Snowmass2021 - Letter of Interest

A next-generation cosmic-ray detector to study the physics and properties of the highest-energy particles in Nature

Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
■ (CF3) Dark Matter: Cosmic Probes
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (NF04) Neutrinos from natural sources
■ (NF10) Neutrino detectors
■ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
■ (IF10) Radio Detection

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Abstract: Nature is providing particles with energies exceeding 10^{20} eV. Their existence imposes immediate questions: Are they ordinary particles, accelerated in extreme astrophysical environments, or are they annihilation or decay products of super-heavy dark matter or other exotic objects? The particles can be used to study physics processes at extreme energies: Is Lorentz invariance still valid? Are the particles interacting according to the Standard Model or are there new physics processes? The particles can be used to study hadronic interactions (QCD) in the kinematic forward direction: What is the cross section of protons at $\sqrt{s} > 10^5$ GeV? If the particles are accelerated in extreme astrophysical environments: Are their sources related to those of high-energy neutrinos, gamma rays, and/or gravitational waves, such as the recently observed mergers of compact objects?

To address these questions, a next-generation observatory will be needed after 2030 to study the physics and properties of the highest-energy particles in Nature. It should have an aperture at least an order of magnitude bigger than the existing observatories. We aim for a detector system with an area of $40\,000$ km^2 or more and all-sky coverage.

Introduction

Nature is providing particles at enormous energies, exceeding 10^{20} eV – orders of magnitude beyond the capabilities of human-made facilities like the Large Hadron Collider (CERN). At the highest energies the precise particle types are not yet known, they might be ionized atomic nuclei or even neutrinos or photons. Even for heavy nuclei (like e.g. iron nuclei) their Lorentz factors $\gamma = E_{tot}/mc^2$ exceed values of $\gamma > 10^9$. The existence of such particles imposes immediate, yet to be answered questions: • What are the physics processes involved to produce these particles? • Are they decay or annihilation products of Dark Matter?[1;2] If they are accelerated in violent astrophysical environments: • How is Nature being able to accelerate particles to such energies? • What are the sources of the particles? Do we understand the physics of the sources? • Is the origin of those particles connected to the recently observed mergers of compact objects – the gravitational wave sources?[3–8] The highly-relativistic particles also provide the unique possibility to study (particle) physics at it extremes: • Is Lorentz invariance (still) valid under such conditions?[9–14] • How do these particles interact? • Are their interactions described by the Standard Model of particle physics? When the energetic particles interact with the atmosphere of the Earth, hadronic interactions can be studied in the extreme kinematic forward region (with pseudorapidities $\eta > 15$): • What is the proton interaction cross section at such energies ($\sqrt{s} > 10^5$ GeV)?

The highly energetic particles, called ultra high-energy cosmic rays, are extremely rare: their flux is lower than one particle per square kilometer per century. To study their properties, large detection facilities are needed in order to collect a reasonable number of them in an acceptable time span. At present, the largest detector is the Pierre Auger observatory in Malargüe, Argentina[15], covering an area of 3000 km^2. To increase its sensitivity to the type of particle, at present, additional components are being installed at the observatory[16–18]. In the northern hemisphere the Telescope Array[19], located in Utah, USA, is covering an area of 700 km^2, presently undergoing an extension[20] to cover about 2800 km^2. Objective of these installations is to measure the properties of ultra high-energy cosmic rays with unprecedented precision in the next decade (until $\sim$ 2030). Key properties include the arrival direction (on the sky), the energy, and the particle type. When the ultra high-energy cosmic rays enter the atmosphere of the Earth they undergo (nuclear) interactions and produce avalanches of secondary particles, the extensive air showers. Secondary products of these air showers are measured with ground-based detectors. This makes it demanding to determine the particle properties, in particular, to identify the particle type is an experimental challenge. It requires an elaborate concept to simultaneously measure several components of the air showers[16–18].

With the existing (upgraded) facilities it is expected to measure a few hands full of particles at the highest energies ($> 10^{20}$ eV) and identify their type until $\sim$ 2030. Of particular interest will be to isolate protons (if they exist at these energies). Maybe there are even a few neutrinos or photons. These particles can be used to address the physics questions stated above. They are expected to point back to their sources (on the sky) since the are electrically neutral (neutrinos, photons) or have a small charge only (protons), and are thus only marginally deflected by the magnetic fields in the Universe. Identifying their type on an event-by-event basis is also needed to study their interactions and thus explore particle physics at extreme energies. However, the flux of particles provided by Nature is small and to address the physics questions raised above, a new facility is needed after 2030 with an acceptance at least an order of magnitude larger than the existing observatories. This approach is complementary to instruments in space[21;22] or large radio antenna arrays[23].

