**Energy spectrum of cosmic rays detected in IceTop**

**Learning goals**

Students should learn to ...

describe the air shower of particles created by the interaction of a cosmic ray, e.g., a proton, with the Earth’s atmosphere

describe how a ground-based detector can observe cosmic rays and describe the geometry and detection principle of IceTop

estimate the air shower properties, like energy and arrival direction, from IceTop data and consider how projections help to reveal patterns

calibrate the energy measurement using simulated events

convert the number of events with an estimated energy in a given range (or bin) into a flux, a quantity that allows IceTop to compare its measurements with other experiments and with theoretical models

**What’s needed**

One computer for every one or two students, connected to the internet

A white board and paper

A copy of the paper “Measurement of the cosmic ray energy spectrum with IceTop-73” (this is the [link](http://arxiv.org/abs/1307.3795) to the version submitted to the arXiv)

**Resources provided**

Online interactive displays (Steamshovel-based) for IceTop, including different sets of events

A presentation to guide the activity ([link](https://docushare.icecube.wisc.edu/dsweb/Get/Document-73038/tutorial_icetop.ppt))

A demo spreadsheet showing how to calculate the calibration curve and the flux ([link](http://go.wisc.edu/rma997)).

**Activity overview**

Either in a short talk introducing this activity or in a previous talk, tutors will introduce the concept of the cosmic ray energy flux spectrum. We want them to understand that a flux is the rate at which cosmic rays arrive at Earth for a given area and a given angle.

Tutors will guide the students to explain why it’s important to measure a flux: we want the students to understand that the total number of cosmic rays that a detector will observe, or even the energy that the detected events will have, depends on the location, geometry and technical specifications of that specific detector. However, using other units, such as a flux, allows us to transform/normalize our results to a quantity that can be compared to results from other experiments and to general theoretical predictions.

At this point, tutors will explain to the students the goal of this exercise: have them measure the energy spectrum of cosmic rays, on their own and using real IceTop Data.

Tutors will start by introducing air showers, the messengers that bring information about their source cosmic rays to IceTop. We want students to be able to describe how a shower forms from a cascade of secondary interactions induced by the interaction of a cosmic ray with the atmosphere. Tutors can show a CORSIKA air shower movie and explain that for each cosmic ray air shower there can be a million or more particles hitting the ground.

We want students to understand some properties of the shower, such as its propagation speed, which is nearly the speed of light. To go all the way around the Earth, light needs just a tenth of a second.

Tutors will introduce, or revisit, what IceTop is like: it is a camera with very few pixels (about 160), but also with an incredible frame rate and with a sensitivity that allows the detection of single subatomic particles. In a standard movie, we see 24 frames per second. IceTop takes 3 billion frames per second. Since the shower develops at about the speed of light, we can see changes of about one meter per frame.

To explain the main properties of an air shower and how they can be measured from IceTop data, tutors will use Steamshovel displays of IceTop events. The students should understand that color shows the arrival times of the particles while the bubble size relates to the signal intensity. Using the arrival times of the different particles in a shower, we can estimate the direction of a cosmic ray. The shower size can be estimated taking into account how the signal intensity varies over the array of IceTop stations, which have a distance of 125 m between stations.

Students will discuss which coordinates are relevant and how they relate to the measured parameters: the shower front coordinates and how they can be calculated from arrival times.

It’s important that students understand that S125 is not a measurement of energy, but it is a quantity that scales with energy. The exact relationship is what the students will need to derive later on. The relation is just a simple formula that is not known a priori. It has to be obtained by a complete simulation of the air shower, i.e., of every single particle, and how this shower will be detected by IceTop. The simulated events look exactly like real events, and they are analyzed as real events.

Tutors will explain how to filter events since they will analyze events that have been filtered. If many events of similar size are observed, one representative event can be selected to analyze. This event then gets assigned a weight, which is the number of similar events that it represents. This allows us to preserve the total event count and the spectrum of events.

Students will now break up into six groups, each one identified by a color: red, orange, yellow, green, blue and violet. Each group will analyze a set of up to 30 events, a 50:50 mix of real and simulated events.

For each event, students will guess whether the event is simulated or real. This shows them how realistic simulations are. In fact, they should be indistinguishable.

The second task is to fit S125 by eye, aligning the data points with the predicted signal LDF and the flat shower front. The students will do this by tweaking the position and the orientation of the shower axis and by scaling the signal LDF. The values that the students pick are registered in the online application and can be reviewed by going back and forth between the events. A “movie” button can be used to see the event develop in time.

Finally, students save their fits to the disk using the "Save data" button.

Students will remain in the same groups. Each group opens a Google spreadsheet and uploads the previously saved data. They will do an energy calibration based on the simulated events, and then they will apply it to real events. The number of events with a given energy will be plotted in a histogram of log10(E). Recommended binning is: 6.4, 6.6, 6.8, 7.0, 7.2, 7.4 and 7.6. The flux is computed by dividing the counts per bin by dE = E[i+1] – E[i] and the exposure for 1/6 day: 8.186 109 m2 sr s.

Tutors will guide students as needed to overcome any difficulty due to lack of experience with spreadsheets. See details at the end of this document.

