Chinese Physics C Vol. 37, No. 1 (2013) 015001

Thermal neutron flux produced by EAS at various altitudes *

Yu. V. Stenkin[1] V. V. Alekseenko[1] D. M. Gromushkin[2] LIU Ye(刘烨)[3]
MA Xin-Hua(马欣华)[4;1)] ZHAO Jing(赵静)[4]

[1] Institute for Nuclear Research of Russian Academy of Sciences, Moscow 411051, Russia
[2] Moscow Physical Engineering Institute, Moscow 115409, Russia
[3] Hebei Normal University, Shijiazhuang 050024, China
[4] Institute of High Energy Physics of Chinese Academy of Sciences, Beijing 100049, China

Abstract: The results of Monte-Carlo simulations of extensive air showers are presented to show the difference of the hadronic component content at various altitudes with the aim to choose an optimal altitude for a PRISMA-like experiment. The CORSIKA program for EAS simulations with QGSJET and GHEISHA models was used to calculate the number of hadrons reaching the observational level inside a circle of 50 m radius around the EAS axis. Then the number of neutrons produced by the hadronic component was calculated using an empirical relationship between the two components. We have tested the results with the ProtoPRISMA array at sea level, and recorded the neutrons which are consistent with the simulation results.

Key words: EAS, detector, neutrons, altitudes

PACS: 96.50.sb, 96.50.sd, 14.20.Dh **DOI:** 10.1088/1674-1137/37/1/015001

1 Introduction

A novel type of extensive air shower (EAS) array (the PRISMA project) was proposed some years ago [1] to study the cosmic ray spectrum and mass composition in the "knee" region. The existing 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 is based on an idea that the main EAS component - the hadrons have to be measured first. Special detectors (en-detectors) have been developed for this purpose. It was proposed to combine the central part of the PRISMA array with the LHAASO project [2] by introducing the en-detectors in the center of the LHAASO array. The en-detectors will make the LHAASO array sensitive to the hadronic EAS component thus making it more powerful and informative.

2 Calculations

We used the CORSIKA program [3] (ver. 6.900) for EAS simulations with QGSJET and GHEISHA models. Calculations were performed for two primaries: proton and iron and for two altitudes: near sea level (170 m a.s.l.) and high mountain 4300 m a.s.l. As the first step we made calculations for fixed primary energies from 10 TeV through 10 PeV and zenith angles 0°–45°. We present here results for the number of hadrons and thermal neutrons produced by the hadrons inside a circle of 50 m radius around the EAS axis as a function of primary energy. The distributions over these numbers are also obtained.

As with any other Monte-Carlo programs for EAS simulation, CORSIKA can not process particles with very low energies. We used the following cuts for particles: 50 MeV for hadrons, 0.5 GeV for muons, 60 keV for electrons and gammas. The mean number of evaporation neutrons $\langle n\rangle$ produced by a hadron in 3-m layer of surrounding soil and/or construction materials has been calculated using an empirical relationship between them and the parent hadron energy (in GeV):

$$\langle n\rangle \approx 36\cdot E_h^{0.56}. \tag{1}$$

This relationship originated from secondary particle production in hadronic interactions and was obtained taking into account the experimental data [4] and atomic mass A dependence of neutron production: $\langle n\rangle \sim A^{0.4}$ [5]. Therefore, the total number of produced secondary neutrons should be summarized over all hadrons:

$$\langle n_{\text{tot}}\rangle = \sum_i 36\cdot E_{h(i)}^{0.56}. \tag{2}$$

Received 17 April 2012, Revised 22 May 2012

* Supported by Russian Foundation for Basic Research (09-02-12380-ofi-m and 11-02-01479a), to the "Neutrino Program" of Russian Academy of Sciences, the Federal Target Program "Scientific and Educational Cadres for Innovative Russia", NSFC (10835007)

1) E-mail: maxh@ihep.ac.cn

It is easy to see that due to slow dependence on hadron energy and due to slow change of hadron mean energy with primary energy, Eq. (2) can be simplified to:

$$\langle n_{\rm tot}\rangle \approx 36 \cdot N_h \cdot \langle E_h \rangle^{0.56}. \tag{3}$$

This means that the total number of evaporation neutrons produced in EAS should be more or less proportional to the number of high-energy hadrons reaching the observation level. The great bulk of these neutrons are thermalized later. Thus through recording thermal neutrons by detectors spread over a big area one could reconstruct the number of hadrons in the EAS. This idea is the basis of the PRISMA project.

