# Cosmic Ray Composition using SPASE-2 and AMANDA-II

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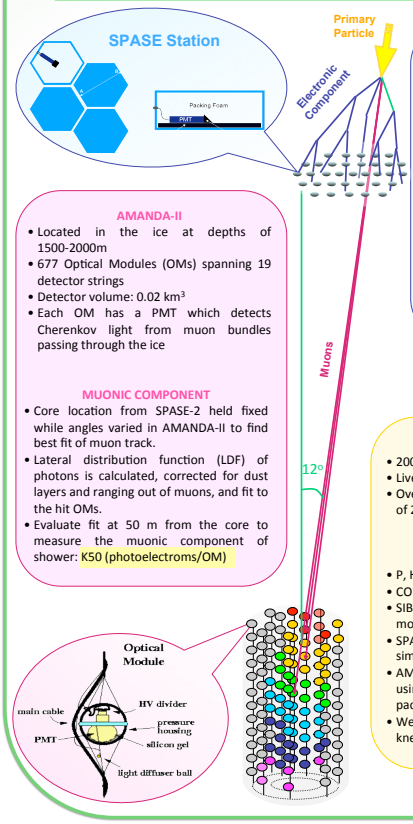
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Abstract: The precise measurement of cosmic ray mass composition in the region of the knee (~3 PeV) is critical to understanding the origin of high energy cosmic rays. Therefore, air showers have been observed at the South Pole using the SPASE-2 surface array and the AMANDA-II neutrino telescope which simultaneously measure the electronic air shower component at the surface and the muonic air shower component in deep ice, respectively. These two components, together with a Monte Carlo simulation and a well-understood analysis method will soon yield the relative cosmic ray composition in the knee region. We report on the capabilities of this analysis.

## INTRODUCTION

The mass composition of high-energy cosmic rays around and above the knee in the energy spectrum (~3 PeV) is dependent upon the mechanisms of cosmic ray production, acceleration, and propagation. Therefore, the study of mass composition is critical to understanding the origins of cosmic rays in this energy region. At energies up to $10^{14}$ eV mass composition can be measured directly using balloon and satellite experiments; however, due to the low flux, composition above $10^{14}$ eV must be obtained from indirect measurements on the ground. Indirect measurements of composition involve a close examination of the air shower produced as a cosmic ray primary smashes into Earth's atmosphere. By utilizing information from more than one component of the shower, such as the electronic and muonic components, the energy and relative mass can be obtained from primary particles with much higher energies than those currently measurable by direct detection techniques. One such indirect measurement is possible using the South Pole Air Shower Experiment (SPASE-2) in coincidence with the Antarctic Muon And Neutrino Detector (AMANDA-II).

## DETECTORS, DATA AND RECONSTRUCTION




**SPASE-2**
- Located on the surface of the ice
- Atmospheric depth of ~685 g/cm$^2$
- 30 Stations in 30 m triangular grid
- Four 0.2 m$^2$ scintillator modules per station

**ELECTRONIC COMPONENT**
- Direction computed from arrival times of particles in SPASE-2.
- Fit lateral distribution of particle density in the scintillators to the Nishimura-Kamata-Greisen (NKG) function to achieve core position.
- Evaluate NKG function at 30m from the core for "shower size": S30(particles/m$^2$)

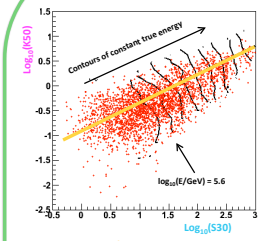
**AMANDA-II**
- Located in the ice at depths of 1500-2000m
- 677 Optical Modules (OMs) spanning 19 detector strings
- Detector volume: 0.02 km$^3$
- Each OM has a PMT which detects Cherenkov light from muon bundles passing through the ice

**MUONIC COMPONENT**
- Core location from SPASE-2 held fixed while angles varied in AMANDA-II to find best fit of muon track.
- Lateral distribution function (LDF) of photons is calculated, corrected for dust layers and ranging out of muons, and fit to the hit OMs.
- Evaluate fit at 50 m from the core to measure the muonic component of shower: K50 (photoelectroms/OM)

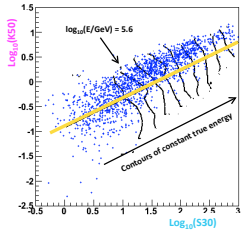
**DATA**
- 2003-2005 coincident data
- Livetime of ~600 days
- Over 100,000 after quality cuts, a factor of 20 above the previous analysis.

**MONTE CARLO**
- P, He, O, Si, and Fe showers
- CORSIKA air shower generator
- SIBYLL / GEISHA hadronic interaction models
- SPASE-2 has GEANT-4 based detector simulation
- AMANDA-II detector response simulated using collaboration's standard software package, AMASIM.
- Weighted to $E^{-2.7}$ spectrum below the knee in energy (3 PeV) and $E^{-3.2}$ above.

