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Cherenkov angle and charge reconstruction with the RICH detector of the AMS experiment

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Abstract

The Alpha Magnetic Spectrometer experiment to be installed on the International Space Station will be equipped with a proximity focusing Ring Imaging Cherenkov (RICH) detector, for measurements of particle electric charge and velocity. In this note, two possible methods for reconstructing the Cherenkov angle and the electric charge with the RICH are discussed. A Likelihood method for the Cherenkov angle reconstruction was applied leading to a velocity determination for protons with a resolution of around 0.1%. The existence of a large fraction of background photons which can vary from event to event implied a charge reconstruction method based on an overall efficiency estimation on an event-by-event basis.

1. The AMS experiment

The Alpha Magnetic Spectrometer (AMS) [1] is a precision spectrometer to be installed by 2005 in the International Space Station (ISS), where it will operate for a period of 3 years. Its main goals are the search for cosmic anti-matter, the search for dark matter and the measurement of the relative abundance of elements and isotopes in primary cosmic rays.

The future installation of AMS in the ISS was preceded by a 10 days engineering test flight aboard the Space Shuttle Discovery in June 1998, at a mean altitude of 370 km. Although the purpose of this experimental flight was the test of the spectrometer design principles, about 100 million events were collected enabling precise measurements of the spectra of high-energy protons, electrons, positrons and helium nuclei [2].

The AMS spectrometer capabilities were extended with respect to those of the experimental flight, through the inclusion of new subdetector systems and the completion of others. The spectrometer design includes a superconducting magnet, a Time-of-Flight system (TOF), a Silicon Tracker, Veto Counters, a Transition Radiation Detector (TRD), an Electromagnetic Calorimeter (ECAL) and a Ring-Imaging Cherenkov Detector (RICH). It will be capable of measuring the rigidity ($R \equiv pc/|Z|e$), the charge (Z), the velocity (β) and the energy (E) of cosmic rays within a geometrical acceptance of $\sim 0.5\ \mathrm{m}^2$ sr. The tracking system, with a cylindrical shape, is made of eight double-sided silicon planes embedded inside a magnetic

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field of about 0.9 T and will provide both charge measurements and momentum measurements with a resolution $\Delta p/p$ of at most 2% up to 100 GeV/c/nucleon. The TOF system, made of four scintillator planes placed at the magnet end-caps, will provide a fast trigger, charge and velocity measurements for charged particles as well as information on their incidence direction. On the top of the spectrometer, the TRD will discriminate between leptons and hadrons, and, on the bottom, the ECAL will contribute to the e/p separation and will measure the energy of the gamma rays crossing AMS. Fig. 1 shows a schematic view of the AMS spectrometer.

The RICH detector will operate between the TOF and the ECAL subdetectors. It was designed to measure the velocity of singly charged particles with a resolution $\Delta\beta/\beta$ of 0.1%, to extend the electric charge separation up to the Iron element and to contribute to the albedo rejection. Its acceptance is of $\sim 0.4\ \mathrm{m}^2$ sr, that is, around 80% of the AMS acceptance. The RICH is a proximity focusing detector with a low refractive index radiator (aerogel) on the top and a pixelized photomultiplier matrix on the bottom, where the radiated Cherenkov photons are collected. The active pixel size is of 8.5 mm. A conical-shaped

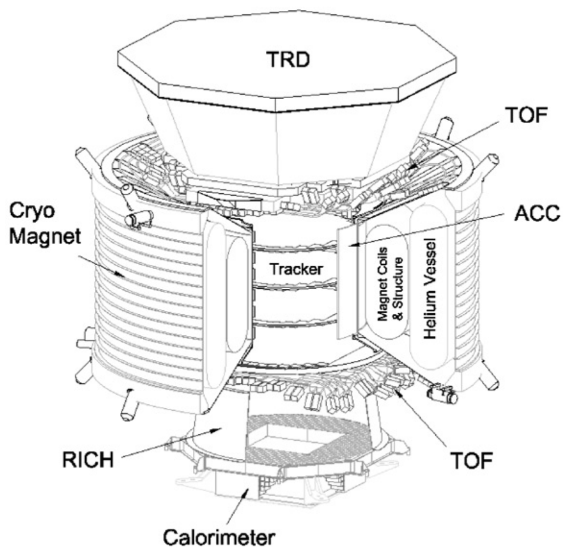

Fig. 1. Whole view of the AMS spectrometer.