3 The simulation results

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 can be fitted with power law functions. All indices for protons are close to 1: the index is ~1.14 at sea level and ~1.05 at 4300 m respectively. For iron the indices are a little bit steeper at these energies. A small difference between a primary proton and iron at the highest energy makes us sure that the reconstruction of primary energy would be more adequate in the knee region. One can also see that the mean number of neutrons at sea level differs from one at 4300 m a.s.l. by a factor of ~10. This means that at Yangbajing level the array threshold energy can be lower by a factor of $10^{1/1.7} \approx 4$ where 1.7 is the index of the cosmic ray spectrum.

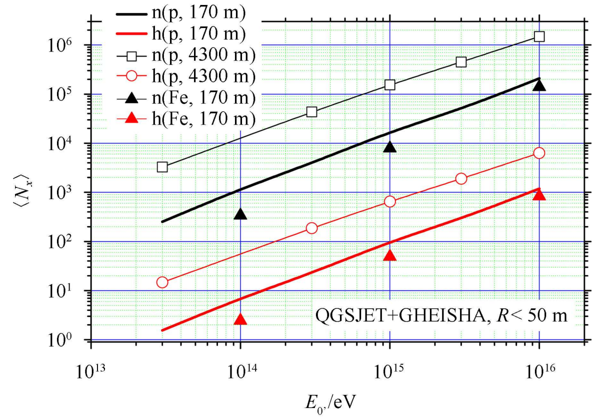

Fig. 1. Mean numbers of hadrons and secondary evaporation neutrons inside a circle of 50 m radius as a function of primary energy at sea level for proton and iron primaries and at 4300 m for the primary proton.

