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Technical Conference Paper

OPPORTUNITIES FOR PARTICLE PHYSICS EXPERIMENTS IN SOLUTION MINED CAVERNS

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SMRI Spring 2016 Technical Conference
25 – 26 April 2016
Galveston, Texas, USA

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Abstract

Thousands of physicists today work in a field called "particle astrophysics", whose concerns include the study of neutrinos and dark matter. Our work often requires us to build large, ultrasensitive particle detectors deep underground; examples include Super-Kamiokande, a 50 kiloton ultrapure water system in Japan, and DUNE, a 30 kiloton liquid argon experiment planned for the Sanford Underground Research Facility in South Dakota. Our needs for more and larger detectors have been stymied by the constraints of working in conventionally-excavated underground spaces. I have been studying the possibility of installing detectors in solution-mined salt caverns, which appear to offer different constraints and opportunities. Some fairly conventional detector technologies might benefit from large roof spans, low radioactivity, site flexibility, and potentially low cost. Other technologies might benefit from the access to high pressure. In this talk I will briefly introduce the field of experimental particle astrophysics, including today's key science goals and the large detector technologies now in use in mines, underwater, and in Antarctic ice. I'll show some early concepts for salt-cavern-compatible detectors, ranging from "easy" experiments previously designed for deep ice drill holes, and the more speculative ideas for high-pressure gas ionization counters (limited to about 100 kg in conventional labs) scaled up to tons or kilotons. I'll highlight what I see as the key cavern- and detector-engineering challenges which I hope can be met via future collaborations.

Key words: cavern instrumentation, cavern utilization, physics, astrophysics

1 Introduction

Thousands of physicists today work in a field called "particle astrophysics", whose concerns include the study of neutrinos and dark matter. Our work often requires us to build large, ultrasensitive particle detectors deep underground; examples include Super-Kamiokande, a 50 kiloton ultrapure water system in Japan, and DUNE, a 30 kiloton liquid argon experiment planned for the Sanford Underground Research Facility in South Dakota. Our needs for more and larger detectors have been stymied by the constraints of working in conventionally-excavated underground spaces. I have been studying the possibility of installing detectors in solution-mined salt caverns, which appear to offer different constraints and opportunities. Some fairly conventional detector technologies might benefit from large roof spans, low radioactivity, site flexibility, and potentially low cost. Other technologies might benefit from the access to high pressure.

In this paper I will briefly introduce the field of experimental particle astrophysics, including today's key science goals and the large detector technologies now in use in mines, underwater, and in Antarctic ice. I'll show some early concepts for salt-cavern-compatible detectors, ranging from "easy" experiments using technology usually deployed in deep ice bore holes, and the more speculative ideas for high-pressure gas ionization counters. I'll highlight what I see as the key cavern- and detector-engineering challenges which I hope can be met in the future.

2 Historical context

Particle physics the field devoted to questions like: what are the fundamental building blocks of matter? What forces govern their interactions with one another? What particles and forces participated in the Big Bang and the evolution of the Universe? Some of this study takes place at high-energy particle collider (for example, the recent Higgs Boson discovery at the Large Hadron Collider in Geneva) but many important questions have been answered without accelerators, by studying the interactions and decays of naturally-occurring particles. Many experiments today are trying to count extremely rare events, which might also be tiny and easily mistaken for simple radioactive events. To get countable numbers of such rare events, we're driven to build large detectors (tons to megatons); to avoid swamping the signal events in uninteresting backgrounds, we make our detectors of ultra-low radioactivity materials and operate them in low-radioactivity labs. This class of experiments has been the basis of fruitful cooperation between physicists and miners since the 1960s

Why is mining involved? The Earth's surface is bombarded by radioactivity, primarily due to high-energy protons bombarding the upper atmosphere from space. The muon rate at the Earth's surface is about 10 per square foot (100 per square meter) per second. The muons and their byproducts can mimic many details of the signals we're interested in. Therefore, low-background experiments are usually installed deep underground, where 1000–6000' (300-2000 m) of rock overburden is able to stop most muons. Today there are large underground labs all over the world, excavated along rail tunnels (Gran Sasso, Italy; Canfranc, Spain), in repurposed mines (Kamioka, Japan; Homestake, South Dakota; and an active Vale nickel mine at SNOLAB, Sudbury, Ontario), or greenfields (Jinpeng, China; Theni, India). Some important work is been done in conventional salt mines at WIPP, New Mexico; Fairport Harbor, Ohio; and most actively Boulby, UK.

