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The use of paleo-detectors to investigate cosmic-ray fluxes throughout the history of Earth

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The measurement of the flux of cosmic rays in the past could give some important information about the sources of cosmic rays, the evolution of the neighborhood of the Solar System in the Galaxy and the Galaxy itself. It could also inform our understanding of key events in the Earth's history such as mass extinctions. The paleo-detector technique proposes to investigate the traces left in natural minerals by energetic particles over geological timescales. A number of works have already suggested the use of paleo-detectors to measure weakly interacting particles such as dark matter constituent particles and neutrinos. Here, we propose for the first time to use paleo-detectors to directly detect secondary cosmic rays. The advantage of this approach is that cosmic rays can be shielded, and thus, in rocks with a particular history, we can measure the flux of cosmic rays at a specific moment in time rather than integrated since the initial formation of the target mineral. For example, evaporites produced in the desiccation of the Mediterranean sea during the Messinian salinity crisis have been exposed to cosmic rays for a very specific (and known) period of time before being submerged by a km-deep overburden of water, possibly retaining information about the flux during the exposure period. In this work, we show the challenges of this kind of study, its proposed targets and the track detection techniques.

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1. Introduction

Natural minerals can be a shrine that holds precious information about astroparticle fluxes in the past. Indeed, minerals are already widely used as solid-state nuclear track detectors (SSTD) [1]. The basic idea behind using minerals as detectors is that when a particle crosses it, it can produce nuclear recoils which then create a trace, i.e. a semi-permanent damage of the crystalline (or amorphous) lattice. This technique was used so far to detect radiation, mostly from within the mineral itself (in particular with the dating purpose). *Paleo-detectors*, on the other hand, is the nickname used for minerals searched for tracks induced by astroparticles. This technique differs radically from standard astroparticle detection techniques, not relying on direct-time observation of events within a target mass in a laboratory.

Even if the term paleo-detector was only coined in 2018 [2], observing tracks from nuclear recoils have been done since decades like, for example, fission tracks observed in natural minerals such as Obsidian and Apatite and used to identify the origin and age of the mineral. Between 1984 and 1997 Paul Buford Price [3] and D.P. Snowden-Ifft [4] pioneered in a series of articles the the use of ancient crystals of Muscovite Mica to search for supermassive magnetic monopoles and dark matter signatures. More recently, paleo-detectors have been presented as an alternative approach to the detection of dark matter-nucleon and neutrino interactions [2].

Good track recording candidate materials are insulators and poor semiconductors with electrical resistivity larger than ~2000 Ω cm [1]. Since the dominant source of background for the majority of the minerals is the radioactive decay of heavy nuclei, specifically spontaneous fission fragments and neutrons coming from the spontaneous fission, it is useful to search for minerals with a low amount of Uranium contamination. Moreover, when considering the neutron background, experimental data has shown that the (α,n) cross sections for lighter target nuclei with atomic numbers (Z) in the range between 3 and 15, mostly for Lithium and Beryllium, are typically remarkable. Consequently, it is commonly preferred to select mineral samples devoid of Li and Be. On the other hand, the presence of hydrogen in the chemical composition of the mineral can significantly alleviate this background as neutrons tend to lose a considerable portion of their energy through a single elastic collision with a hydrogen nucleus. Once formed, the tracks remains in the mineral, unless it is heated above a certain temperature T_{ann} in geological timescales. This track fading effect, called *annealing*, happens at different temperatures for different minerals. Since the history of temperatures of a mineral on geological timescales is practically impossible to be known, minerals with T_{ann} high enough to be above values normally reached in the Earth's crust are best suited for paleo-detectors.

As tracks can vary in size from few nm to almost a mm, a variety of microscopy techniques can be envisaged to detect them. The trade-off for each technique is represented by the spatial resolution against the maximum volume that can be scanned. In general, dark matter and low-energy neutrinos leave tracks shorter than ~ μm and require techniques beyond optical microscopy. The recent whitepaper about the paleo-detector technique [5] offers an ample review of different techniques and ongoing efforts to test this kind of tracks, which we will not describe in detail here. Larger tracks, such as those expected from cosmic rays or atmospheric neutrino interactions, can in principle be accessible to optical microscopes. So far, no track clearly connected to an astroparticle interaction has been yet identified. Fission tracks, which have been extensively studied, are measured by enlarging them via a chemical attack, or *etching*.

