Challenges for cosmic-ray experiments

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Abstract. This paper is a commentary on presentations at ISVHECRI 2016 related to cosmic-rays, gamma-rays and neutrinos. Its goal is to highlight the unanswered questions raised during the conference about the sources of these cosmic particles and the relations among them.

1. Introduction

A current theme of astro-particle physics is "multi-messenger astronomy," which emphasizes use of gamma-rays and neutrinos to address still unanswered questions on the origin of high-energy cosmic rays. With this theme in mind, I review the presentations on cosmic-ray spectra and composition, gamma-ray astronomy and neutrino astronomy presented at ISVHECRI 2016. The role of hadronic interactions is addressed in the review paper of Tanguy Pierog [1].

2. Some cosmic-ray questions

Figure 1 gives a global view of the cosmic-ray spectrum. The abundant elements of the primary cosmic-ray spectrum are measured accurately to energies higher than a TeV per nucleon with spectrometers in space [2–4]. Calorimetric measurements with balloon-borne detectors [5,6] extend direct measurements to higher energy but with somewhat less precision. This means that we have good coverage of the composition with direct measurements up to about 100 TeV energy per nucleus. Indirect measurements with large detectors on the surface are needed for the higher energy cosmic rays. There are several questions of current interest associated with the various features in the energy spectrum:

- What is the composition in the knee region and how does it connect with direct measurements at lower energy?
- What is the cause of the hardening of the spectrum around 20 PeV?
- Where is the transition from Galactic to extra-galactic cosmic rays and how is it related to composition around the ankle?
- What is responsible for the apparent end of the spectrum around 100 EeV?
- Does the difference between the Auger and the TA spectrum in the cutoff region show that the cosmic-ray spectrum is different in different regions of the sky?

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2.1. The knee region

Most air shower measurements have a threshold around a PeV, while direct measurements extend only to ∼100 TeV. An exception is the ARGO-YBJ RPC carpet detector at high altitude in Tibet, which has the potential to cover the gap between direct and indirect measurements [8]. TAIGA-HISCORE is also starting to measure the spectrum down to ∼300 TeV [9]. ARGO-YBJ have reported measurements of both the all-particle spectrum and the spectrum of the light (p + He) component [10]. The measurements cover the energy range from ∼10 TeV to the knee region. While the measurement of the all-particle spectrum agrees with several other EAS measurements through the knee region, the light component appears to steepen starting around 700 TeV [8,10]. In contrast, KASCADE [11,12] shows the proton steepening above a PeV. In his presentation, DiSciascio compares the ARGJO-YBJ result with the Hörandel parameterization [13] of p + He, which also steepens at higher energy. The IceCube/IceTop composition analysis [15] starts around 3 PeV, too high to provide insight on this question.

Indirect measurements of the composition with EAS detectors are difficult, and the ARGO-YBJ result points to an ambiguity that needs to be resolved. A practical aspect is its implication for the atmospheric neutrino flux at high energy relevant for IceCube. Calculation of the flux of atmospheric neutrinos depends on the spectrum of nucleons as a function of energy per nucleon, which is dominated by protons and helium. If the proton and helium components steepen at 700 GV, then there should be a compensating increase in heavier nuclei to keep the all-particle spectrum constant. The sketch in Fig. 2 illustrates the effect, which would likely be a suppression of the flux of nucleons in a range around a PeV that arises if the all-particle spectrum is dominated by heavy nuclei in this region. This in turn would significantly reduce the flux of muons and muon-neutrinos around 100 TeV.

