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Status of the AQUA - RICH project *

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[a]dedicated to T. Ypsilantis

Abstract. We describe a 1 Mt water volume in form of a RICH - detector suitable for detection of NNN (Neutrinos, Nucleon decay and superNovae). It has a 124 m diameter outer geodesic dome supporting 3000 inward facing, 1 m diameter hybrid photo diodes mHPDs (3.5% cover) each with 512 pixels of 40 x 40 mm^2 looking through transparent holes in a 124 m diameter spherical mirror balloon. An inner geodesic dome of 62 m diameter supports 3800 outward facing dHPDs (25% cover). The dHPDs see focused Cherenkov rings which give the best pattern recognition and determine particle momentum from multiple scattering. The mHPDs determine the direction of tracks and their vertex point in space. The photon energy acceptance of mHPDs is 5 times that of dHPDs thus they both detect about 200 photons per meter tracklength. This device can detect about 30000 atmospheric neutrinos per year, be sensitive to proton decay with lifetime $\gtrsim 6.2 \cdot 10^{35}$ years and detect supernovae out to a radius of 1 Mpc (includes Andromeda). The algorithms and calculations to determine particle momentum, direction and vertex as well as the current status will be presented.

1 Physics motivation

With the growing evidence for massive neutrinos (for recent reviews see Zuber (1998)) coming from atmospheric neutrino data, solar neutrinos and the LSND - experiment, prospects to explore the physics beyond the standard model in form of GUT-theories should be attacked again. One process always considered within this context is proton decay. Early predictions of non-supersymmetric minimal SU(5) resulted in life-times of about 10^{28} yrs for a decay mode $p \rightarrow e^+\pi^0$, which is ruled out by current Super-K data of $\tau/BR(p \rightarrow e^+\pi^0) > 1.6 \cdot 10^{33}$ yrs with 90 % CL Shiozawa (1999). Other models emerged favouring now the decay mode $p \rightarrow \bar{\nu}K^+$, where Super-K gives a limit of $\tau/BR(p \rightarrow \bar{\nu}K^+) > 6.7 \cdot 10^{32}$ yrs with 90 % CL Hayato (1999). For a recent review on proton decay see Pati (2000). As is stated in Pati (2000), the decay $p \rightarrow \bar{\nu}K^+$ should show up in most of the currently discussed GUT models with a life-time of around 10^{34} yrs, maybe a little less, but only marginally reachable with Super-K if at all. With AQUA-RICH such a life-time should lead to several ten events within one year because the sensitivity should be higher than 10^{35} years. Furthermore the branching ratio into an alternative mode, $p \rightarrow \mu^+K^0$ gives discrimination power among GUT-models. While it should be unobservable (BR of about 10^{-3}) in supersymmetric SU(5) it can go up to 20 - 40 % of the $p \rightarrow \bar{\nu}K^+$ decay mode in SO(10) or string inspired G(224) models. In that case AQUA-RICH could distinguish between both scenarios.

Beside that, the existing evidences of atmospheric neutrino oscillations should be further investigated. The Super-K result seems to indicate a solution in form of $\nu_\mu - \nu_\tau$ oscillations centering around $\Delta m^2 \approx 4 \cdot 10^{-3} eV^2$ and $sin^2 2\theta \approx 1$ Totsuka (1999). With respect to the atmospheric neutrino problem AQUA-RICH is especially interesting. First of all it could directly measure atmospheric neutrino interactions and search for the oscillation pattern under the assumption of being able to perform a reasonable momentum measurement. Secondly it could be used in accelerator based long baseline experiments, be it with beams in preparation like Fermilab-Soudan or CERN-Gran Sasso or the proposed beam from a neutrino factory. Because of its large target mass, it could be build even at larger distances from the factory to explore other neutrino parameters. Furthermore for the first time it could be envisaged to detect also the prompt ν_τ flux in the atmosphere.

