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# A Measurement of Cosmic Iron at $E > 3 \times 10^{13}$ eV

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**Abstract**

We present results from the initial flight of the Balloon Air CHerenkov (BACH) experiment. BACH detects air Cherenkov radiation from the primary nucleus as coincident flashes in two optical modules in order to provide data on the absolute iron spectrum up to $10^{15}$ eV, and the relative abundance of iron and silicon in the decade from $3 \times 10^{13}$ eV to $3 \times 10^{14}$ eV. The intial flight (dubbed PDQ BACH) took place on April 22, 1998 from Ft. Sumner, New Mexico. We obtained an exposure of 2.75 hours, with a typical threshold energy for iron nuclei of $2.2 \times 10^{13}$ eV. We observed 5 events which are cleanly identified as iron group nuclei. Preliminary analysis suggests a flux slightly below but consistent with that reported by the JACEE collaboration.

## 1 BACH: Balloon Air CHerenkov

It is important to determine cosmic-ray composition in the energy range $10^{13} - 10^{16}$ eV. This range includes the knee of the cosmic ray spectrum, which plausibly marks the transition between two distinct sources of cosmic rays. A change in composition in this region could hold the key to understanding cosmic ray acceleration. Balloon emulsion techniques have been used to determine composition on the lower end of this range, but with moderate statistics. Air shower techniques may be used on the upper end. We have previously described (Evenson and Seckel, 1995) an experiment for determining the flux of iron nuclei at energies greater than $3 \times 10^{13}$ eV which employs the Balloon-borne Air CHerenkov (BACH) technique, explored by Sitte (1965) and Gough (1975), and pioneered by Sood (1983; Sood and Panettieri, 1981). We have since constructed and flown our first payload (PDQ BACH), and here give a preliminary account of our results.

We summarize the technique. A high energy iron nucleus entering the atmosphere will interact at some 14 gms of air, initiating an atmospheric cascade. Before that first interaction a sufficiently high energy nucleus will radiate photons via the Cherenkov process. These photons travel nearly colinearly with the primary, forming a “light pool” of known characterisitics. The radius of the light pool is of order 10 m. For an iron nucleus, the photon intensity within the light pool is greater than 2000 m$^{-2}$. By sampling the photon flux with a light collector coupled to a phototube, one may detect flashes of light that far exceed the counting fluctuations inherent to observing the night sky over a few nanosecond interval. By observing coincident flashes in two collectors, one may reduce other forms of background to acceptable levels and thus explore the iron flux with an aperature far exceeding competing techniques.

## 2 Design of PDQ BACH

Our design strategy for a BACH payload was driven by technical considerations affecting statistical and systematic uncertainties. Given the intrinsic $\sim 100$ psec structure of the light flash, our primary objective was to reduce the noise integration time. This enables the use of smaller, lighter optical components and, eventually, a higher total geometry factor by mounting several detectors on the same payload. To this end, we employ Hamamatsu R4143 three inch photomultipliers with a risetime of $\sim 2.4$ nanoseconds at our operating point of -1200V.

We designed light collectors (208 cm long, 24 cm radius aperature) based on concepts developed by Winston and colleagues (1989) that have a nearly flat response within a well defined $7.5°$ field of view.

Separation of the two collectors by 3 meters eliminates a background due to lower Z nuclei encountering the payload with small impact parameter, where the light pool is most intense. The "Winston cones" were constructed using a precision machined aluminum mandrel. Sections of the detectors were formed on the mandrel with carbon-fibre epoxy composite material. Each collector consisted of two upper and two lower 180° sections. A reflective aluminum coating was evaporated onto the molded sections, which were then assembled.

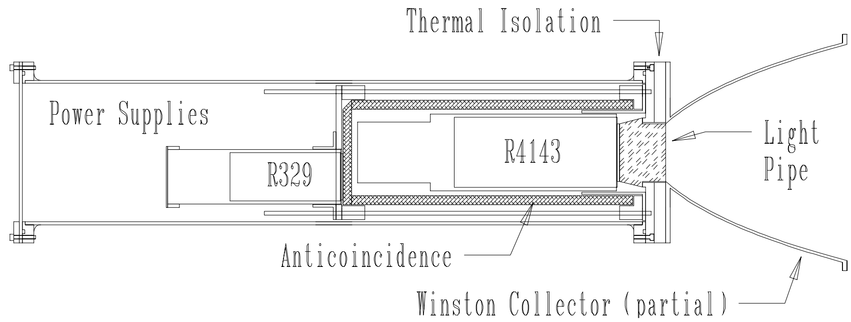


**Figure 1:** The BACH Pressurized Optical Detector

A Pressurized Optical Detector (POD) was developed from the need to run the photomultipliers (PMT) with a high DC current due to starlight, measure the DC component accurately, and still maintain the high frequency response of the PMT. By using negative high voltage, the anode signal can be directly coupled to the data acquisition system, providing a straightforward solution to these problems. However, a phototube faceplate kept at high, negative potential and exposed to low atmospheric pressure poses an unacceptable risk of corona discharge. Our solution was to operate the PMT at one atmosphere, and to couple it to the Winston collector via a 2" long light pipe, of Bicron UVT acrylic, with an RTV pad to optically couple the light pipe to the phototube. The lightpipe extends from the POD to allow thermal isolation of the POD and collector. Surfaces of the lightpipe are polished and kept from contacting the POD structure except for a 1/8" lip which provides the pressure seal. The cylindrical and conical surfaces are internally reflecting for almost all photon trajectories. The POD also contains a R329 phototube coupled to a plastic scintillator guard designed to detect charged particles passing through the lightpipe.

