Simulation of Cosmogenic Neutrino Spectra with the GZKFast Event Generator

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Abstract

GZKFast is a low-cost astrophysical event generator designed to simulate photohadron processes resulting from ultra high energy cosmic ray fluxes. GZKFast is an easy to use event generator which specifically addresses issues relevant to cosmogenic neutrinos and the ultra high energy (UHE) neutrino spectrum. GZKFast injects UHE particles into a simulated cosmic microwave background (CMB) using a Monte Carlo approach. The interaction of each particle is simulated and the resulting detectable events are spooled to log files. Although GZKFast uses a simplified particle physics model and limited accelerator data it generates event distributions which are comparable with more thorough simulations such as the event generator SOPHIA [1].

1 Advertisement

GZKFast is a capable event generator which produces results comparable with applications that incorporate far more substantial particle physics kinematics and accelerator data.

GZKFast provides...

- A full featured simulation with rich run time configuration.
- Monte Carlo event generation.
- Management of individual astrophysical sources.
- Individual event simulation and tracking including relevant particle kinematics.
- Modular C++ design.
- Histogram and extensive tabular output.
- Practical standalone approach designed for ease of use, portability, and redistribution.
- Reusable program library for easy incorporation into new projects.
- GNU Library General Public License.

2 Introduction

This year the “GZK Effect” of Greisen [2] and Zatsepin and Kuz’min [3] is celebrating its fortieth anniversary. These authors independently realized that a uniform cosmic microwave background would provide an optically thick background for the highest energy cosmic rays. Cosmic ray protons of sufficiently large energy would be likely to interact with CMB photons over suitably large distances.

Accelerator experiments predict that the important channels for such interactions would be direct photopion production and the resonance channels for the $\Delta$ [4].

\[ p + \gamma \rightarrow n + \pi^+ \]
\[ p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \]
\[ \ldots \rightarrow p + \pi^0 \]  

(1)

The stable daughters of these processes may be observable in Earth based detectors. Therefore we wish to predict the expected fluxes of these particles.

Four momentum invariance of these reactions implies that in the proton rest frame [5]:

\[ s = M_p^2 + 2M_pE_\gamma \]

where \( M_p \) is the proton mass and \( E_\gamma \) is the energy of the photon in the lab frame. Therefore the measured cross section for photo-hadron interactions, \( \sigma(s) \), determines the likelihood for proton attenuation. The expected attenuation length can be characterized by a mean free path, \( \lambda \).

\[ \lambda = \frac{1}{n\sigma} \]

The mean free path also depends on the average density of CMB photons \( n_{\text{avg}} \). The average density may be found by assuming the CMB is characterized by a black body spectrum and integrating the Bose distribution. Including redshift, the average density of the CMB is given by (2).

\[ n_{\text{avg}} = (1+z)^3 \frac{2\zeta(3)k^3T^3}{\hbar^3c^5\pi^2} \]  

(2)

Here \( \zeta(x) \) is the zeta function defined in statistical mechanics texts and \( T \) is the temperature of the microwave background today. Using accepted values, at present this quantity is:

\[ n_{\text{avg}} = 410.5 \text{cm}^{-3} \]

The cross section for (1) can be determined from the Breit-Wigner formula using the measured data for the expected resonances. The relativistic form can be found in most introductory particle physics texts.

\[ \sigma(s) = \sigma_{\text{max}} \frac{M_0^2\Gamma^2}{(s - M_0^2)^2 + \Gamma^2M_0^2} \]  

(3)

The peak of the resonance is scaled by \( \sigma_{\text{max}} \) which may be measured experimentally. \( M_0 \) is the mass of the resonance, and \( \Gamma \) is the width.

The mean attenuation length for a cosmic ray proton of a given energy is the energy fraction of scattering times the attenuation length.

\[ L_0 = \left( \frac{E}{\Delta E} \right) \lambda \]

For photopion production the energy fraction can be deduced from kinematics, and averages roughly \( \Delta E/E = 15\% \) in the relevant energy regime. We can estimate the mean attenuation length of a \( 10^{20} \text{ eV} \) cosmic ray proton, taking an average value of \( \sigma, 500 \mu b \):

\[ L_0 = \left( \frac{E}{\Delta E} \right) (n\sigma)^{-1} \approx 10^{25} \text{ cm} \approx 10 \text{ Megaparsec} \]

A cosmic ray traveling a distance, \( L \), would have a survival probability less than \( P_{\text{survival}} \).

\[ P_{\text{survival}}(L) = 1.0 - \exp \left( -\frac{L}{L_0} \right) \]

Therefore, the flux of ultra high energy cosmic rays should be significantly attenuated on cosmological scales. The product of these photohadron interactions is a flux of electrons, photons, protons, neutrons and neutrinos. However, only the neutrinos travel without attenuation on these cosmological distances. These cosmicogenic neutrinos could be detected by Earth based experiments.

