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Subrelativistic Particle Searches with the AMANDA-II detector

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Abstract: Supermassive particles like magnetic monopoles, Q-balls and nuclearites may emit light at subrelativistic speeds through different suggested mechanisms. One of them is nucleon decay catalysis by magnetic monopoles, where the decay products would emit Cherenkov radiation along a monopole trajectory. The emitted secondary light from subrelativistic particles could make them visible to the AMANDA-II neutrino telescope, depending on the resulting luminosity. We present first experimental results from a search with AMANDA-II for events of this kind.

Introduction

The Grand Unified Theories (GUT) predict the existence of magnetic monopoles with expected mass of the order of $10^{16} - 10^{17}$ GeV[1]. These supermassive monopoles might become accelerated above virial velocities due to magnetic fields, but not relativistic [2].

Rubakov and Callan have indepentendtly proposed a mechanism by which SU(5) GUT monopoles are able to catalyse nucleon decay with a detectable cross section [3, 4]. The main decay channels would be $e^+\pi^0$, μ^+K^0 for protons and $e^+\pi^-$, μ^+K^- for neutrons, see [5] and refs. therein. The catalysis cross section has been suggested to be $\sigma = \sigma_0\beta^{-1}$ [3] or, at sufficiently low speeds, $\sigma = \sigma_0\beta^{-2}$ [6, 7], where σ_0 is a cross section typical of strong interactions. Nuclear attenuation factors have also been proposed, expressing nuclear spin effects on the decay catalysis [7]. The expected mean distance between nucleon decays catalysed along a monopole trajectory in ice, reaches down to submillimeter scales (following the cross sections above). Above the meter scale, the signal falls below our detector threshold.

In a neutrino telescope, the signature of these catalyzing monopoles would be a series of closely spaced light bursts produced along the monopole trajectory. Each burst would be Cherenkov radiation from an electromagnetic shower whose energy is close to the proton mass.

Other massive particles have also been hypothesized to exist in cosmic radiation. Two that might be detectable with neutrino telescopes are: Nuclearites (nuggets of strange dark matter) [8] and Q-balls (supersymmetric coherent states of squarks, sleptons and Higgs fields, predicted by supersymmetric generalizations of the standard model) [9].

Electrically neutral Q-balls would dissociate nucleons, emitting pions, which give them the same experimental signature in a neutrino telescope as catalyzing monopoles. Their cross section for nucleon dissociation is their geometric size. By limitations given in [10], it ranges from $\sim 10^{-26}\,\mathrm{cm}^2$ and many orders of magnitude upwards.

Nuclearites and charged Q-balls might also be detectable, as, travelling through matter, they would generate a thermal shock wave which emits blackbody radiation at visible wavelengths [8, 11]. Their luminosity as given by [8] is determined by their geometric size, which is atomic or larger, and would exceed that of magnetic monopoles and neutral Q-balls by several orders of magnitude.

So far we have only considered magnetic monopoles.

The AMANDA-II Neutrino Telescope

AMANDA-II is a neutrino telescope located at a depth between 1500 m and 2000 m under the ice at the geographic South Pole. A cylindrical volume of roughly 200 m diameter of the Polar ice was instrumented with a total of 677 optical modules (OMs), consisting of a photomultiplier tube (PMT) and supporting electronics enclosed in a transparent pressure sphere. The OMs were deployed on 19 vertical strings.

A variety of triggers are used. First, the 24-fold multiplicity trigger requiring a minimum of 24 OMs hit within a fixed coincidence window of 2.5 μs, and second, a so-called correlation trigger, requiring n OMs to be hit in any group of m adjacent OMs on the same string (m, n typically $\sim 6, 9$). For each triggered event, PMT pulse data is recorded over a time window of $\sim 33\,\mu$s. The vast majority of triggers are due to down-going atmospheric muons, yielding an average event rate of roughly 90 Hz.