Data are acquired with a Tektronics TDS640A digital oscilloscope, which can capture 2 gigasamples per second in four channels simultaneously. Internal oscilloscope logic was used to detect triggers. This scope comes equipped with a GPIB interface, so we developed a microcontroller based unit to interface the scope to the command and telemetry system. This unit also controlled the high voltage on the detector phototubes.

# 3 Calibration

Crucial to the scientific return of the BACH payload is an absolute calibration of photomultiplier gain and pulse height distribution, and efficiency of the light collectors. High voltage for each tube is controlled by an 8-bit programmable supply, adjustable in flight. With the voltage at its maximium (-2150 V) we record single photoelectron pulses in the lab and determin both the pulse height distribution and integrated charge response. We then "bootstrap" the gain calibration down to the typical flight setting of -1205 V, using an adjustable LED as a light source. As the HV amplitude is lowered the increase in transit time requires an additional reduction of $\sqrt{2150/1205} = 1.34$ in the pulse height response relative to the change in gain.

The full optical assemblies were calibrated for efficiency and alignment within the Ft. Sumner hanger. A 1" diffuse light source was moved horizontally and vertically across the field of view of each collector at a distance of 7.5 m from the front of the cone. The results of these tests are compared with predictions from our numerical model of the collector/POD assembly in Fig. 2. The overall normalization is adjusted to match our head on model efficiency, defined relative to the quantum efficiency of a R4143 phototube averaged over a Cherenkov spectrum. The model includes losses due to reflection from the Winston collector 4%, absorbtion by the aluminum coating 20%, absorbtion in the lightpipe 12%, and losses from the optical path 4%. The dip in predicted and measured efficiency near 5 degrees is a consequence of the construction of the photomultiplier, which has a hemispherical photocathode on the inside of a rather thick glass envelope with a flat faceplate.

Note that for a light source at infinity the field of view is quite sharp, but for a close source our model correctly predicts the softening at the edge of the field of view. Close inspection of Figure 2 reveals that CAU-1 data are offset slightly with respect to that from CAU-2. ("CAU" refers to Christian Albrechts Universitaet, where the collectors were manufactured). The residual alignment error of $\sim 1/4°$ is small compared to the $7.5°$field of view.

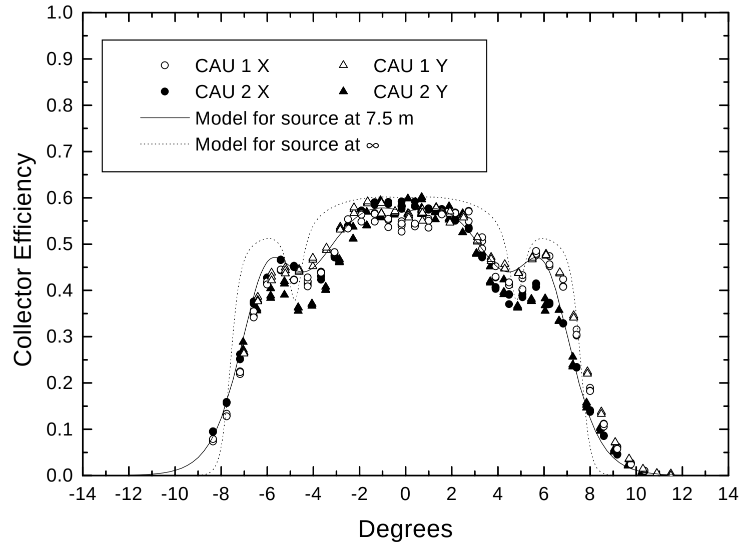


**Figure 2:** Results from collector response and alignment test.

Naturally occurring pulses can be used to verify the phototube calibration and collector efficiency. Muons passing through the lightpipe serve to check the lightpipe model and phototube gain. Once the Winston collectors (with covers) were attached to the PODs, we were able to detect ground level muons and electrons passing through the collector volume on trajectories nearly parallel to the optical axis. Analysis of these events yields a less than 5% correction to the pulse height distribution inferred from our gain calibration procedure.

# 4 The flight of PDQ BACH

PDQ BACH was launched at sunset from Ft. Sumner, NM, on April 22, 1998 and cut down some 6 hours later in accordance with NSBF downrange safety policies. We had a useful exposure of 2.75 hours. Pressure at float varied from 8.05 to 8.5 mb, corresponding to a threshold energy for iron of $2.2 \times 10^{13}$ eV.

