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Method to Determine Neutrino Cross Section using ANITA

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Abstract: The balloon-borne ANITA high energy neutrino telescope successfully launched on December 15, 2006 and remained aloft for about 35 days. Its primary mission is to detect astrophysical neutrinos with energies in excess of 10^{19} eV. Neutrino interactions in Antarctic ice produce short, intense radio pulses that can be detected by ANITA at distances as large as 600 km. The usual detection scenario involves nearly horizontal neutrinos interacting in the bulk ice of the Antarctic ice sheet to produce detectable radio signatures. In this paper, we describe an alternative detection channel from interactions within the coastal Ice Shelves. Recent studies of the Ross Ice Shelf confirm earlier work that indicate that most of the ice-water boundary beneath the shelf behaves like a very good mirror at radio frequencies. This property and the relatively long attenuation length create the opportunity to observe reflected radio pulses from the bottom. The interaction rate from the relatively thin ice shelves is more sensitive to neutrino cross-section than the rate from the bulk ice. With sufficient statistics, the cross-section can be determined by comparing the rate of neutrino interactions in the ice sheet to ice shelf. This paper describes the method, its advantages and limitations, and possible systematic contributions to the uncertainty.

Introduction

With the successful completion of the first flight of ANITA (called ANITA-I here), the search for diffuse neutrino sources at the energy frontier is poised to take a dramatic leap forward. ANITA-I launched on December 15, 2006 and remained aloft for almost 35 days. ANITA-I is sensitive in the energy interval between 10^{19} and $5\text{x}10^{20}$ eV, creating an excellent opportunity for discovery [1]. The most secure predictions for neutrino fluxes at these energy scales are generated by the Greisen-Zatsepin-Kusmin (GZK) mechanism [2], which depends on the detailed assumptions associated with the distribution and evolution of the sources of extragalactic cosmic rays, the injected energy spectrum, and the composition of the elemental components of the cosmic rays [3].

Flux measurements depend on the neutrino cross-section, σ, which has factor of 2 uncertainty at the energies relevant to ANITA [4]. In addition to the uncertainties associated with standard model extrapolations, a tantalizing possibility exists that the energy scale of cosmogenic neutrino interactions is sufficient to reach a threshold for the onset of new physics, manifesting itself as a rapid increase in the cross-section relative to standard model extrapolations [5].

Neutrino Cross-Section

Cosmogenic neutrinos collide with proton and oxygen nuclei in the ice with center of mass energies at ~100 TeV, thereby providing an opportunity to study physics at unprecedented energies. It has been noted that the neutrino σ at high energies can provide a powerful probe of new physics at energies that may be beyond the reach of terrestrial accelerators. Several ideas exist in the literature to measure the total neutrino cross-section at extremely high energy [6] and several limits on the cross-section were inferred by assuming the existence of a neutrino flux [7].

This paper describes a method that uses ANITA data to determine the neutrino cross-section without strong assumptions on the normalization of energy spectrum. The central idea takes advantage of two strikingly different ice formations in Antarctica - the thick *ice sheet* and floating *ice shelves*. The detection rate of direct events, primarily generated by neutrinos interacting within the ice sheet, is relatively insensitive to cross-section, but the rate of reflected events observed from the ice shelf depends linearly on the cross-section. The term “direct” refers to radio signals that are generated by neutrino interactions in the ice that propagate directly from the emission region to the air-ice surface and then refract toward ANITA. "Reflected" radio signals first travel downward and then reflect from the bottom interface. The amplitude of signals reflected from the bottom of the ice sheet is greatly attenuated and scattered by the fragmented, rocky bottom, so they are typically undetectable by ANITA. However, the bottom of the *ice shelf* (large ice structures floating on sea-water) strongly reflects radio signals with very good temporal fidelity [8].

If solely considering direct rays, the ANITA telescope can observe neutrinos with trajectories within a few degrees above and below the horizontal plane defined by the ice-air interface. Upwardly propagating neutrinos with $E_\nu > 10^{17}$eV are absorbed by the earth if the zenith angle is more than a few degrees below the horizon. Therefore, attenuation limits the view of ANITA to downgoing and earth-skimming horizontal trajectories. The direct rays of downward propagating neutrinos with zenith angles more than a few degrees above the horizon are not observable by ANITA because the rays are trapped by total internal reflection. ANITA simulations [9] and simple geometrical arguments [10] for nearly horizontal trajectories indicate that the event rate due to directly emerging rays from the *ice sheet* depends somewhat weakly on cross-section. This feature reduces the error in the flux measurement due to uncertainties in the neutrino cross-section factor. In contrast, the rate of reflected signals from the saltwater-ice interface at the bottom of the Ice Shelves depends linearly on the cross-section because the pathlength for downward traveling neutrinos is a small fraction of an interaction length.