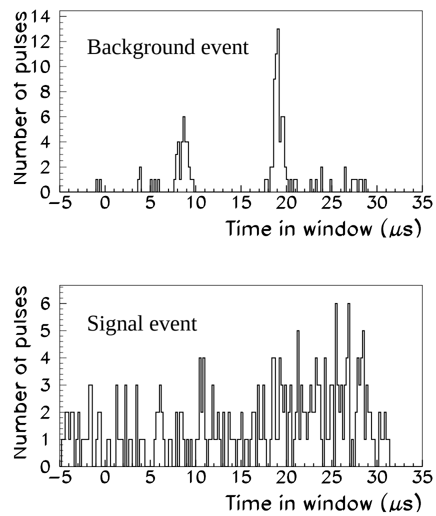

Figure 1: Upper: a background event with a non-triggering muon (left) and a triggering muon (right). Lower: a simulated signal event from a particle traveling at speed $\beta = v/c = 0.01$.

Simulation

The detection of slow particles builds on the fact that relativistic muons emit light during $\sim 3\,\mu$s, whereas slow particles emit during a large fraction of the 33 μs time window. A comparison is shown in Fig. 1. The upper picture shows a background event with the triggering muon at time 19 μs, and an accidental early non-triggering muon at 9 μs. The lower picture shows a simulated signal event. The signal separation from background is based on hits at times when no light from triggering muons is expected, the *early and late hits* outside the interval 16-24 μs.

In the simulation of sub-relativistic particles, all light output was expressed as Cherenkov radiation from electromagnetic showers arising from nucleon decay. All slow particles were simulated with isotropic directions and with speed $\beta = v/c = 10^{-2}$. In the simulations, the luminosity was expressed as the mean distance λ between two electromagnetic showers. So far, the simulated λ were in the range 2 mm - 60 cm.

For monopoles, only the decay of hydrogen protons was considered, and only the catalysis decay channel $p \rightarrow e^{+}\pi^{0}$ (with a branching ratio of 0.9 or higher [12]). It creates an electromagnetic shower with energy close to the proton mass, whereas other channels lose some of their shower energy to neutrinos.

If a slow particle would approach the detector, atmospheric muons would cause contributing hits and possibly fire a trigger. These muons were included in the simulation.

The catalysis cross sections σ that correspond to the chosen λ are $3 \cdot 10^{-25}\,\mathrm{cm}^2 - 9 \cdot 10^{-23}\,\mathrm{cm}^2$. These are at the upper edge of what appears to be allowed by theoretical considerations.

Data analysis and results

A period of 113 days in 2001 when a constant correlation trigger definition was used, is considered here. It required a multiplicity of 6 within any 9 adjacent OMs in four strings and a multiplicity of 7 within any 11 adjacent OMs in the remaining strings. The simulations show that the correlation trigger was substantially more sensitive to this type of signal than the multiplicity trigger.

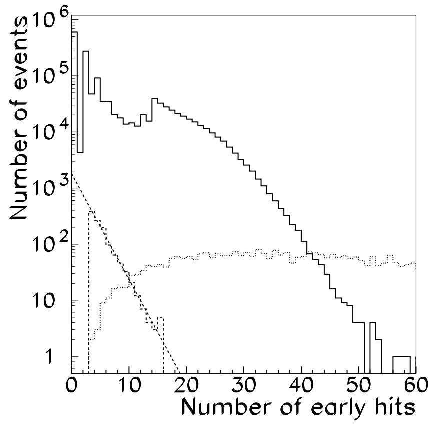

Figure 2: Number of early hits. *Solid*: Experimental data after first level filtering and cleaning. *Dashed*: Experimental data after second level filtering with an exponential fit. *Dotted*: Simulated signal after second level filtering ($\beta = 10^{-2}$, $\lambda = 2\,\text{cm}$).

The background properties and a preliminary expected sensitivity was determined using 20% of the data. A first filter reduced the data by 99%, requiring a total of at least 14 early and late hits.