PDQ BACH collected 1793 triggers, each consisting of 250 ns (500 samples) of waveform from four channels: the two Hamamatsu R4143 tubes (CK1 and CK2), and the two R329 tubes being used as antis (A1 and A2). Since the signals resulting from the Cherenkov light are only a few nanoseconds wide, the bulk of the waveform data was available for monitoring the skylight background. Expecting only a handful of true iron events, the trigger thresholds on CK1 (6 mV) and CK2 (4 mV) were intentionally set to acquire events at a rate of approximately $0.1$ Hz.

The observed trigger rate is consistent with photon counting from a sky background that changes intensity depending on the field of view. This time dependent background is monitored via the observed DC current levels. Fluctuations in the bakground are consistent with Poisson statistics. Trigger rates can be estimated analytically given the threshold in each channel, and are commensurate with those observed during flight.

We recorded a variety of events. Five of these are exactly what we expect as a result of Cherenkov radiation from cosmic iron - strong sharp signals well above threshold in both channels and no signal in either anti. Of the remainder, the majority have amplitudes just above threshold, and are most likely due to simultaneous fluctuations in the skylight counting rate. The rate of such triggers is correlated with the amplitude of the DC current observed in the waveforms outside the pulse region. Some of these triggers are probably due to silicon, but we have not completed an analysis to separate sky fluctuations from lower $Z$ cosmic rays. We have numerous asymmetric events where CK1 records a strong signal and CK2 is just above threshold, indicative of a charged particle passing through the CK1 lightpipe accompanied by a counting fluctuation in CK2. The rate of these events is consistent with expectations. About 80% are tagged by A1, consistent with our modeling for the efficiency of the anti's. A few events have strong pulses in both channels but are clearly not caused by cosmic iron, since both anti's are present and one signal leads the other by about 10 ns. These features are consistent with a single charged particle passing through both light pipes. Although excluded by our anti's, we could discriminate against these events on the basis of timing alone.

# 5 Analysis

Our observed pulse height distribution is compared to a model of the instrument response when exposed to a known background of skylight and a flux of cosmic ray nuclei of assumed composition and spectrum. The incident flux is taken to be isotropic over the field of view of the collectors with impact parameters that allow for all positions and orientations of the payload. Knowledge of the light pool, impact parameters, and POD/collector efficiency yields an expected number of photoelectrons, which in turn is the basis for drawing from a Poisson distribution. The pulse heights follow by multiplying by the average gain for each phototube. The pair of pulseheights thus determined is placed on a scatterplot, for comparison with our flight data. To eliminate events due to background fluctuations, lightpipe hits, etc, we make conservative cuts in the pulse height scatterplot. To extract a flux measurement, the overall flux normalization in the simulation is adjusted to match the events counted during flight.

The result depends weakly on the assumed iron spectrum. With a small number of events we cannot determine the spectrum. A long duration flight with several fields of view would gather 1000's of iron nuclei and allow a differential spectral measurement over about one decade of energy. Our result also depends on the composition, as silicon nuclei can imitate the pulse from iron for unusual impact parameters. By adjusting the cuts in the scatterplot, and making a pulseshape cut to further discriminate against skylight events we hope to achieve an independent measurement of silicon. Currently we estimate a 5% contamination of iron by silicon. Corrections were made for hadronic interactions of iron in the atmosphere (estimated 9 percent), and for contamination of the iron flux by nuclei with $Z = 17 - 25$ (estimated 10 percent).

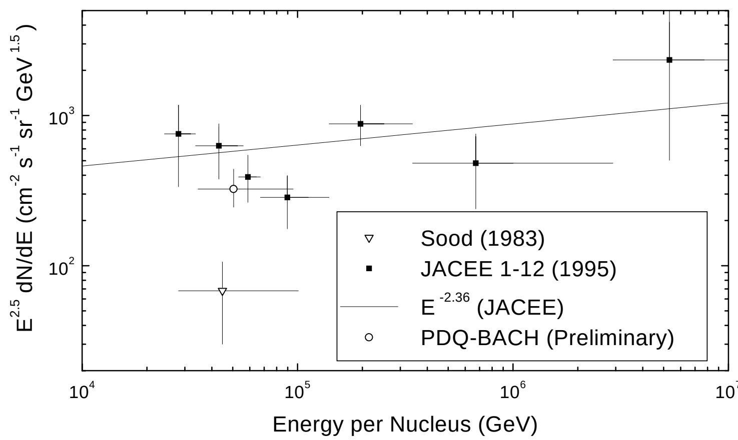


**Figure 3:** Measurements of the cosmic ray iron spectrum

Our result may then be compared easily to the JACEE (Asakimori 1995) data also shown in Fig. 3. Poisson statistics were used to estimate the statistical error in the flux, whereas the horizontal error bar corresponds to the halfwidth of the peak which results from convolving the instrument response with the assumed $E^{-2.5}$ spectrum.

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