2.2. From the knee to the ankle

Figure 3 (left) compares measurements of the spectrum by KASCADE-Grande [12,16], TUNKA-133 [17,18] and IceTop [15,19,20]. The solid line shows a spectrum with a constant differential index of −3. The data show clear structure between the knee and the ankle, with a
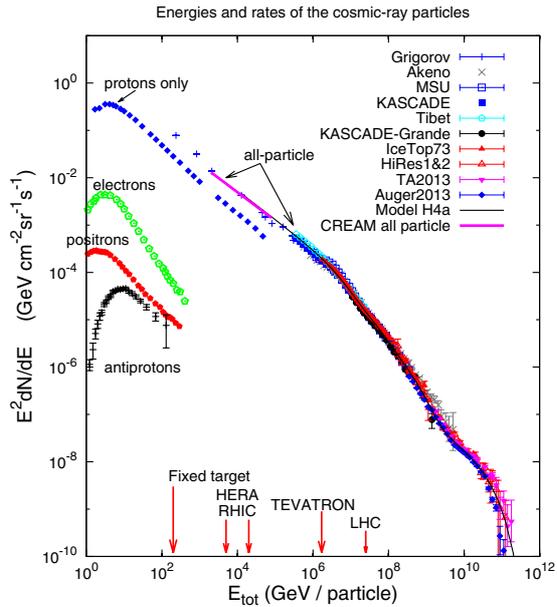
Figure 1. Overview of the energy spectra of various components of the cosmic radiation (Fig. 2.1 of [7]).
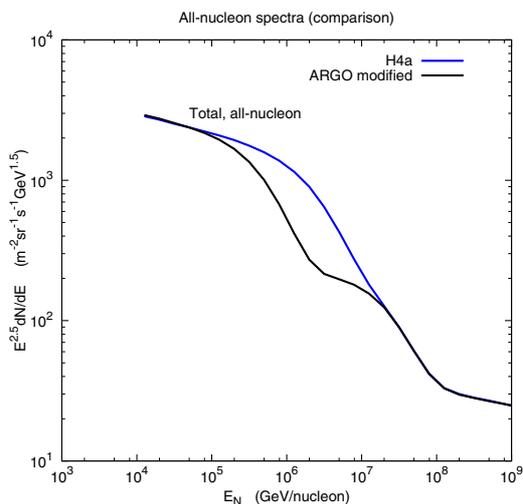
Figure 2. The spectrum of nucleons for the H4a model [14] compared with a modified version in which the cutoff rigidities for p and HE are reduced to 700 GV and the all-particle spectrum is restored by increasing the contribution of the CNO and Fe groups.

hardening around 2×10^{16} eV and a second knee above 10^{17} eV. The KASCADE-Grande analysis uses the fraction of muons to separate the spectrum into light and heavy components [12,21]. The data suggest that the sub-dominant light component increases relative to the heavy component as energy increases toward the PeV region, as shown in Fig. 3 (right). A possible interpretation is that the increase of the light component reflects the population of cosmic rays from extragalactic sources, while the steeper heavy component is the end of the Galactic population.

2.3. The highest energy cosmic rays

Measurements of the cosmic-ray spectrum to the highest energy were presented at ISVHECRI 2016 from both Telescope Array (TA) [22] and Auger [23]. They are in excellent agreement with each other through the ankle

region within their systematic uncertainties in energy. However, after shifting the Auger energy assignment up by 8% (or the TA spectrum down by a similar amount) the TA spectrum remains somewhat higher than the Auger spectrum above 10 EeV.

The question of composition of the highest energy cosmic rays has long been an important unresolved issue. Both TA and Auger find a large fraction of protons in the EeV range, above which the interpretations differed, with Auger preferring heavier and TA lighter composition. Inferences about composition are based on both the mean depth of shower maximum as a function of energy and on fluctuations in depth of maximum in each energy bin, and they depend on the hadronic interaction model used to make the interpretation. The TA presentation [22] includes a plot of mean depth of maximum for both experiments obtained by the joint composition working group that includes members of both experiments. The results of the two experiments are not inconsistent with each other. In comparison with the interaction model QGSJETII-03 the depth of maximum measurements are between protons and iron, but closer to the proton limit. Thus at present the composition at the highest energy remains an open question.

