Radiowave neutrino detection

(ARENA06 Conference Summary talk, Newcastle, UK, June 28–July 1, 2006)

Dave Z. Besson
U. Kansas Dept. of Physics and Astronomy, Lawrence KS 66045-2151

“I am often asked how radio works. Well, you see, wire telegraphy is like a very long cat. You yank his tail in New York and he meows in Los Angeles. Now, radio is exactly the same, except that there is no cat.” (Attributed to A. Einstein)

1. Introduction
Depending on whether you search www.google.com, www.google.it, or www.google.ru, radiofrequency (RF) signal transmission was first developed at the turn of the century by either Gugliemo Marconi in June, 1896, (see the Wikipedia pages in Italian), or Alexander Popov (see the Wikipedia pages in Russian) in May, 1895. Nikola Tesla, working about 400 km due east of the University of Kansas along Interstate 70, might rightfully be considered the progenitor of the modern-day wireless industry; his innovative suggestions regarding the possible propagation of surface waves has also been the subject of neutrino detection schemes[1], among others[2].

Since radio wavelengths are ‘macroscopic’, for several applications they have advantageous signal production and transmission properties. For a typical antenna, the effective height, which is directly proportional to the voltage produced by an incident electric field, is of order the antenna length. Machining a piece of copper of scale 1 m is considerably easier than machining a piece of copper two orders of magnitude larger or smaller. At meter-scale radio wavelengths (in comparison to atomic dimensions) dielectric media with only atomic-scale impurities may be largely radio-transparent. For example, the attenuation length of radiowaves in South Polar ice has been measured to be $\sim 1.5–2$ km over the frequency range 200 MHz - 800 MHz at the South Pole[3].

For these and other reasons, the initial assertion by Askaryan[4] that high-energy electromagnetic showers will produce RF signals in dense media stronger than their optical counterparts, has (inevitably) engendered a very recent flurry of activity in this field. Whereas, a decade ago, there was only one active experiment (RICE) seeing detection of ultra-high energy (UHE) showers in dense media via radio detection, the re are now several active groups.

2. Motivation
The GZK-effect[5] implies that 100 EeV charged particles arriving at Earth must originate from within a sphere of radius $\sim 10$ Mpc. This is a remarkably tiny volume, corresponding roughly to the scale of the Local Galactic Group. In terms of redshift, relative to the 14 Gyr history of the Universe, we are sensitive only to those Ultra-High Energy Cosmic Rays (UHECR) produced in the last 30 Myr. If the Universe evolved through a past epoch where particle acceleration mechanisms were present in the past that have not been active during last 0.3% of the temporal history of the Universe, we could not observe the resulting UHECR’s. Neutrinos suffer no GZK-attenuation and therefore, in principle, probe all redshifts.
Detection of ultra-high energy neutrinos offers unique insights into the most energetic processes in the Universe. Super-massive black holes (Active Galactic Nuclei), the collapse of bizarre twists of spacetime left over from the Big Bang (topological defects) and Weakly Interacting Massive Particles (WIMP’s) are only some of the sources that would be probed by an ultra-high energy electromagnetic (and hadronic) shower detector. There is also a great deal of particle physics information which can be deduced, for instance, from the angular distribution of upward-coming neutrino events through different chords of the earth. As recently emphasized by proponents of ARIANNA[6], such data could be used to measure weak cross-sections at energies unreachable by any man-made accelerator, and thereby probe the internal structure of protons at length scales orders of magnitude smaller than those currently achievable. This capability of probing such minute length scales may also reveal new physics (extra dimensions, micro-black-holes)[7] for the first time.

