Snowmass2021 - Letter of Interest

Mass composition of ultrahigh-energy cosmic rays

Thematic Areas:

■ (CF7) Cosmic Probes of Fundamental Physics
■ (Other) EF06, EF07

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Abstract:

The knowledge of the mass composition of ultrahigh-energy cosmic rays is mandatory to study particle physics and astrophysics at extreme energies. However, the inference of the nature of primary cosmic-ray particles from the properties of the air showers is challenging due to theoretical uncertainties of hadronic interactions at energies beyond human-made accelerators. In this letter, we discuss the unique opportunities to solve this problem by dedicated mass-composition studies at ultrahigh energies.

Introduction

Ultrahigh-energy cosmic rays (UHECRs) offer the possibility to study fundamental physics and astrophysics at extreme energies. The center of mass energy in proton-nucleus collisions of UHECR in the Earth's atmosphere can exceed 400 TeV and the beam energy provided by cosmic accelerators is known to be $> 10^{20}$ eV. Yet the composition of this cosmic particle beam is not well known at ultrahigh energies.

A precise determination of the cosmic-ray composition is however crucial to expand further our knowledge at extreme energies. In particular, a reliable mass-identification of cosmic rays will enable

a) studies of hadronic interactions at energies way beyond human-made accelerators,
b) searches of new physics e.g. signatures of Lorentz invariance violation or superheavy dark matter,
c) constraints of the properties of ZeVatron accelerators of UHECRs,
d) prediction of astrophysical fluxes of high-energy photons and neutrinos,
e) constraints on models of super-heavy dark matter,
f) charged-particle astronomy and the study of the Galactic magnetic field.

Recent examples of the study of UHE hadronic interactions with cosmic-ray experiments are the measurement of the proton-air cross section at around a center of mass energy of 60 TeV [1, 2]. A prerequisite for these studies is obviously the establishment and identification of protons in the cosmic-ray particle beam. Likewise, the precise quantification of the deficit of muons in current air shower simulations also depend crucially on the cosmic-ray composition [3–5] and any search for proposed new physics at UHE [6–11] will rely on a good handle of the nature of primary cosmic rays.

The astrophysical importance of the cosmic-ray composition is on the one hand due to the inference of the rigidity of cosmic rays ($R \propto E/Z$) that governs the acceleration of particles and their propagation in magnetic fields and on the other hand due to the need to know the Lorentz-factor ($\gamma \propto E/A$) that determines the interaction with extragalactic photon fields and the production of secondaries (some examples for items c)-f) can be found in [12–19]).

Our current knowledge of the cosmic-ray composition is inferred from the observation of air showers (see [20] for a review). At moderately high energies ($\gtrsim 10^{18}$ eV) the two state-of-the-art experiments for UHECRs (the Pierre Auger Observatory [21] and the Telescope Array (TA) [22]) report air shower observations [23–26] that point consistently to a predominantly light composition with a large fraction of primary protons [27–29]. At even higher energies ($\gtrsim 10^{19}$ eV), the data of the Pierre Auger Observatory suggest a gradual increase of the average primary mass of cosmic rays. The data of TA do not yet have the statistical power to test the composition at these energies. At ultrahigh energies ($E > 10^{19.6}$ eV), the total number of detected events with a high-precision measurement with fluorescence detectors (FDs) is less than a hundred [30, 31] and therefore the composition at these energies is still an open question.

These statistical limitations can and will be overcome by observing UHECRs with a larger exposure in the near future. But in addition the determination of the cosmic-ray composition suffers from theoretical uncertainties due to the reliance on hadronic interaction models to interpret air shower data, see e.g. [32–34]. These systematics can be reduced by further laboratory measurement of multiparticle production in hadronic interactions as proposed in [35, 36]. At the same time, a high-statistics observation of cosmic rays at UHE can help significantly to resolve the mass vs. interaction ambiguity as will be detailed in the following.