However, as our detectors have gotten bigger, underground excavation operations have not gotten cheaper; several current proposals have billion-dollar price tags, with hundreds of millions of dollars in excavation alone. This motivates us, to begin with, to consider new ways of getting our future detectors underground. My research hopes to identify several detector technologies which might be deployed in solution-mined cavern space. It appears that this approach offers a number of interesting opportunities, on one hand for cost savings relative to conventional mining, and on the other hand for exploiting caverns as pressure vessels for previously-impossible large detectors. To design and evaluate these experiments, we are working to understand how our familiar detector technologies interact with the pressure, temperature, and access constraints of these caverns.

3 Overview of physics goals and detector technologies

To understand the goals of this project, it might be useful to have an overview of some of today's large detector technologies and the physics topics we chase with them.

3.1 Giant water and scintillator detectors for neutrinos

Neutrinos are elusive and hard-to-detect particles in the Standard Model of Particle Physics. They're close relatives of electrons, but unlike electrons have no electric charge; this makes them pass silently through most matter. Although they are hard to detect, they're easy to *create*, and are common among the decay products of unstable particles and nuclei. We have detected the neutrinos naturally emitted by the Sun, by the Earth's radioactivity, by nuclear reactors, by cosmic rays in the atmosphere; we have also created neutrino beams in special particle accelerators. When a neutrino does interact, it most does so by delivering all of its energy to a charged particle that we can detect—an electron, muon, or nucleus—but the interactions are so rare that to require very large detectors.

For one example, the Super-Kamiokande collaboration built a 50 kiloton tank of ultrapure water and surrounded it with 11,000 20" (50 cm) photomultiplier tubes (PMTs). About eight times a day, a neutrino interacted in the water, where its daughter particles produced a brief flash of light, resulting in a few thousand photon signals caught by the PMTs. The Sudbury Neutrino Experiment, viewing a 1000 ton "heavy water" (D2O) target with 9000 8" (20 cm) PMTs, was able to catch low-energy neutrinos from the

Sun, whose interactions had to be identified using only few dozen photons each. Together these experiments have three Nobel prize citations. Other detectors, like KamLAND and Borexino, use thousands of PMTs to collect light from radiation-sensitive liquid scintillators. Borexino, in perhaps the greatest feat of low-background counting, searched for low-energy neutrinos emitted by radioactivity in the Earth. Over five years of monitoring 300 tons of scintillator, they identified about 25 geoneutrino interactions.