It is a topical goal of the astrophysics community to measure and characterize the flux of ultra high energy neutrinos. Still, no contemporary experiment is capable of measuring the cosmicogenic neutrino flux, so suitable Monte Carlo event generators must be available to support ongoing research. Here we present the C++ code named gzkfast as one possible avenue for simulation of this process.

### 3 Program Operation

GZKFast is principally comprised of two components, a reusable library and a command line event generator. The reusable program library, libgzkparticle, is written in C++ and designed to be modular and portable across platforms. The simple invocation program, gzkfast, gives command line access to the key functionality provided in the GZK library.

When a user invokes the gzkfast program, a universe is created with a simplified particle physics model. Cosmic ray point sources are inserted at random locations and managed by an EventGenerator thread. The event generator thread iterates through the point sources and injects subsequent ultra high energy particles into an EvolutionThread with momentum oriented towards the Earth.

Cosmic ray events are managed in particle queues of the evolution thread modules using a “round robin” strategy. As a result execution time is divided relatively equally between available threads.

Each evolution thread maintains a list of relevant Space objects, including the CMB, and extragalactic space, or BFieldSpace. The evolution
threads also maintain a list of suitable Earth based Detector objects.

Particle evolution continues as particles propagate through each of the known spaces and are given a chance to be detected by known detectors. Basic particle kinematics are used for propagation. In the extragalactic B field, assumed to be static and uniform over distance $dx$, the kinematics of particle propagation are governed by a few simple relations.

$$\frac{dp}{dt} = \frac{e}{c} v \times B$$

$$p = p + \frac{dp}{dt} \delta t$$

$$x = x + v \delta t$$

$$t = t + \delta t$$

The time step, $\delta t$, is defined based on the user specified distance step, $dx$. Particle interactions with CMB photons are evaluated with an accept-reject strategy. Then after propagation, each particle is allowed to decay with probability $P_{\text{decay}}$.

$$P_{\text{decay}}(t) = 1.0 - \exp (-t/\tau)$$

Decay products are reinserted into the evolution thread particle queue. If no decay or particle production takes place during propagation, each known detector is tested to see if it can see the particle. If the particle “hits” the detector the particle becomes an “event.”

Each event is logged to a relevant output location. Particle evolution continues until the user specified number of events have been detected. Once the specified number of events have been recorded, event generation is halted. Program execution then terminates once all particle queues are empty.

4 Basic Results and Spectra

Each run of gzkfast is configurable to allow the user to explore different aspects of cosmogenic neutrino phenomenon. With suitable configuration it is easy to produce a wide variety of relevant data.

GZKFast uses integrated data provided by the Particle Data Group [7] to sample the proton-photon cross section versus $\sqrt{s}$. Accelerator data provided in the PDG dataset are linearly interpolated from point to point to produce a complete distribution as depicted in Figure 1.

Using (3) to determine the cross section for the $\Delta_{1232}$ and $\Delta_{1600}$. These data are tabulated in the file specified by the “cmb” basename, with “_sigmaplot.dat” appended.

The cosmic microwave background is uniformly sampled as a black body distribution at 2.725 K [6]. These data are output in the file specified by the “cmb” basename, with “_photonhist.dat” appended.

At program termination the gzkfast program produces a variety of output spectra for the various processes that it tracked. Most importantly GZKFast is capable of producing neutrino spectra resulting from super-GZK cosmic rays. These
data are output in the file specified by the “neutrino” basename, with “hist.dat” or “event.dat” appended depending on if the data set is a histogram or event file.

Figure 3: The neutrino histogram gives the energy distribution of an expected neutrino flux.

GZKFast also provides individual event data for protons and neutrons, neutrinos and photons. These event data can be utilized in detector simulation or since they also include right ascension and declination information they can be used to produce sky maps with variable sources, distances, and other configuration differences.

GZKFast source code is available to the public upon request.

5 Acknowledgment

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6 GZKFast Reference

6.1 Class Listing

CMB The Cosmic Microwave Background Object samples the cross section of $p\gamma$ and the distribution of a user specified black body spectrum to determine if an interaction with a cosmic ray will occur.

CMBDist Sample the distribution of a black body radiation of a given temperature.

Delta Program representation of a $\Delta$ (1232 MeV) particle. Provides decay kinematics and particle properties.

Delta1600 Program representation of a $\Delta$ (1600 MeV) particle. Provides decay kinematics and particle properties.

