How to solve the cosmic ray knee problem?

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Abstract. It is shown that recent experimental data in the knee region contradict each other
and new approaches to the so-called “knee problem” are needed to solve this complicated and
old problem. The PRISMA project proposed by us is based on an idea that the main EAS
component - hadrons have to be measured first of all. Special detectors have been developed
for this purpose. It is shown using Monte-Carlo simulations that only full-scale recording of
hadronic component could give us a key to the solution. The location of such experiment
should be at high altitude (the higher, the better) and that is why we proposed to combine the
central part of the PRISMA array with that of the LHAASO project array to be constructed in
Tibet. If the proposal will have success then the “knee problem” will be solved in a few years.

1. Introduction

The “knee problem” in cosmic ray physics exists more than 54 years. A lot of experiments were
performed using an indirect EAS (Extensive Air Shower) method with array of detectors installed at
the Earth’s surface. Very few experiments were specially designed in the recent years to solve this old
problem. The best of them, namely, KASCADE and Tibet ASγ gave very precise and interesting but
contradicting each other results [1] and they did not solve the problem. It became even less clear:
KASCADE concluded that the knee in EAS size spectrum is connected with proton primaries while
the conclusion of Tibet AS experiment was: "Our results show that the main component responsible
for the knee structure of the all particle spectrum is heavier than helium nuclei”. The world’s data on
cosmic ray mass composition obtained by the EAS method in the “knee” region are abnormally wide
spread being put into one graph. As a result no conclusion could be made now about the mass
composition of primary cosmic rays nor about the primary nuclei responsible for the “knee”
appearance.

On my opinion only new approach based on the new ideas could solve this complicated problem.
The idea of a novel type of array for EAS study proposed by us for the first time in 2001 [2] has been
developed in 2008 to the PRISMA (PRImary Spectrum Measurement Array) project. It is based on a
simple idea: as the hadrons are the main EAS component forming its skeleton and resulting in all its
properties at an observational level [3], then hadron component should also be the main component to
be measured in experiments. Therefore, we have developed a novel type of EAS array detector (en
-detector) capable to record hadronic component through thermal neutrons detection (n) and electron
component (e) as well [4, 5]. Spreading these detectors over a large area on the Earth’s surface one
could obtain both an EAS array and a hadron calorimeter of practically unlimited area.
2. The PRISMA project

2.1. Introducing remarks

As it was already mentioned, the PRISMA experiment is aimed to solve the “knee problem” in cosmic ray spectrum. The best way to do so could be direct cosmic ray spectrum measurements. Unfortunately, it can not be performed due to very low intensity of cosmic rays with energy above 1 PeV. That is why we are pressed to use an indirect EAS method. But, as a payment for that, one has to make very complicated and model dependent recalculations from measured parameters to primary ones. Solving the inverse task one should be sure that: i) solution exists and ii) measured parameters are connected with real ones by the known dependencies. Both points are not known a priori. Solving the direct task one also have to introduce many parameters by hand, concerning the using model details, cosmic ray mass composition, existence or absence of the “knee” in primary spectrum etc. [6].

Traditionally EAS arrays measure electron component first of all. This is not the best choice but the simplest one and the most convenient one because the electron component is the most numerous one and it produces a great bulk of ionization, which is used for the detection. However, it is the secondary EAS component that is mostly sensitive to EAS longitudinal development, which is formed by the cascading high-energy hadrons. These two components are in a dynamic equilibrium. But, the equilibrium exists only while cascading hadrons exist. When the cascading hadrons are fully exhausted (note that the number of such hadrons is rather small well below the maximum of shower development and exponentially decreases up to 0 with the depth in the atmosphere), the equilibrium violation occurs. This occurs at primary energy of ~100 TeV/nucleon at sea level due to rather thick Earth’s atmosphere. It changes the EAS properties dramatically and results in a visible break (“knee”) in electromagnetic components (including Cherenkov light as a tertiary component). In our approach [6, 7] the knee in EAS size spectrum is a result of a wrong interpretation of the experimental data in the energy range of 100 TeV - 5 PeV where EAS’s originated from different primaries are at different stages of their development and thus can not be processed in a same manner. That is why interpretation of the data obtained with traditional EAS arrays is very complicated and ambiguous. The best way to overcome the difficulties is to record the primary EAS component, namely hadronic one and select showers in the same stages of its development (excluding so-called coreless showers). Special detectors are needed for this and we have developed them (en-detectors). Sure, other EAS components should be recorded as well but, mostly for additional and inter-calibrating purposes.