Composition from 1–100 EeV is the key to what is one of the most important open questions in cosmic-ray physics, namely, the cause of the apparent cutoff in the spectrum at 100 EeV. There are two possibilities. If protons dominate at high energy, the natural interpretation would be the GZK process [24,25], energy loss to photo-pion production during propagation in the cosmic microwave background radiation. The other possibility is that the accelerators are reaching their maximum rigidity, as suggested by the Hillas plot [26]. The Auger presentation [23] illustrates the different energy-dependent compositions that characterize each of these possibilities [27]. The GZK explanation requires mostly protons at the highest energy while in the Hillas case an increasing fraction of heavy nuclei would be expected as the cutoff in rigidity affects protons first. In both cases effects of nuclear fragmentation during propagation must accounted for in addition to the source composition.

Both TA and Auger have initiated upgrades aimed at understanding the composition and the related question of anisotropy of the highest energy cosmic rays. TA × 4 will expand the surface detector with two large scintillator arrays (grid spacing 2.08 km) adjacent to the present array. One of the main aims is to get a better understanding of the hotspot observed in the TA data [28], which persists after seven years of observation.

The upgrade of the Pierre Auger Observatory [29] includes installation of a scintillator on top of each tank, improved electronics and underground muon detectors. With improved ability to separate the muon signal from the electromagnetic signal in the surface detector, the upgraded array surface array will have sensitivity to primary composition with 100% duty cycle. The goal is to determine the origin of the flux suppression at the highest energy and to determine the feasibility of astronomy with cosmic-ray protons.

2.4. Cosmic-ray overview

Using its low energy extension (TALE), the TA group has presented a combined spectrum that extends all the way
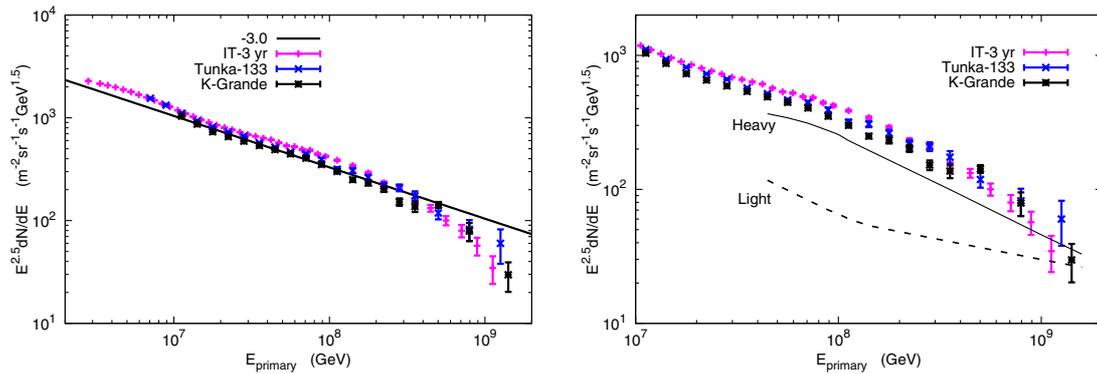
Figure 3. Measurements of the spectrum between the knee and the ankle, Left: compared to a constant E^{-3} differential spectrum (Fig. 17.2 of [7]) and Right: showing the heavy and light fractions as measured by KASCADE-Grande [21] separately (Fig. 17.3 of [7]).
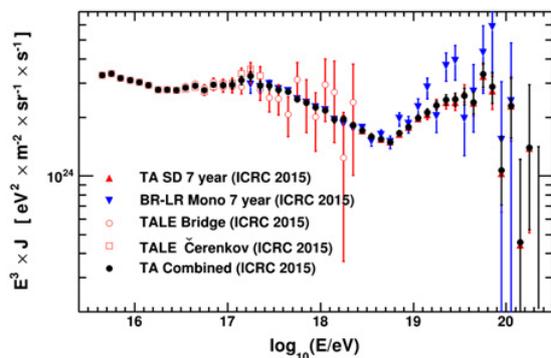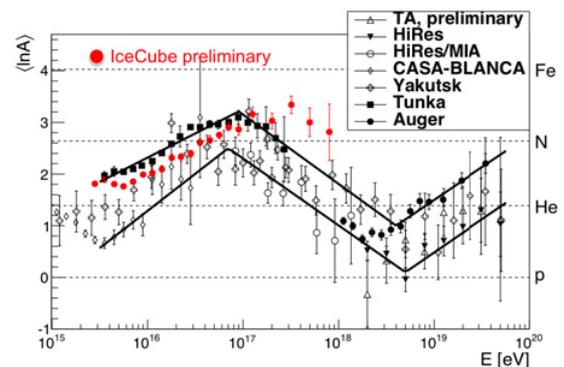