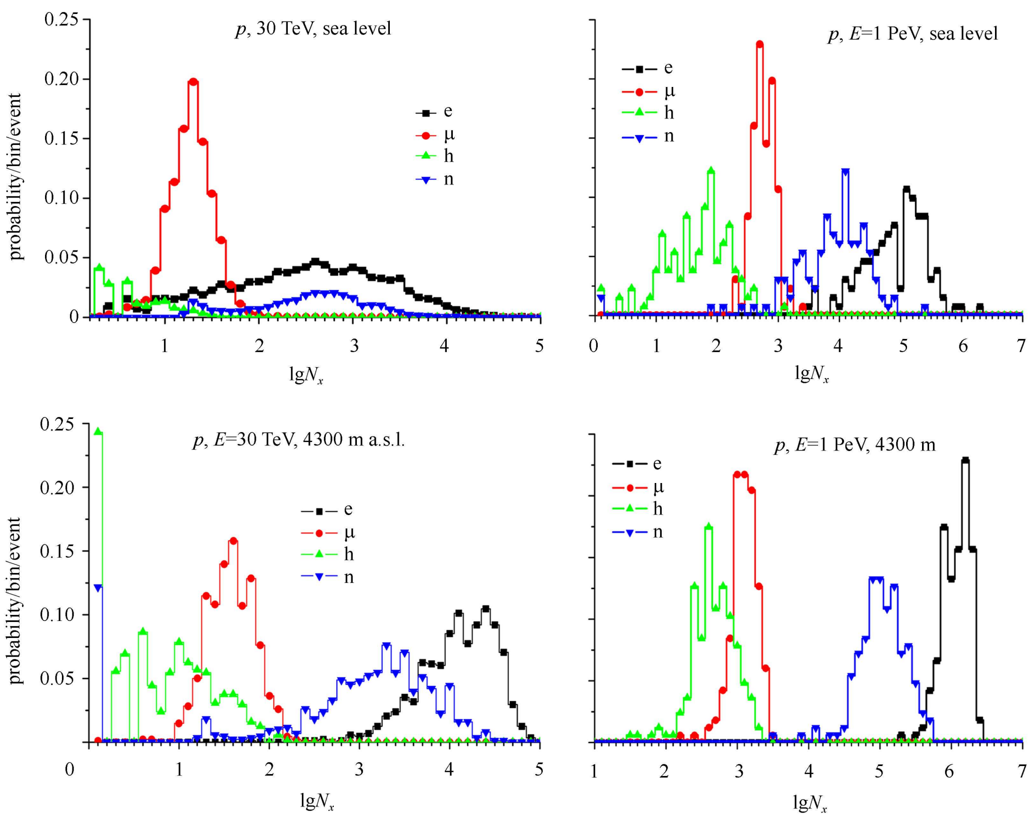

Fig. 2. Different EAS components size distributions for primary protons and primary energies equal to 30 TeV (left panel) and 1 PeV (right panel) for sea level (upper panel) and for 4300 m a.s.l.(bottom panel).

Figure 2 shows the distribution of numbers of different EAS components inside 50 m around the axis for 2 primary energies: 30 TeV and 1 PeV. An interesting issue here is a rather high mean number of produced neutrons in comparison with hadrons and muons. This and the features shown in Fig. 1 make the number of thermal neutrinos induced by a shower very useful in the shower composition and energy determination. Figs. 1 and 2 also show that at high altitude, within the primary energy range 30 TeV–10 PeV, the secondaries have higher quantities and that is why a high altitude is preferable for such experiment. It is necessary to test these simulation results experimentally at different altitudes.

4 Test at sea level

4.1 The ProtoPRISMA array

We have made several tests with the PRISMA prototypes in Moscow. A prototype of the PRISMA project array (ProtoPRISMA) [6] has been developed and started running on a base of the NEVOD-DECOR detector at National Research Nuclear University MEPhI in Moscow (170 m a.s.l.). It consists now of 32 inorganic scintillator en-detectors situated inside the experimental building at on the 4th floor just around the NEVOD water pool. The neutron recording efficiency of the en-detector is equal to $\epsilon_{\rm d}\approx 20\%$. The detectors have a cylindrical shape with the scintillator area equal to 0.36 m^2. Now our standard en-detector is made on a base of polyethylene (PE) tank with a volume of 200 liters. The scintillator thin sheets are situated on its bottom and are viewed by a single 6″ PMT (FEU-200). The scintillator compound ZnS(Ag)+ LiF enriched with ^{6}Li up to 90% is a very effective scintillator for heavy particle detection. It produces 160000 photons per a neutron capture through the reaction ^{6}Li (n, α)t+4.8 MeV. It allows us to collect more than 50 photoelectrons from the PMT photo-cathode per n-capture. Due to a thin scintillator layer (30 mg/cm^2), a single relativistic charged particle produces a very small signal. But, in the case of EAS passage, the correlated signals from many particles are summarized and can be measured. Therefore, the same detectors are used to measure two EAS components: hadronic (neutrons) and electromagnetic. That is why we call them en-detectors (electron-neutron). The array consists now of 2 clusters with 16 detectors each. The clusters have their own triggering systems and work independently. Coincidence of 2 or more hit detectors within the time of 2 μs produces a simple trigger and an on-line program preprocesses data, selects EAS events and marks them in accordance with different mathematical trigger conditions. All pulses are integrated with a time constant of 1 μs and are digitized using 10 bits flash ADC with a step of 1 μs. In the case of a powerful EAS, a full pulse waveform of 20 ms duration is stored. For energy deposit measurements in a wide range we use 2 signals from each detector: from the last 12th dynode and from an intermediate 7th dynode as well. Due to this we have a dynamic range of more than 10^4. The delayed pulses from the thermal neutrons captures are measured in each detector in the time gate 0.1–20 ms.

In order to test our simulations at sea level, we have processed the experimental data accumulated for 2 winter months with the aim of checking the normalization factor from Eq. (1). It is obvious that an absolute value of neutron yield depends on the experimental conditions. In our case the array is not situated in open air, but inside the building. Therefore, the result can be regarded as an estimation only. Detailed neutron yield measurements will be performed later when the next PRISMA prototype runs in the Yangbajing area in real conditions.