In this proceedings, we present two different considerations and perspective on the possible detection of cosmic rays with paleo-detectors: firstly, in section 2 we propose an example of minerals with a know history of exposure to cosmic rays and then in section 3 we suggest the possibility to use muon-induced fission to have easily detectable tracks. The works presented up to now to the astroparticle scientific community have suggested the use of paleo-detectors to measure weakly interacting particles.We propose instead the study of cosmic rays over geological timescales. Cosmic rays are high-energy particles that originate and are accelerated from outer space, reaching and interacting constantly with our atmosphere. By examining the effects of secondary cosmic ray interactions with different materials over time, paleo-detectors can offer insights into the history of the cosmic-ray fluxes, and thus of their sources. The fact that cosmic rays are shieldable, while neutrinos are not, makes it easier, in principle, to isolate the flux of cosmic rays in a certain period. Moreover, they interact much more than neutrinos and dark matter and thus the number of tracks they generate is expected to be larger than those suggested so far. Paleo-detectors could prove to be invaluable tools for astrophysical studies, providing insights into the history and characteristics of high-energy cosmic ray flux and transient sources such as gamma-ray bursts (GRBs) and tidal disruption events (TDEs). Therefore they could offer a unique opportunity to directly study the history of our Galaxy, as they potentially allow us to investigate the past events and phenomena that have shaped our cosmic environment and gain a deeper understanding of its evolution.

Cosmic ray interactions in minerals have already been studied in the case of meteorites [6]. Here, however, we focus on interactions of secondary cosmic rays with minerals on the Earth surface. Amongst the components of the extensive air showers produced by cosmic rays in the interaction with the atmosphere, the electromagnetic one has a minimal chance of causing nuclear recoils. We will focus then in the following on the muonic component, which is abundant and has the advantage of being also capable of penetrating small overburdens of rock. This is crucial, as we cannot know the history of the sheltering of each sample with a water-equivalent centimeter precision.

Once the mineral with the appropriate characteristics has been selected, the principle of trace detection in a paleo-detector is as follows. When a charged particle traverses an insulating solid, it induces radiation damage along its path within the material. With respect to other paleo-detector applications, the length of tracks induced by cosmic rays is expected to be higher, up to $o(0.1 \text{ mm})$. Moreover, if the density of the damaged material reaches a sufficient level, a chemical reagent can be employed to etch the affected region, resulting in the formation of a distinct channel or hole aligned with the trajectory of the particle. The chemical reagent persistently attacks the bulk material of the solid from all directions, causing the inner diameter of the channel to progressively expand. After this treatment, the etched track becomes visible under an optical microscope even if the original radiation damage region along the trajectory before etching, called the latent track, was not.

2. Controlled exposure conditions: the example of the Messinian age

To investigate the historical cosmic ray flux using paleo-detectors the best samples are those created and exposed to cosmic rays for a known and relatively brief period of time. Following this exposure, these samples are subsequently shielded by a substantial overburden of material that effectively mitigates the influence of secondary cosmic rays up until the present time. This way, the

