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Exotic Particles Searches with IceCube

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Abstract: The IceCube neutrino observatory, currently under construction at the South Pole, offers a novel environment to search for particles beyond the Standard Model. With IceCube nearly 20% complete it is currently the largest operating neutrino telescope. The large instrumented volume and clear glacial ice allows for a big improvement of the sensitivity to many types of exotic cosmological relics. Exotic particles that IceCube is sensitive to include magnetic monopoles, nuclearites, and Q-balls. Estimated sensitivities for these particles will be presented.

Introduction

In 1931, Dirac [1] quantified the charge of a magnetic monopole by demonstrating that $g = Ne/2\alpha$, where α is the fine structure constant. Forty-three years later, t'Hooft and Polyakov independently found solutions to certain groups of Grand Unified Theories (GUTs) that matched the charge of the Dirac Monopole [2, 3]. This allowed estimates for the masses of magnetic monopoles to be $\sim \Lambda/\alpha$, where Λ is the symmetry breaking scale. This results in a mass range from 10^8 GeV to 10^{17} GeV for various GUT models. A lower limit is set by choosing Λ to be the electroweak unification scale, leading to a mass of 10^4 GeV. IceCube will expand the search for magnetic monopoles in two regimes. A magnetic monopole traveling through the detector above the Cherenkov threshold ($\beta > 0.76$) will emit radiation roughly 8300 times that of the bare muon [4].

At very large masses, monopoles may move with virial velocities ($\beta \sim 10^{-3}$). A slow-moving, super massive magnetic monopole will not emit Cherenkov radiation, but may be observed in other ways. Rubakov proposed that supermassive magnetic monopoles will catalyze nucleon decay. The nucleon decay products (primarily pions) will produce relativistic electrons that produce Cherenkov radiation. If the catalysis cross-section is sufficiently high, the supermassive magnetic monopole will appear as a slow moving track in the detector.

A similar signature would accompany the passage of a electrically neutral supersymmetric Q-ball though the IceCube array. A Q-ball is a soliton produced during the decay of the proposed Affleck-Dine condensate in the early universe. Sufficiently massive Q-balls would be absolutely stable and could account for some or all of the required dark matter in the universe. A neutral Q-ball passing near a nucleon will absorb the baryon number and emit ~1GeV of energy in the form of pions [5]. The cross-section for this process is governed by the size of the Q-ball and can therefore be quite large [6].

It is also possible that novel forms of nuclear matter could be absolutely stable for very large baryon number [7]. Strangelets are a hypothetical state of nuclear matter with nearly equal up, down, and strange quark content. If such a state is the ground state of dense nuclear matter, cosmic-ray strangelets (aka nuclearites) could be produced in neutron star collisions. These heavy strangelets would have atomic sizes but nuclear densities. As they pass through the South Pole ice, they would produce a thermal shock emitting black-body radiation. This black-body radiation would register in the IceCube photomultiplier tubes and cause the strangelet to appear as a slowly moving track.

Detector

IceCube is a kilometer-scale neutrino telescope currently being built between 1450 to 2450 meters below the Antarctic ice surface. It is designed for up to 80 strings of 60 Digital Optical Modules (DOMs), spaced out in a hexagonal pattern. For the data presented, we use the configuration of IceCube as of 2006, that is a total of 540 DOMs in 9 strings. The instrumented volume is ∼0.625 km^3, compared to the AMANDA instrumented volume of ∼0.016 km^3 The DOM is the cornerstone of the detector [8]. It is configured to detect photon signals via a Hamamatsu 10 inch Photomultiplier Tube(PMT). Onboard electronics contain two waveform digitizers, a fast Analog to Digital Converter (FADC) and an Analog Transient Waveform Digitizer (ATWD). The FADC has a nominal sampling rate of 25 ns/sample and can read up to 256 samples of the incoming waveform produced by the PMT. The ATWD digitizes the wavefrom across 3 channels representing different gain values. It runs with the nominal sampling rate of 3.3 ns/sample and can read up to 128 samples. In 2006, the number of samples was limited to reduce bandwidth. The highest gain ATWD channel was set to keep all 128 samples, while the two lower gains were only set to record the first 32 samples. Meanwhile, the FADC only kept the first 50 samples for a time window of 1.25μs. Since monopole events are extremely bright, their waveforms largely saturate the highest gain and hence information from the ATWD beyond 100 ns is greatly reduced. Though the FADC saturates before any ATWD channel, the longer time scale provides greater distinction between the signal and background. Hence, this study uses data provided by the FADC.