Figure 4. The combined spectrum of TA presented at this conference [22]) and shown here by kind permission of John Matthews.


Figure 5. Mean value of the natural logarithm of the primary mass as a function of primary air shower energy. The plot is from the paper of Kampert & Unger [30]), and the solid lines indicate the ranged of data summarized there. Preliminary composition data from IceCube [31] are interpolated in the same way and added to the Kampert & Unger plot in red.

down to 5 PeV (Fig. 4). The data are consistent with those shown in Fig. 3 in the overlap region. The hardening of the spectrum at 2×10^{16} eV and the second knee just above 10^{17} eV are clearly visible, as well as the ankle and the suppression above 10^{20} eV.

The composition also shows an energy dependence with features that may be correlated with the spectrum, as illustrated in Fig. 5 [30]. The plot is made by interpolating the value of each measured depth of maximum between theoretical curves for protons and iron on a plot of X_{max} vs energy (in this case using SIBYLL 2.1 [32]). The increasing fraction of heavy nuclei up to 10^{17} eV, for example, can be interpreted naturally as a rigidity-dependent effect as Galactic accelerators reach their maximum energy. This is followed by an increase in the proton fraction that reaches a maximum (minimum in $\langle \ell n(A) \rangle$) at the ankle. The preliminary IceCube result [19,31] is shown in red in Fig. 5. It agrees with the trend of the data up to 10^{17} eV, but remains at a high level above that energy, although with large uncertainties.

In his presentation Ptuskin [33] reviewed the standard model of cosmic-ray origin, with Galactic supernovae of different types producing the cosmic-ray spectrum observed at Earth up to $\sim 10^{17}$ eV and an extra-galactic component dominating above 10^{18} eV. Analysis of low-energy iron isotopes [34] shows that there must have been at least two nearby supernova remnants within one or two million years of each other. The general picture of supernovae in the disk of the Galaxy exploding randomly and each accelerating cosmic rays for a period of time short

compared to the propagation time is explored in Ref. [35]. The contribution of a particular supernova to the cosmic-ray flux currently observed at Earth will be determined by the energy-dependent residence time of cosmic-rays in the Galaxy coupled with time of the explosion and its distance from Earth. Such considerations also have implications for the observed anistropy of cosmic rays [36], which will reflect to some extent the particular history of supernova explosions in the Milky Way.

