Snowmass2021 - Letter of Interest

Searches for exotic particles with the IceCube Neutrino Observatory

NF Topical Groups: (check all that apply □/■)

□ (NF01) Neutrino oscillations
□ (NF02) Sterile neutrinos
■ (NF03) Beyond the Standard Model
■ (NF10) Neutrino detectors
■ (CF01) Dark Matter: Particle-like
□ (CF02) Dark Matter: Wave-like
■ (CF07) Cosmic Probes of Fundamental Physics
■ (EF08) Model specific explorations
□ (EF09) More general explorations

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Collaboration: IceCube and IceCube-Gen2

Abstract: (maximum 200 words)

The Standard Model of particle physics has proven to be successful and precise but incomplete. New fundamental particles are predicted by theories which could also describe many ”anomalous” experimental results. Some of these exotic phenomena can only be observed at high energies or over long distances and timescales and they can only be probed using particles from space or the early Universe.

The IceCube Neutrino Observatory[1] is the largest instrumented particle detector on Earth by instrumented volume and therefore has excellent sensitivity for rare high-energy particles from the Big Bang and non-thermal astrophysical processes. Despite its sparse instrumentation, IceCube's detector uncertainties are well understood and establish it as a precision instrument for ultra-high energy particle physics.

Analysis of IceCube data has achieved world-best sensitivities and exclusion limits for relic magnetic monopoles covering most of the parameter range in energy and mass. Building specialized detectors for these and other particles with comparable sensitivity would not be feasible. Instead, large-volume neutrino detectors, such as IceCube, as well as the IceCube Upgrade[2] and IceCube-Gen2[3], will provide excellent data for future analyses aiming to discover new fundamental physics.

Introduction: particle detection at IceCube

The IceCube Neutrino Observatory comprises 5160 optical modules instrumenting one cubic kilometer of natural ice at the geographic South Pole. The standard detection channel for particles is Cherenkov light which is emitted by charged particles exceeding the speed of light in the medium. These particles are mostly muons from cosmic ray air showers or interaction secondaries from neutrino interactions. The brightness of a signature in IceCube depends on the charge, the velocity or the energy of a particle.

Magnetic Monopoles

Importance & Status: Magnetic Monopoles are particles carrying at least one magnetic charge[4]. They are proposed by almost all theories extending the Standard Model of particle physics[5–8]. Relic Monopoles are supposed to be created shortly after Big Bang with masses beyond 10^7 GeV. Depending on the mass they are decelerated and gravitationally trapped or accelerated by magnetic fields to relativistic speeds[9]. Detecting magnetic Monopoles would provide unique and fundamental information about particle physics as well as the development of the early Universe. Current best exclusion limits are achieved with large-scale multi-purpose instruments[10–12] using Cherenkov light at high speeds or the model dependent catalysis of proton decay[13,14] at low speeds as detection channels. IceCube[1] has covered most of this velocity space over the past 5 years with world-best exclusion limits and sensitivities[15–17].

Outlook & Priorities: The unique signatures of Magnetic Monopoles can also be searched using data from the proposed IceCube-Gen2[3]. For bright signatures at high and low speeds the sensitivity will mostly scale with the detection volume which increases by about a factor of 8. A new detection channel for neutrino telescopes, luminescence of ice, was investigated successfully in 2019[17]. Using this channel, the coverage of the parameter space can be further increased to intermediate velocities and a model independent search is possible at low velocities[17]. The Upgrade of IceCube, which provides an infill array that lowers the energy threshold to ~ 1 GeV,[2] will extend the range of detectable Big Bang relic Monopoles to even slower velocities and fainter signatures.

Q-Balls

Importance & Status: Supersymmetric extensions of the Standard Model predict the production of Q-Balls after the Big Bang – spherical objects filled with coherent states of squarks, sleptons and the Higgs field conserving baryon number[18]. An observation of a Q-ball would support the existence of supersymmetry and provide an explanation for the origin of Dark Matter in the Universe[19].
Electrically neutral Q-Balls leave signatures in IceCube which are comparable to Magnetic Monopoles catalysing proton decay[18], so searches proceed using similar analysis techniques. Previous flux exclusion limits by neutrino detectors[20,21] are exceeded by the reinterpretation of IceCube's slow monopole limits[16] reaching into the expected flux region (above a catalysis cross section of 10^{-25} cm^{-2})[22].
Charged Q-Balls have not been searched by neutrino detectors so far. Apart from the charge, the exclusion limits[23] are mass dependent in contrast to neutral Q-Balls.

