Mineral Detection of Neutrinos and Dark Matter

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Book of Abstracts

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DMICA: exploring Dark Matter in natural muscovite MICA

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Searching for dark matter typically requires a large amount of material to capture extremely rare interactions. However, natural mineral crystals like mica have been around for geological time scales, offering plenty of exposure even in small samples. These crystals can hold onto nuclear recoil tracks —evidence of dark matter interactions—for periods longer than the Earth's age. When etched, these tracks appear as observable pits. Building on this, Snowden-Ifft and colleagues in 1995 studied natural Muscovite mica that was 500 million years old, covering an area of just 0.08 square millimeters. We're now planning the DMICA experiment to significantly expand upon this initial research, covering much larger areas. In this presentation, we'll discuss our preliminary experiments aimed at replicating Snowden-Ifft's work as a stepping stone for DMICA. We'll also cover how sensitive the DMICA experiment could be in detecting dark matter, emphasizing that mica's large surface area to volume ratio is particularly useful for detecting very heavy dark matter particles.

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Directional Detection of Dark Matter with Nitrogen-Vacancy Centers in Diamond

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Nitrogen vacancy (NV) centers in diamond have been identified as a promising future platform for directional detection of weakly interacting massive particle (WIMP) dark matter. WIMP particle induces nuclear recoil in the diamond, resulting in a direction-dependent sub-micron damage track. This damage track induces crystal stress variations which shift the energy levels of NV centers, enabling localization of the track through spectroscopic interrogation. Subsequently, further nanoscale characterizations to determine the length and direction of the track can be performed. This method would distinguish between WIMP-induced tracks from tracks produced by known sources, providing a strategy to overcome the background solar neutrino problem. In this talk, I will present an overview of the proposed detection method as well as recent experimental progress in our group towards demonstrating the required imaging techniques, such as high precision strain mapping using quantum interferometry and x-ray diffraction microscopy.

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Dark Matter and Neutrinos under the Microscope

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Despite the recent advances in physics, Dark Matter (DM) still eludes detection by modern large-scale experiments and puzzles the minds of physicists. Paleo-detectors represent a drastically different approach to DM detection, which necessitates the use of microscopy and computational techniques to read out and analyze nm-sized damage features produced by interactions of DM particles and neutrinos with nuclei of ancient minerals.

Karlsruhe Institute of Technology (KIT) possesses a wide range of cutting edge nm-scale manipulation and imaging technologies, including among others AFM, FIB-SEM, TEM, and HIM. Additionally, KIT has several institutes with expertise in geology, data acquisition, and processing. Hence, KIT is uniquely positioned to facilitate close cooperation between state-of-the-art microscopy research, geology, computer science, and astroparticle physics, making it the perfect place for a paleo-detectors project.

At present, we aim to conduct several key feasibility and calibration studies for the use of minerals as paleo-detectors. To that end, we have established a dedicated small-scale laboratory equipped with a high-temperature furnace and ancillary tools. Additionally, we have obtained several samples, which will be irradiated with low- and high-energy particles, giving rise to a variety of damage features and tracks. Subsequently, we will cooperate with KIT microscopy facilities to read out the resulting damage tracks with a number of high-resolution microscopy techniques. In this talk, the latest developments in the paleo-detector program at KIT will be presented.

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A cosmic ray harvest in the dried-out Mediterranean basin

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Paleo-detectors have so far been considered to detect weakly interacting particles, and the possible cosmic-ray background is ignored supposing to use samples collected from large depths in the Earth's crust. We reverse here this approach by proposing Paleo-detectors to measure cosmic ray fluxes in the past. We use the fact that cosmic rays can be shielded to have specific exposure windows. We take the example of the dessication of the Mediterranean Sea in the Messinian period ($\sim$ 6 Myr ago), when lots of evaporites have been formed. These evaporites were exposed to secondary cosmic rays for $\sim$500 kyr and then submerged again. The large number of tracks expected with respect to other paleo-detectors applications potentially enables the measurement of $\sim$1% variation of the cosmic ray flux in the exposure period. We discuss also other possible scenarios where a similar approach can be used.