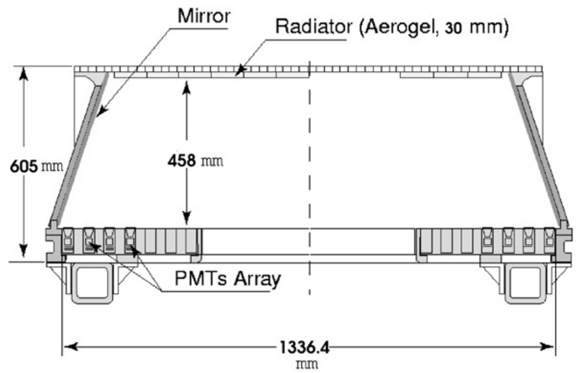

Fig. 2. RICH detector.

mirror surrounds the whole set, increasing the detector reconstruction efficiency. Constraints on the amount of heterogeneous matter in front of the downstream electromagnetic calorimeter have imposed a large non-active (empty) readout area in the detection plane. For a more detailed description of the detector see Ref. [3] in these proceedings. Fig. 2 shows a view of the RICH detector and of its dimensions.

2. Velocity reconstruction

A charged particle crossing the RICH radiator material of refractive index n emits photons if its velocity (β) is larger than the velocity of light in that medium. The aperture angle of the emitted photons with respect to the radiating particle is known as the Cherenkov angle, θ_c, and it is given by [4]

$$\cos\theta_c = \frac{1}{\beta n}. \qquad (1)$$

It follows that the velocity of the particle, β, is straightforwardly derived from the Cherenkov angle reconstruction.

The emitted photons can suffer interactions in the aerogel radiator (Rayleigh scattering, absorption), can be reflected or absorbed on the mirror surface and can fall on the active area composed of solid light guides on top of the photomultipliers. As a consequence, the reconstruction of the Cherenkov angle has to deal with two kinds of photons: those which are only slightly deviated

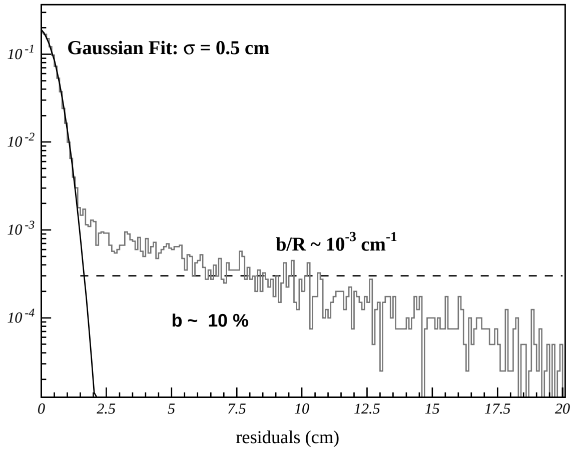

Fig. 3. Distribution of the hit residuals with respect to the expected Cherenkov pattern.

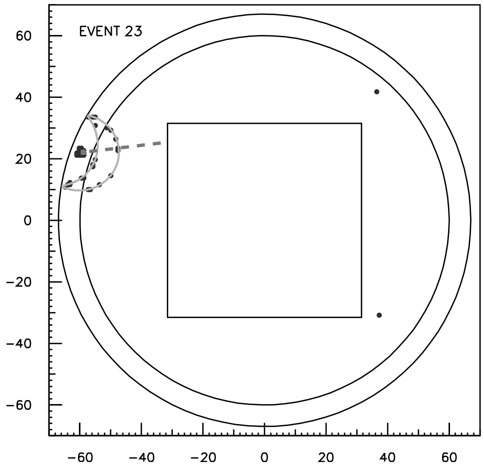

Fig. 4. Reconstruction of a simulated helium event. The reconstructed photon pattern (full line) includes both reflected and non-reflected branches. The inner and outer circular lines correspond, respectively, to the upper and lower boundaries of the conical mirror. The square is the limit of the non-active region.

from the expected photon pattern due to the pixel granularity, radiator thickness and chromaticity effects, and those which spread all over the detector, faked by photomultipliers noise and due to photon scattering. The former, corresponding to the signal, produce the Cherenkov photon pattern. They are Gaussian distributed, with a width $\sigma \sim 0.5$ cm, reflecting essentially the uncertainty related to the pixel size. The latter constitute an essentially flat background modulated by the geometry of the detection plane. Fig. 3 shows the distribution of the hit residuals with respect to the expected Cherenkov pattern for a 3 cm thick, 1.03 refractive index aerogel radiator. The probability density function for a detected hit to belong to the pattern is therefore expressed as

$$p = (1-b)\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{r_i}{\sigma}\right)^2\right] + \frac{b}{d} \quad (2)$$

where b is the photon background fraction, b/d is the background fraction per unit of distance ($\sim 10^{-3}$/cm) and r_i is the closest distance from the hit i to the photon pattern.