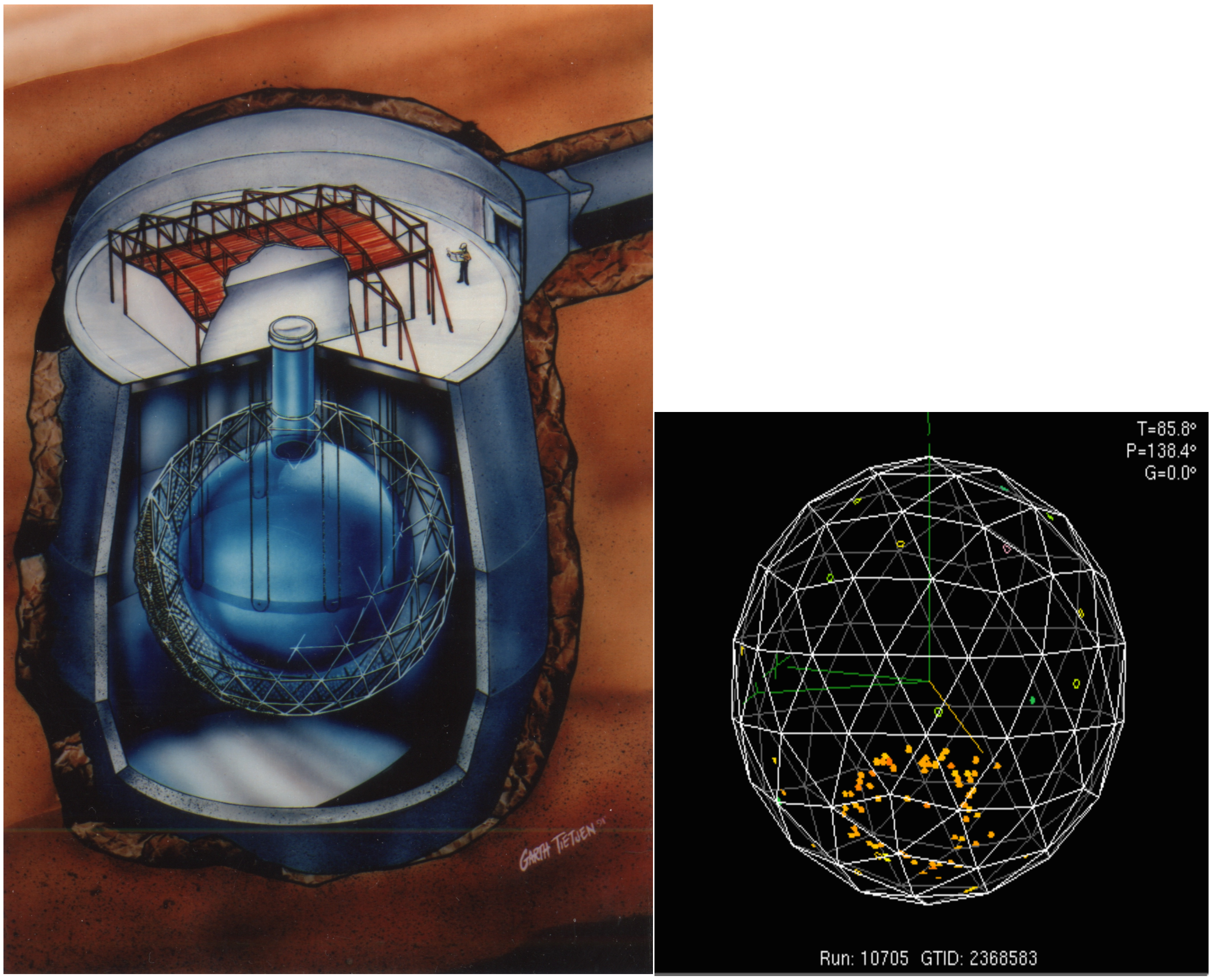

Figure 1: Sudbury Neutrino Observatory (SNO) experiment (1999-2006), located at the 6800' (2070 m) level of the Creighton Mine, Sudbury, Ontario. Right: Artist's cutaway of the experiment. Visible are the 40' (12m) acrylic sphere containing heavy water and 50' (17 m) geodesic sphere carrying photomultiplier tubes (PMTs). Left: PMT hit pattern typical of a solar neutrino interaction in the heavy water. Courtesy of the SNO experiment.