3. Multi-messenger astronomy

Photons and neutrinos, being electrically neutral, propagate from their sources in straight lines, unlike charged cosmic rays, which are bent in Galactic and cosmic magnetic fields. Therefore, to the extent that cosmic-rays interact in or near their sources, gamma-rays and neutrinos should be good probes of cosmic-ray sources. Neutrinos have the extra advantage of not being affected by interactions in transit (and the corresponding disadvantage of being difficult to detect). High-energy gamma-rays can be produced electromagnetically, for example by inverse Compton scattering by electrons, as well as from decay of π^0 produced in hadronic interactions. Neutrinos can only be produced by hadronic interactions. Just as atmospheric neutrinos are produced by interactions of cosmic rays in the atmosphere, any high-energy neutrino
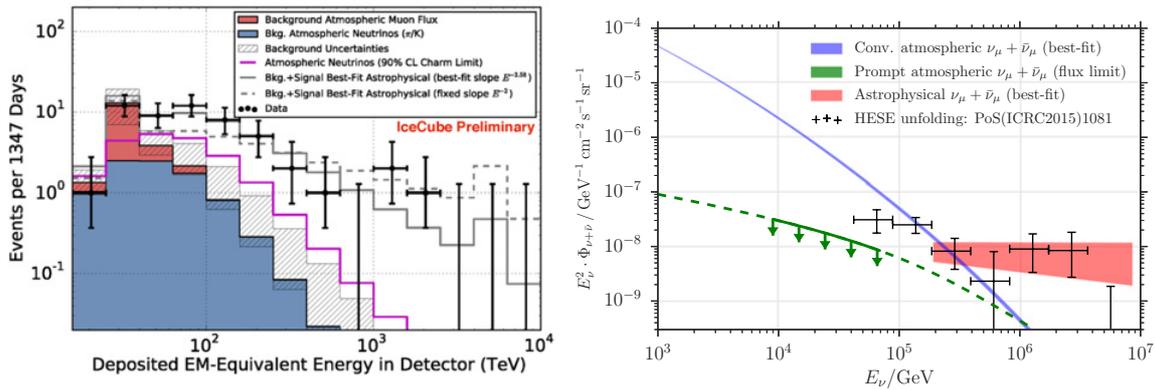
Figure 6. Spectrum of high energy neutrinos from IceCube, Left: 4-year HESE analysis [37]; Right: 6-year upward muon analysis [42].

of extraterrestrial origin will have been produced by the interaction of a proton (or less likely a nucleus) somewhere in the cosmos. The interaction may be with gas or by photo-pion production, but in both cases gamma-rays would be produced through the corresponding neutral pion channel. (The possibility of γ-rays and neutrinos from dark matter is not considered here.)

3.1. High-energy neutrinos in IceCube

Figure 6 shows the observation by IceCube of a hard spectrum of astrophysical neutrinos extending above the steeply falling background of atmospheric neutrinos. The signal is seen consistently in two channels. The high-energy starting event (HESE) analysis [38] requires the event to start well inside the instrumented volume of IceCube in such a way that the outer layers of optical modules exclude atmospheric muons from above, as well as atmospheric neutrinos of sufficiently high energy to be accompanied by a muon [39,40]. The astrophysical signal can be identified to lower energy by increasing the veto region and correspondingly reducing the size of the fiducial volume [41]. In the upward muon analysis [42], the Earth is used as a shield to exclude atmospheric muons. The signal then consists mainly of neutrino-induced muons. The astrophysical component is distinguished only by its hard spectrum extending to high energy.

Accompanying each of the neutrino analyses is a list of the highest energy events with their locations in the sky (right ascension and declination). In the case of the HESE analysis, the event type is given as cascade (ν_e and most ν_τ) or track (ν_μ). The four-year sample includes 54 events with deposited energy of 30 TeV and higher, of which fewer than twenty are background. For the upward muon analysis, all events are tracks, and 29 events with estimated muon energy $E_\nu > 200$ TeV are singled out as being the most likely to be of astrophysical origin. Sky maps are made for both cases, but no source of high significance emerges. The most energetic event in the upward muon sample has a deposited energy in the detector of 2.6 ± 0.3 PeV and an estimated muon energy of 4.5 PeV. The probability distribution for the parent neutrino energy peaks just below 10 PeV [42].

The spectral index that characterizes the astrophysical flux depends on the energy range of the analysis, and the possibility of a break and or a cutoff in the spectrum is not ruled out. A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured

with several IceCube analyses gives a value of the energy flux of all neutrino flavors of

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} \approx 2 \times 10^{-8} \text{ GeV cm}^{-2}\text{sr}^{-1}\text{ s}^{-1} \quad (1)$$

at $E_\nu = 1$ PeV assuming the spectrum is a single power law [43]. The fitted differential spectral index, is -2.5 ± 0.09. It is interesting to note from Fig. 1 that the energy flux of cosmic rays has the same value at the ankle, which may be interpreted as indicating that the energy flux of the extragalactic population of cosmic rays is somehow related to the astrophysical neutrino flux, as suggested by Waxman and Bahcall [44,45].