Complex photon patterns can occur at the detector plane due to mirror reflected photons, as can be seen in Fig. 4. The Cherenkov angle reconstruction procedure relies on the information of the particle direction provided by the Tracker, which, once extrapolated to the radiator, provides an estimation of the mean photon emission vertex. The tagging of the hits signalling the passage of the particle through the solid light guides in the detection plane provides an additional track element. This can be used as an additional track selection criterion. The best value of θ_c will result from the maximization of a likelihood function, built as the product of the probabilities that the detected hits belong to a given (hypothesis) Cherenkov photon pattern ring:

$$L(\theta_c) = \prod_{i=1}^{\text{n hits}} p_i[r_i(\theta_c)]. \quad (3)$$

The RICH setup was fully simulated with GEANT3 [5] for radiators with different thickness and refractive index. In order to trust the reconstruction, only events with at least 3 hits close (within ~ 1.5 cm) to the reconstructed photon pattern were selected. Fig. 5 shows the reconstructed Cherenkov angle for simulated protons with various momenta. The Cherenkov angle single-hit resolution, obtained with aerogel of 1.03 refractive index and 3 cm thick, was $\Delta\theta_c \sim 5$ mrad. This resulted in a velocity resolution $\Delta\beta/\beta$ slightly better than 0.1% for protons ($\beta \sim 1$) and better than 0.05% for helium nuclei.

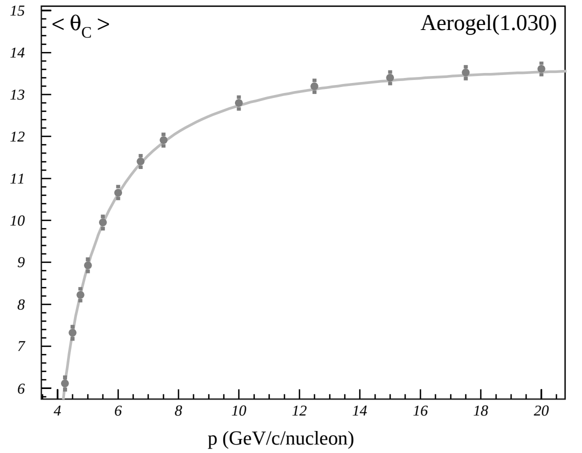

Fig. 5. Cherenkov angle reconstructed as a function of particle momentum for an aerogel radiator.

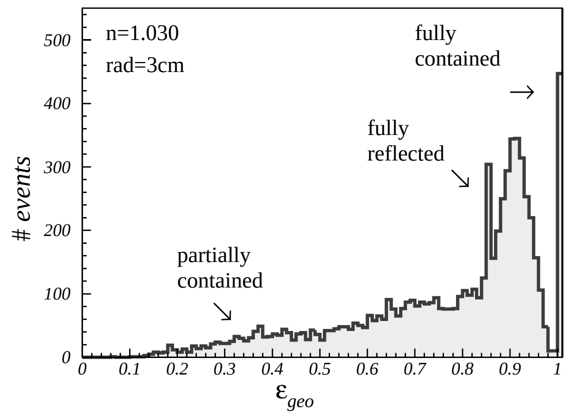

Fig. 6. Photon geometrical acceptance for events in the RICH detector.

3. Charge reconstruction

The Cherenkov photons are uniformly emitted along the particle path inside the dielectric medium, L, and their number per unit of energy depends on the particle's charge, Z, and velocity, β, and on the refractive index, n, according to the expression [4]

$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \propto Z^2 L\left(1 - \frac{1}{\beta^2 n^2}\right). \tag{4}$$

Various factors contribute to the loss of some of these photons in the RICH; radiator interactions ($\varepsilon_{\rm rad}$), geometrical acceptance ($\varepsilon_{\rm geo}$), light guide efficiency ($\varepsilon_{\rm lg}$) and photomultiplier quantum efficiency ($\varepsilon_{\rm pmt}$). Accordingly, the number of counted photoelectrons in the detector is given by

$$n_{\rm pe} \sim N_\gamma\ \varepsilon_{\rm rad}\ \varepsilon_{\rm geo}\ \varepsilon_{\rm lg}\ \varepsilon_{\rm pmt}. \tag{5}$$