3.2 Dark matter

Astrophysicists believe that the Milky Way is held together by gravity from "dark matter"; other than its gravitational effects, nothing else is known. One leading theory is that dark matter is a bath of massive particles whose interactions are even rarer than those of neutrinos—but not quite zero. Large experiments have been built searching for ultra-rare events (none seen yet) involving a Milky Way dark-matter particle crashing into an atomic nucleus; the disturbed nucleus leaves a trail of light-emitting atoms and/or ionized atoms behind, which we detect with various combinations of photon detectors, ionization, and thermal . The LZ experiment, for example, searches for scintillation/ionization signals in 7 tons of cryogenic liquid xenon. A worrisome source of "fake" signals in a dark-matter experiment can occur when a high-energy muon passes near (but not through) the apparatus, launching a high-energy neutron into it. The LZ xenon will be surrounded on all sides with 10' (3 m) of liquid scintillators and water, called a "muon veto", to ensure that muons cannot pass unnoticed this close.

By putting dark matter detectors into solution-mined salt caverns, we might have space to instrument a muon veto quite far from the detector (> 30' (10 m)). This could be done with a small number of PMTs in a freshwater or scintillator balloon, or possibly (if the brine has adequate optics) in the cavern brine itself.

3.3 Neutrinoless double beta decay

Nuclear physicists have a vast catalog of known radioactive decays, with some measured only recently in ultrasensitive detectors: for example, Tellurium-130 can decay into Xenon-130, with the decay emitting two electrons and two neutrinos, but a given nucleus takes an average of 7×10^{20} years to do so. A related class of decays, "neutrinoless double beta decays", is predicted to occur (albeit even more slowly) **if** neutrinos have certain hypothesized properties. We search for these decays in massive beta-decay sensors (750 kg (1500 lb) of tellurium in CUORE, 200 kg (450 lb) of isotopically-enriched xenon in EXO) which must be built for the highest possible energy resolutions. EXO, a ionization counter using cryogenic liquid xenon, can measure 2500 keV beta decays with an energy spread of 37 keV.

It has long been known that *gaseous* ionization counters have higher resolution than liquid counters. By switching from cryogenic liquid to room-temperature gas, the NEXT-100 experiment (Alvarez 2012) has shown energy resolution at least 2.5x better than EXO. This behavior seems to hold for pressures up to 5 Mpa. However, it is very hard to build large masses at these pressures—either the volumes are small or the pressure vessels are huge, costly, and a source of radioactive background. A solution mined salt cavern might serve as giant, low-radioactivity pressure vessels for a future multi-ton high pressure ionization counter.

3.4 Neutrino beams from accelerators

The DUNE project, a large international project, involves a neutrino *source*. Accelerators at Fermilab in Batavia, IL will be modified to produce a "neutrino beam" aimed through the Earth towards Lead, SD. A very small number of them would interact along the way, including in new detectors installed underground at the Homestake mine. The chosen detector technology is a 30 kiloton liquid argon time projection chamber, which will give photographically-detailed information about each neutrino interaction seen. However, it requires an expensive cryostat and ventilation system in addition to the detector hardware. Super-Kamiokande-like water-based detectors were also an option but would need to be larger (>100 kilotons) for the same sensitivity.

Intriguingly, the southern edge of the Pine Salt formation (Zieglar 1956) is within the fringes of this beam, and a detector sited there might be able to piggyback on the DUNE beam investment.

4 Methods for deploying a detector in a salt cavern

My goal in salt-cavern deployable detector design is to rely, as much as possible, on (a) standard detector technologies and (b) what I hope to be as close as possible to standard solution-mining practices.

The basic installation would be, in most cases, something like this:

1. We obtain and survey a cavern with a *somewhat* enlarged well bore. We keep the well under halmostatic conditions and the wellhead open.
2. We construct a large balloon which, when inflated, will conform to the cavern walls and roof. We lower the balloon into the cavern, either (a) preattached to its own string or (a) with additional hardware capable of mating to the casing string.
3. Within the balloon and string, we replace the brine with fresh water. This provides (a) a less-corrosive environment for the detector systems, (b) water of known clarity for muon-detection

instrumentation, and (c) a membrane, pressed against the cavern roof by the freshwater's buoyancy, which we speculate provides some level of protection against small rockfall events.

