Measurements of Light Nuclei near 100GeV/n by RICH

E. Diehl, D. Ellithorpe, D. Müller, and S. Swordy
Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, IL 60637, USA

Abstract

A large Ring-Imaging CHerenkov (RICH) has been used in high altitude ballon flights in 1996 and 1997. These experiments are specifically aimed at measuring the energy spectra of light nuclei near 100GeV/n. The RICH method, which measures particle Lorentz factor, has a fundamentally different character from other techniques used in this energy region. The establishment of energy scale and the quality of background rejection is discussed.

1 Introduction:

Protons and helium are the most abundant cosmic ray species, and yet, the existing data on their energy spectrum and intensity at highly relativistic energies are still affected by sizeable statistical and systematic uncertainties, precluding a determination of the power- law spectral index to better than $\sim$0.1, and leading to uncertainties in the absolute intensities of at least 25%. Thus, subtle differences in spectral shape between protons and helium, as predicted by supernova shock acceleration models as a consequence of the large difference in charge/mass ratio of these two species (Ellison 1993), were reported at very high energy (above $\sim$1TeV/n, Asakimori et al 1997) but may remain hidden in the uncertainties of the bulk of the data between 10 GeV/n and a few hundred GeV/n. These uncertainties also set limits to the accuracy with which the intensities of important interstellar secondaries such as gamma rays, positrons, and antiprotons can be determined.

These considerations have motivated us to construct a new balloon-borne detector for measurements up to several hundred GeV/n which uses a ring-imaging Cherenkov counter (RICH) for energy determination. The RICH concept permits accurate energy measurements with small and well understood fluctuations, absolute energy calibration, and negligible background. A first version of this detector was successfully used to determine the intensity of helium nuclei (Buckley et al 1994). The present paper describes an improved instrument design that also includes protons in the measurement. This instrument was flown on balloons in 1996 and 1997.

2 Experimental Technique:

The RICH technique does neither require a nuclear interaction to occur, nor does it depend on the use of a heavy magnet spectrometer; hence the detector can achieve a large sensitive area at relatively modest weight. For a gaseous radiator, the Cherenkov angle θ is measured which is related to the particle Lorentz factor as $\theta^2 \approx 1/{\gamma_0}^2 - 1/\gamma^2$. For the present instrument we use the gas C_4F_{10} (perfluorobutane) with a threshold $\gamma_0 \approx 21$, or C_3F_8 (perflouropropane) with $\gamma_0 \approx 24$ at the flight pressure and temperature. The experiment determines γ for about a decade in energy above threshold, and, unlike in integrating Cherenkov counters, the measurement of θ is fully decoupled from the measurement of the charge Z.

The instrument (see Fig. 1) uses a gas radiator of about 3m depth; Cherenkov photons are reflected from a spherical mirror of 3m radius of curvature, and form a ring shaped image in the focal plane of the mirror. The radius of the ring is then a measure of θ and γ, respectively. The most delicate part of the detector is the position sensitive photon detector located in the focal plane: we use a multiwire proportional chamber with a fused silica window and a pixellated (1cm^2) anode plane. The chamber is made photosensitive over the range 160 to 220 nm through the introduction of TMAE with the ethane carrier gas. For readout of the $\sim$20,000 anode pixels, we use AMPLEX multichannel VLSI chips (Beuville et al 1990).

Additional detector elements in the instrument include (1) a pair of plastic scintillators on top and on bottom of the instrument, each 2×2m^2 in area, to provide a coincidence trigger, to measure the charges of the cosmic ray particle, and to reject those nuclei that interact en route through the detector; (2) two identical sets of four drift proportional chambers, located above and below the RICH counter, respectively. These chambers determine the trajectory of each particle with a resolution of about 1mm, and the integrated charge signals also measure Z for each nucleus. Finally, a lead plate, 2 radiation lengths thick, covers the entire instrument aperture above the RICH counter. This plate eliminates electron background to the proton measurement by either absorbing low energy electrons, or inducing electromagnetic showers at higher energy.

3 Data Collection and Analysis

The instrument was flown first in October 1996 from Fort Sumner, New Mexico. A second flight was made from the same location in October 1997.

The general scheme of the data analysis is as follows. First, the hodoscope is used to determine the particle trajectory. This trajectory is reflected through the spherical mirror to predict the possible position of a ring center in the photon detector. A ring search around this position is then made. The trajectory is also used to make a pathlength correction to the scintillator pulse height needed for particle identification. As a measure of the particle charge from the scintillator we use the sum of the signals of all but the largest photomultiplier (PMT) signal in an event. This modified sum is found to be less sensitive to ”hot spots” near PMTs than the sum of all PMT signals, and thus is more reliably corrected with a position response map. Single events from the 1996 flight are shown in Figures 2 and 3. Figure 2 is a Z=1 particle and Figure 3 is helium, Z=2. Here the filled squares represent the locations of pads hit in the photon detectors. A circle is fit to the photon positions, and the asterisk indicates the center of the circle. The small circle near the center represents the prediction of the ring center position based on the hodoscope tracking alone. The large circle represents the best fit ring to these hit pads. Some of the hits in Figure 3 show how a single photon can fire a cluster of detector pads which must be allowed for in the analysis. The corresponding value of γ and errors is given in each panel.