All the efficiency factors, but the PMT efficiency, depend on the particle direction and of its incidence point on the radiator. The radiator factor depends on the distance, d, traversed by the photons inside the radiator. It is calculated by integrating the probability of a photon not to interact in the radiator, $\bar{p}_\gamma = \mathrm{e}^{-d(z,\varphi)/L_{\rm int}}$, along the radiator thickness and along the photon azimuthal angle (φ). The geometrical acceptance accounts for photons lost through the radiator walls or totally reflected on media transitions, photons absorbed by the mirror and photons falling into the non-active detection area. It is calculated taking into account the portion of the visible photon pattern in units of photon azimuthal angle, $\varepsilon_{\rm geo} = \Delta\varphi/2\pi$. Fig. 6 shows the geometrical acceptance calculated for an aerogel radiator of 1.030 and for events within the AMS fiducial volume. The extreme variation of $\varepsilon_{\rm geo}$ from event to event is clear. The light guide efficiency factor depends on the incidence angle of the photons (θ_γ) on the top of the light guide. It is calculated using the probability of a given photon to get to the photomultiplier cathode once it entered the light guide, and by integrating it along the reconstructed photon pattern.

The charge of the radiating particles is derived from the number of photoelectrons, $n_{\rm pe}$, close to the previously reconstructed photon pattern (see Section 2). The number of radiated photons is obtained by correcting $n_{\rm pe}$ by the overall event efficiency, which can be written as

$$\varepsilon_{\rm tot} = \frac{1}{2\pi H_{\rm rad}} \int_0^{H_{\rm rad}} \mathrm{d}z \sum_i^{n_{\rm paths}} \rho_i \times \int_{\varphi_i^{\rm min}}^{\varphi_i^{\rm max}} \mathrm{d}\varphi [\mathrm{e}^{-\frac{d(z,\varphi)}{L_{\rm int}}} \varepsilon_{\rm lg}(\theta_\gamma)\varepsilon_{\rm pmt}] \tag{6}$$

where $H_{\rm rad}$ is the radiator thickness, $n_{\rm paths}$ is the number of visible branches constituting the reconstructed pattern (i.e. reflected and direct branches) with ρ_i being the reflectivity for the ith path.

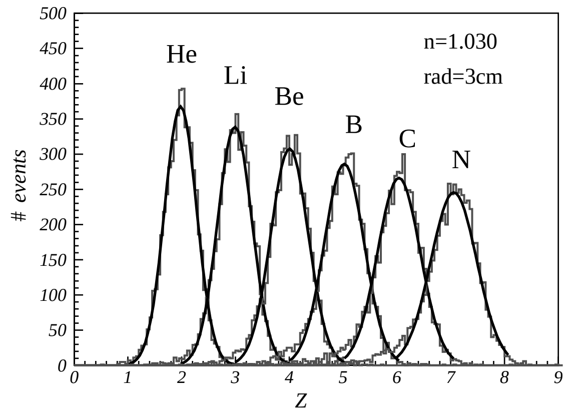

Fig. 7. Charge reconstruction with simulated data in the RICH detector. Gaussian fits are superimposed to the distributions.

The charge is then calculated according to expression (4), where the normalization constant can be evaluated from a calibrated beam of charged particles. In the case of the present results it was obtained from 10,000 simulated helium nuclei events. Fig. 7 shows the reconstructed charge for elements ranging from helium to nitrogen. It was obtained using a 3 cm thick, 1.03 refractive index aerogel radiator, for events with geometrical acceptance greater than 60%. The charge resolution ranges from $\Delta Z/Z \sim 15\%$ for helium to $\Delta Z/Z \sim 5.5\%$ for nitrogen.

4. Conclusions

AMS is a spectrometer designed for anti-matter, dark matter searches and for measuring relative abundances of nuclei and isotopes. Its installation in the International Space Station is scheduled to 2005, where it will operate for a 3-year period. The instrument will be equipped with a proximity focusing RICH detector based on an aerogel radiator, enabling velocity measurements with a resolution of about 0.1% and extending the charge measurements up to the iron element. The velocity of the cosmic rays is measured through the reconstruction of the Cherenkov angle using a maximum likelihood approach. The method consists on finding the Cherenkov angle maximizing the overall probability of the detected hits to belong to its corresponding pattern. Charge reconstruction is made in an event-by-event basis. It is based both on the velocity reconstruction procedure, which provides a reconstructed photon pattern, and on a semi-analytical calculation of the overall efficiency to detect the radiated Cherenkov photons belonging to the reconstructed photon ring.

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