3. Radio signals from neutrino-generated showers in dielectrics

For definiteness, consider a $\nu_e$ undergoing a charged current interaction, $\nu_e + N \rightarrow e + N'$. The primary UHE neutrino transfers most of its energy to the electron, which quickly builds an exponentially increasing shower of $e^+e^-$ pairs. The number of pairs $N_e$ scales like the primary energy. In the most populated region of the shower, at the “bottom” of its energy range, a charge imbalance develops as positrons drop out and atomic electrons scatter in. Detailed Monte Carlo calculations by Zas, Halzen and Stanev (ZHS)[8] and supported by subsequent GEANT simulations[9] and subsequent refinements of ZHS[10], find that the net charge of the shower is about 20% of $N_e$. The electric field produced by this relativistic pancake is dominated by coherent Cherenkov radiation for wavelengths in the radio frequency region. Equivalently, for wavelengths large comparable to the transverse size of the shower ($\sim 2r_{Moliere}$, or $\sim 10$cm in ice), the relativistic pancake can be treated as a single, extended, radiating charge. (Clearly, in the limit $\lambda \rightarrow \infty$, the radiating region approaches a point charge.)

3.1. Laboratory Verification

Laboratory tests of the radio signal resulting from a charged particle beam have been ongoing for the last decade, with the most definitive tests occurring in the last five years. The GLUE/ANITA team has performed a sequence of measurements, beginning with an electron beam incident on a sand target[11], a photon beam on a salt target[12], and most recently, ANITA has calibrated their antenna response in a SLAC testbeam on an ice target[13], as shown in Figure 1. The signals observed in a variety of radio antennas and receivers track the expected signal strength (Fig. 2), near-field complications notwithstanding. Surface roughness effects are relevant to both the beamtest as well as the flight itself. Studies of signal transmission through the firm, as well as data scaled-up from a clever optical wavelength set-up, indicate that surface roughness should, if anything, enhance the number of detected events.

3.2. Active Experiments

Initial projects exploring radio Cherenkov signals at the South Pole (RAND[14]) or at Vostok[15] date back to the early-90’s. Currently, two Antarctic projects (ANITA[16] and RICE[17]) are in the data-taking phase. ANITA, largely funded by NASA as part of the LDB (Long Duration Balloon) program, will launch from McMurdo Base, Antarctica, sometime around December 1, 2006 for an extended circumpolar flight. Two prototype ANITA antennas mounted on the TIGER payload during December 2003 provided essential experience and data, in preparation for the main flight. During its planned 45-day December-January flight of this year, comprising three full revolutions around the Antarctic continent, ANITA will synoptically (from an elevation of 38 km) view a cylindrical volume of ice 700 km in radius, 2 km thick on average, and with an average angular aperture of approximately 0.1 radians. With an effective threshold of $10^{19–20}$
eV (set largely by the typical distance to the interaction vertex), ANITA will offer the best sensitivity to date to the GZK-neutrino parameter space.

The RICE experiment, which has been taking data since 1999, has a threshold approximately two orders of magnitude lower, with an effective volume also approximately two orders of magnitude smaller than ANITA at 100 EeV. Nevertheless, with radio antennas 50-100 meters apart, RICE will continue to have excellent sensitivity in the 100 PeV-100 EeV energy regime, not to be superceded until the advent of either the ARIANNA\cite{16} or RICE-successor (AURA)\cite{18} experiments. A compilation of the current RICE limits on the incident neutrino flux, superimposed on both experimental limits as well as theoretical predictions, is presented in Figure 3. The null search for in-ice showers can quickly be translated into a limit on the diffuse neutrino flux from gamma-ray bursts\cite{17}. Additionally, a dedicated gamma-ray burst (GRB) coincidence study was performed to quantify limits on neutrino-generated showers from specific GRB’s\cite{18}. The GRB sample coincidence sample used was, unfortunately, a preferentially high-redshift sample. Accordingly, the limits are rather weak relative to model expectation (Fig. 4).

As originally pointed out by Wick et al.\cite{26}, a radio detector would also have excellent sensitivity to an incident, relativistic, highly-ionizing magnetic monopole. Briefly, at large distances from a radio array, the monopole will leave a trail of ionization, boosted in magnitude relative to a muon by the large monopole charge. This trail of ionization is less susceptible to LPM effects than a single UHE neutrino since the monopole energy loss is distributed over a long pathlength. As shown in Figure 5, the preliminary limits from RICE are competitive.