The PRISMA experiment will realize this approach. Similar to a simple optical prism, which splits white light to its components, the PRISMA will measure EAS in hadronic, muonic and electronic components separately. Separate triggers for each component are foreseen for this purpose. Due to exponential attenuation of hadrons in the atmosphere, the higher is array location altitude, the better. The best location could be the Yangbajing highland plateau in Tibet (China) where the LHAASO project is now under developing [8].

2.2. Simulations

To confirm the above proposal we have made the simulations [9] using the CORSIKA program [10] (ver. 6.900, QGSJET and GHEISHA models). Calculations were performed for two primaries: proton and iron for near sea level (170 m a.s.l.) and for Tibet level (4300 m a.s.l). Mean numbers of produced neutrons and hadrons inside a circle of 50 m as a function of primary energy are shown in Fig. 1 for primary proton and iron near sea level. As one can see, all dependencies (both for hadrons and for neutrons) are almost parallel and can be fitted with power law functions. The indexes for protons are equal to ~1.14 and that for iron ~1.3. Small difference between primary proton and iron at the highest energy makes us sure that reconstruction of primary energy would be more adequate above the knee region. This means that the number of neutrons produced by EAS hadrons can be used as a good primary energy estimator. In fact this is a realization of a huge area hadronic calorimeter by the simplest way. Fig. 2 shows expected normalized EAS size distributions in different EAS components simulated for the PRISMA detectors. Simulations were made only for primary protons and for pure
Figure 1. Mean numbers of hadrons and secondary evaporation neutrons inside a circle of 50-m radius as a function of primary energy at sea level for proton and iron primaries.

Figure 2. EAS size distributions in various EAS components expected for the PRISMA. Power law spectrum with differential spectrum index equal to 2.7. The total number of different particles recorded by the PRISMA detectors were calculated for each event passed triggering conditions. An interesting issue here is that EAS size spectra in neutrons and in muons also follow power law, while in electrons not. This confirms that reconstruction of primary spectrum using electromagnetic component is the most difficult – it produces “the knee” even in a case of pure power law primary spectrum. Moreover, the position of this “visible knee” in energy scale is different for different primary mass (~100 TeV/nucleon) and depends on altitude. In contrary, neutron bursts size distribution is very close to the pure power law distribution and its slope is very close to -1.
2.3. Prototyping

Central part of the PRISMA (en-Carpet) will consist of a large area (at least 100 x 100 m²) covered with en-detectors ~1 m² each) as a rectangle or hexagonal grid with 5 m spacing. This area is enough to obtain ~ 10⁴ events a year in the “knee” region with cores lies inside it. These detectors will record hadronic (thermal neutrons “vapor”) and electromagnetic components (charged particles). Note that thin scintillator layer has low but non-zero response to relativistic charged particles. In a case of EAS when many particles pass synchronically the signal becomes large enough and can be measured. This is one of the project advantages because the same detectors will record two EAS components.

Several stages of the PRISMA prototyping have been done up to now [11, 12]. Now we have running prototype (ProtoPRISMA-32) made of 32 en-detectors around the NEVOD-DECOR experimental complex in MePhI (see Gromushkin et al. The ProtoPRISMA array for EAS study: first results. This Conference). The array’s area is equal to ~500 m² (~1/20 part of the PRISMA en-Carpet) and it is running now as an independent EAS array. The same detectors are used for triggering, for Ne measurements and for thermal neutron counting. Preliminary results obtained with the ProtoPRISMA-32 showing its good performances are now available. We have checked the simulated neutron production yield shown in Fig. 1 by the experimental points obtained with ProtoPRISMA-32 and have found a reasonable agreement [9].

3. Conclusion

The measurements of EAS hadronic component were started many yeas ago using hadronic calorimeters, emulsion chambers and neutron monitors (for example in Leeds, in Yakutsk, in Tian-Shan (“Hadron”, LPI ), in KASCADE etc.). But, the area of these detectors was relatively small while threshold high. As a result they measured only negligibly small part of EAS hadrons and never the hadrons were the main recording component. Only now, using en-detectors, it is possible to record hadrons with practically zero energy threshold at practically unlimited area and to reconstruct full hadronic component thus solving the problem.

The project of a novel type of EAS array (PRISMA) is proposed and partially realized. We do believe when running this array will solve the “knee” problem because it will reconstruct primary spectrum using the main EAS component - hadrons. Simulations showed that the number of secondary thermal neutrons produced by EAS hadrons in surrounding soil and construction materials is proportional to the number of these hadrons and its dependence on primary energy follows power law in a wide energy range. This is why the “thermal neutron vapor” accompanying EAS passage is a good primary energy estimator. The number of produced neutrons can be measured by the en-detectors spread over a large area on the ground surface. This allows one to measure EAS size spectrum in hadrons thus excluding hadronless (coreless) showers and adequately recover the primary cosmic ray spectrum.

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