Signal and Background Simulations

Relativistic Magnetic Monopoles

The simulation of relativistic magnetic monopoles is done in three stages.

Magnetic monopoles are generated uniformly on a disk located 600m from the center of the detector pointing back towards it at various orientations. For this study, 10,000 monopole events were generated at binned angles theta and phi of 45 degrees, for a total of 260,000 events per dataset. A dataset was generated for four different speeds, β= 0.99, 0.9, 0.8, and 0.76.

Energy loss of the magnetic monopoles as they pass through the ice is modeled using the Bethe-Bloch formula as adapted by Ahlen [9]. Future plans are to extend this to include delta electrons, which will add to the overall light deposition in the detector.

The light output and propagation is modeled by a version of `PHOTONICS` [10] specifically generated to work with cone angles associated with the different speeds simulated. The light amplitude is scaled up using the formula of Tompkins [4].

Background

For this study, a 20% sample of the data for 2006 is used as the background. This sample consists of every fifth data event that passed the online high energy filter, in place to reduce the data rate over the satellite. The filter is set to accept events with the number of hit DOMs greater than 80. This filter reduced the number of triggered data events from $\sim 3.5 * 10^8$ to $\sim 3 * 10^5$.

Estimated Sensitvity to Relativistic Monopoles

The brightness of the magnetic monopole is the primary distinguishing feature. Therefore, we use parameters associated with the light yield in the first level of cuts. The two chosen are the number of hit DOMs (NDOM) and the total integrated FADC waveform (FCHARGE). The event rates are normalized to the expected rate for the 137.4 days of live time recorded by IceCube in 2006. For the monopole signal, a flux of $5 * 10^{-17} cm^{-2} s^{-1} str^{-1}$ is used, representing the lowest limit set by BAIKAL [11]. To get a conservative estimate on the sensitivity of the detector, a tight cut is made to eliminate all the 20% data sample. Figures 1 and 2 plot the signal and data for

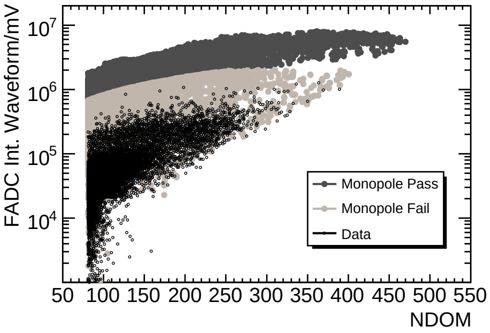

Figure 1: The effect of applying the linear cut to the integrated charge versus the number of hit DOMs distribution. Shown are the monopole signal simulation for $\beta = 0.99$ and data. The dark grey dots are signal events that pass the cut while the light grey signal dots and data (black) are rejected.

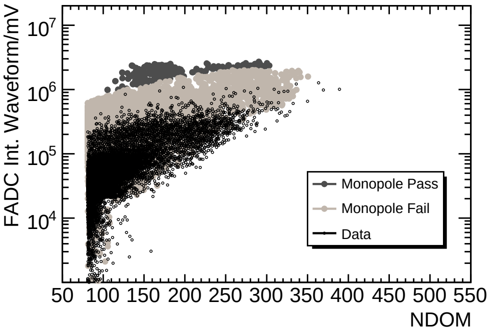

Figure 2: The effect of applying the linear cut to the integrated charge versus the number of hit DOMs distribution. Shown are the monopole signal simulation for $\beta = 0.76$ and data. The dark grey dots are signal events that pass the cut while the light grey signal dots and data (black) are rejected.

β	$A_{eff}(km^2)$	Exp Signal	Φ_{90}
0.99	0.3	19.05	$7 * 10^{-18}$
0.9	0.26	16.34	$7 * 10^{-18}$
0.8	0.08	4.92	$3 * 10^{-17}$
0.76	10^{-3}	0.09	$2 * 10^{-16}$

Table 1: Passing rates for linear cut. Expected signal and sensitivity for a full year of data.

FADC vs NDOM at the largest and smallest values of β studied. The following linear cut is chosen:

$$(FADC > 10^6 + 7500 * (NDOM - 125))$$

OR

$$(FADC > 3 * 10^6)$$

Table 1 shows the effective area of the signal resulting from this cut for each of the four monopole speeds. Assuming no events are seen, the flux sensitivity is calculated for the 90% C.L.