Perhaps the primary virtue of the in-ice strategy is the ability to vertex sources within the ice itself. Over the next several years, AURA will (hopefully) take advantage of the timely opportunity presented by the IceCube drilling to extend the RICE strategy. The AURA array will serve as a prototype for a future radio+acoustic hybrid array, over a surface area of 100-km$^2$ at the South Pole, centered around IceCube. The AURA strategy is to re-package the IceCube digital optical modules with radio electronics, with four breakouts to a cluster of antennas.

\footnote{The original acronym advocated by the author for this experiment (Retrofitted OptiCal SysTem Adapted for Radio) was, unfortunately, not favored by my collaborators.}
Figure 3. Experimental upper limits on neutrino flux, as a function of energy, for various neutrino flux models. Upper bounds on total (all flavor) neutrino fluxes for AGN models of PR[19] and MB[20], GZK[5] neutrino models of ESS[21], PJ[22], KKSS[23], and DSS[24], and the topological defect model of PS[25], due to all flavor NC+CC interactions, based on 1999-2005 RICE livetime of about 20500 hrs. Dashed curves are for model fluxes and the thick curves are the corresponding bounds. The energy range covered by a bound represents the central 80% of the event rate. Note that RICE limits are 95% c.l.; other experimental limits shown are at 90% c.l.

Figure 4. Expected fluxes (solid) and limits (dashed) on UHE neutrinos from GRB’s.

3.2.1. Radio detection in salt As reported by Amy Connolly at this conference, SALSA will employ the in situ approach, using salt as the target medium rather than ice. The site being studied most closely is Cote Blanche Dubois in Mississippi, where signals have been observed

Figure 5. RICE monopole flux limits.
propagating through 300 meters of dome salt at a depth of approximately 500 m. Advantages of using salt as a target are its higher density compared to ice (i.e., greater likelihood of contained events) its year-round accessibility and the likelihood that water and metal in the soil layer above the dome provides RF insulation; disadvantages are the limited, and often irregular volume comprised by salt domes, high drilling costs compared to ice ($1M/hole compared to $50K for a 1km deep, 15 cm diameter hole in ice). Nevertheless, if the attenuation length can be shown to be of order 500 meters in the 100 MHz - 1 GHz interval, salt may be an extremely promising candidate, the large cost of a 15 kilochannel array (~250 M) notwithstanding.

3.2.2. Planned Surface Arrays  
ARIANNA[6] is unique not only in its coupling radio antennas to the surface of the ice, but in its use of shelf ice, rather than interior compressed snow as the target. This approach offers the advantage of a non-varying index-of-refraction in the target medium. In this scenario, the Ross Ice Shelf will be populated with a large array of down-looking horn antennas; the limited depth of the shelf ice (~250 m) is compensated for by the expectation that signals resulting from distant interactions will multiply reflect within the shelf ice ‘waveguide’ before being captured in the surface horn antennas. Signal communications will be patterned after the wireless AUGER model. Measurements in December 2006 will quantify the attenuation length of the shelf ice at radio frequencies using techniques similar to those used to measure the ~1.7 km radiofrequency attenuation length of ice at the South Pole.

An elevated array, at a height $h$ would view the horizon out to a distance $l = \sqrt{2r_E h}$; with $r_E = 6360$ km, an array of 50-meter high, wind-powered towers at Vostok would view the cold, 3.2 km thick ice there out to a distance of 25 km. Provided the problem of finding bearing lubricants functional in the ~80 C winter temperatures can be solved, RICE could be recommissioned as ROAST (“RICE On A STick”) in 2-3 years.

3.2.3. Hardware  
Crucial to the success of any radio experiment is a highly efficient antenna and a fast (ns-time scale), high-bandwidth data acquisition system[29]. Both the tripolarization scheme planned for AURA (Fig. 6), as well as the dual-polarization horns that will fly on the ANITA gondola (Fig. 7) will offer excellent Cherenkov geometry constraints.

ANITA have developed custom digitizing electronics, based on a switched-capacitor array; triggering is ‘launched’ by an external trigger. This system has already demonstrated 1.3 GHz bandwidth at 2 GSa/sec, and will form the basis of the future RICE successor array (AURA), as well. Frequency banding of the input trigger signal allows rejection of possible continuous wave backgrounds, as well as consistency with the expected Askaryan frequency spectrum. A multi-tiered trigger also facilitates rejection of random thermal noise hits (by requiring at least a two-fold coincidence at L1) or, in the case of a buried array, rejection of down-coming anthropogenic transients.

