# 4. MC Simulation of the Soudan 2 Experiment

This chapter deals briefly with the Soudan 2 simulation software package, to be referred to as the Monte Carlo, or MC. The presentation of the simulation of atmospheric neutrino Physics and the operation of the detector only scrapes the surface and is given here only for the reader's reference. The MC is described in detail in [18] and [47].

The full Monte Carlo simulation of an event in Soudan 2 involves a series of different tasks, broadly grouped into two categories: the event generator and the detector simulation.

## 4.1 The Event Generator

The event generator will select the initial and final states of the neutrino interaction. The initial state is defined by the incident neutrino, which is described by its four-vector and lepton type, and the struck nucleus, which is chosen by considering the relative abundance of different nuclei types in the detector, plus the struck nucleon which is assigned some Fermi momentum. The products of the neutrino interaction depend upon the cross-sections of the available neutrino scattering processes at the neutrino incident energy and are described by the particle types and four-vectors.

Atmospheric neutrinos are the decay products of particles (mainly pions and muons) which are part of particle cascades that have been produced by the interactions of cosmic rays in the upper atmosphere, typically at a height of 20 km from the surface of the Earth.

The atmospheric neutrino fluxes on the surface of the Earth are inferred by measurements of the cosmic ray composition conducted in balloons in the upper atmosphere or in satellites during the 1960’s and 1970’s [71]. From there on, a simulation of the cosmic-ray particle cascades yields the neutrino fluxes as a function of energy and zenith angle for each neutrino flavour and lepton type [19]. Such a simulation takes into account experimentally measured cross-sections, branching ratios and decay rates. Attention is also given to geomagnetic factors and to the effect of solar wind on the cosmic ray flux. The solar wind is a magnetic field trapped in expanding solar plasma and produces a barrier which cosmic-ray protons travelling to the Earth must penetrate. Its magnitude is correlated with the solar cycle (which has a period of 11 years) and its modulations can be monitored by the sunspot count: the cosmic ray flux will decrease with increasing sun activity. Alternatively, the fluxes of cosmic-ray neutrinos are related to those of neutrons generated in cosmic ray cascades in the atmosphere because their production is due to the same processes. Hence, the fluctuations in the neutrino flux can be inferred by neutron monitor data, which measure the flux of hadrons produced in cosmic ray cascades in the atmosphere. Neutron monitor data [22] was available for the normalisation of neutrino fluxes only for the early period of the life of the Soudan 2 experiment, namely up to 1995 (run 50000). For the later period, the MC sample generated for this thesis uses a sinusoidal approximation of the solar cycle.

The neutrino interaction cross-sections are based on theoretical models, which are fitted to data from neutrino scattering experiments on various targets. For the energy range relevant to atmospheric neutrinos, cross-sections have been measured in bubble chamber experiments. At low energies, charged current neutrino-hadron interactions are predominantly quasi-elastic and single pion production, in which the neutrino scatters off an entire nucleon rather than the constituent partons. Neutrino charged current interactions can also produce baryon resonances, which decay to final states consisting of a proton or neutron and at least one pion. Deep inelastic interactions in which the neutrino scatters off individual partons in the nucleus contribute little to the atmospheric neutrino interaction cross-sections, since they come into effect above 5 GeV.

In the present thesis, the following separation into quasi-elastic, inelastic and neutral current processes will be adopted:

$$\begin{aligned}
\text{quasi-elastic:}\quad & \nu + N \rightarrow \ell\ \text{(lepton)} + p \text{ or } n \\
\text{inelastic:}\quad & \nu + N \rightarrow \ell\ \text{(lepton)} + p \text{ or } n + \text{(one or more) } \pi\ \text{(producing hadrons)} \\
\text{neutral current:}\quad & \nu + N \rightarrow \nu + N(+\pi)
\end{aligned}$$

Nuclear Fermi momentum and its effect on the final state momentum of the event is incorporated in the Monte Carlo. The nucleus is described as a degenerate fermion gas with filled energy states up to the Fermi momentum. A final state nucleon produced with momentum less than the Fermi momentum for the material is forbidden by the Pauli exclusion principle. Pauli blocking is incorporated in the Soudan 2 MC for elastic and quasi-elastic events. Finally, the final state nucleus may be produced in an excited state, from which it will decay by emitting low energy particles. Such nuclear decays are not simulated by the Soudan 2 MC.

## 4.2 The Detector Simulation

Once the Event Generator has defined the four-vectors of the final state, the products of the neutrino interaction will be tracked through the detector medium. The MC knows the exact detector configuration (i.e. the position of active modules and that of their internal components) at the epoch of the simulated event by interrogating the Soudan 2 database. The performance of each module at the time is also known through the use of a condensed version of the Half-Tube database.

The interactions of electrons and photons are simulated using the EGS library of routines while hadronic interactions, including nuclear elastic and inelastic scattering, nuclear capture and meson absorption, are simulated using routines largely based on GHEISHA. Multiple Coulomb scattering, ionisation energy loss and energetic delta ray production are all simulated for charged particles. Unstable particles can decay in flight.