4. We lower one or more payloads of waterproof, pressure-hardened physics equipment, preattached to their power/fluid/readout cabling. If the payload fits down the well "in one piece", we're ready to operate immediately. Alternatively, some payloads may fit down the well only in a deflated or folded state, or in pieces. These payloads would enter the cavern and hang there while we "inflate" them with surface-supplied fluid; or be manipulated by remotely-operated deployment or assembly systems.

Some of these deployment methods are familiar from past particle-physics experiments, and some are unfamiliar. I will give three examples (low, medium, and high complexity) of detector technologies which are potentially compatible with this type of deployment.

4.1 <u>Low complexity example: standard detectors in pressure hulls</u>

One collection of particle-physics experiences corresponds very closely to the salt-cavern installation needs. A large National Science Foundation-funded project, the IceCube Neutrino Observatory, has been built in the icecap at the South Pole. It consists of 86 "strings" lowered into hot-water-drilled boreholes up to 7000' deep in the ice. 60 photon detector modules, each housed in a 13" glass pressure vessel, are mounted along each string. The array was installed 2005–2010 with zero string or pressure-vessel failures. (The KM3Net experiment, now under construction, is placing similar high-pressure photon detector modules in 10,000' deep water in the Mediterranean; construction is being done by remotely operated submarines.) The DM-ICE experiment is a small dark matter experiment, consisting of an ultra-low-background scintillator crystal housed in a steel pressure vessel, which was co-installed in one of the IceCube boreholes. The point of this is simply to put the DM-ICE crystals into low-radioactivity surroundings; ice is so much cleaner than rock that it made the additional South Pole challenges worthwhile.

For a "simple" use of a salt cavern for a physics experiment, we are considering a simple detector string consisting of (a) several DM-ICE like dark matter search packages and (b) 10–20 IceCube-like photon sensor packages, inside (c) a freshwater-filled rubber balloon 50' in diameter. The fresh water serves as an ice-like ultra-low-radioactivity environment for the dark matter equipment, and the photon sensors additionally allow the water to detect passing muons and veto their byproducts. The entire detector/balloon/cable array could fit down a 16–18" bore.

Figure 2. Two pressure-hardened physics experiments deployed in hot-water-drilled holes in the South Pole ice cap in 2010. Left: IceCube experimenters deploying a string of photomultiplier tube modules (DOMs). Photo credit Peter Rejcek. Right: Schematic of DM-ICE prototype dark matter detector. Drawing courtesy Physical Sciences Laboratory, Wisconsin

4.2 Medium complexity: a one-piece inflatable gas proportional counter

The high-pressure gas proportional counters is a valuable technology which is particularly difficult to implement in conventional lab environments. Such a detector would typically consist of a stainless steel gas pressure vessel containing arrays of delicate wires, meshes, or circuit boards, which place various high voltages around carefully-shaped open gas volumes. When filled with an appropriate gas, with appropriately high purity, radiation events in the gas lead to electron avalanches which are detectable on the wires. In one familiar configuration, the main gas volume is a simple, electrically-grounded cathode cylinder. A smaller cylinder, placed concentrically in the first, carries the anode array and high-voltage electronics. The gas volume between the two cylinders is the ionization-sensitive region.

To deploy a similar system in a salt cavern, we would make a long, thin anode cylinder that fits down an obtainable borehole. We would surround this with a cathode balloon, which would be furled around the anode while being lowered down the well. Similar balloon-in-a-vessel deployments have precedent in neutrino physics: the Borexino and KamLAND experiments successfully installed (and inflated) multiple, nested nylon balloons via a narrow access port. To insert a gas balloon into a brine-filled cavern, the balloon must first be filled with an incompressible buffer fluid. Once in the cavern, we displace the buffer and inflate the balloon into a cylinder leaving the anode hanging in the center. Applications can be envisioned for both deep-cavern, high-pressure (10-20 Mpa) detectors and shallower medium-pressure (5 Mpa) systems; interesting fill gases include xenon (for dark matter or double beta decay), neon (for dark matter and solar neutrinos), and methane or hydrogen (for nuclear reactor monitoring and geoneutrino detection). Methane and hydrogen are interesting cases because, despite having many attractive properties, large quantities would never be permitted in a conventional underground lab for safety reasons. Hydrogen is also of prohibitively low density to store at quantity in mines where space is at a premium. In a high pressure salt cavity, neither of these disadvantages are present.