4. Radio detection of air showers  
Coherent radio Cherenkov studies go back to Allan and Jelly, who first studied radio signals from cosmic ray air showers[30, 31]. As an air shower develops in the earth’s magnetic field, a lateral separation of electric charge, of typical scale 10 meters ($\sim$30 MHz) is produced by the Lorentz force, resulting in a dipole field spiraling in towards the Earth for the orientation where the charges gyrate around $\vec{B}_{Earth}$, or simple charge separation when the field lines are parallel to the Earth’s surface (horizontal) and the charges are incident along the vertical. The field strength is obviously a strong function of the inclination angle of the shower relative to the earth’s magnetic field – both the azimuthal ($\phi$) and polar ($\theta$) angles, as well as the orientation and strength of the local geomagnetic field are all important. The shower detection threshold is set by various factors. Background-limiting factors include proximity to anthropogenic noise source in the tens of Megahertz frequency regime. The ambient galactic radio noise is also considerably
larger than kTB thermal noise in this regime. It is additionally noteworthy that solar flares, auroral storms and lightning have all been observed to result in substantial transient bursts in this frequency regime\textsuperscript{[33]}. Signal-limiting factors include the typical distance from shower max to the ground based observatory (\(~500\ g/cm^2\), or of order 5 km).

4.1. Experimental Air Shower Detection Efforts

After an extended hiatus, there is a new generation of air-shower experiments which are now coming online. To date, anthropogenic backgrounds have limited the ability of such arrays (thus far, modest in size) to self-trigger, generally requiring a coincidence trigger with a co-located particle detector array to keep such backgrounds manageable. As realized since the 1940’s, the photomultiplier tubes often used to readout scintillator arrays are, unfortunately, themselves often a source of considerable noise, which is not surprising given the few ns rise-time of typical photomultiplier tube signals.

Efforts within the last decade include those of Rosner and Wilkerson at the Fly’s Eye/HiRes site (Dugway AFB) in Utah\textsuperscript{[32]}, the LOPES\textsuperscript{[33]} prototype at the KASCADE site in Karlsruhe, Germany, which is intended to serve as a prototype for an adaption of LOFAR for air shower detection, and the CODALEMA\textsuperscript{[34]} experiment in France. There have also been discussions regarding the augmentation of IceCube/ICETOP with a radio air shower array, and the development of a similar array at the TUNKA site at Lake Baikal, Russia. Of these, the LOPES and CODALEMA efforts are currently the most advanced. The first LOPES data collection was performed in 2004 on a ten-element array consisting of linearly polarized, east-west oriented “inverted V” dipole antennas, sensitive over the interval 40-80 MHz, embedded within (and triggered by) KASCADE. Seven months of data-taking, with an effective air shower threshold of 50 PeV, yielded 862 candidate coincidence events, of which approximately 40% turn out to be well-reconstructed. Imposing the condition of full radio coherence can substantially improve
the angular resolution and shower parameter estimates just based on the ground array data; improvements of factors of 2-3 are not uncommon. The basic element of the current LOPES-30 array and the observed signal are shown in Figures 8 and 9 respectively. Ultimately, one would like to include air shower detection trigger electronics for the full, planned 25000 element LOFAR array. In the interim, a radio air shower detector may be added to the AUGER observatory.

**Figure 8.** Basic antenna element of LOPES array.

**Figure 9.** Total radio power observed by LOPES, 2004 data.

The French CODALEMA collaboration uses 11 log-periodic antennas (37-70 MHz) for air shower detection, also with an energy threshold of 50 PeV. Initially, a four-fold coincidence of particle detectors on the ground were required to provide an event trigger; since then, signal recognition algorithms have advanced to allow for self-triggering by the radio array alone. CODALEMA currently observes \( \sim 1 \) high-energy air shower per day, and is planning an upgrade to supplement the current log-periodic array with dipoles.