Non-triggering muons contribute largely to early and late hits. The aim of the final filtering was to separate them from possible signal events. Hits from non-triggering muons arise within a short time span compared to hits from slow particles, as can be seen in Fig. 1. We defined hit clusters as collections of early hits that were separated by less than 2 μs. Each event was characterized by its cluster with most hits.

After trigger cleaning, we performed second level filtering using two cluster based cuts and one based on the events' geometries, as signal events are fairly well localized. The remaning events after filtering have an exponential distribution in the number of early hits. It is shown in Fig. 2, along with an exponential fit.

About 80% of signal events would be expected to have more than 20 early hits (cf. Fig. 2). Since none were found in the filtered data, the data must be almost signal free. Thus, the fit parameters are suitable for background estimation. They were used for calculating the expected number of background events at varying cuts in the number of early hits.

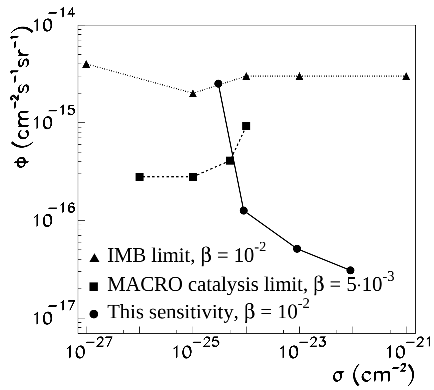

Figure 3: Flux limits (90% C.L.) and preliminary sensitivity (expected flux limit) at varying catalysis cross section.

We optimized the final cut following the scheme described by [13] in order to achieve the optimum sensitivity, which is the 90% C.L. flux upper limit that we would obtain if no true signal were present.

The optimal final cut for the 80% sample requires > 27 early hits. The resulting sensitivities, without systematic uncertainties, are given in Fig. 3. For comparison, limits at similar particle speed are included: the MACRO limit based on nucleon catalysis from [5] and the IMB limit from [14]. Limits at lower velocities have been presented by Baikal and Kamiokande [15, 16].

Discussion and Outlook

The AMANDA neutrino telescope is an excellent instrument to search for several postulated super heavy exotic particles. In this document, we present first studies of the sensitivity of AMANDA to sub-relativistic particles. The given sensitivities are still preliminary. Specifically, systematic uncertainties are not yet included. So far, we have used relatively small sub-sets of the available AMANDA data in order to outline our analysis strategies. The sensitivity of the analysis will improve substantially with more data.

This analysis used data from the original AMANDA data acquisition system (DAQ). For each channel, the analog signal from the PMT is recorded using Time To Digital Converters (TDCs) and Peak Sensing Analog to Digital Converters (ADCs). The original AMANDA DAQ system is unable to precisely characterize multi photoelectron events. In addition, the DAQ suffers from a $\sim$ 1 millisecond dead time after each triggered event while the ADCs/ TDCs are read out. For events with slowly moving particles, this means that the DAQ system is unable to record the bulk of the signal.

Beginning in 2003, the AMANDA data acquisition system was upgraded to include full waveform readout and to reduce the detector deadtime. Each channel is now connected to a Transient Waveform Recorder (TWR), a flash ADC that samples at 100 MHz with 12 bit resolution. Although the readout window for the upgraded DAQ is shorter than for the original DAQ (10.24 μs vs. 33 μs), the upgraded DAQ is able to record nearly continuously. In addition to the improved characterization of each event using the waveforms, the new DAQ allows for a reduction in the detector trigger threshold. Prior to 2004, AMANDA was generally run requiring a 24 channel coincidence in a 2.5 μs period, The upgraded DAQ can operate with a threshold of 18 optical modules. Additionally, events with between 13 and 17 hits are processed separately using a software trigger algorithm that looks for events where nearby optical modules are hit. The ability to almost continuously monitor the trajectory of a slowly moving particle, combined with the reduced trigger threshold, will greatly improve the sensitivity of AMANDA detector to such particle events.

AMANDA is now integrated with IceCube, and will continue to take data for several years. The analysis of the data from the integrated detector should give the best limits on the fluxes of slowly moving massive particles.

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