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# Recent results from the RICE experiment at the South Pole

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ABSTRACT

The RICE experiment on detection of UHE neutrinos has been running over a decade. The experiment comprises an array of radio antennas buried in ice to the depth of up to 300 m near the geographic South Pole, and is designed to observe neutrino interactions in ice employing the radio Cherenkov technique. We discuss new limits on the diffuse UHE neutrino flux that now include the full dataset accumulated over 10 years and benefit from new analysis techniques. We also present our recent measurements of birefringent properties of ice at the experiment location.

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## 1. Introduction

Detection of Ultra High Energy (UHE) neutrinos with energies $E>100$ PeV is currently an active area in experimental cosmic ray physics. A number of experiments have been performed over the last 15 years resulting in limits on the flux of UHE neutrinos. These experiments are based on the radio detection technique: it is expected that a neutrino interacting in a dense medium would create an electromagnetic or hadronic shower, where a charge excess moving above the speed of light in the medium would develop, eventually causing coherent Cherenkov emission at radio frequencies [1]. The primary difference between the experiments is the nature of the medium: media such as salt [2], ice [3,4], and lunar regolith [5] have been exploited. Radio Ice Cherenkov Experiment (RICE) is the first experiment based on the radio detection technique, which started operating in 1999.

The sensor array of the original RICE experiment consists of 20 dipole antennas submerged in ice in the vicinity of the South Pole station in a 3D grid. The dipoles are tuned to 200–500 MHz bandwidth in ice, and are located 100–300 m below the surface. Analog signal is carried to the counting house via coaxial cables and digitized at the surface. The trigger system is designed to detect coincidental signal with four or more antennas above a voltage threshold within 1.25 μs window, while the DAQ captures a 8 μs-long waveform sampled at 1 ns from each channel for each triggered event. The position of the source of the coincidental signal from several antennas is calculated based on the timing of each pulse, giving the location of either neutrino interaction candidate, or the location of a background source.

In 2008–2009, RICE has been extended into Neutrino Array Radio Calibration (NARC). NARC includes 20 more channels, co-deployed with IceCube, and also four new surface channels. The NARC results obtained with the new in-ice channels are discussed in Ref. [6], and are part of the R&D toward the ARA experiment [7]. Some of the NARC results with data from new surface channels are presented in this contribution, and are part of the R&D toward a possible future RASTA experiment [8].

In this report we present the new neutrino flux limits from RICE/NARC (Section 2). Studies of bulk ice properties that at RICE location are shown in Section 3. Finally, environmental studies for a possible future surface radio array, such as RASTA, are described in Section 4.

## 2. Neutrino flux limits

Previous neutrino flux limits from RICE, based on five years of data-taking, were published in 2006 [3]. In this report, the updated flux limits, using largely unchanged analysis methods, are presented. The neutrino flux is related to observables and detector parameters through the following equation:

$$\frac{dN}{dE} = V_{eff}(E)\sigma_{\nu N}(E)n\Phi(E)\varepsilon L\Omega$$

where $dN/dE$ is the event count per unit of energy, $V_{eff}$ is the effective volume, $\sigma_{\nu N}$ is the neutrino–nucleon interaction cross-section, $n$ is the target density (nucleons per m$^3$), $\Phi$ is the neutrino flux, $\varepsilon$ is the efficiency of the event reconstruction, $L$ is the livetime of data collection, and $\Omega$ is the solid angle in steradians (close to $2\pi$ for RICE).

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A RICE event is a coincident firing of at least four antennas. The position of the source of an event is reconstructed from relative signal timing using two independent algorithms: numerical calculations on a grid, and an analytic solution method. Vertex reconstruction and selection are applied to the full RICE dataset of 2000–2009 contains total 1.78 M events. Among the most important selection criteria are: good source vertex with small time residuals is required, the two vertex-finding algorithms have to give consistent results, the time over threshold for each channel is above a certain threshold, reconstructed source is below 150 m depth, events with double pulse structure are rejected. After selection, zero neutrino interaction candidates survive, leading to the limit on the expected events of 2.3 at 90% C.L.

One of the primary parameters of a neutrino detection experiment, such as RICE, is the amount of bulk matter, interactions in which can be detected by the sensors of the experiment. For RICE, the effective volume is the volume of ice convoluted with the probability for a radio pulse, caused by a neutrino interaction and subsequent shower, to be seen by the antennas above a threshold. The $V_{eff}$ is calculated using simulation, as shown in Fig. 1. It is an energy-dependent quantity as more energetic neutrinos lead to a signal that can be detected by the radio array from a larger distance.

