Selection of events

$\nu_\mu, \bar{\nu}_\mu$ events with interaction vertex and muon track end inside the detector instrumented volume

- $\nu_\mu$: 225000 events
- $\bar{\nu}_\mu$: 216000 events

65m horizontal distance from detector center
50m vertical distance from detector center
Light from muon-/hadronic vertex (\(\nu_\mu\) events)

Increasing the neutrino energy events with higher inelasticity are chosen (edge effect)

Bars represent RMS
Light from muon+/hadronic vertex ($\bar{\nu}_\mu$ events)

Increasing the neutrino energy events with higher inelasticity are chosen (edge effect)

Bars represent RMS

- Total
- From muon
- From Hadronic vertex

Graphs show the number of pes as a function of neutrino energy.
Detected light from decaying/captured muon-

Subtract photon travel time \[ t_c = t - \frac{D}{u_g} \]

Number of pes from decayed/captured muon- in a time window 10ns

38% of $\nu_\mu$ CC fully contained events have at least one detected photon created by the muon- decay/capture

D = distance between muon track end position and DOM
\[ u_g = \text{group velocity at maximum QE} \]

Number of pes from decayed muon+ in a time window 10ns

41% of $\bar{\nu}_\mu$ CC fully contained events have at least one detected photon created by the muon+ decay
Dense ORCA detector configuration (for optimization studies)

2181 Strings on a 3m x 3m grid
51 DOMs per string, 3m spaced
2.85 Mt instrumented volume

111,231 DOMs

~200 CPU sec/event for full GEANT4 simulation
Low energy neutrino generation run – Dense ORCA detector

- 1-30 GeV Bartol flux (solar minimum) for $\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$
- 1-30 GeV $E^2$ flux for $\nu_\tau, \bar{\nu}_\tau$

Files will be available soon in /sps/km3net/users/tsirigot/ORCARunDense/bartol_genie_gene/run20
Summary & Outlook

- HOURS simulation code has been updated with the inclusion of muon-/pion- capture processes by a nucleus.
- Parts of HOURS are available in Lyon with basic script documentation. More documentation to come.
- In 90% of the cases you cannot tell a $\nu_\mu$ from a $\bar{\nu}_\mu$ CC event by looking at the light produced at the muon track end. In the remaining 10% of the cases the identification depends on the detection efficiency of the produced light and the background ($^{40}\text{K}$ and atmospheric muons).
- Event generation and simulation is produced for a dense detector layout for ORCA optimization purposes.