Particular challenges involve handling the balloon's buoyancy and the need to circulate gas to the surface for purification. In some cases we might prefer this to operate in a nitrogen- or air-filled rather than a brine-filled cavern.

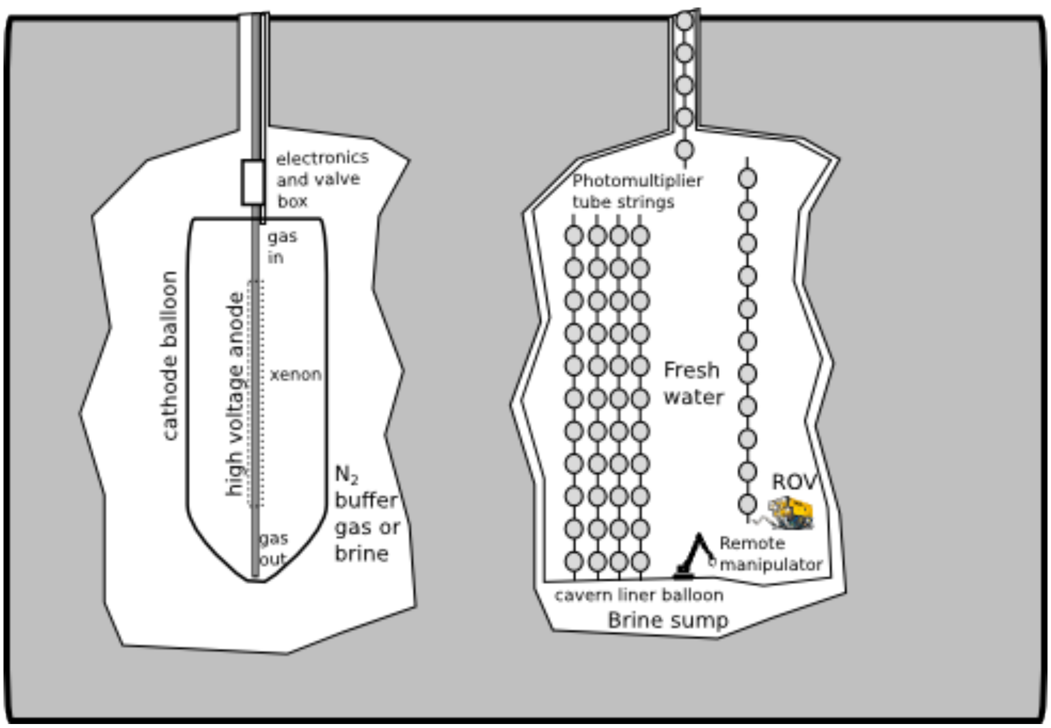

Figure 3: Examples of of medium- and high-complexity detector assemblies. Left: cylindrical gas ionization detector. The detector consists of a cylindrical anode, with associated gas piping and electronics, which hangs in the center of a cylindrical gas balloon. The assembly enters the cavern in one piece before inflation to full size. Right: To install a photomultiplier tube array in a large, lined, freshwater-

filled cavern, we would use in-cavity manipulators or ROVs to distribute buoyant "strings" of sensors around the cavity.

4.3 High complexity: in-cavern assembly

Many broadly-recognized physics goals require multi-kiloton to megaton-scale detector targets; conventional projects designed/proposed at this scale include DUNE in South Dakota (30 kilotons argon, as cryogenic liquid), JUNO in China (20 kilotons linear alkylbenzene scintillator), and Hyper-Kamiokande in Japan (1000 kilotons water). Solution mining clearly offers single-cavern *capacity* at these scales, and at a much lower cost than mining. However, it is no longer so plausible to imagine a "one-step" inflation or deployment operation; such large detector must probably be constructed, robotically, out of small components that fit down the well bore.