Outlook & Priorities: Joint searches for Q-Balls and Magnetic Monopoles in IceCube data can exceed current best limits by 2 orders of magnitude due to the increased detector volume, 10 years of available data and improved trigger capabilities[17].
Future searches for charged Q-balls will use the new detection channel, luminescence of ice (see section "Magnetic Monopoles"). This mass independent approach (above $\sim 10^{11}$ GeV) can exceed previous exclusion limits at small charges and challenge them at high charges.
For both kinds of analyses, using IceCube-Gen2 will add another factor of 8 in volume to the sensitivity.

Nuclearites

Importance & Status: Nuclearites are heavy particles consisting of up, down and strange quarks which are proposed to be stable states in the Standard Model in certain thermodynamical processes in quark plasma[24,25]. Nuclearites are close to neutral and therefore Dark Matter candidates. In ice and water nuclearites produce a thermal shock wave that is optically visible[25,26].

Outlook & Priorities: The light yield of photon production by Nuclearites needs to be investigated[27]. This process could also lead to additional photons produced in Magnetic Monopole or Q-Ball interactions with water (particles described in above sections). Previous exclusion limits for Nuclearites[20,28,29] can be exceeded by 2-3 orders of magnitudes analysing IceCube[30] and IceCube-Gen2 data for Nuclearites with masses above $\sim 10^{13}$ GeV due to the large volume of the detectors.

Anomalously charged particles and long-lived charged massive particles

Importance & Status: The Standard Model does not constrain the elementary charge. Therefore, theories predict fractionally charged states or milli-charged composite objects which could be contributing to Dark Matter[31,32]. The signature in neutrino detectors is experimentally distinct due to the low energy loss in combination with low light emission. Recently a sensitivity was derived from IceCube data[33] which exceeds previous exclusion limits[34] by up to an order of magnitude.
A similar signature is expected for long-lived charged massive particles (CHAMPs) which are predicted by many extensions of the Standard Model. For example in Super-Symmetric theories the right-handed stau could be the meta-stable next-to-lightest particle[35]. Under certain conditions stau pairs produced in high energy neutrino or cosmic ray interactions in matter could be observed as parallel tracks. A model independent exclusion limit was derived from IceCube data which is exceeded by model dependent searches at CERN[36].

Outlook & Priorities: The detection of these comparably dim particles is not yet limited by IceCube's sparse instrumentation[33] but rather by missing dedicated triggers[30,36]. Using a larger volume detector, IceCube-Gen2, would increase sensitivity further and yield higher chance of detection for this fundamental property of particles with the development of appropriate triggers.

Evaporating black holes

Importance & Status: Black holes are predicted to loose mass during their lifetime via Hawking radiation, with mass loss increasing rapidly as the mass decreases[37]. Neutrinos are radiated by black holes via direct production, or the production of particles, such as muons and pions that then decay into neutrinos[38]. Primordial black holes (PBHs), created early in the Universe, with a mass of $\sim 5 \times 10^{14}$ g have an evaporation time equal to the age of the Universe. PBHs are a candidate for dark matter[39]. Gamma ray observations exclude PBHs to be a major contributor to dark matter if they all had an initial mass of 5×10^{14} g[40,41]. The current best limit for density rate of PBH is $\dot{\rho} < 3400$ pc^{3}yr^1 at 99% C.L.[40] (or one PBH evaporation within 0.04 pc per year). But under the more natural assumption that there is initial mass distribution, PBHs remain a viable candidate of dark matter.

Outlook & Priorities: A preliminary study of IceCube's sensitivity has been conducted matching the last $\sim$day of life of PBHs[42]. During this period the temperature of the black hole has increased to the level where $\gtrsim$100 GeV neutrinos are produced copiously. The PBH neutrino signature is distinctive both in energy spectrum and time profile, which would allow a detection to be distinguished from astrophysical phenomena. Recent theoretical work has focused on the spin of PBHs, which increases the evaporation lifetime. In the near future, these calculations will be included in IceCube's sensitivity[43]. Over the next decade IceCube-Gen2 will improve on IceCube's sensitivity to PBH evaporation by over one order of magnitude.

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The complete list of IceCube authors can be found here: https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube
The complete list of IceCube-Gen2 authors can be found here: https://icecube.wisc.edu/collaboration/authors/snowmass21_icecube-gen2

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