Detector Abstract virtual class interface for GZKFast spherical detectors. A detector is a volume of space which can be hit by a simulated particle.

Electron Program representation of an $e^-$ particle. Provides decay kinematics and particle properties.

EventGenerator Threaded object which iterates through cosmic ray sources producing particle events from a predetermined energy spectrum and inserting them into the particle queues.

EvolutionThread Threaded object which iterates through a specific particle event queue and propagates the particles through one of an arbitrary number of spaces. After the particle propagates, the detectors are given a chance to detect it.

G4Vector A 4 vector representation.

GGuard Guard a critical section.
6.2 Command Line Reference

| Parameter       | Units   | Default | Description                                                                 |
|-----------------|---------|---------|-----------------------------------------------------------------------------|
| -sources        | Number  | 3       | The number of cosmic ray sources to add to the simulation. Sources are added randomly to a shell of size specified by -near and -far. |
| -events         | Number  | 100     | The number of neutrino events to simulate before stopping.                  |
| Option | Type | Value | Description |
|--------|------|-------|-------------|
| -threads | Number | 2 | The number of asynchronous execution paths simultaneously processing input events. |
| -alpha | Number | -2.7 | Simulate a proton input spectrum of the form \(E^\alpha\). |
| -low | EeV | 50 | The starting energy for the input proton distribution. |
| -hi | EeV | 50000 | The ending energy for the input proton distribution. |
| -near | Mpc | 150 | The distance to the nearest cosmic ray source. |
| -far | Mpc | 200 | The distance to the furthest cosmic ray source. |
| -dx | Kpc | 250 | The distance corresponding to one iteration or step of the Monte Carlo integration. |
| -rad | Kpc | 250 | The radius of the “detector” volume. The “detector” is defined to be a volume of given radius centered about the earth. Any particle which will intersect the “detector” is considered to be an “event.” |
| -bfield | Gauss | 1e-9 | The maximum magnitude of the uniform extragalactic magnetic field. |
| -quality | Number | 5e-9 | The precision of the beta decay Monte Carlo. |
| -proton | File Name | “proton” | The base name of the files for writing proton events and histogram output. |
| -2nd | File Name | “secondaryproton” | The base name of the files for writing secondary proton events and histogram output. |
| -v | File Name | “neutrino” | The base name of the files for writing neutrino events and histogram output. |
| -cmb | File Name | “cmb” | The base name of the files for writing the cmb photon energy histogram and cross section sample data. |
| -photon | File Name | “photon” | The base name of the files for writing photon events and histogram output. |

### 6.3 Program Output

$ gzkfast: \text{-[ arguments ] } ... \$

Simulate a flux of ultra high energy neutrinos from cosmic ray sources.

- **-sources #** - The number of sources.
-events #  - The number of events to simulate.
-threads #  - The number of processor threads.
-alpha #    - Simulate E^alpha spectrum.
-low #      - Least energy [EeV].
-hi #       - Highest energy [EeV].
-near #     - Least source distance [Mpc].
-far #      - Highest source distance [Mpc].
-dx #       - distance step [Kpc].
-rad #      - detector radius [Kpc].
-bfield #   - B field strength [Gauss].
-quality #  - The precision of Monte Carlo convergence.
-proton file - Name of file for input protons.
-2nd file   - Name of file for secondary protons.
-v file     - Name of file for neutrinos
cmb file    - Name of file for cmb distributions
gamma file  - Name of file for photons.

6.4 File Formats

| Energy [eV] | E dN/dE [cm^{-2}s^{-1}sr^{-1}] |
|-------------|----------------------------------|
| 4.235324597282258e+16 | 6.20560549060830e-05 |
| 4.82921343876459e+16   | 5.812199626341997e-05 |
| 5.506379003919574e+16  | 1.066115138632034e-04 |

Table 3: Example neutrino_hist.dat output.

| RA [deg] | Dec [deg] | E [eV]   | p_x [eV] | p_y [eV] | p_z [eV] |
|----------|----------|---------|----------|----------|----------|
| 73.8507  | -31.1954 | 4.2491+16 | 2.6999+16 | -7.5372+15 | -3.1932+16 |
| 73.8507  | -31.1954 | 8.9698+18 | 5.6996+18 | -1.5911+18 | -6.7409+18 |
| 82.8030  | -90.6093 | 1.0938+16 | -3.6303+15 | 3.6691+15 | -9.6441+15 |
| 82.8030  | -90.6093 | 1.4671+19 | -4.8691+18 | 4.9212+18 | -1.2934+19 |

Table 4: Example neutrino_event.dat output.

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