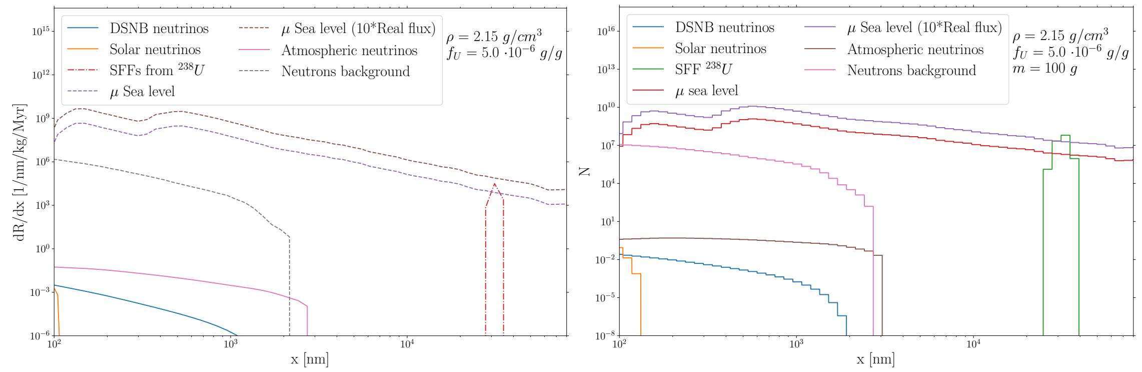

Figure 1: Left: differential track length spectra in a fixed sample of halite for all the sources of background and for the muon flux at the sea level as derived at the present time (grey) and increased by a multiplication factor of 10 (yellow). Right: expected number of tracks obtained integrating on the mass of the mineral, the track length range, and the exposure time t$_{exp}$ to the muon flux, or the age time t$_{age}$ for the backgound contributions (DSNB means diffuse supernova neutrino beackgound, SFF spontanous fission fragments).

mineral can preserve the information about the cosmic-ray flux at the time of its exposure potentially for a very long time.

A case-study for this is the Messinian Salinity Crisis (MSC). The MSC was as a geological event of remarkable complexity, leading to a profound metamorphosis of the Mediterranean Sea and with sensible effects all over the planet. In its most accepted interpretation, between 5.97 and 5.33 Myr [9] the strait of Gibraltar sealed off, triggering the evaporation of a substantial portion of the Mediterranean Sea. This transformation resulted in the creation of an immense saline basin, distinguished as the largest in the recent Earth's history. Developed in three main stages of evolution, the MSC geological record consists of evaporites, mainly halite (NaCl) and gypsum ($CaSO_4\,2(H_2O)$) deposits with an estimated volume of more than 106 km^3 accumulated in both shallow-water and deep-water settings [10].

The evaporites, formed during the period of the Messinian Salinity Crisis, experienced different conditions. Some of them were exposed directly to secondary cosmic rays, while others were shielded by a thin layer of high-salinity water. The Messinian Salinity Crisis lasted approximately 500 kyr, when the strait of Gibraltar reopened leading to a rapid refilling of the Mediterranean Sea in what is known as the *Zanclean flood*. This event, which may have occurred within just a few years, caused a sudden and significant increase in the sea's water level, reshaping the landscape and leaving a distinct geological record. A large part of the evaporites created during the MSC were then submersed by a large water shield and, in some case, dragged by the water tide to the deepest abysses, where they stayed until now, shielded from the last $\sim$ 5 Myr of cosmic rays flux.

We note here that, while the picture of the MSC reported here is currently the most accepted by the geological community, some scholars propose different scenarios for the creation of this large amount of evaporites and set limits on the entity of the desiccation of the sea [11]. The analysis proposed in the following could also help verify the different hypotheses proposed so far.

We made a simulation to understand the feasibility of using a mineral abundant in this geological event as a paleo-detectors. We chose Halite as target material and considered muons in the cosmic ray showers as the main signal[1]. We used the measured muon spectrum at sea level from [12]. We then simulated the nuclear recoil in Halite using the GEANT software [13]. The muon flux decreases with energy with a limited quantity of muons reaching sea level at the highest energies. However, at these energies, the nuclear recoil produced by muons can have hundreds of keV kinetic energy, resulting in traces in the mineral that can be as long as 10^3 μm. Using the *paleopy* software [14], we extracted the track length spectrum dR/dx of the muon signal for various background sources, as shown in Figure 1, left. It is possible to see that for tracks up to a length of a few μm, the main background source is represented by neutron-induced nuclear recoils. However, as the length range increases, for tracks between 20 and 30 μm, the only expected background is due to spontaneous fission fragments. The track length spectrum dR/dx is then integrated to obtain the actual number of tracks N_{trk} expected in a real sample. The integration is performed considering the mass of the examined mineral, its age and the exposure time to the muon flux for the muon signals at sea level, while the total life time of the mineal for the background sources. In this case we considered a 100 g sample, created at the beginning of the Messinian period (5.97 Myr ago) and exposed for 500 kyr for geological reasons to the muon flux. The results are reported in 1, right. We can see that a large number of tracks is expected with limited background contamination, making it feasible to detect such tracks even with current techniques.