5. Radio observations of astronomical objects

As originally proposed by Askaryan, the moon provides a convenient, otherwise radio-quiet, and nearby, “target-in-the-sky”. Neutrino collisions with moon rock would result in a coherent radio pulse escaping through the surface. In the absence of an atmosphere, ultra-high energy cosmic rays would result in a similar signal. The Puschino observatory off the banks of the Osa River, approximately 100 km south of Moscow, has had a long history of lunar observation. More recently, the Goldstone dish was adapted with trigger and data-acquisition electronics appropriate for measurement of a neutrino-generated radio signal[35]. At this conference, the nuMoon[36] project was described, using as receivers the Westerbork antenna array in Europe, consisting of 14 25-m diameter radio dishes, with reception peaking at \( \sim 150 \) MHz. Given the very precise angular resolution anticipated for LOFAR, Westerbork could serve as a testbed for the signal recognition algorithms that would be used for such an extensive radio array. All these experiments typically use the ability to frequency band to discriminate the electric field spectral properties expected for Askaryan-type signals \( (dE/d\omega \sim \omega) \) from backgrounds. Note that, despite the fact that the electric field strength is increasing with frequency, the higher angular spread of low-frequency components of the Askaryan pulse result in more detections with an array tuned to 150 MHz rather than 1.5 GHz.

6. Summary of Extant and Planned Experiments

The various techniques are summarized in the table below, showing approximate thresholds, and neutrino flux sensitivity in a given amount of livetime.
### Experiment Details

| Experiment | Status | Antennas | $E_0$ (PeV) | Comment |
|------------|--------|----------|-------------|---------|
| ANITA      | 2006 Launch | 36 dual-pol horn | $10^4$ | 45-day 06-07 flight |
| ARIANNA    | R&D | 10000 horn | 100 | $L_{atten}$ TBD Dec., 06 |
| AURA       | R&D | (36 cluster)(4 Rx/cluster) | 100 | RICE successor |
| RICE       | active | 20 in-ice dipole | 100 | data-taking→2008 |
| SALSA      | R&D | 14000 dipole | 100 | Cote Blanche, MS |
| CODALEMA   | active | 11 dipole | 100 | air showers |
| LOPES      | active | 30 dipole | 100 | air showers |
| nuMoon     | planned | 14 25-m dishes | $10^3$ | |

### 7. Backgrounds

Perhaps the main advantage of the optical technique is that the primary background (atmospheric neutrinos) is, with the exception of angular distribution, otherwise identical to the signal. In the absence of atmospheric neutrinos at $>\text{PeV}$ energies, radio backgrounds are, in general, locale-specific. At the South Pole, in proximity to South Pole Station, the RICE backgrounds are anthropogenic and can quickly (~1 microsecond) identified as originating from the surface with $>99\%$ efficiency. Backgrounds arising from thermal noise, compounded by the system temperature of active electronics, present the most obvious single-channel ‘fake’ signals, and define the minimum voltage threshold required to run the data acquisition system at tolerable rates; at first glance, such backgrounds can look very similar to ‘true’ signals (Fig. 10). Galactic radiofrequency noise has a falling power spectrum and can be explicitly suppressed by use of a 200 MHz high-pass filter.

Physics backgrounds to the ice-based experiments at hundreds of PeV are expected to be small. Many processes have been considered – direct radiofrequency signals from extensive air showers (EAS) which propagate into the ice, as measured by the CODALEMA and LOPES experiments, give signals which peak in the tens of MHz regime. There should be a signal resulting from the impact of the shower core with the ice, producing the same kind of Cherenkov radiation signal that RICE seeks to measure. Nevertheless (Fig. 11), the expected EAS signal rate should be almost immeasurably small.

