Snowmass2021 LoI: Paleo Detectors

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■ (CF1) Dark Matter: Particle Like
■ (NF10) Neutrino Detectors
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■ (IF3) Solid State Detectors and Tracking

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Abstract:

Paleo detectors are a proposed experimental technique to search for rare events. The fundamental idea of paleo detectors is to use $\mathcal{O}(100)\,\mathrm{Myr} - \mathcal{O}(1)\,\mathrm{Gyr}$ old natural minerals found on Earth as Solid State Track Detectors for nuclear recoils. The physics case for paleo detectors has been made in a series of papers: In [1–3] paleo detectors have been proposed for the direct detection of (WIMP) dark matter with sensitivities significantly beyond those of current conventional direct detection experiments. In [4] paleo detectors have been proposed as a technique to measure the galactic core collapse supernova rate, and in [5] the prospects of measuring the cosmic ray flux over Gyr timescales has been investigated. In this LoI, we will first give a brief overview of paleo detectors, and then list relevant studies which should be undertaken towards demonstrating the feasibility of paleo detectors.

1 Paleo Detectors

If an atomic nucleus in a regular crystal lattice receives a “kick” of a few keV of kinetic energy, as can happen via scattering of neutrinos or dark matter particles off the nucleus, this nucleus will travel a distance of order $10\,\mathrm{nm}$ through the crystal. Along its path, the nucleus deposits its kinetic energy in the electrons and nuclei comprising the crystal, giving rise to a lasting *damage track* in the otherwise regular crystal lattice. These damage tracks can be measured using a variety of techniques, including electron beam microscopy [6, 7], helium ion beam microscopy (HIBM) [8, 9], small angle X-ray scattering (SAXs) [10–12], optical microscopy [13–15], and positron annihilation spectroscopy (PAS) [16], making the crystal a (Nuclear) Solid State Track Detector [6, 13, 17, 18]. While the damage tracks do fade over time, the characteristic time scales over which such fading occurs are of order Gyr, or even longer, in many natural minerals (e.g., $\tau_{\rm ann} \sim 10^{59}$ yr at room temperature for $\mathrm{CaMgSi_2O_6}$ [6]).

In a nutshell, the *paleo detector* idea is to search for nuclear recoil damage tracks in $\mathcal{O}(1)$ Gyr old natural minerals with modern microscopy technology [1–5] (see also [19–23] for similar older ideas). The spatial resolutions feasible with modern technology ($\sim 1\,\mathrm{nm}$ with HIBM, $\sim 15\,\mathrm{nm}$ with SAXs) hold promise for the possibility of reconstructing damage tracks from nuclear recoils with recoil energies as small as a few keV (and even lower with high resolution techniques such as HIBM). The extremely long exposure times allow paleo detectors to achieve enormous exposure: imaging $100\,\mathrm{g}$ of $1\,\mathrm{Gyr}$ old target material (e.g. with SAXs) yields an exposure of $\varepsilon = 0.1\,\mathrm{kg\,Gyr} = 100\,\mathrm{kt\,yr}$. Thus, paleo detectors potentially allow for exposures comparable to that of large water Cherenkov detectors such as Super-Kamiokande and nuclear recoil energy thresholds comparable to what has been achieved in modern direct detection type experiments such as liquid Xe time projection chambers.

In addition to providing sensitivity to rare events, the $\mathcal{O}(1)$ Gyr exposure times of paleo detectors also holds promise for the unique possibility of obtaining information about changes in any signal occurring over geological time scales. While in any individual sample, one would only measure the average signal rate over the age of the sample, it is possible to obtain (coarse-grained) information about the time-dependence of the signal by studying a series of mineral samples of different ages. The age of geological samples can be determined with an accuracy of a few percent using standard methods [24–26], allowing one to detect changes of the signal rate larger than $\mathcal{O}(10)\,\%$ if they occur on timescales $\gtrsim \mathcal{O}(10)\,$Myr.

