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Thomas Meures

Development of a Sub-glacial Radio Telescope for the Detection of GZK Neutrinos

Doctoral Thesis accepted by
the Université Libre de Bruxelles, Belgium

Springer

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ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-319-18755-6 ISBN 978-3-319-18756-3 (eBook)
DOI 10.1007/978-3-319-18756-3

Library of Congress Control Number: 2015938744

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Supervisor's Foreword

What better place than the South Pole to conduct a pioneering experiment hunting for extremely rare particles from the edge of space? This singular virtual point at the bottom of the Globe has attracted brave pioneers for over a century. So it was that Mr. Thomas Meures, now Dr. Meures, the young adventurer, came to contact me in January 2010, asking what kind of work would be involved in the pursuit of the Ph.D. I replied with a short response saying that it would include some electronics and analysis of data from a to-be-constructed radio frequency neutrino detector. Neither he, nor I for that matter, had any idea what we were getting into. It is probably fortunate that we were both oblivious: any reasonable graduate student with full knowledge of the challenges lurking square in the middle of the path to the Ph.D. degree endgame would certainly never begin the undertaking. Had I been aware of everything, it would have placed me in the morally dubious situation of having to partially conceal the true difficulty of this Ph.D. topic for fear of scaring off students.

Our goal was the construction, deployment, operation, and analysis of data from an array of radio antennas fixed in the glacial ice at South Pole: the Askaryan Radio Array, or ARA, detector. This detector, we thought then and we still think now, is the best way to detect ultrahigh energy elementary particles called neutrinos which, if we understand the laws of particle physics correctly, must be produced when energetic charged protons slam into the 2.7 K relic photons from the early Universe. These chargeless particles carry a kinetic energy equivalent to macroscopic ping pong balls but ironically could penetrate tens of kilometers of lead. Because of these unique properties, they are the only known elementary particle which can carry information about the most energetic processes taking place outside of the cosmologically microscopic sphere of radius 100 megaparsecs surrounding our home planet, Earth. Conversely, these properties also make construction of a cosmic ping-pong ball detector exceedingly difficult: one can only provoke interactions by bringing massive amounts of target material to bear. Since tens of kilometers of lead is hard to find, saying nothing of instrumenting such a mass with detectors, we settled on the South Pole where there is no lead but plenty of cold ice. Cold ice is extremely radio transparent and dense enough to catch a handful of cosmic neutrinos per cubic kilometer per century. When these particles interact they create electromagnetic showers which radiate broadband RF power. Because of the long attenuation lengths, many tens of cubic kilometers can be instrumented for reasonable cost thus bringing the expected event rate to something more of order a few events per year.

There were still many challenges designing and implementing a detector in ice. The instrumentation for the detectors is almost completely custom and had to be designed to amplify the weak signals near the thermal noise floor and digitize them at high sampling speeds (3.2 GSPS). This must be done cheaply, consuming low power, and with hardware robust enough to withstand the extreme freezing temperatures of the Antarctic Polar Plateau. Fortunately, we collaborated with a number of other research teams internationally who developed the electronic data acquisition systems. The antennas which make up the detection elements must be deployed 100–200 m below the top layer of packed snow, so drilling holes to 200 m is necessary. Thomas went to Pole for two seasons (2011–2012 and 2012–2013) to act as an ice driller to deliver the holes for the first three stations.

And then, in 2013 we had data coming back from Pole, but this was far from the end of the story. In fact, there was still a lot of data analysis to be done. First, we had to understand the custom-built instrument. It took Thomas many months to collect the various calibration data sets taken when the instruments were still in the North in the testing and characterization phase. This data was needed to understand the behavior of the digitizer ASIC, the IRS2 which was designed specifically for this experiment. Among other things, his Ph.D. thesis documents and explains how to turn the digital data stream from this chip into useful voltage and time samples. While this ASIC is unlikely to be used elsewhere, it is the parent or grandparent of other ASICs currently being planned for use in other astrophysics experiments, so this documentation is interesting to an audience broader than the ARA collaboration. Because his thesis was the first to use the ARA station data, he had to develop geometry and sensitivity calibrations, ab initio. Finally, he developed the background rejection and event reconstruction algorithms which yielded no cosmic neutrino events, none were expected from the limited exposure time and from only two of the fully planned 37 detector stations, but which clearly demonstrates the power of the radio technique for ultrahigh-energy neutrino detection.

Brussels Prof. Kael Hanson
March 2015

Abstract

GZK neutrinos are interesting messenger particles since, if detected, they can transmit us exclusive information about ultrahigh energy processes in the Universe. These particles, which hold energies above 10^{16} eV, interact very rarely. Therefore, detectors of several gigatons of matter are needed to discover them. The ARA detector is planned and is currently being constructed at the South Pole. It is designed to use the Askaryan effect, the emission of radio waves from neutrino-induced cascades in the South Pole ice, to detect neutrino interactions. With antennas distributed in 37 stations in the ice, such interactions can be observed in a volume of several hundred cubic kilometers. Currently, two ARA stations have been deployed in the ice and are taking data since the beginning of the year 2013.