In this context, it is interesting to note that detection of cosmogenic neutrinos from photo-pion production by interactions of ultra-high-energy cosmic rays with the CMB could resolve the origin of the cutoff of the cosmic-ray spectrum at 100 EeV. A search by IceCube for events of extremely high energy (EHE) with seven years of data [46] finds no neutrinos with energy $> 10^7$ GeV. This result places significant constraints on some models of cosmogenic neutrinos. Because neutrinos produced by interactions of cosmic-rays with energy-per-nucleon $> 10^9$ GeV would produce neutrinos with $E_\nu > 10^7$ GeV, the result also disfavors some models of astrophysical neutrinos associated with sources of ultra-high-energy cosmic rays.

3.2. Extragalactic source candidates

The tables of high-energy neutrinos [38,42] constitute a small fraction of the $\sim$100,000 neutrinos per year reconstructed in IceCube. Most of these are atmospheric neutrinos. Nevertheless, the most sensitive searches for point sources of astrophysical neutrinos use the larger data samples that extend down to the TeV energy range. Maximum likelihood techniques that take account of the angular resolution and the deposited energy of each event are used to look for point sources of neutrinos emerging from the smooth foreground of atmospheric neutrinos. An all-sky analysis produces a sky map of significances. In addition, a list of sources selected, largely on the basis of gamma-ray observations, to be likely neutrino sources is investigated. The most sensitive search so far [47] uses seven years of data and finds no source of high significance in the all-sky analysis and places upper limits on the targeted sources.

The relation between a total observed intensity from all directions and the number of events to be expected from nearby sources is addressed in general in [48] and in the context of the IceCube discovery in [49]. Upper limits on extragalactic sources, together with an assumption about the cosmological evolution of the source class, lead to a lower limit on the density of sources. A recent analysis [50] of the total astrophysical intensity of neutrinos and the current upper limits of IceCube suggests that the density of extra-galactic sources should be $> 10^{-7} (\text{Mpc})^{-3}$. Blazars and Gamma-Ray Bursts (GRB) are among the rare, luminous sources that are being constrained by this line of argument [51]. Moreover, there are experimental upper limits from IceCube on the contribution to the IceCube signal of both blazars [52] and GRBs [53].

Starburst galaxies are relatively abundant and have been proposed as a likely source of neutrinos [54]. The idea is that, because of the greater rate of supernova explosions and the turbulence they generate, there would be a higher intensity of cosmic rays produced and they would be confined in the host galaxy sufficiently long that most protons would interact (calorimetric limit). Since the target for the neutrino production is gas in the galaxy, the spectrum of neutrinos and gamma-rays would extend down to low energy. Fermi observations of the diffuse gamma background [55] have been used to constrain the starburst model [56,57]. In order to avoid producing more diffuse gamma-radiation than observed, the spectra of cosmic-ray induced neutrinos and photons must have a hard spectrum (differential spectral index $-\alpha$ with $\alpha < 2.2$ [56]. On the other hand, since most of the isotropic gamma-radiation comes from blazars [58], it would be surprising if there were not also neutrinos at some level [59].

Another possible neutrino source, discussed at this conference by Ptuskin [33], is Type IIn supernovae in external galaxies [60]. These are rare core-collapse supernovae that accelerate protons into the dense wind of the progenitor star. The environment of the progenitor wind is sufficiently dense that the SN expansion slows down on a time scale of 30 years. Like the starburst scenario, the target for neutrino (and gamma-ray) production is gas, so the spectra extend to low energy and the Fermi isotropic gamma limit applies (so the accelerated spectrum of protons must be hard). A maximum energy of 10^{17} eV/proton is found, which is sufficient to produce neutrinos up to $\sim PeV$ (but not beyond). Assuming a rate of 1% of all core collapse supernovae, a diffuse spectrum in rough agreement with the IceCube spectrum is found. Moreover, two tracklike events are in the direction of known Type IIn supernovae. HESE event 47 with 74 TeV deposited energy [37] is 1.35° from SNIIn 2005bx and event 11 of the upward muon sample with an estimated energy of 240 TeV [42] is 0.3° from SNIIn 2005jq.