### 8. Comparison with acoustic

Acoustic detection of neutrinos has undergone equally rapid development over the last few years, as outlined elsewhere\[38, 37, 39\]. The acoustic detection technique offers three very large advantages relative to radio detection: a) propagation speeds, and absorption lengths are set by the acoustic properties of the target medium; for ice, the slow propagation speeds mean that signals are spread over timescales of microseconds and are therefore $1000\times$ less exacting than the nanosecond time scales of radio pulses. Additionally, at these low frequencies, cable losses are sufficiently small that signals can be digitized in an accessible surface, rather than an inaccessible in-ice receiver. b) the signal geometry is in a domain where the source length is much larger than the wavelength of the propagating signal, so that the signal geometry is cylindrical, with amplitude losses as $\propto 1/\ln(r)$, and c) for ice, the attenuation length is expected to be a factor $10\times$ larger than radio; for salt, estimates give values an additional factor of $10\times$ larger\[40\]. Both techniques offer the possibility of constraining the signal geometry using polarization information, with the exception of acoustic detection in salt, for which coupling to the shear wave will be difficult. The long time scale for the signal leads, however, to the one large disadvantage of acoustic - the substantially larger $1/f$ noise for acoustic detection forces the detection threshold up to around 100 EeV or so.
9. Perspectives

Although promising, the radio technique is still being developed, and still must surmount several obstacles before gaining widespread acceptance. The problem is not so much signal detection, but understanding backgrounds. The air detection experiments have made enormous strides within the last five years – the demonstrated ability to measure the same air shower event as a ground array provides instant credibility, however, anthropogenic backgrounds and naturally generated noise such as electrical discharges in the atmosphere require frequency filtering, as well as restrictive data selection. The next milestone here may be an absolutely normalized air shower primary energy spectrum which shows good agreement with the existing data. The demonstrated ability to self-trigger is also a *condicio sine qua non* for a self-sustaining array. In the absence of such self-triggering, the ability to improve the angular resolution of air showers is, nevertheless, sufficient cause for expansion of this effort. Estimates of neutrino detection in dense media rests on three primary pillars: a) the radio transparency of the medium, b) the weak interaction cross-section at high energies, and c) the relationship between shower characteristics and radio signal strength. The attenuation length of Antarctic ice has been measured to be \(1.5-2\) km, \(\sigma_\nu\) can be extrapolated within the Standard Model to within 25% or so at 10 EeV, and the SLAC testbeam experiments have (I believe, conclusively) validated the signal strength estimates obtained using Monte Carlo simulations. Thermal backgrounds can, in principle, be removed statistically based on channel-to-channel correlations and also frequency spectra, however, our experience with RICE indicates that individual-channel thermal 'hits' can be extremely similar to expected neutrino 'signal' hits, as shown in Figure 10; large bandwidth is required to separate the two in the frequency domain.

Clearly, a single experiment with the potential of simultaneously offering detection of air showers, both with radio and a conventional ground particle detector array, plus detection of showers-in-dense-media, combining optical + acoustic + radio capabilities, would be perhaps the most powerful realization of a 'multi-messenger' detector. Obviously, the optimal scenario would be a single laboratory which could support simultaneous measurement of optical + radio + acoustic signals, with all possible polarizations. Currently, several groups are working...
towards the realization of such an observatory at the South Pole ("CONDOR") which, given, e.g., the inability to propagate radio waves through water, is likely the only place on Earth capable of supporting such an effort. Mature simulations indicate measurable registered neutrino coincidences in one year[41].

10. Acknowledgments
I would like to thank everyone who is currently active in this very dynamic field. I am particularly indebted to Peter Gorham, Daniel Hogan, Shahid Hussain, Soeb Razzaque, and David Saltzberg for their contributions to this talk.