Last not least neutrino astrophysics is still in its fancies and very large experiments are in the preparation phase (like AMANDA, ANTARES, NESTOR). They have a relatively high threshold for astrophysical neutrinos in a region where the flux is low. On the low energy end of astrophysical neutrinos the interest relies on supernova detection, the only successful event observed still being SN 1987A. AQUA-RICH would fit

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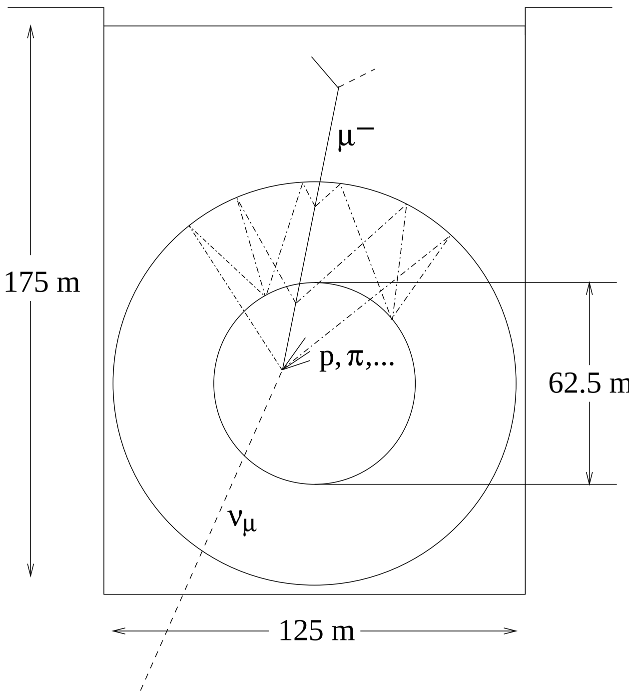

Fig. 1. A schematic view of the 1Mt AQUA-RICH detector and an upward going ν_μ charged current interaction. The inner dome (62.5 m diameter) supports 3125 outward looking dHPDs (20% coverage). The outer 125 m diameter sphere is reflective and supports 2185 mHPDs (3.5% coverage). From the top of the mirror sphere to the water level there are 50 m water to stop downward going muons with momenta below 10 GeV/c.

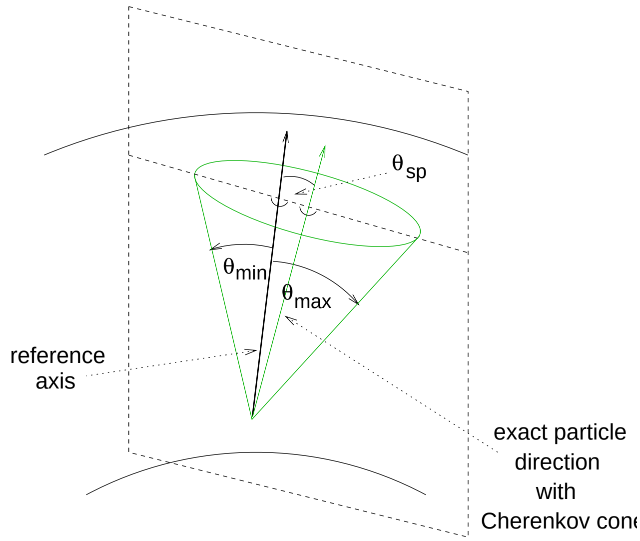

Fig. 2. Geometry of photon emission. The angle of the particle relative to the reference axis is θ_{sp} and the photon emission angles are reconstructed with respect to this axis. The emission vectors of the photons with the maximal and minimal polar angle $\theta_{max} = \theta_c + \theta_{sp}$ and $\theta_{min} = \theta_c - \theta_{sp}$ are in the plane determined by the reference axis and current particle direction. For these photons, the azimuthal angles of the photon and the particle are equal.

in these two regimes quite nicely, because it would observe a supernova signal like the one from SN1987A even in a range of 1 Mpc, therefore including most of the Local Group and definetely M31. Using such a range and the currently assumed supernova rate for galaxies, within a period of 10 yrs one has a high probability for an observation. For a supernova in the region of the galactic center, the observed event rate would be enormous (about 10^5). AQUA-RICH could also be used for higher energy neutrinos - but still below the above mentioned detectors - so it would fill a gap, where no other experiment is running.