Fig. 1 shows the simulated geographic distribution of direct and reflected events for the flight of ANITA-1, assuming $\sigma_\nu=100\sigma_{sm}$ and $E_\nu=10^{20}$ eV. Reflected events are clustered over the Ross Ice Shelf, and direct events are more uniformly distributed over the ice sheet. The simulation incorporates the exact flight path of ANITA-I, which spent a large fraction of its flight viewing the Ross Ice Shelf and none viewing the other large shelves. The event rate from the ice shelves is dominated by reflected events. Consequently, the reflected event rate can be reliably determined from neutrino signals emerging from the ice shelf. For this paper, we assume that the number of reflected and direct events can be determined with no ambiguity.

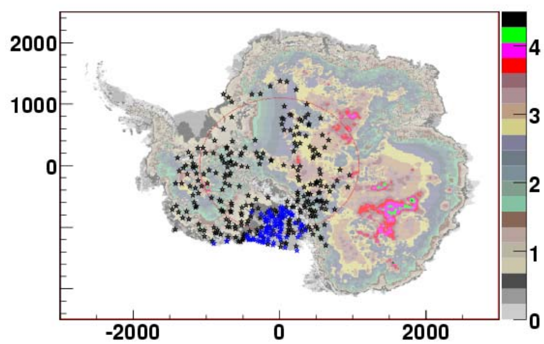

Figure 1: Simulated geographic distribution of direct (black stars) and reflected events (blue stars) assuming neutrino interaction cross-section is a factor of 100 larger than standard model. Legend on right indicates thickness of ice (in km).

This technique requires good specular reflection from the water-ice boundary beneath the Ross Ice Shelf. Neal [11] shows that the reflection loss is typically less than -3dB over a majority of the Ross Ice Shelf, and also argues that large values for reflection efficiency are correlated with a relatively small amount of surface roughness at the saltwater-ice interface. He shows that the variation in depth from a smooth surface is 0.03m in a region of the Ross Ice Shelf that exhibits low reflection losses. More recently, excellent reflection properties were observed at Moore’s Bay on the Ross Ice Shelf, about 68 miles south of McMurdo Station, for radio frequencies between 100 MHz and 1 GHz [8]. The simulated rate of reflected events incorporate the preliminary measurements of the frequency dependent attenuation length from Moore's Bay and geographic variation of reflectivity.

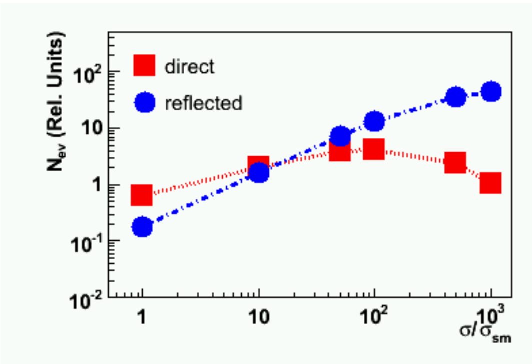

Figure 2: Relative number of events, N_{ev}, integrated over energy for both direct (squares) and reflected (circles) as a function of total neutrino interaction cross-section, scaled in units of the standard model extrapolation [12]. The calculations include all neutrino flavors and assume GZK energy spectrum (ESS-Fig9).

New physics contributions to the standard model cross-section typically manifest themselves as an enhanced rate of particle cascades. To bound potential contributions, we assume two distinct classes: (1) a simple energy-independent scaling of the total cross-section, where σ/σ_{sm} is a fixed ratio, and (2) a simple energy independent scaling of the neutral current cross-section, where σ/σ_{sm}^{nc} is a fixed ratio. In the simulations presented here, we assume that the neutrino flavor ratio is 1:1:1 and that the new physics contributions do not alter the y-distribution. We also plan to investigate specific models that alter the neutrino cross-section, taking into account potential variation in the y-distribution and non-standard energy losses.