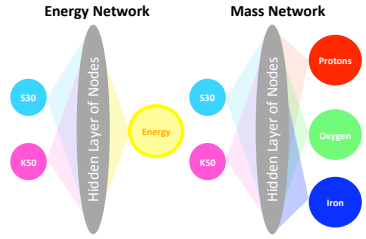
## NEURAL NETWORK ANALYSIS



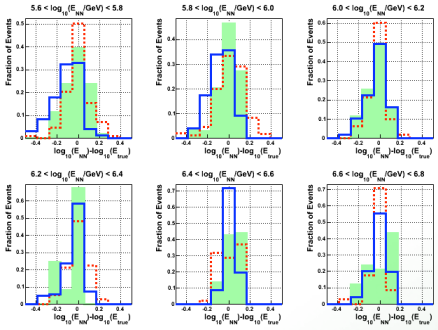

Orange Reference Line approximates a division between p and fe

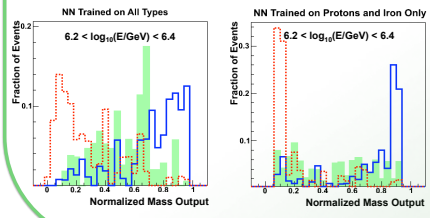



The nearly linear relationship between the K50/S30 parameter space and the Mass/Energy parameter space (as seen at the left) is well-suited for a neural network analysis. We train two fully-connected multilayer perceptrons (see below) over a number of training cycles on one-third of the Monte Carlo proton, iron and oxygen sample and validate the perceptrons on an independent set of the same three particle types to prevent over-fitting. We then run the validated networks on a third, independent set of all five particle types for testing, error analysis and, in the future, comparison with data.




*The energy resolution ($Log_{10}E_{reco}$ – $Log_{10}E_{true}$) of the Energy Network output for **proton**, **oxygen** and **iron** showers, shown in slices of Monte Carlo true Energy which correspond to the bands in the K50/S30 plots above. The energy resolution for all particle species from 1-10 PeV is σ($Log_{10}E$)=0.065. As more simulation is still being generated, these curves will become even tighter and the overall energy resolution even smaller.*




*The output of the Mass Network for proton, oxygen and iron showers in one slice of Monte Carlo true Energy. Note that for each event only one apparent mass, or A*, is assigned, thus A* is most useful when analyzing a collection of events. Hereafter these outputs will be referred to as apparent mass curves for a given simulated particle species, or $N_{species}(A^*)$.*

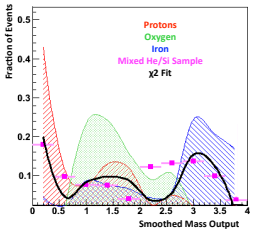
## RECONSTRUCTING MASS

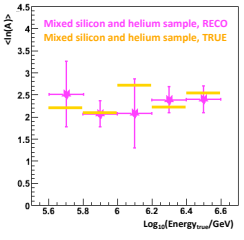
One possibility for stepping from A* to <lnA> is to perform a likelihood anallysis to find the combination of $N_s(A^*)$ which gives the best fit to the data. In our case of three species we utilize the constraint:

$$1 = f_p N_p(A^*) + (1-f_p)\left\{f_i N_i(A^*) + (1-f_i)N_o(A^*)\right\},$$

where $f_p$ and $f_i$ are the fraction of proton- and iron- like events, and are the parameters which a minimizer uses to find the minimum value of $\chi^2$. For each bin in energy, one fraction $F_p$ and $F_i$ are found which are the best representation of the data in that bin.

In this section, **magenta** is used to mark a test sample constructed from a known combination of simulated silicon and helium events. Neither of these types was used in the training of the network (as we have very few events); however, their use here provides a helpful test of how well the combination of the neural networks and the likelihood analysis perform on "unknown" species.




***Above Left** is an example of minimized output for one bin in $Log_{10}(E_{true}/GeV)$. The apparent mass curves have been smoothed for readability. The black line, representing the most likely combination of the **proton**, **oxygen** and **iron** curves, is a reasonable reproduction of the **mixed he/si sample**; however, it is clear that the analysis method would improve if given more types for training. This will be our next step. **Above Right** is the mean log mass vs energy for the mixed he/si sample. Although the sample size is very small, the **true values** for each bin in $Log_{10}(E_{true}/GeV)$ are well within the error bars of the **reconstructed values**. This is very promising.*

## DISCUSSION AND OUTLOOK

The SPASE-2/AMANDA-II cosmic ray composition analysis has lately acquired new Monte Carlo simulation, a new detector simulation and a revised surface-array reconstruction algorithm. Aided by these three new features a great deal of progress has been made. It can clearly be seen that the use of a neural network analysis together with a minimization technique provide an accurate reconstruction of the energy and mass of cosmic ray primaries in the region of the knee in the cosmic ray spectrum. With increased statistics in the Monte Carlo simulation, an energy spectrum and composition result will soon follow.

## ACKNOWLEDGEMENTS

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