Towards a model-independent estimate of the mass composition of UHECRs

There are several possibilities to decrease the theoretical uncertainties on the mass composition due to our limited understanding of hadronic interactions using the data of air shower experiments. The correct mass scale needs to be established for at least one of the mass-sensitive air shower observables (shower maximum, number of muons, muon production depth, etc.) and transferred then to all other observables via cross-calibration.

Self-Consistency An example of the power of air-shower data to perform data-driven tests of the consistency of hadronic interactions and the inferred cosmic-ray composition is the analysis of the first two moments of the distribution of shower maximum [24, 37] with which it could be shown that the $X_{\max}$ values predicted by air-shower simulations with the hadronic interaction model QGSJet-II.04 [38] are incompatible with the data. Even more powerful consistency checks are possible with the inclusion of ground-level particle densities, see e.g. [39, 40]. Many of these self-consistency checks have been performed at low energies, where the current experiments collected a lot of events. Similar studies at UHE will need much larger exposures for high-quality, event-by-event measurements of multiple mass-sensitive air showers observables.

Cosmic Spectrometer Another possibility for the study of composition at UHE relies on the detection of point sources in the arrival directions of cosmic rays. Recently there have been tantalizing hints with significances of up to 4.5 σ for a clustering of cosmic rays at intermediate angular scales [41, 42]. If these "hot spots" in the cosmic-ray sky are corroborated by future data, then the study of the arrival directions can open a window of opportunity to determine the cosmic ray composition without the use of hadronic interaction models. The location of the apparent image of the sources will be distorted by the Galactic magnetic field [43], which acts as a particle spectrometer on the charged cosmic rays [44–46]. An even more direct handle on the cosmic-ray composition could be provided by the discovery of multiplets of magnetically-aligned arrival direction of cosmic rays [47–50]. Both of these potential studies call for a large-exposure detection of cosmic rays with event-by-event mass sensitivity.

Cosmic Mass Degrader Another advantage of a high-statistics measurement of cosmic rays at ultra-high energies is that extragalactic photon fields limit the propagation distance of cosmic-ray nuclei. At ultrahigh energies the interaction length is largest for proton and iron particles and therefore it is very plausible (if the cosmic-ray flux is dominated by (> 10 Mpc) sources) that the particle beam arriving at our Galaxy consists of only protons and iron nuclei and is devoid of intermediate-mass nuclei, as these are more efficiently photo-disintegrated. The observation of a bi-modal distribution of air shower observables, e.g. in the muon-number/shower-maximum plane, could set the mass scale for these two variables with high precision and without the need to resort to air shower simulations.

Mass composition in the next decade

The main goal of the near-term and future programs to solve the ambiguity between mass composition and hadronic interactions is the collection of high statistics air-shower observations with multiple observables at ultrahigh energies[1].

AugerPrime [57–59] is installing scintillation detectors on top of the water-Cherenkov stations of the Auger surface detector. This will enable the separation of the electron and muon components in air showers with zenith angles < 60 degrees. At larger zenith angles, mass-composition sensitivity will be achieved by observing the radio emission of air showers with radio antennas installed on each surface detector station. The upgraded Observatory will be able to measure events with mass composition sensitivity at a 10-fold rate than currently with the FD and validate novel methods for the measuring the composition with ground-level particle detectors [60–66] that can then also be applied to the full Auger data set.

TA×4 [67] will increase the area of the surface of TA from 700 km^2 to 3000 km^2. With the larger amount of data collected it will be possible to observe more precisely the anisotropy features, energy spectra and mass compositions in the Northern hemisphere at energies above 10^{19} eV.

Future Observatories A significant increase of the exposure is required for collecting sufficient statistics at extreme energies with composition-sensitive detectors. New experiments, such as POEMMA [68, 69], CRAFFT [70], FAST [71, 72], GRAND [73] and GCOS [74] with apertures of more than one order of magnitude larger than that of Auger, are currently in the design stage. The design of these observatories will benefit from the knowledge that will be gained in the next decade with the data of AugerPrime and TA×4.

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[1] Additional insights on the modeling of air showers will be possible by studying cosmic-ray showers at low energies around 10^{17} eV, i.e. close to the center of mass energy of the LHC [51–56].

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