In both panels in figure 1, two signal lines are present: one using the currently measured muon flux and one considering a factor ten higher flux. This is a simple example and in future work we will investigate muon fluxes expected from changes in the primary cosmic ray spectrum and specific astrophysical transient events. Transient events of interest could be supernovae, tidal disruption events and nearby gamma-ray bursts. However, the Messinian timescale has an interesting superopsition with another event that could have changed the cosmic-ray emission within the Galaxy. Two lobes of plasma extending from the Galactic Center have been discovered in X-ray and gamma-ray bands from observations made by the ROSAT (and than eRosita [15]) satellite and the Fermi Gamma-ray Space Telescope [16]. These so-called Fermi Bubbles extend above and below the Galactic Plane for approximately 14 kpc. The Fermi Bubbles are theorized to be remnants of AGN-like activity in the Milky Way that occurred in the past. AGN have been long sought as candidates for accelerating cosmic rays, so if the Galaxy had been active in the past it is reasonable to expect that this affected the flux of cosmic rays. Estimates on the age of the Fermi bubbles [17] interestingly coincide with the period of the Messinian Salinity Crisis. The study of paleo-detectors formed and exposed to the flux of high-energy cosmic rays during the MSC could therefore be a feasible and highly valuable technique to investigate the activity of the Fermi Bubbles. However, it must be considered that the direct association between the cosmic ray flux potentially detectable with the paleo-detector technique and the Fermi Bubbles can be complex, as the effect of the Galactic magnetic field, which influences the trajectory of CRs, can produce a delay on the ground of the flux.

3. Induced fission

One of the current challenges of the paleo-detectors technique is that the feasibility of detecting tracks induced by light nuclei with low-energy recoils has yet to be experimentally verified, although

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[1] We are currently carrying on also a study of the effects of neutrons, which will be reported in future publications.

multiple efforts are now being devised [5]. Cosmic-ray detection, however, has an advantage in that respect. Fission tracks from heavy elements are routinely observed since decades in laboratories with simple and inexpensive equipment. Etching techniques are used with many materials (such as Zircon, Apatite, Obsidian...) to make fission tracks visible with simple optical microscopes. Muons have been proved to induce fission in different elements [18], including ^{238}U and ^{232}Th[2]. The latter, in particular, has a very low probability of spontaneously decay via spontaneous fission (BR= 1.1×10^{-11}) but has a a number of fission per muon stopped of $0.02(\pm\, 0.01)$ .Using a mineral suitable to be used as SSTD, rich in Thorium and potentially poor in Uranium, it is possible to isolate the contribution of cosmic-ray induced tracks. The primary background for this type of analysis is provided by the tracks of spontaneous fission of these nuclei, which are indistinguishable from those induced by external particles.

Consider a mineral with a content of f^{Th} of Thorium and f^{U} of Uranium. The number N of traces from fission in this mineral can be calculated as $N = N_s^U + N_s^{Th} + N_i^U + N_s^U$, i.e. the sum of the four contributions of induced N_i and spontaneous N_s fission of Uranium U and Thorium Th. The number of traces from each contribution can be rewritten as the product of the fraction of nuclei and exposure time or age time depending on the fission contribution (exposure time t_{exp} for the induced fission, age time t_{age} for the spontaneous) and a factor C that takes into account the nature of fission related to U and Th. For the spontaneous fission the factor C can be expressed as the product of the branching ratio, the number of atoms per grams and the decay rate. Whereas for the induced fission C is the number of muons per second which are stopped within the mineral, calculated with the integral of the muon flux at sea level in a certain energy range, multiplied by the density of the paleo-detector and the expected number of induced fission per stopped muon.

We can see that to isolate the flux of muons in this way, one would need a good understanding of the age and exposure time of the sample. However, in the same geological event (e.g. volcanic eruption), different crystal of the same mineral can be produced with slightly different contamination of Uranium and Thorium. In this case, the dependence on t_{age} and t_{exp}, which are very hard to know, can be removed. If we consider two minerals of the same species but with different contents of Thorium and Uranium, we can express the ratio between the track numbers N_1 and N_2 of the two paleo-detectors. Taking into account the fact that the branching ratio of Thorium is much lower than that of Uranium, the spontaneous fission term for Thorium can be neglected to simplify the ratio, which in the further case of the presence of only spontaneous fission it is further simplified in the ratio between the fraction of Uranium in the second and in the first mineral.