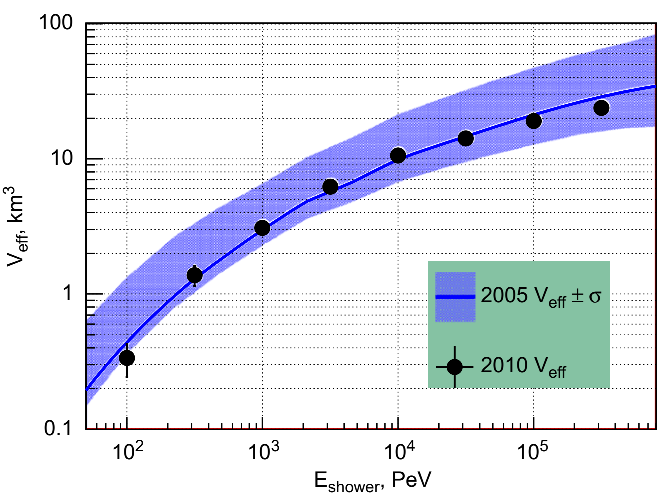


**Fig. 1.** The effective volume for the 2000–2009 period of data taking, as compared to the effective volume reported in the previous RICE flux paper.

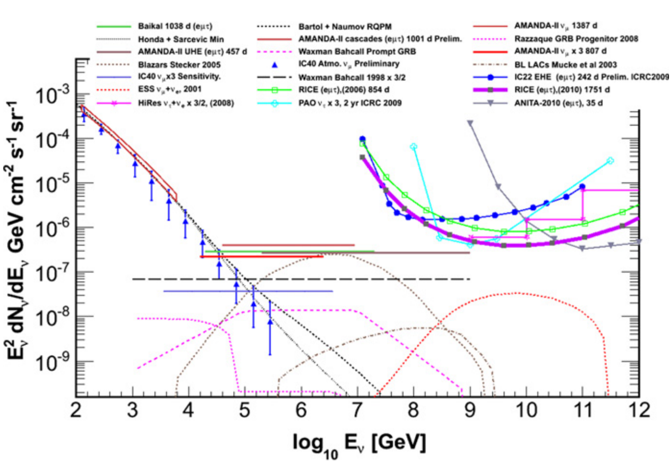


**Fig. 2.** New RICE flux limits as compared to RICE 2006, other experiments, and theory.

The livetime $L$ for the 2000–2009 dataset is $\sim 1700$ days, which is $\times 2.5$ times more than the livetime reported in Ref. [3]. The surface veto electronics board introduced since the last paper has improved livetime by $\sim 7\%$ due to faster rejection of dominant backgrounds.

The efficiency for a true neutrino event to pass selection has been estimated using simulation as well as noise events collected with an unbiased trigger with embedded simulated neutrino signals. This efficiency is $71.4 \pm 1.0\%$. Note: the efficiency for a neutrino event to cause hits on at least four antennas is accounted for by $V_{eff}$, as described above.

Combining all these components leads to the energy-dependent neutrino flux limit shown in Fig. 2. The new limits are factor $\times 2$ improvement over the previously published result.

## 3. Polar ice birefringence measurements

In order to design and operate next generation larger scale experiments that use ice at the South Pole as a neutrino target, the best possible knowledge of the complex permittivity of ice for all polarizations and propagation directions is desirable. At present, it is known that for radio frequencies the attenuation length in vertical direction is on average 600 m, the depth-dependent index of refraction is measured to 0.5–1.0% accuracy, and birefringence is possible (0.3% level in the upper 1.5 km of ice has been reported at Dome Fuji [9]).

Direct time-domain birefringence measurements have been performed at the RICE experiment location in January 2010, which is also the chosen site for ARA [7]. Short ns-duration pulses were broadcast vertically down using TEM horn antenna on the surface (Tx in Fig. 3), and the reflected signal was recorded at 2 GS/s by a TEM horn Rx. As the antennas are linearly polarized, one can study propagation properties of pulses at different polarizations. A difference in propagation speed for different polarizations was observed (Fig. 3): it is faster for polarizations close to the direction of the ice flow, and slower for the orthogonal polarization, with the difference $\Delta c/c \approx 0.3\%$. Furthermore, partial reflections of the pulses from reflective layers in ice at intermediate depths were observed. Comparing timing of partial reflections at different polarizations, it was possible to conclude that birefringence is confined primarily to the lower part of the ice sheet, while partial reflections from the top 1.5 km come in sync.

Dispersive effects in ice were studied with the same experimental setup. Different frequency components of the pulse reflected from the bedrock were observed to arrive simultaneous within 4 ns. This limits dispersion to be less than $10^{-4}$ for frequencies 100–1000 MHz.

As a by-product, the thickness of ice sheet at the RICE/ARA location was measured to be $2857 \pm 5 \pm 30$ m, where the second error reflects the uncertainty in the knowledge of $n(Z)$ profile. This is one of the best measurements of the thickness currently available.

## 4. Environmental studies for a future surface radio array

As the possibility of deploying a surface radio array for neutrino detection at the Pole is presently being considered, several environmental studies were performed. Four surface antennas of the fat wire dipole type ($\times 10$ size of a typical RICE in-ice dipoles) had been manufactured by University of Wuppertal and integrated into the RICE DAQ system.

In the first study, a short pulse was broadcast from the surface, and the position of the pinger was reconstructed with data from the new surface channels collected via RICE DAQ. A set of pinger