2 AQUA-RICH

The basic principle and ideas of AQUA-RICH are summarized in a recent paper Antonioli (1999). By using the RICH technique, particle velocities can be measured by the ring radius and direction by the ring center. An improvement over existing Cerenkov detectors is that higher ring multiplicities and therefore more complicated events can be investigated. The main new idea is to measure also momenta via multiple scattering. Considered is a 1 Mt detector, where the actual design might vary according to local requirements or specific tasks. One possible design discussed is shown in Fig. 1 Ypsilantis (1999).

The outer sphere of 125 m diameter is the mirror equipped with 2185 inward looking Hybrid Photo Diodes (mHPDs). The 62.5 m diameter inner dome supports 3125 outward looking dHPDs. The 3.5% detector coverage on the mirror surface (between mirror segments) are used to determine vertex and direction of each track, whereas the HPDs on the detector surface (dHPDs) will allow to determine momentum. Their coverage is about 20%. To reduce background, the upper 50 m of water will stop downward going muons with momenta below 10 GeV/c.

The total of 5310 HPDs (each of 1 m diameter) with 396 pads of $45 \times 45\ mm^2$ on the photocathode surface, electrostatically demagnified to $9 \times 9\ mm^2$ on the silicon sensor, will have a time resolution of less than 1 ns and provide the total number of 2.1 Mpixels for readout (Super-K: 11200 PMs, 0.5 m diameter, 11.2 kpixels). To reduce chromatic aberrations, the photon energy acceptance of the dHPDs will be limited to 2.3 to 2.9 eV (ΔE = 0.6 eV) or even less to obtain a good momentum resolution. The mHPDs, only used to determine vertex and track direction, have a larger acceptance of ΔE = 1.7 eV.
A 3 ton cylindrical prototype exists at CERN, which will be equipped with 200 PMTs in 2000 to measure rings of atmospheric muons and possibly also muons from a test beam. Also the first HPDs are close to functionality.

3 Momentum reconstruction

As stated, one of the main goals of AQUA - RICH is to measure particle momenta vie multiple scattering. Multiple scat-

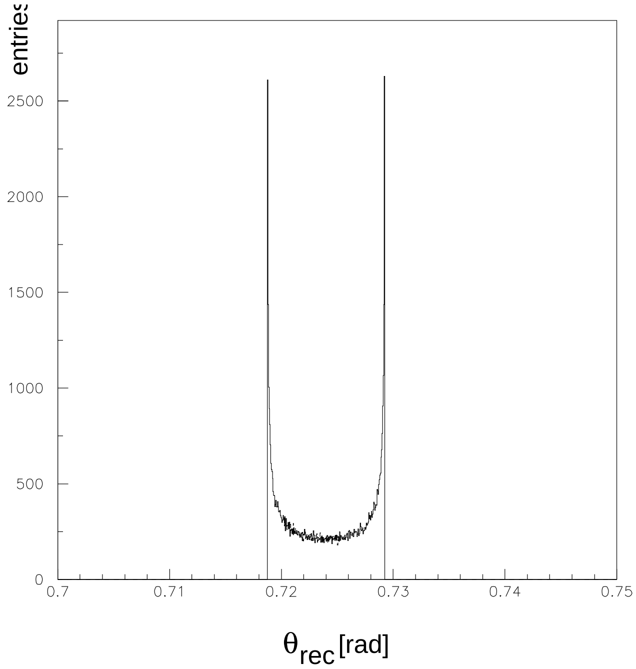

Fig. 3. Distribution of reconstructed Cherenkov angles θ_{rec} for a particle moving with a constant angle θ_{sp} to the reference axis (cf. Fig. 2). In case of this run the deviation is $\theta_{sp} = 5$ mrad, i.e. the spikes are at $724 - 5$ mrad and $724 + 5$ mrad. The true Cherenkov angle in water is approximately 724 mrad (with $\beta = 1,\ n = 1.33$). Each spike contains roughly 10% of all entries.