The details of the ANITA simulation are presented elsewhere [9]. The simulation does include the flight path and livetime of ANITA-1, and approximate realization of the trigger and band masking criteria. The latter conditions were adjusted in flight to reduce the trigger rates from anthropogenic noise sources when viewing the large research bases of Antarctica. ANITA-1 often viewed the ice shelves and research stations at the same time.

Fig. 2 and Fig. 3 show preliminary results from the ANITA simulation, and summarize the critical information. Fig. 2 shows the relative rate of direct (N_{dir}) and reflected (N_{ref}) events as a function of neutrino cross-section, using the ESS-Fig9 [3] model for neutrino flux. As expected, N_{ref} depends linearly on total cross-section, while N_{dir} grows more weakly, plateaus at $\sigma = 50\ \sigma_{sm}$, and then decreases at large cross-section because the interaction length becomes comparable to the horizontal thickness of the atmosphere (~380 m.w.e.). Atmospheric absorption is also responsible for the nonlinear scaling of N_{ref} at the largest cross-sections.

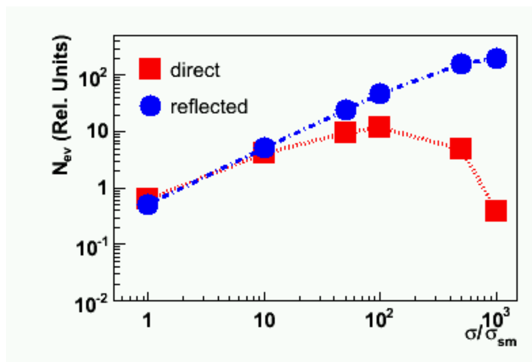

Figure 3: Same as Fig. 2, except that the calculations assume a differential energy spectrum proportional to E^{-2}.

Given sufficient statistics, the numerical value of the cross-section would be determined from relative counts of direct and reflected events within a small energy interval. The expected resolution of ANITA is more than sufficient, given the broad energy interval spanned by the cosmogenic energy spectrum. If the statistics is limited to a few or less, we plan to integrate over all energies in the sample, which introduces a modest spectral dependence. Fig. 3 shows the same information as Fig. 2, except that the differential energy spectrum is assumed to be proportional to E^{-2}.

The interdependence of flux and cross-section on the measured event rate is shown in Fig. 4 for the "no detected events" scenario. We consider the specific neutrino energy spectrum predicted by ESS-Fig9 multiplied by an overall normalization, or scale factor, S. This procedure is approximate because the precise cosmogenic neutrino energy spectrum depends on model parameters, which will be explored more completely in future work. Reflected events from the Ross Ice Shelf improve the constraints for large enhancements of cross-section.

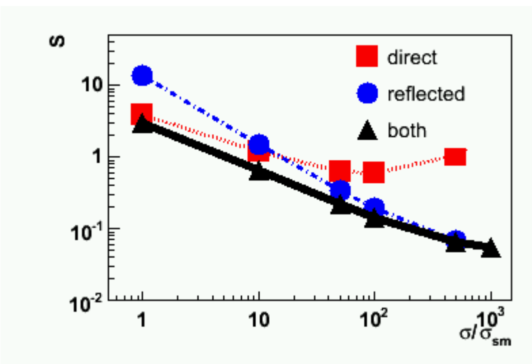

Figure 4: Upper limit on scale factor, S, for baseline ESS-Fig9 flux as the total neutrino cross-section is varied, for the scenario that no neutrino events are detected by ANITA-I. "Both" includes the sum of direct and reflected. The reflected events provide improved constraints beginning at $\sigma_\nu=10\sigma_{sm}$. The same parameters as Fig. 2 are assumed.

Discussion

Previous work [7] has discussed bounds on the neutrino cross-section at high energies. In this paper, we present a new idea to extract the neutrino cross-section for lab frame energies above 10^{19} eV using ANITA data. The technique exploits two distinct event topologies – one of which is relatively insensitive to cross-section and the other depends linearly on the cascade producing-portion of the cross-section. For low statistics, we plan to integrate over all energies. To illustrate the dependence on the specific choice of energy spectra, a differential energy spectrum proportional to E^{-2} was considered in addition to "GZK-like" energy spectra. We caution that Fig. 4 contains preliminary *projected* sensitivities based on the assumption that no neutrino events are observed for the flight of ANITA-I. Experimental constraints can only be determined after the full data set of ANITA is analyzed.

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