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Muon-induced tracks in minerals

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One of the main challenges in the paleo-detectors technique consists of the identification of the tracks generated by the recoiling particles. However, tracks left by heavy fission fragments are routinely seen in the dating of minerals (obsidians, apatites, zircons …). Apart from spontaneous fissions, the heavy nuclei (^{238}U, ^{232}Th) can complete fissions induced by muons. However, to find the signal left by the astroparticles, one should precisely know the exposure time and the age of the minerals. We could remove the time dependencies taking two minerals generated in the same geological event and finding the ratio between the tracks found in the two minerals. As a case of study, we consider two zircons, generated in the same volcanic eruption (of $\mathcal{O}$(kyr) ago), but with different Uranium and Thorium contents: since Uranium and Thorium have different decay times and different cross sections of induced fission per muon stopped, we could verify the presence of tracks left by cosmic rays using standard track detection techniques.

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Measuring solar neutrinos over gigayear timescales with paleo detectors

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Measuring the solar neutrino flux over gigayear timescales could provide a new window to inform the solar standard model as well as studies of the Earth's long-term climate. We demonstrate the feasibility of measuring the time evolution of the B8 solar neutrino flux over gigayear timescales using paleo detectors. We explore suitable minerals and identify track lengths of 15–30 nm to be a practical window to detect the B8 solar neutrino flux. A collection of ultraradiopure minerals of different ages, each some 0.1 kg by mass, can be used to probe the rise of the B8 solar neutrino flux over the recent gigayear of the Sun's evolution. We also show that the time-integrated tracks are sensitive to models of the Sun.

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Accurate modelling of track length distributions with SRIM to search for new physics with light mediators and WIMPs

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Paleo detectors have been proposed to search for new physics by counting nuclear recoil tracks in minerals deep underground. These tracks have a very low signal-to-background ratio, it is therefore particularly important to accurately model the expected signals. In the literature, an one-to-one relationship between recoil energy and track length was assumed. However, using the simulation software SRIM that simulates transports of ions in lattices, we found a single recoil energy results in a distribution of track lengths, specifically subkeV recoils have dispersions x/E_{recoil} ~ 2 nm keV^{-1} . Low energy recoils, which with the one-to-one assumption would otherwise result in tracks below resolution, could in fact have measurable contributions to longer, detectable tracks. We used this improved calculation to model nuclear recoils by WIMPS and search for new physics with light mediators through neutrino-nucleus scatterings.

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Q-ball search with mica

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The paleo detector is new approach for rare event search in astroparticle physics such as dark matter. The mica is good candidate for the paleo detector because of its cleavage, transparency and relatively low threshold of track formation to the energy deposition due to particles.
In this study, we are focusing on the Q-ball. The Q-ball is non-topological soliton in the early universe, and it is important theoretical model for the baryogenisis, beyond standard model and dark matter. And, the Q-ball can have electric charge, therefore the mica is expected to detect that as long tracks.
In this talk, current status of detector calibration using ion beam, evaluation of the detection performance and optical scanning system will be reported, and discuss about future subjects and physics case.

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Supernova burst detection with mineral detectors

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I will discuss some thoughts about supernova neutrino burst detection with mineral detectors.

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Welcome

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Mineral Detectors for Dark Matter - overview

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Paleohistory of Paleodetectors

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I will start with a tale of early paleodetector events, squarely at the boundary of the humorous and the tragic, responsible for setting this field back a good three decades. The speaker will then display a semblance of penitence by discussing fullerenes as geochemical detectors for highly-ionizing exotica, and presenting a primo spot to attempt the hardest trick in this carnival.

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Materials Selections for Dark Matters/Neutrinos Detections

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We will briefly summarize the materials that have been considered for detection of dark matters/neutrinos in the literature. Then we will focus on mineral detectors especially on olivine. Our recent studies on natural olivine will be presented.

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Understanding control and modulation of color center defects from first principles

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Neutron Detection

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Neutron Detection

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Discussion Session: What are ”tracks”?