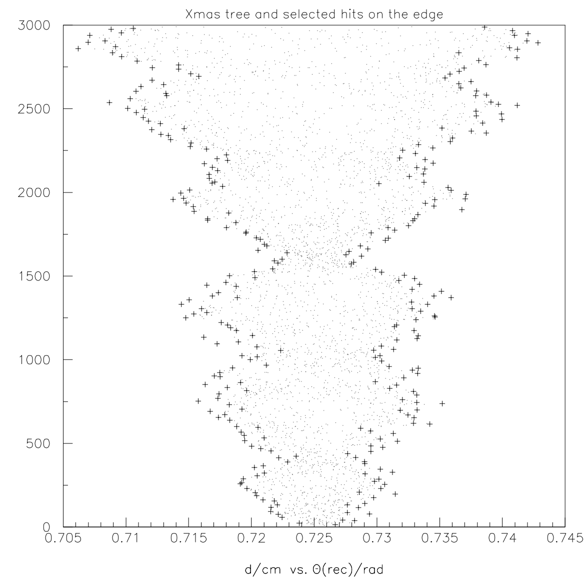

Fig. 4. Θ_{rec} as a function of travelled path length under the influence of multiple scattering. A typical simulated "Xmas - tree" and the hits on the edge (crosses) can be seen, that were selected with slices of $\Delta d = 20\ cm$ (muon with 14 GeV/c and 30 m track length; including measurement and evaluation errors). The algorithm of selecting the hits on the edge of the X-mas tree ("EoX - method") is a very simple one so far and may be improved.

tering causes a displacement and an angular change as a particle moves through a medium. The projected angular distribution $\theta_{b;c}$ of a particle with velocity β, momentum p and charge Z after traversing the path L in a medium of absorption length X_0 is Gaussian with the width

$$\sigma_{ms} = \theta_{b;c}^{rms} = \frac{k_{ms}}{\beta c p} Z \sqrt{\frac{L}{X_0}}, \tag{1}$$

with $k_{ms} = 13.6$ MeV as the multiple scattering constant.

Since multiple scattering can be regarded independently within two planes, the $nonprojected$ scattering angle θ_{sc} is obtained from the $projected$ ones $\theta_b,\ \theta_c$ with

$$\tan^2\theta_{sc} = \tan^2\theta_b + \tan^2\theta_c, \tag{2}$$

or, in the small-angle approximation (surely valid for angles of a few mrad),

$$\theta_{sc}^2 = \theta_b^2 + \theta_c^2. \tag{3}$$

Consider the geometry of the photon emission, displayed in Fig. 2. If the particle emits a complete cone of Cherenkov photons, the distribution of reconstructed polar emission angles θ_{rec} would have explicit spikes at $\theta_c + \theta_{sp}$ and $\theta_c - \theta_{sp}$ (Fig. 3). For the hits in these spikes (i.e. with the maximal (minimal) θ_{rec}), the emission vector, the particle vector and the reconstruction axis are in the *same plane*. This means, that the azimuthal angle of the particle direction in the basic reference system equals the azimuthal photon emission angle ϕ_{rec}, which was obtained with the RICH reconstruction algorithm, i.e. $\phi_p = \phi_{rec}$. Details can be found in Großheim (1999). It is then straightforward to calculate the polar particle direction, which is given by $\theta_p = \theta_{rec} \mp \theta_c$, respectively. Thus, for a certain percentage of all photons, the exact particle direction at their emission point can be determined.