Therefore, being able to study two different minerals with the same geological history, and measure their Thorium and Uranium contamination, it is possible to derive the ratio $\rho = \frac{N_1}{N_2}$. The resulting outcome will enable verification as to whether the mineral has been exposed to cosmic ray flux, as it would exhibit a number of tracks consistent with both induced and spontaneous fission.

To give some real numbers and test the order-of-magnitude feasibility of this concept, we apply the considerations done so far to the blue zircons from Vesuvius. These are zircons emitted in the volcanic ejecta from the western flank of Vesuvius volcano (Campania, Italy), of which eruptions have been recognized dating back up to about 25 kyr ago. In a recent publication [19], natural blue

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[2] We will ignore ^{235}U, as its branching ratio for spontaneous fission is very low and also the muon-induced fission is rare for this isotope.

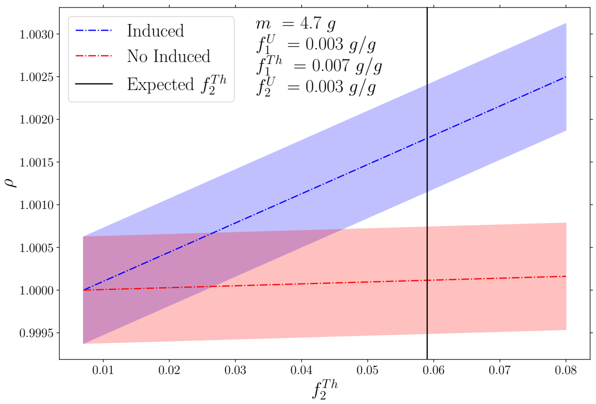

Figure 2: The ratio of the measured number of tracks between two different samples with the same Uranium fraction as a function of the Thorium fraction of the second sample. The blue line represents the case where cosmic-ray induced fission is present, the red one the case where it is not. Values are for a 4.7g zircon sample, the black vertical line marks the maximum Thorium fraction reported in [19] for the Vesuvius blue zircons.

zircons from an eruption of 4 kyr ago were studied and a fraction of ^{238}U and between 0.3-1.8% and ^{232}Th in the range 0.7-5.9% was measured. Using these quantities, we did the test with the result shown in the figure 2. We have assumed to select two zircon samples of 4.7 g each, the first with Uranium and Thorium concentration at the minimum values of the possible ranges. We consider the second sample to have the minimum concentration of Uranium and studied the evolution of the number of tracks when changing the Thorium fraction from the minimum of 0.003 g/g up to 0.059 g/g. We then plot the ratio ρ between the number of traces as a function of the Thorium concentration in case of muon-induced fission (blue line) or with the sole occurrence of spontaneous fission (red band). The error bands include the statistical error on the number of tracks and assume an uncertainty of 1ppm on the concentrations. Starting from approximately f_2^{Th} ~0.035 g/g and for the parameters fixed as described, it is in principle possible to discriminate between the scenario with and without traces of induced fission. This value is well within the variability of the Vesuvius zircons (the range is delimited by the black line). Although this is only a case study and a deeper study with also different, more general hypotheses needs to be performed, this simple example looks promising for a real-world application in the near future.

4. Conclusions

This contribution presented some preliminary study about how paleo-detectors could offer a unique and valuable approach to the study of our Galaxy over geological timescales. We have shown, with the example of the Messinian Salinity Crisis, how it is geologically possible to have suitable samples exposed to secondary cosmic rays only for a certain amount of time in a known time period. We will study other opportunities in the future, like minerals created during a volcanic eruption and then covered by the material ejected in a subsequent one.

In parallel, the study of induced fission tracks showed that the detection of tracks induced by cosmic rays is feasible with relatively simple instruments, as it falls back into the well known and amply performed measurement of fission tracks. Together, these two case studies show that not only the use of paleo-detectors to study the past flux of cosmic rays is in principle feasible, but it is possibly closer than the applications of paleo-detectors suggested so far, as it does not involve the search for sub-μm tracks formed by the recoil of low-Z nuclei, which have not been observed experimentally so far. The fundamental steps that need to be taken in the future of this research concern the improvement and optimization of track recognition: from techniques for preparing samples, to the best microscopy techniques for observing samples and scanning them with high resolution, to image recognition algorithms that allow, once images of the minerals have been acquired, a high number of samples to be studied in a reasonable time. With the rapid development of AI techniques and their application to image recognition, however, this will probably be easily overcome in the next future.

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