11. References
[1] J. Ralston, private communication.
[2] J. and M. White, http://en.wikipedia.org/wiki/The_White_Stripes
[3] S. Barwick, D. Besson, P. Gorham, D. Saltzberg, J. Glac. 04J067 (2005).
[4] G. A. Askaryan, JETP 14, 441 (1962), JETP 21, 658 (1965).
[5] K. Greisen, Phys. Rev. Lett. 16, 748 (1966) G. Zatsepin and V. Kuzmin, JETP Lett., 478 (1966).
[6] A. Connolly, contributed to this conference, and S. W. Barwick, arXiv:astro-ph/0610631 Proceedings of 2nd Workshop on TeV Astrophysics.
[7] S. Hussain, D. Marfatia, D.W. McKay, and D. Seckel, Phys. Rev. Lett 97 (2006) 161101; S. Hussain and D.W. McKay, Phys. Lett. B634 (2006) 130-136.
[8] E. Zas, F. Halzen, and T. Stanev, Phys. Lett. B257, 432 (1991); E. Zas, F. Halzen, and T. Stanev, Phys. Rev. D45, 362 (1992)
[9] S. Razzaque et al., Phys.Rev. D65, 103002 (2002).
[10] Jaime Alvarez-Muiz, Enrique Marques, Ricardo A. V zquez, Enrique Zas, Phys.Rev. D74 (2006) 023007; J. Alvarez-Muniz, E. Marques, R. A. Vazquez, E. Zas, Phys.Rev. D68 (2003) 043001;
[11] D. Saltzberg et al., Phys.Rev.Lett. 86 (2001) 2802-2805
[12] P. Gorham et al., Phys.Rev. D72 (2005) 023002
[13] S. Hoover, contributed to this conference; manuscript in preparation.
[14] aether.lbl.gov/www/projects/neutrino/rand/rand.html
[15] A.L. Provorov and I.M. Zheleznykh, Astroparticle Physics 4 (1995) 55.
[16] S. Barwick et al., Phys.Rev.Lett. 96 (2006) 171101.
[17] I. Kravchenko et al., Phys.Rev. D73 (2006) 082002
[18] K. Hoffman, contributed to this conference; D. Williams, contributed to this conference.
[19] R. J. Protheroe, astro-ph/9607165
[20] K. Mannheim, Astropart. Phys. 3, 295 (1995).
[21] R. Engel, D. Seckel, and T. Stanev, Phys. Rev. D64, 093010 (2001).
[22] R. Protheroe and P. Johnson, astro-ph/9506119, Astropart. Phys. 4, 253 (1996).
[23] O. E. Kalashev, V. A. Zatsepin, D. V. Semikoz, and G. Sigl, Phys. Rev. D66, 063004 (2002).
[24] Daniel De Marco, Todor Stanev, and F.W. Stecker, arXiv:astro-ph/0512479 Phys. Rev. D73 043003 (2006).
[25] R. J. Protheroe and T. Stanev, Phys. Rev. Lett. 77, 3708 (1996); ibid 78, 3420 (1997).
[26] D. Besson, S. Razzaque, J. Adams, and P. Harris, accepted in Astropart. Phys.
[27] J. Bahcall and E. Waxman, Phys. Rev. D59, 023002 (1999); Phys. Rev. D64, 023002 (2001).
[28] S. Wick, T. Kephart, T. Weiler and P. Biermann, Astropart.Phys. 18 (2003) 663-687.
[29] G. Varner, J. Chao, M. Wilcox and P. Gorham, arXiv:physics/0509023
[30] H.R. Allan, Prog. in Elem. Part. and Cos. Ray Physics, 10 (1971), 171.
[31] J. V. Jelly et al., Nature 265 (1967), 327.
[32] K. Green, J. Rosner, D. Suprun, J. Wilkerson, Nucl.Instrum.Meth. A498 (2003) 256-288.
[33] P. Isar, S. Nehls et al., contributed to this conference; A. Huangs et al., contributed to this conference.
[34] D. Ardouin et al., arXiv:astro-ph/0608550 accepted for publication in Astroparticle Physics.
[35] P. Gorham et al., Phys.Rev.Lett. 93 (2004) 041101.
[36] O. Scholten et al., contributed to this conference.
[37] R. Nahnhauer, conference summary talk (this conference).
[38] J. Vandenbroucke, G. Gratta, and N. Lehtinen, Astrophys.J. 621 (2005) 301-312.
[39] S. Böser, Ph.D. thesis (2006), unpublished.
[40] P. B. Price, arXiv:astro-ph/0506648 submitted to Journal of Geophysical Research - Solid Earth.
[41] D. Besson, S. Böser, R. Nahnhauer, P. B. Price, J. A. Vandenbroucke, Int.J.Mod.Phys. A21S1 (2006) 259-264.