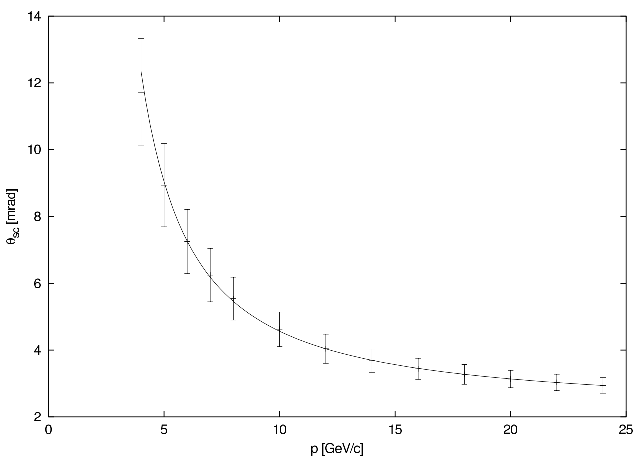

Fig. 5. Momentum calibration curve. The correlation of momentum and scattering angle is used to find the calibration function, which allows to reconstruct the momentum to any measured θ_{sc}.

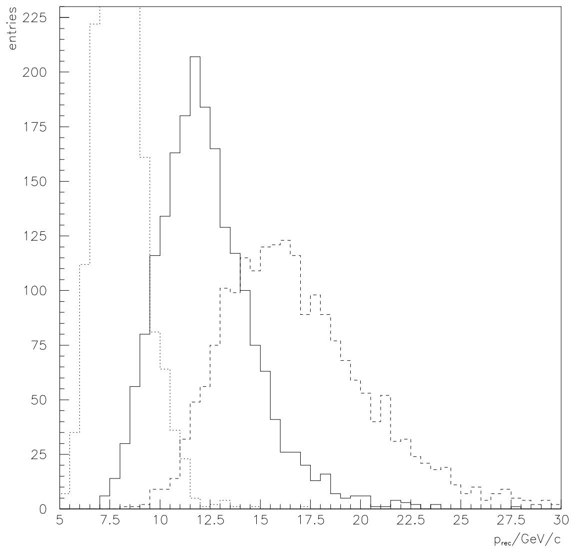

Fig. 6. Distributions of reconstructed muon momenta using the EoX - method. Exemplary, 8, 12, 16 GeV/c (left to right) muons are shown. Only 10 m of track length are used for reconstruction, this can still be improved by using the full track.

Hence, the problem of determining the scattering width σ_{ms} for a certain track is reduced to a measurement of the distribution of nonprojected scattering angles θ_{sc}. This can be done by tracking the particle with high precision. Then, the angles between the particle directions (represented by $\theta_p,\ \phi_p$) at equidistant points can be determined, which results in the desired distribution of θ_{sc}.

We studied muons in the range of a few GeV up to 100 GeV with the help of a GEANT based simulation. Fig. 4 shows such a "X-mas" tree as a particle moves along. It can be clearly seen how multiple scattering is changing the reconstructed θ.

By using 10 m of track length, the calibration curve - the relation between momentum and θ_{sc} - shown in Fig. 5 is obtained. Typical momentum resolutions are of the order of 10 - 20 %. A distribution of reconstructed momenta for various muon energies is shown in Fig. 6. However high energy muons have longer tracks, therefore several independent measurements can be performed along one track. Even including achromatic and pixel errors the momentum resolution can still be improved to be typically 7 % for 20 GeV muons. For details see Großheim (1999).

4 Summary and conclusion

A 1 Mt AQUA - RICH detector has an enourmous potential for nucleon decay, atmospheric neutrino observation, long baseline experiments and supernova neutrino searches. Several possible designs can be invisaged for realisation. A reconstruction algorithm was developed, which allows a momentum determination for GeV muons of less than 10 %. Therefore the claimed goal of measuring reasonable momenta of particles seems to be achieved. A 3 ton prototype detector exists at CERN, which should produce ring images in 2000.

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