3.3. Neutrinos and γ-rays from the Milky Way

Several of the events in the high-energy samples come from near the Galactic plane and could be of local origin in the Milky Way [61]. In fact a local component is expected because both neutrinos and photons are produced by cosmic-ray interactions of cosmic rays with interstellar gas during their diffusive propagation in the Galaxy. In his paper on neutrinos, Stecker [62] pointed out that these neutrinos would have the same spectrum as that of

the primary cosmic rays ($\alpha \approx 2.7$). At high energy the spectrum of atmospheric neutrinos is one power steeper, so the Galactic neutrinos should become relatively more prominent as energy increases. In addition, the cosmic-ray spectrum in the central region of the Galaxy could have a harder spectrum than observed locally at Earth [63].

The Galactic diffuse γ emission is measured up to ≈ 100 GeV by Fermi [64]. It is concentrated along the Galactic ridge and is mostly from π^0-decay. The ARGO-YBJ measurements of the diffuse γ-emission up to a TeV are consistent with an extension of the Fermi measurement [65]. The corresponding spectrum of $\nu_\mu + \bar{\nu}_\mu$ should have the same shape and a magnitude of 2/3 that of the gamma-rays at production and 1/3 after oscillations [7]. In the presentation at this conference [8] the high intensity of gamma-rays from the region of the Cygnus Cocoon [66] was also described. This too should have a counterpart in neutrinos. The ANTARES neutrino detector has placed a limit [67] on the intensity of multi-TeV neutrinos from the Galactic plane that is approaching the higher prediction of Ref. [63].

Using gamma-ray data from Fermi-LAT as a template, predictions for Galactic neutrinos in the TeV to PeV range are examined in detail in Ref. [68]. The conclusion is that less than 10% of the high-energy events are of Galactic origin. Limits are also placed on the Galactic contributions in the TeV range.

4. Summary and outlook

Understanding the origin of ultra-high energy cosmic rays and whether their sources also produce neutrinos remains a key question [46]. It is possible that the sources of the astrophysical neutrinos seen by IceCube are not the sources of UHECR. The current status of neutrinos and cosmic-rays observed by IceCube is the subject of a recent review [69].

To improve the ability to identify the sources of high-energy astrophysical neutrinos, IceCube has started a real-time alert system [70]. Its goal is to maximize the ability to find electromagnetic counterparts of astrophysical neutrinos seen in IceCube. There are several types of alerts. Single track-like events (with good pointing and high energy) in the HESE and EHE samples generate alerts. Alerts for follow-up by optical, X-ray and γ-ray detectors trigger on multiple events from a single point in the sky in a limited time interval.

The discovery of high-energy astrophysical neutrinos motivates efforts to accumulate more data with new and larger detectors. Construction of KM3NeT is starting, with the deployment of test lines at the Italian site, Capo Passero [71] and a Letter of Intent [72]. The proposal is to build a high-energy unit called ARCA at Capo Passero and a densely instrumented array called ORCA at the French site near Marseille [71]. The first cluster of an expansion of Baikal to a Gigaton Volume Detector (Baikal-GVD) [73] was installed in 2015. Plans for a next generation IceCube-Gen2 are underway [74,75]. IceCube-Gen2 will include a densely instrumented subarray for neutrino physics [76].

The high-energy expansion of IceCube-Gen2 aims to increase the target volume by an order of magnitude. To reach the much larger volumes needed to detect a large number of cosmogenic neutrinos, the radio technique is being pursued. The first detectors of ARIANNA [77]

and of ARA [78] prototypes are already in operation in Antarctica. A review of the current status of high-energy neutrino astronomy that covers current and future detectors and the science they will address is in preparation [79].

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