Charged particles travelling through the Ar/$CO_2$ gas in the drift tubes lose energy as determined by ionisation fluctuations [4] by sampling from the appropriate dE/dx distributions in 1mm steps along the particle's path. There is no tracking of the deposited ionisation drifting to the wireplane. Instead, the pulse shape is determined by calculating the energy loss due to electron diffusion and oxygen attachment; the effect of module efficiency is also simulated.

The electron avalanche on the wireplane, and its amplifying effect on the signal, is not simulated in detail but is folded instead with the digital and analogue electronics response to give a final count figure in the analogue card RAMs. The output of this process is calibrated by the comparison to real cosmic-ray muon pulses in the main detector. Finally, included in the electronics simulation is the presence of cathode cross-talk.

Finally, Soudan 2 modules had been placed in muon and electron test beams of various energies and angles of incidence (at the Rutherford Appleton Laboratory, UK). The Monte Carlo faithfully reproduced the data. On an every-day basis, the Monte Carlo pulse-height response is calibrated against cosmic ray muons tranversing the main detector.

### 4.2.1 Detector Configuration and Noise as a Function of Time

The **MC** event sample generated for this analysis follows correctly the detector behaviour and evolution. This is done by overlaying the generated neutrino interactions on randomly sampled **PULSER** events over the lifetime of data taking.[7] **PULSER** events have been collected by pulse-triggering the detector several times every run, recording both the main detector

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[7] I would like to thank Prof. Earl Peterson for providing me with the software for randomly selecting **PULSER** events.

noise (due to breakdowns or radioactive hits) as well as the random shield activity (due to radioactivity from the rock). In this fashion, MC events are made indistinguishable from real events, simulating faithfully any systematic effects.

## 4.3 MC Samples for any General Neutrino Mixing Scenario

The standard Soudan 2 MC package generates a set of atmospheric neutrino interactions according to the Standard Model neutrino Physics, as described above. Alternatively it will produce MC-simulated samples where the neutrino is allowed to oscillate (according to a neutrino-mixing model and parameters chosen by the user) from its production point to the detector, where it interacts. This is accomplished by weighting accordingly the atmospheric neutrino energy and angular spectra for the two initial neutrino flavours while a tau neutrino spectrum is also introduced if the model so requires.[8] If one wishes to compare distributions of real data with those from a wide variety of neutrino-mixing models, the only option under the circumstances is to produce a MC sample for each one of these models. This may prove to be a very tedious and time-consuming business. Such a task is not feasible, if the ultimate aim is to measure the best fit of neutrino-mixing parameters to the data, where, in principle, the number of MC samples is infinite.

An elegant way to bypass this inconvenience requires a simple, albeit significant, addition to the MC [8]. Neutrinos will be generated with a *production* flavour and an *interaction* flavour, which may or may not be the same. The neutrino production family, energy and zenith angle are chosen according to the relevant distributions of atmospheric neutrinos, exactly the same way as in the generation of non-oscillated atmospheric neutrino events. However, the neutrino is allowed to interact with another flavour. The neutrino interaction flavour will be chosen at random between the three flavours e, μ or τ *but* with a

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[8] This work was undertaken by Hugh R. Gallagher.

weight assigned to each flavour and in proportion to that flavour's interaction cross-section with the detector medium. Thus, for example, for a neutrino energy of 50 MeV an electron final flavour will be more probable because the other two flavours can only have neutral-current interactions and their cross-section is less than that of the electron flavour which can have charged-current interactions as well.

The generation of a very large **MC A**ll **F**lavours (**MCAF**) sample in this way allows us to rapidly simulate distributions for quantities of interest for MC-simulated experiments of any neutrino-mixing model without any restriction. Each event is assigned a weight $w_i$ that is equal to its lepton transition probability, which is a function of the mixing parameters of the model, the event's initial and final flavours and its true $L/E_\nu$ phase. The examples in Table **4.1** illustrate the method.

| | | |
|---|---|---|
| $\nu_\mu \leftrightarrow \nu_\tau$ **mixing** | $f_{production} = e \rightarrow f_{interaction} = e$ | $w_i = 1$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = \mu$ | $w_i = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = \tau$ | $w_i = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | All other combinations | $w_i = 0$ |
| $\nu_\mu \leftrightarrow \nu_e$ **mixing** | $f_{production} = e \rightarrow f_{interaction} = e$ | $w_i = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = e \rightarrow f_{interaction} = \mu$ | $w_i = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = \mu$ | $w_i = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = e$ | $w_i = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | All other combinations | $w_i = 0$ |
| **Maximal mixing** | $f_{production} = e \rightarrow f_{interaction} = e$ | $w_i = 1 - 8/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = e \rightarrow f_{interaction} = \mu$ | $w_i = 4/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = e \rightarrow f_{interaction} = \tau$ | $w_i = 4/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = \mu$ | $w_i = 1 - 8/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = e$ | $w_i = 4/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |
| | $f_{production} = \mu \rightarrow f_{interaction} = \tau$ | $w_i = 4/9 \sin^2(1.27\Delta m^2 L/E_\nu)$ |

• **Table 4.1:** Oscillation weights assigned to different combinations of production and interaction flavours for three neutrino mixing models.

In a similar fashion, the **MC N**o **O**scillations (**MCNO**) sample can be defined by selecting all events whose production and interaction flavours are the same. This corresponds to assigning unit weight to events whose flavour remains unchanged, i.e. events that do not oscillate, and zero weight to all other events.