4.2 The experimental results

The mean number of recorded neutrons as a function of EAS size ($N_{\rm e}$), which is measured by en-detectors, is shown in Fig. 3 in comparison with full-scale Monte-Carlo simulations made using CORSIKA (with the parameters mentioned above) and the ProtoPRISMA array simulations. For neutron production we use a formula similar to Eq. (1) but with a normalization factor taking the neutron recording efficiency into account. The efficiency can be estimated as follows: $\epsilon\approx\epsilon_{\rm d}\cdot\epsilon_{\rm em}\cdot\epsilon_{\rm area}$, where $\epsilon_{\rm em}\approx 0.04$ is a probability for the neutrons produced in soil (concrete) to escape to air [7] and $\epsilon_{\rm area}$=0.028 is a ratio of the total detectors area (13.5 m^2) to the array area (484.5 m^2)(coverage). Taking these efficiencies into account one can transform Eq. (2) to:

$$\langle n_{\rm tot}\rangle\approx C\cdot\epsilon\cdot 36\cdot E_h^{0.56}\approx C\cdot 0.0080\cdot E_h^{0.56}. \qquad (4)$$

This relationship was used in the simulations of the experiment. The normalization factor (C) was varied to

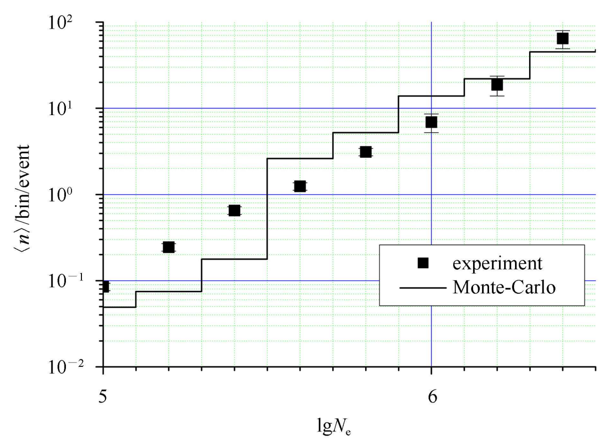

Fig. 3. The mean number of recorded neutrons as a function of EAS size for Moscow site. Points - experiment, Histogram - simulations.

adjust it to the experimental points. Points in Fig. 3 were obtained with C=0.625.

The mean number of recorded neutrons in the ProtoPRISMA experiment is $\sim 1/C$=1.6 times lower than the expected one. The reason for this could be found in the experimental details: detectors are placed inside the building (not in open air), the structure of the array is asymmetrical and the detector coverages in 2 clusters are different [6] and finally, the existence of a large water pool inside the array undoubtedly affects the neutron yield by making the neutron yield lower.

5 Summary

In the frame of a Russian-Chinese collaboration Monte-Carlo EAS simulations have been performed and normalization of the experiment has been studied. We obtained a rather low yield of neutrons at the ProtoPRISMA location in Moscow due to the specifics of the experiment. Nevertheless, even at such yield and at sea level it is possible to obtain some new results using a novel type of EAS array. We are looking forward to making such experiments at high altitude in the Yangbajing region. It will make it possible to check the method at high altitude, to make a calibration using the ARGO-YBJ facilities and to measure the real neutron yield on the future experimental site. The present calculations show that the number of produced neutrons at the Yangbajing level is a factor of 10 higher than that at sea level in EAS of equal energy.

Special thanks go to the Computational Cluster of the Theoretical Division of INR RAS where the numerical calculations were performed, and special thanks should go to to Grigori Rubtsov for his help and discussions.

References

1 Stenkin Y V. Nucl. Phys. B (Proc. Suppl.), 2009, **196**: 293
2 CAO Zhen. Chinese Phys. C (HEP & NP), 2010, **34**(2): 249
3 Heck D et al. FZKA report 6019, Forshungzentrum Karsruhe, 1998
4 Niemenen M , Torsti J J, Valtonen E. Phys. Rev. D, 1982, **26**(5): 1036
5 Hatton C J. The Neutron Monitor. Progress in Elementary Particles and Cosmic Rays Physics. 1971, 1. Vol. X
6 Stenkin Y V, Alekseenko V V, Gromushkin D M et al. Proc. of the 32nd ICRC. Beijing, 2011, **3**: 259
7 Stenkin Y V. Study of Neutron EAS Component as a Novel Method of UHE Cosmic Ray Investigation (Ph.D. II Thesis). Moscow: Institute for Nuclear Research, RAS, 2010