As in any rare-event search, mitigating backgrounds to the largest extent possible is crucial. While the advantage of natural minerals is that they promise exposures many orders of magnitude larger than what is imaginable in conventional experiments with similar energy thresholds, the downside is that one has to use a target material found in nature instead of running a controlled laboratory experiment. Background studies for paleo detectors have been carried out in [2] (see also [1, 3–5]). Similar to conventional laboratory experiments, cosmogenic backgrounds can be reduced to an acceptable level by using target material which has been shielded from cosmic rays by a large natural overburden. Different from multi-ton conventional detectors, paleo detectors require at most a few kilograms of target material. Such modest amounts of material can be sourced from much deeper than conventional underground laboratories, for example from the cores of (existing) deep boreholes. Another major source of backgrounds is natural radioactivity. While β- and γ-decays are much less problematic than in conventional detectors, since electronic recoils do not give rise to lasting damage tracks, radiogenic neutrons are a more severe problem than in conventional detectors. The lack of timing information precludes the possibility of suppressing neutron-induced nuclear recoils with coincidence timing. While neutron-induced backgrounds in paleo detectors are somewhat lower in targets containing H (protons moderate the radiogenic neutrons), it is crucial to use minerals as radiopure as possible for paleo detectors. As discussed in detail in the appendix of [4], the most promising classes of target minerals are *ultra-basic rocks* and *marine evaporites*.

2 Feasibility Studies

The recent work on paleo detectors in [1–5] has studied their physics case. In order to bring paleo detectors closer to realization, a series of more experimental studies must be undertaken. We briefly sketch some of the required studies here.

Read-Out: Several techniques are considered for identifying damage tracks from nuclear recoils. It is crucial that the read-out and sample preparation process does not anneal away the sought features, or induce artefacts similar to the signal. Imaging techniques, such as electron beam microscopy, atomic force microscopy, and HIBM can capture physical images of lattice damage, but these can only be applied to relatively small samples of $\mathcal{O}(\mu\mathrm{m}^3)$. Since high energy imaging beams (such as keV electrons) can induce lattice damage, a dedicated campaign is needed to ensure these techniques do not introduce backgrounds. Similarly, sample preparation must be non-destructive. Focused ion beam (FIB) can be used to mill samples with $\mathcal{O}$ (μm) dimensions suitable for microscopy methods, but this must be shown to be non-invasive. Otherwise alternative techniques like mechanical polishing must be explored. Non-imaging techniques like PAS and SAXs can scan much larger sample sizes, allowing easier scaling to a rare event physics experiment. As these are non-destructive, they are less susceptible to imaging-induced backgrounds. They can also possibly alleviate concerns of sample preparation, since associated artefacts are likely to exist at surfaces and the surface to volume ratio decreases for larger samples.

Background Studies: Once non-destructive imaging and sample preparation techniques are in place, determination of the cause of the tracks must be established. Dedicated calibration campaigns are needed for these studies. Calibrations of nuclear recoils, electronic recoils, alphas, and fission fragments must be performed to determine the ability to identify nuclear recoils while discarding backgrounds. Given the small size of paleo detectors, high irradiation doses are required, such as reactor neutron sources. Calibration samples for fission fragment, α-particle, and low-energy ion induced features can be prepared at ion implantation laboratories, while accelerators facilities can provide samples with muon induced tracks. By performing these calibrations on the different sample preparation and damage reconstruction techniques, and by quantifying the detection efficiency and threshold of each method, the best method(s) for physics applications of paleo detectors can be identified. Combining multiple techniques possibly allows for cross checks and the reduction of systematics.

In addition to quantifying neutron induced backgrounds, calibrations of alpha and fission tracks can be used to determine background discrimination capabilities. These backgrounds are expected to have very different characteristics from nuclear recoils, so discrimination is likely, but this must be demonstrated and quantified to evaluate background rates from these sources.

Geology: Neutron induced nuclear recoils will be indistinguishable from rare event signals, hence, the radiopurity of target samples and their shielding against cosmogenic backgrounds are crucial for rare event searches. Radioassay for intrinsic U and Th concentration in samples must be performed to estimate exposures to fission and (α, n) neutrons. Additionally, surveys for muon tracks, which should be physically longer, can provide estimates of muon induced neutron backgrounds. An in depth radioassay campaign that addresses each of these is necessary for all potential targets for paleo detectors. The geological provenance of the minerals may also have a non-negligible impact on the impurity content in the mineral, as well as the overburden for cosmogenic shielding, making the screening campaign even more important.

Finally, although the annealing timescales are thought to be long compared to the exposure time of paleo detectors, the effects of annealing in the different potential materials must be characterized. For instance, over geological timescales minerals undergo large changes in pressure and temperature which may alter the annealing rates.

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