Students are now ready to compute the flux = (bin count)/(energy interval per bin)/(exposure), with exposure = 49.117 109 m2 sr s. They will produce a scatter plot that shows the flux vs. <log10(E)> per bin.

Finally, the results are compared between groups and discussed.

A last step, optional but interesting, would be to add the histograms obtained by the different groups and compute the flux again. This result should be closer to the official flux from the IC73 publication. See table at the end of this document.

**Details to guide the calibration curve and to compute the flux**

(See also demo spreadsheet [here](http://go.wisc.edu/rma997))

Students will first separate real events (E = 0) from simulated events (E > 0). Hint: right click on selection, click “short range” and use the energy column to separate events.

Then they will compute log10(E) for simulated events and log10(S125) for both. Hint: make new column, with =LOG10(…).

Students will then make a scatter plot from the simulated events, plotting log10(E) vs. log10(S125). Hint: select data, click “insert” in menu and click “chart,” Then, in wizard, click “Charts” tab, click “Scatter,” and choose first version.

At this point, students will add a trend line in the scatter plot. Hint: click chart symbol in the upper right, click “advanced edit,” choose “Trendline” : “Linear” and “Label” : “Use equation.”

Compute log10(E) for the real events based on the trend line formula. Hint: make new column with =A\*…+B, A and B from the trend line.

Students will make a histogram with binning from 6.4 to 7.6 in log10(E) in steps of 0.2 and fill sum of weights of real events into each bin.

They will then compute the energy interval per bin. Hint: make new column with =E[i+1]-E[i] for bin i.

Students are now ready to compute the flux = (bin count)/(energy interval per bin)/(exposure), with exposure = 49.117 109 m2 sr s. Hint: make new column with =… (bin count)/… (energy interval)/8.186 109.

They will produce a scatter plot that shows the flux vs. <log10(E)> per bin. Hint: make a new column, with =0.5\*(E[i] + E[i+1]) for bin i, and follow previous steps to make a scatter plot. Click “Advance edit,” choose “Axis” : “Vertical” and check “Scale” : “Log scale.” The flux needs to be scaled by a factor of 1016 to show reasonable labels on the y-axis.

**Cosmic-ray flux published by the IceCube Collaboration**

| log10(E0) | log10(E1) | Flux [dN/dlnE] | Flux | <log10(E)> | Scaled Flux |
| --- | --- | --- | --- | --- | --- |
| 6.20 | 6.30 | 1.05E-06 | 5.90E-13 | 6.25 | 5.90E+03 |
| 6.30 | 6.40 | 7.25E-07 | 3.24E-13 | 6.35 | 3.24E+03 |
| 6.40 | 6.50 | 4.94E-07 | 1.75E-13 | 6.45 | 1.75E+03 |
| 6.50 | 6.55 | 3.67E-07 | 1.10E-13 | 6.525 | 1.10E+03 |
| 6.55 | 6.60 | 2.97E-07 | 7.90E-14 | 6.575 | 7.90E+02 |
| 6.60 | 6.65 | 2.38E-07 | 5.65E-14 | 6.625 | 5.65E+02 |
| 6.65 | 6.70 | 1.91E-07 | 4.05E-14 | 6.675 | 4.05E+02 |
| 6.70 | 6.75 | 1.52E-07 | 2.86E-14 | 6.725 | 2.86E+02 |
| 6.75 | 6.80 | 1.21E-07 | 2.03E-14 | 6.775 | 2.03E+02 |
| 6.80 | 6.85 | 9.58E-08 | 1.43E-14 | 6.825 | 1.43E+02 |
| 6.85 | 6.90 | 7.56E-08 | 1.01E-14 | 6.875 | 1.01E+02 |
| 6.90 | 6.95 | 5.92E-08 | 7.03E-15 | 6.925 | 7.03E+01 |
| 6.95 | 7.00 | 4.61E-08 | 4.88E-15 | 6.975 | 4.88E+01 |
| 7.00 | 7.05 | 3.61E-08 | 3.41E-15 | 7.025 | 3.41E+01 |
| 7.05 | 7.10 | 2.80E-08 | 2.35E-15 | 7.075 | 2.35E+01 |
| 7.10 | 7.15 | 2.19E-08 | 1.64E-15 | 7.125 | 1.64E+01 |
| 7.15 | 7.20 | 1.72E-08 | 1.15E-15 | 7.175 | 1.15E+01 |
| 7.20 | 7.25 | 1.35E-08 | 8.02E-16 | 7.225 | 8.02E+00 |
| 7.25 | 7.30 | 1.09E-08 | 5.78E-16 | 7.275 | 5.78E+00 |
| 7.30 | 7.35 | 8.55E-09 | 4.05E-16 | 7.325 | 4.05E+00 |
| 7.35 | 7.40 | 6.84E-09 | 2.88E-16 | 7.375 | 2.88E+00 |
| 7.40 | 7.45 | 5.50E-09 | 2.07E-16 | 7.425 | 2.07E+00 |
| 7.45 | 7.50 | 4.43E-09 | 1.48E-16 | 7.475 | 1.48E+00 |