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Towards a prototype paleo-detector for supernova neutrino and dark matter detection

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Using ancient minerals as paleo-detectors is a proposed experimental technique expected to transform supernova neutrino and dark matter detection. In this technique, minerals are processed and closely analyzed for nanometer scale damage track remnants from nuclear recoils caused by supernova neutrinos and possibly dark matter. These damage tracks present the opportunity to directly detect and characterize the core-collapse supernova rate of the Milky Way Galaxy as well as the presence of dark matter. Current literature presents theoretical estimates for these potential tracks, however, there is little research investigating the experimental feasibility of this technique. At the University of North Florida, we have contributed to the field by searching for and analyzing these damage tracks in prototype detectors constructed from selected minerals, including: halite, Muscovite mica, and Phlogopite mica. Our research characterizes the applicable backgrounds in these prototype detectors. We have employed non-destructive techniques, including laser confocal and atomic force microscopy to identify and characterize damage tracks in the minerals. Chemical etching and plasma etching of target minerals is used to enhance the detectability of these damage tracks at the expense of altering some of their geometrical attributes. With the use of an etching rate model and automatic track detection via Python, damage track lengths are reconstructed. Our data is compared to current theoretical predictions to pursue the practical implementation of paleo-detectors as local core-collapse supernova neutrino and dark matter detectors.

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Calibrating for WIMPs and beyond: paleodetection activities at Queen's University

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The use of ancient minerals for the detection of dark matter requires a systematic understanding of the full pipeline from energy deposition, to track creation, to readout, and a detailed theoretical mapping at each step, verified by experiment. I will provide a brief overview of some of the activities at Queen's University that aim to fill in some missing elements in this pipeline. This involves an exploration of the expected signal produced by WIMPs, but also other dark matter candidates (composite dark matter), and new physics in other sectors. On the experimental side, I will describe our accelerator-based calibration technique, the minerals that we are exploring, and the methods that we plan to use to connect these results with expected signals of dark matter.

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The Lorandite Neutrino Experiment + UCL activities

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Discussion Session

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Astrophysical neutrinos with paleo detectors

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Neutrinos offer unique probes of astrophysical systems, yet their detections are challenging due to neutrinos' weak interactions. Natural mineral detectors—paleo detectors—can record the history of neutrino fluxes and offer an unparalleled view into astrophysical phenomena. In this talk, I will focus on motivations and sensitivities for supernova neutrinos and solar neutrinos.

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Imaging Atmospheric Neutrinos with Paleo-detectors

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I will present the status and plans of the University of Michigan effort to image atmospheric neutrinos in Olivine.

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Lightsource opportunities using coherent X-ray diffractive imaging to visualize dark matter and neutrino tracks in the rock record at scale

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Minerals provide unique sensitivity for discovering composite dark matter and other cosmogenic particles, as large amounts of energy are deposited into minerals – resulting in characteristic damage (e.g., localized amorphization, phase change, grain morphology modification). Large cross-section tracks in minerals from possible dark matter and neutrinos can have widths ranging from nanometers to microns and extend along a straight trajectory, cross-cutting mineral grains in a rock specimen. Here, we explore the opportunities afforded at hard X-ray lightsource facilities, from synchrotrons to XFELs, to visualize in 2D and 3D the damage tracks with/without preparation of an internal surface and etching. Coherent X-ray diffractive imaging (CXDI) methods, e.g., X-ray phase contrast imaging, direct imaging, and ptychography, have all the benefits of a laboratory-based X-ray μ-CT (e.g., non-destructive imaging and reconstruction of pores, particles, defects, amorphous zones, phase contrast for density mapping) with 10s nm spatial resolution and multi-scale or high through-put imaging via tiling and stitching of diffraction images. Several examples of mineral benchmarks will be discussion with applications to future dark matter track discovery campaigns at lightsources.

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Paleodetection at Queen's: proton irradiation studies to test theory against experiments

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Discussion Session: Analysis and Simulation Tools for Mineral Detection

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Optical measurements of irradiated crystals for PALEOCCENE

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Optical Detection of Neutrons via CaF2 for PALEOCCENE

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Nuclear recoil events resulting in color centers can be caused by neutron scattering, coherent elastic neutrino nucleus scattering (CEvNS) or dark matter scattering opens the door to the creation of durable, mineral-based, solid-state detection modalities. In this talk, we present measurements of Radiation-Induced Luminosity (RIL) in CaF 2 crystals. We report on the change in RIL as a function of dose, persistence of the RIL over time, and explore the role that Sm2+ and Sm3+ impurity sites in RIL.

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Light sheet microscopy for PALEOCCENE

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Discussion Session

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