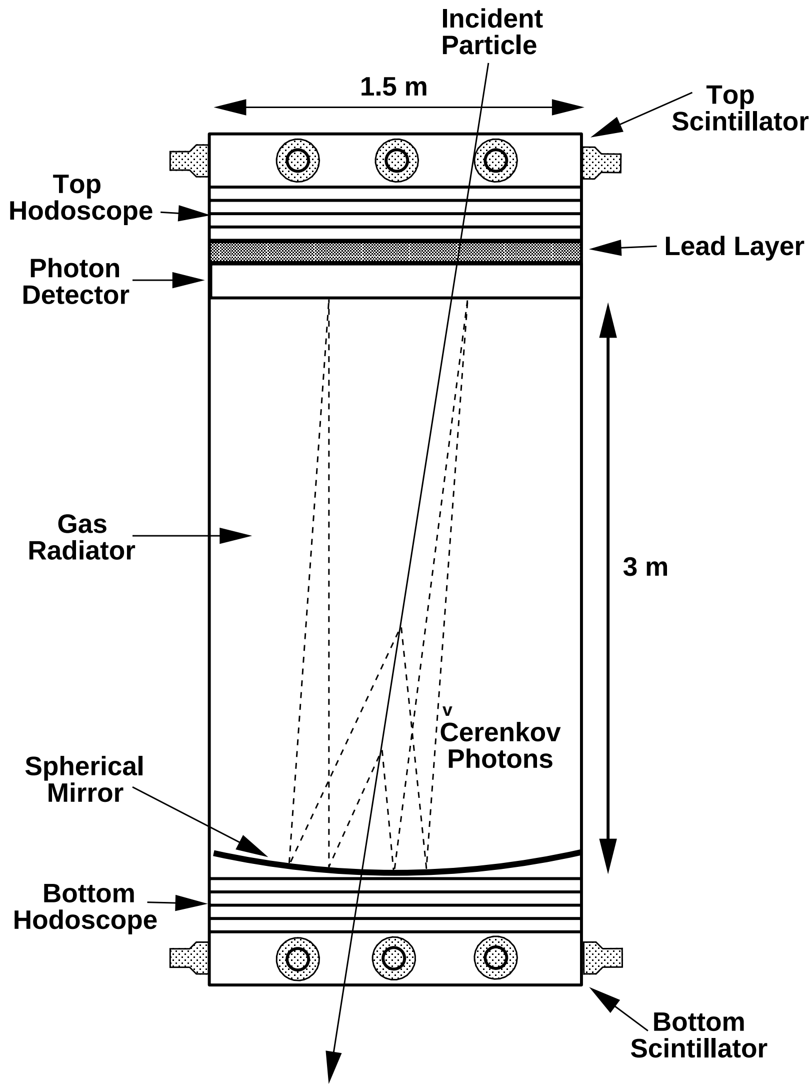

Figure 1: The RICH instrument in cross section

To initiate ring analysis, all pads fired are grouped into clusters of adjacent pad hits. These clusters are classified into a number of categories: ionization clusters, fired by the passage of an ionizing particle; noise hits; and possible photon hits.

Ionization clusters are defined as clusters of five or more pads, although, typically 20 pads are fired. The position of the ionization cluster coincides with the particle trajectory, and for most events, lies well away from the region of the Cherenkov ring due to the reflection of the Cherenkov photons by the spherical mirror. The presence of ionization clusters permits two useful cuts on event quality: an event must not have more than one ionization cluster (while interacting particles often produce multiple ionization clusters); and the hodoscope track must pass through the ionization cluster. Noisy pads are defined as those which have a high average occupancy, and are removed from analysis. Pads which are not ionization clusters or noise hits are considered potential Cherenkov photon hits.

At this stage in the analysis we only use events with 3 or more Cherenkov photon hits. This enables a simple fit procedure for a circle to these hits. The Cherenkov ring is determined by a simultaneous fit of the radius, r, and ring center positions. The predicted ring center from the hodoscope track is used to constrain the search region: only photon detector hits within 20 cm of the predicted ring center are used in the fit, and the fitted ring center is required to be less than 2.5 cm away from the predicted ring center.

The RICH response is characterized by two parameters: the maximum ring size, $\mathrm{r_{max}}$, which is related to the index of refraction of the Cherenkov gas; and the photon yield, i.e. the average number, $\mathrm{N_o}$, of photoelectrons generated by a particle in saturation (i.e. at $\mathrm{r_{max}}$).

A precise value of $\mathrm{r_{max}}$ is determined by comparing the measured ring distribution with simulated data from a Monte Carlo program. The simulated data are obtained by passing particles of known Lorentz factor through a computer model of the detector. For the 1996 flight we derive a value of $\mathrm{r_{max}} = 14.4 \pm 0.04$ cm, corresponding to a Lorentz factor threshold of 20.7 ± 0.06. The simulation is also used to correct for the small elliptical distortion of measured ring radii for off-axis tracks. This distortion is small, at most 2%.

