Chapter 9

SUMMARY AND FUTURE SCOPE

The work on the simulation of the hadron response of the ICAL detector and their contribution to the enhancement in the ICAL sensitivity to the neutrino oscillation study, and the development of the multigap RPC detectors which may be probed to further enhance the reconstruction of the muon and the hadrons in the ICAL; which have been discussed in the preceding chapters, have been summarized here. The future scopes to improve this work have also been highlighted.

9.1 SUMMARY

The INO collaboration plans to study the neutrino oscillations in the atmospheric sector, with a 50 kt magnetized ICAL detector. The R&D program for the ICAL is now running at a full pace. This detector is primarily designed to measure the muon momentum. The magnetic field would also allow us to distinguish between the muon and the antimuon, and hence between the incident neutrino and the antineutrino.

The main aim of the detector is to identify the true mass hierarchy, through the study of the Earth matter effects experienced by the neutrinos and the antineutrinos, separately. Apart from that, ICAL would also contribute in the precise measurement of the atmospheric neutrino parameters $|\Delta m^2_{32}|$, $\theta_{23}$ and its octant. The ICAL would also look for the hint of any new physics. Apart from the muons, ICAL is also ca-
pable of detecting the hadron shower and measure its momentum. The information on the hadrons provides an additional boost to the physics potential of ICAL.

A simulation study has been performed to quantify the detector response to the muons and hadrons produced in the atmospheric muon neutrino interactions. The muon leaves a long track in the detector, and its momentum and direction is obtained through a track reconstruction algorithm based on the Kalman Filter techniques. However, the hadrons produce a shower of hits within a close proximity of the interaction vertex. The hadron energy, parametrized in terms of $E'_{\text{had}} \equiv E_\nu - E_\mu$, is estimated from the hadron hit multiplicity which follows the Vavilov PDF. A calibration of $E'_{\text{had}}$ for the number of hadron hits in an event has also been obtained. The hadron energy resolution of ICAL is in the range $(80\% - 35\%)$ for $E'_{\text{had}}$ between $1 - 15$ GeV. The calibration of the hadron energy from the hadron hits, in terms of the Vavilov fit parameters, may further be used to reconstruct the hadron energy for the ICAL physics potential analysis.

The shower shape and spread, in terms of the position vectors of the hits, are further used to reconstruct the average direction of the hadron shower, either by obtaining the direction of the centroid of the shower, or by forming an orientation matrix to take care of the higher order moments. This information enables to study the hadron energy response as a function of the shower direction, which shows marginal direction dependence. The shower spread is also used to discriminate between the DIS and RS events.

The energy and direction of the incident neutrino in CC interaction events, are then reconstructed using the reconstructed information of the muon and the hadrons, via the conservation of the four momentum. The neutrino energy response of the ICAL is in the range $20\% - 25\%$, while the zenith angle resolution is $7^\circ - 15^\circ$. On the other hand, the hadron shower is the only hint of an NC interaction event.

The reach of ICAL is then studied using the correlated information on the muons and the hadrons. A statistical $\chi^2$ analysis procedure, with the events divided in bins
of the muon energy, the muon zenith angle and the hadron energy, is performed, and it is found that the inclusion of the hadron information enhances the ICAL physics potentials by significant amounts. It is found that the ICAL, with 500 kt–yr exposure, would be able to determine the neutrino mass hierarchy with a significance of $\Delta \chi^2_{\text{ICAL-MH}} \approx 9$, which implies about 40% enhancement over the muon-only analysis. The atmospheric neutrino mixing parameters can also be measured more precisely by the inclusion of hadron energy information. It has been found that, 10 years of running of the ICAL would be able to constrain $\sin^2 \theta_{23}$ to a relative 1σ precision of 12% and $|\Delta m_{32}^2|$ to 2.9%.

The time information from the RPC detectors in the ICAL, with respect to the trigger, would be used to determine the direction of the muon track. It would also be used in an approach to measure the average hadron shower direction. The RPC time resolution is about 1 – 1.5 ns, and an improvement in the time information would make it possible to boost the direction reconstruction of the muons and the hadrons in ICAL. As a part of the extended R&D in ICAL, MRPC detectors, which are much faster as compared to the RPCs, are fabricated and their performance are studied in order to probe their potential in the upgrades of ICAL as well as other applications such as, TOF experiment.

A stack of MRPC detectors, with six sub gaps in each of them, has been developed. The design and construction of these detectors have been optimized after several trials, and they are characterized as a function of various input parameters, e.g., the operating voltage and the gas mixture. The gas mixture has also been optimized to obtain improved efficiency and the time resolution. A time resolution of about 60 ps has been obtained. As a first attempt to probe their potential, the MRPCs have been used in the external trigger system for the characterization of single-gap RPCs. The stack, comprising of three MRPC detectors, is now being operated under stable condition for a substantial time and is ready for further probes.
The work documented in this thesis, has thus facilitated the enhancement of the ICAL potential in attaining its goals. The study of the hadron response of ICAL has been quite effective, as the inclusion of this information has significantly improved the sensitivity of the detector in determining the neutrino mass hierarchy and the atmospheric mixing parameters. The successful development of the MRPC detectors, and their satisfactory performance provides lead to the scope of studying their applications in the future upgradation in the ICAL as well as other experiments that would require faster detectors.

9.2 FUTURE SCOPE

The ability of ICAL in reconstructing the hadron energy and direction has provided plentiful opportunity to extract and use the information to improve on the detector’s potential. The work described in this thesis assumes that, the muon and hadron hits in the ICAL are separable with a cent percent efficiency. However, the separation of the muon track and the hadron shower hits would be crucial to use the real data, once ICAL becomes operational. Thus a simulation study to develop an efficient track-shower separation algorithm is important.

The hadron energy response has been obtained using the number of hits in each shower. An attractive alternative approach would be to use the shower shape and spread to reconstruct the energy. A quantity parameterizing the shower shape may be picked to calculate the energy response. A possible improvement in the energy response would provide better sensitivity of the physics study with ICAL. Also, the neutrino response of the ICAL is coarse, and can be improved by stricter cuts, and with possible improvement in the measurements of the muon momentum and the hadron momentum.

The statistical approach, that has been used to study the ICAL physics reach, uses the CC interaction events only. Since partial information on the NC events, in terms of the hadron shower, are also available, this approach may be extended for the NC
events. A possible way to use the NC events would be a one dimensional binning of the events with the observable $E'_{\text{had}}$. The hadron direction resolution may also be included in the further study of both the CC and NC events. Another promising work is to modify the oscillation analysis algorithm to study the ICAL potential to detect the sterile neutrinos.

The MRPC detectors show good stability, good detection efficiency and time resolution, and they are now ready to be tested for possible applications as trigger detector, and in TOF experiments.