There is some precedent in neutrino physics for doing this type of construction. Several particle experiments have, via narrow access necks, deployed complex, articulated arms and tilting beams into large detector volumes. On a small scale, the DEAP-3600 experiment was able to sand, polish, and sputter-coat the inside of a 66" (1.7 m) sphere with a folding arm inserted through a 9" (20 cm) port (Boulay 2012). The SNO experiment was centered on a 39' (12 m) diameter acrylic sphere full of deuterated water, accessed only via a 3' (1 m) diameter neck. In 2003-2004, SNO installed 36 long, vertical subdetector strings, underwater, inside the sphere. The strings were assembled inside the neck, handed off to a small, custom-built remotely operated submersible, and "flown" to preinstalled tiedowns on the acrylic (Amsbaugh 2007). The process was reversed during decommissioning. One can imagine a similar process, on a much larger scale, installing large numbers of IceCube-like PMT strings around the perimeter of a large solution-mined cavern. Commercially-available marine construction ROVs might fit down a 36" (1 m) shaft.

Another partial precedent is DUNE. Though constructed "dry" in a conventional mine, will be built under severe access restrictions. Its large membrane cryostat will be built first, with only a small access chimney. Complex detector components will be lowered down the chimney, hung on trolleys on guide rails, and rolled to the back of the cryostat. DUNE will have human-installed guide rails and human-assisted trolley operations, but we can envision a process, controlled only by surface winch operations and in-cavern manipulator arms, which similarly would allow components to be lowered down a narrow borehole, then rolled sideways into some hard-to-access final location.

5 Questions, goals, and outlook

5.1 Questions and uncertainties

In developing this research program, since so many different detector technologies and physics goals are on the table, I am seeking comments from a wide range of particle physicists. At the same time, moving further will require input—brainstorming and sanity checks now, but later hopefully actual design, engineering, and construction work, and cavern access—from the solution-mining community.

Here I list some questions whose answers would help even at the brainstorming stage:

- What, if anything, is known about small-scale rockfall behavior of cavern roofs? How do we quantify and minimize the risk of large block falls? What size of rockfall should we accept as inevitable, and design our detector balloons to withstand?
- What, if anything, is known about the optical clarity of the brine in a new or undisturbed cavern? A brine optical characterization experiment might be a good candidate for a "trial run" experiment for giving particle physicists our first hands-on work in a solution mining context.
- What issues might govern the construction of larger well bores? While 18"–24" (50–60 cm) wells appear to permit many interesting small experiments, many users might want (and be willing to pay for) 36" (100 cm) and larger access. Could a cavern with a large wellbore be converted to high-pressure gas?

- Are there depths, cavern shapes, and/or roof spans where we can safely depressurize the cavern entirely? Some detector-assembly sequences might be easier in air.
- The Pine Salt formation is of special interest due to its location near a planned neutrino beam from Fermilab; what is known about the cavern sizes and shapes possible there?

5.2 Outlook and status

My group at UCSB is in the early stages of designing particle-astrophysics experiments, particularly dark-matter experiments, compatible with deployment in solution-mined salt caverns. This work has been funded so far by the Department of Energy, Office of High-Energy Physics, whose portfolio includes dark-matter searches, high energy neutrinos, and proton decay. Other possible avenues of funding might be the DOE Office of Nuclear Physics (interested in low-energy neutrinos), the National Nuclear Security Administration (interested in neutrino-based nuclear reactor monitoring), and the National Science Foundation. We are assembling an interest group to discuss designs ideas for a range of such detectors. We welcome any interest or involvement from the solution-mining community, whether from owners, engineers, or university and government labs.

6 Acknowledgements

This work was supported by the Department of Energy under grant DE-SC0013892.

7 Further reading

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