The number of hits in the proton rings is small so a correction must be applied for detection efficiency based on the value of $\mathrm{N_o}$. Since the photon yield increases as the square of the particle charge, Z, a reliable value for $\mathrm{N_o}$ can be determined from ring events from heavier nuclei and scaled with Z^2 to accurately determine the mean numbers of photoelectrons expected in proton rings.

4 Backgrounds

The only significant background problems occur for Z=1 events. Electrons, muons, and pions constitute a background of singly charged particles which may simulate proton events. The background from Deuterium is well below 1% which is a much less significant background in this experiment than in magnetic spectrometers since these measure rigidity rather than energy per nucleon.

The contamination of electron secondaries is greatly reduced by the two radiation length lead layer above the Cherenkov radiator. Electrons are either completely absorbed in the lead or produce showers which are removed by data cuts. They produce background only if a single shower electron continues through the whole detector. This contamination is determined with the use of a GEANT(1995) Monte Carlo simulation of the instrument. The secondary electron spectrum of Stephens(1981) is used to generate simulated data which are analyzed with the flight data analysis program. We find that electrons with energies below 50 MeV are absorbed by the lead layer and do not trigger the instrument. A small background contribution comes from electrons with energies between 50 MeV and 1 GeV, all of which affect only the highest energies measured.

Muons and pions are not affected by the lead. In fact, muons are detected with a higher efficiency than protons since they do not undergo hadronic interactions in the detector. We make an estimate of the contamination of muons and pions based on the spectra of Stephens(1981), and using the instrument Monte Carlo simulation.

Events which produce light from either local knock-on electron production or by interactions which produce energetic pions in the instrument material are heavily suppressed by the stringent restrictions in angular phase space required for the ring location. To form any level of serious background secondary high γ particles must be produced within a solid angle of $\sim 10^{-4}$ sr of the primary particle track.

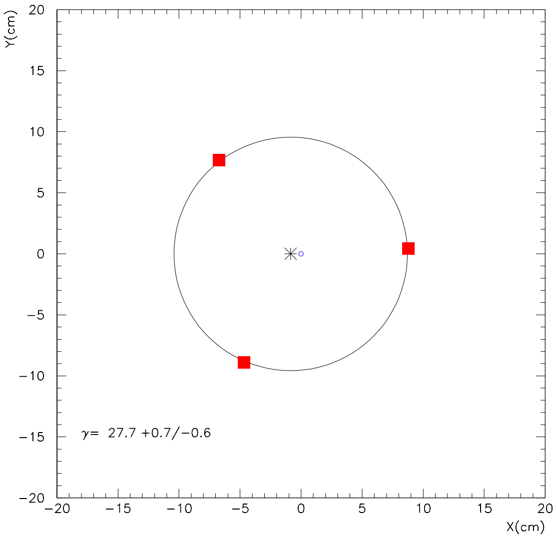

Figure 2: *Z=1 ring with fit*

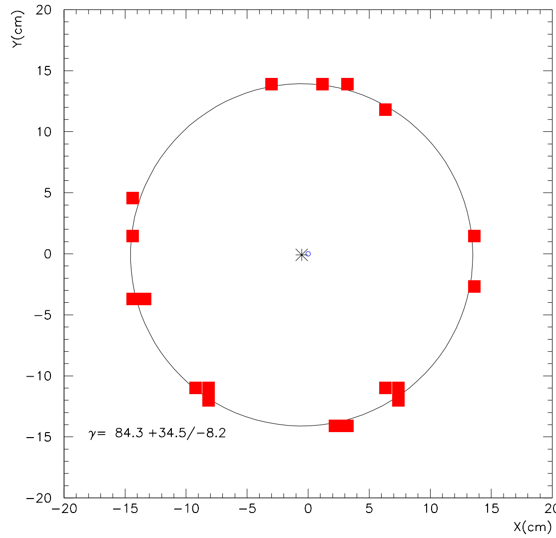

Figure 3: *Z=2 ring with fit*

5 Energy Scale and Flux Measurements

A fundamental advantage of RICH detectors over other methods for measuring particle energy is the accuracy with which the energy scale can be calibrated. In essence this amounts to the identification of the maximum ring radius measured in the data themselves. With the flights of this instrument this value is determined with a fraction of percent accuracy.

To reconstruct accurate absolute fluxes the efficiency of various parts of the detector system must also be known. In this instrument a strategy which involves some of the redundancy between the detector systems can be used. For example, a particle passing through the photon detector leaves a large cluster of hit pads from ionization loss which is readily detected as a 'blob' of adjacent hits. This location can be used together with a subset of hodoscope planes to test the efficiency of tracking in the remaining hodoscope layers. We have tried to test the efficiencies of all the detector systems in a similar manner by selecting clean events in other detectors and testing the response of the system of interest.

We expect to present absolute flux measurements from a combination of these flights at the conference.

6 Acknowledgements

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