The first part of this thesis summarizes the current theories concerning the GZK mechanism and the Askaryan effect to explain the interest in GZK neutrinos and in the used detection method.

In the second part the ARA detector is described and calibrations of different detector parts are presented. In this work, the digitization chips have been calibrated concerning their timing precision and signal amplitude. In this way a timing precision of 100 ps between antennas could be achieved. Furthermore, the geometry of the antenna clusters is determined by fits based on external signals to allow for a proper radio vertex reconstruction.

In the third part of the thesis the development of methods to distinguish radio signals from thermal noise are presented. Moreover, a reconstruction method, developed to determine the position of radio sources, is described. With only two stations operational a discovery of GZK neutrinos is not expected and in fact no signal candidate has been found in the analysis of the data. A neutrino flux limit is calculated. This limit is not competitive yet with the current best limits, but is promising for the full ARA detector. The work shows that after completion this detector is expected to be capable of a neutrino discovery.

Acknowledgments

There are many people that I am very grateful to and which contributed to the completion of this work. Probably I will forget some names which should be in the following list. Please forgive me if I forgot somebody at the moment that I am writing this.

Many thanks go to my supervisor Kael Hanson, for always being available for discussions and questions. Thanks for creating a relaxed and familiar atmosphere. In your guidance I found this a nice mix of input and freedom to develop my own ideas. Furthermore, thank you for giving me the opportunity to take responsibilities within the ARA project and to spend two very exciting months at the South Pole and at many other places.

I would like to thank the members of my Jury: Stijn Buitink, Gilles De Lentdecker, Olaf Scholten, and Petr Tiniakov. Thank you to agree to read my work, to spend the time to evaluate it and to supply corrections and suggestions for improvement. Special thanks go to Petr Tiniakov and Gilles De Lentdecker as members of my Committee d'accompagnement, who had to listen to my annual reports and supply many signatures.

Thanks to the members of the IceCube group in Brussels, which I have encountered. I got a warm welcome from everybody and always found you a very enjoyable company. During coffee breaks, pizza lunches, and other social activities one could forget all work-related (or unrelated) problems. Furthermore, the Belgian colleagues were always available to help out the foreigners among us with administrative issues. I would especially like to thank the current members, namely: David Heereman, Jan Lüneman, Gwenhaël De Wasseige, Martin Casier, Lionel Brayeur, Geraldina Golup, Elisa Pinat, Jan Kunnen, Giuliano Maggi, Aongus Ó Murchadha, Krijn De Vries, Catherine De Clercq, Nick Van Eijndhoven, and Kael Hanson. Thanks for the support when finishing my thesis, for discussions on cosmic rays and the Askaryan effect, and for all the proofreading and rehearsal talks.

I would like to thank my office mates Rachel, David, Aongus, Mark, and Alberto for coping with hours of my ARA phone calls, for medical and life advices, and for always creating a nice atmosphere in the office.

Thanks to the DAQ team of the lab which gave me a good start into my working life and which I always enjoyed working with.

I would like to thank Audrey Terrier, Marleen Goeman, Danielle Peymans, and Fatimé Pero for their help with the university administration. I think Marleen and Audrey are unsurpassed in making the IIHE a nice place to work at. In fact I want to thank all members of the IIHE for the good working environment which I encountered in the lab. This was not possible without the friendly lead from the directors of the lab: Catherine De Clercq, Daniel Bertrand, Pierre Marage, Jorgen D'Hondt, and Laurent Favart. In particular, I would like to thank the former director Pierre Marage, who would always listen to the trouble of a Ph.D. student and help where he could.

Many thanks go to Dave, Dennis, Jim, Jef, Darrel, Terry, James, Gary, and Andrew for allowing the German Ph.D. student on the drill team and for giving me the best time.

I would like to thank the ARA Collaboration for their support and scientific input during my Ph.D. This support went from hosting me for test measurements, providing simulations and continuously poking into my analysis until it was solid work.

Thanks to all my friends for all the small things, which are not measurable, but which in the end keep you going.

Thanks to Bettina and David for the possibility to share all good and bad things during fresh-air breaks. Thank you for many evenings of recreational discussion at “Le Phare” or at the beach in Buzios.

Ich möchte meinen Eltern und Geschwistern danken: dafür, dass ihr immer an mich geglaubt habt und mich konstant unterstützt habt, in dem was ich tue. Das hat mich schlussendlich bis hierher gebracht. Ich habe viel Glück mit meiner Familie.

Danke Kathleen, dass du mich durch die stressige Zeiten begleitet hast und nie den Mut verloren hast. Danke vor allem dafür, dass du mich immer daran erinnerst, dass die Doktorarbeit nicht das wichtigste im Leben ist.

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