A next-generation cosmic-ray detector

Size/Area At the highest energies ($E \geq 10^{19.6}$ eV) a rate of the order of 500 particles per year is expected for a detector covering an area of 1000 km^2 and 2π acceptance[24;25]. We assume that of the order of 5% of those are light particles[26–28] (protons or even photons or neutrinos) which could be used to address the physics questions. We also conservatively estimate a combined detection and reconstruction efficiency of 50%. Assuming one or a system of detectors with a total aperture of 40 000 km^2 or more and maximum sky coverage one could collect more than 5 000 light particles with energies exceeding $10^{19.6}$ eV in a decade. A simple estimate yields that the particles could originate from less than a dozen of sources[29].

Location To identify the sources, all-sky coverage would be desirable. This can be achieved by a split observatory with sites in the northern and southern hemisphere, which would also allow to distribute the efforts needed to build and operate the observatory. Alternatively, a single array can achieve nearly full sky coverage, provided it has 2π acceptance and is located near the equator.

Angular resolution To identify the cosmic-ray sources it is desired to isolate light particles at the highest energies, which are expected to point back to their respective sources. Neutral particles, such as photons and neutrinos would be ideal candidates, since they are not affected by any magnetic fields inside our outside the Milky Way. Also protons (with charge $Z = 1$) are expected to be only marginally ($<$ few degrees) deflected by magnetic fields at extreme rigidities[30–32]. Thus, a next-generation detector should have an angular resolution for the arrival direction similar to the one of existing observatories[16;20] around 1°.

Energy resolution At energies above $10^{19.6}$ eV the energy spectrum of cosmic rays is steeply falling[25;33]. It is therefore crucial for an observatory to have a good energy resolution in order to cleanly measure the properties of cosmic rays[34]. It is important to reduce upward fluctuations in the energy measurement to a minimum. An energy resolution of 10% to 15%, similar to the one achieved by the current experiments seems to be a realistic target.

Particle type/mass resolution The most critical issue will be to identify the type of the incoming particle since the nature of the air showers limits the achievable resolution. The measurable quantities are only proportional to the logarithm of the nuclear mass A of the primary particle. One needs to measure the ratio of the electromagnetic to the muonic shower components with a resolution around 15% or, alternatively, the depth of the shower maximum with a resolution better than 20 g/cm^2 in order to achieve a resolution in $\ln A$ of 0.8 to 1[16;35].

Multi-Messenger sky observations Observing the high-energy Universe with all messengers (cosmic rays, neutrinos, gamma rays, gravitational waves) will be a key to fully understand (astro)physical processes under extreme conditions. The design of the future observatory will be optimized for maximum impact on muti-messenger (astro)physics, with optimal sensitivities for cosmic rays, neutrinos, and gamma rays.

Example design Potential designs of detectors have been discussed recently[36;37]. As an exemplary illustration we sketch a potential design as part of a Global Cosmic Ray Observatory[38]. Most critical will be a good mass resolution. This necessitates the measurement of several air shower components simultaneously. A promising approach is the use of segmented water Cherenkov detectors[39;40]. They will be used to measure the muonic component for all air showers with full sky coverage. The will also measure the electron-to-muon ratio for vertical showers. Radio antennas on top of the detector, e.g. similar to the ones from the Auger Radio Detector[18;41], will provide a calorimetric measurement of the electromagnetic shower component with high precision. In particular, this will allow to measure the electron-to-muon ratio for horizontal air showers. Fluorescence detectors could be included[42–45] to measure the calorimetric shower energy and the depth of the shower maximum, or, also a large stand-alone array of fluorescence detectors could be an option. A possible implementation is illustrated in Figure 1:[41;46] About 10 000 detector stations are arranged with about 2 km spacing on an area of 200×200 km^2 complemented by fluorescence detectors.

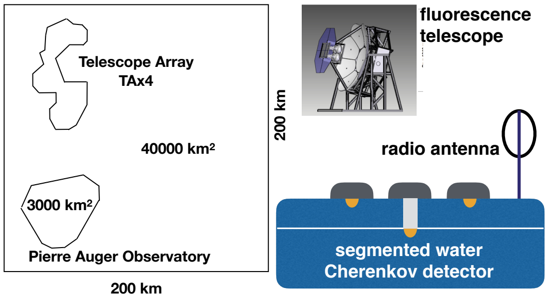

Figure 1: Exemplary illustration of a next-generation cosmic-ray experiment, covering an area of 40 000 km^2 with an array of segmented water-Cherenkov detectors and radio antennas[46] as well as fluorescence telescopes. For comparison, the circumference of the existing observatories is indicated.

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