Estimated Sensitvity to Subrelativistic Particles

Slowly moving particles that traverse IceCube will appear as a connected series of small electromagnetic showers. The defining characteristic of the events is the length of time that photons remain in the detector. For a typical downgoing muon event, the mean event length is $\sim$1-2 μs, whereas a slowly moving particle will last hundreds of microseconds or even milliseconds. IceCube DOMs run as autonomous data collection devices and events are selected using a software trigger based on the individual DOM data. This makes IceCube very sensitive to slowly moving particle events. As long as the light output remains sufficient, the trigger will continue to add the DOM data to the triggered event. Currently, the IceCube sensitivity to Q-balls, Rubakov monopoles, and supermassive strangelets is limited by the high trigger threshold (8 DOMs in 5μs). Investigations are underway, however, of topological and tracking algorithms in the IceCube trigger system. Such a trigger will improve the sensitivity to slowly moving particles that produce less light.

Figure 3 shows the expected flux sensitivity to slowly moving massive particles ($\beta \sim 10^{-3}$) for the 2007 IceCube configuration (1320 DOMs in 22 strings) and the eventual full IceCube array. With the full IceCube array, we expect sensitivities more than two orders of magnitude better than the current experimental limits.

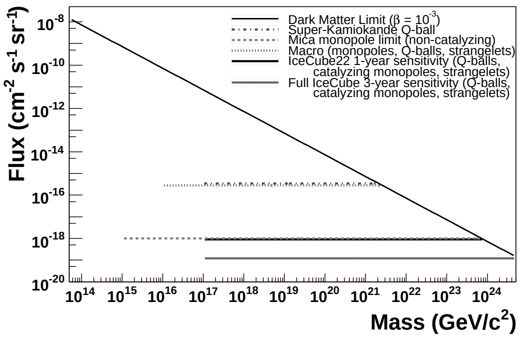

Figure 3: Current Limits [12, 13, 14] and Projected Sensitivities for Slowly Moving Massive Particles that may be seen by IceCube

Outlook and Conclusion

Each year, IceCube's capability to search for exotic particles will increase dramatically. With the 9 string detector alone, competitive limits on the flux of relativistic magnetic monopoles are achievable. However, these results are preliminary and will be refined. Background simulation will start with cosmic ray air showers produced by `CORSIKA`. Since only the high energy events are considered, weighting methods will be used. The asymmetry of the detector will require further analysis of the signatures produced at different angles. Finally, a log likelihood or neural network analysis may be employed to refine and optimize the cuts. With the additional analysis for slow moving exotics, IceCube will become a valuable tool in the search for these particles.

References

[1] P. Dirac, Quantized Singularities in the Electromagnetic Field, Proc. Roy. Soc.A 133 (1931) 60.

[2] A. Polyakov, Spektr tschastiz w kwantowoi teorii polya, Pisma Zhournal ETP 20 (1974) 430.

[3] G. t'Hooft, Magnetic Monopoles in Unified Gauge Theories, Nucl. Phys. B 79 (1974) 276.

[4] D. Tompkins, Total Energy Loss and Cherenkov Emission from Monopoles, Phys. Rev. B 138 (1965) 248.

[5] J. K. et. al, Experimental Signatures of Supersymmetric Dark-Matter Q-Balls, Phys. Rev. Lett. 80 (1998) 3185.

[6] D. B. et. al, Energy losses of Q-balls, Astropart. Phys. 15 (2001) 137.

[7] A. D. Rujula, S. Glashow, Nuclearites - a novel form of cosmic radiation, Nature 312 (1984) 734.

[8] I. C. A. A. et al, First Year Performance of the IceCube neutrino telescope, Astropart. Phys. 26 (2006) 155.

[9] S. Ahlen, Stopping Power Formula for Magnetic Monopoles, Phys. Rev. D 17 (1978) 229.

[10] J. L. et. al, Light tracking for glaciers and oceans – Scattering and absorption in heterogeneous media with Photonics, arXiv:astro-ph/0702108, submitted to Nucl. Instr. and Meth. A.

[11] K. A. et al, Search for Relativistic Magnetic Monopoles with the Baikal Neutrino Telescope, Proc. of the First Workshop on Exotic Physics with Neutrino Telescopes. C. de los Heros (editor) Uppsala University, January 2007. ISBN 978-91-506-1913-3 astro-ph/0701333 80.

[12] M. A. et al., Final results of magnetic monopole searches with the MACRO experiment, Eur. Phys. J. C 25 (2002) 511.

[13] Y. T. et al., Search for Neutral Q-balls in Super-Kamiokande II, arXiv:hep-ex/0608057.

[14] P. Price, M. Salamon, Search for Supermassive Magnetic Monopoles using Mica Crystals, Phys. Rev. Lett. 56 (1986) 1226.