PROCEEDINGS OF SCIENCE

Search for gamma-ray emission above 50 TeV from Crab Nebula with the TAIGA detector

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The TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma-Astronomy) observatory is designed to study the gamma ray sources and galactic cosmic rays. It is located in the Tunka Valley 50 km from the lake Baikal (Siberia). The first part of TAIGA called the EAS Cherenkov array TAIGA-HiSCORE currently consists of 28 wide-angle (0.6 sr) stations, distributed over an area of 0.25 km^2. The Crab observation exposure was about 115 hours during the winter seasons of 2016-2017. The expected gamma quanta excess depends on the array energy threshold and a model of the Crab energy spectrum extrapolation to the higher energies. We present preliminary results of experimental data and MC simulations comparison as well as energy threshold and angular resolutions. The experimental data is in a good agreement with the simulations. An excess of events (about 25 events in the region 30-63 TeV) observed from the Crab direction is compatible with the expected one.

35th International Cosmic Ray Conference – ICRC2017

10-20 July, 2017
Bexco, Busan, Korea

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1. Introduction

In recent years, gamma-ray astronomy became the most dynamically developing field of astroparticle physics. The observatory TAIGA (Tunka Advanced Instrument for cosmic rays and Gamma-Astronomy) [1,2] is planned and currently being implemented as a complex hybrid detector system. It is aimed to study gamma rays of the highest energy range (>30 TeV) and cosmic rays (>100 TeV), in particular to search for 100 TeV gamma and corresponding cosmic ray PeVatrons. The most distinctive feature of the TAIGA gamma observatory is a new detector concept based on a combination of imaging air Cherenkov telescopes (IACTs) with air Cherenkov wide-angle timing detector stations HiSCORE (High Sensitivity Cosmic ORigin Explorer) [3]). Such a combination is unique and will provide a hybrid reconstruction method optimized for the multi-TeV to PeV energy range [1-3].

The most bright source of HE gammas seen from Tunka site is a famous Crab Nebula remnant of SN 1054. It is usually used as a reference source in TeV astronomy and is a reliable beam of high-energy photons to use for calibrating and understanding of new TeV gamma-ray instruments. But beyond 30 TeV, the uncertainty in experimental data is very large. So far just single events were detected. The energy region 40-100 TeV to be explored by the HiSCORE array is of special importance. In Fig.1 a compilation of experimental data obtained by several experiment are presented together with corresponding fits.

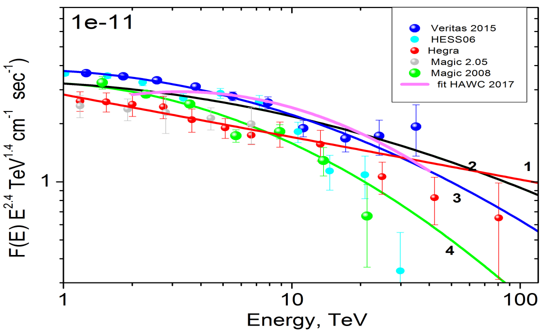


Figure 1: Flux of gamma rays from Crab, measured in different experiments: VERITAS, fit (3)[4]; HEGRA, fit (1) [5]; MAGIC, fit (4)[6]; HAWC fit [7]. Fit (2) is an optimistic fit: $F(E)=3.2310^{-11}E^{(-2.47-0.1\lg E)}$

In this paper we present the first preliminary results obtained with the TAIGA-HiSCORE array from October 2016 to February 2017. The Crab is observed during about 115 hours in moonless, good weather nights. In accordance with the different extrapolations, presented in Fig.1, one can expect from a few events (MAGIC fit) to 30 events (optimistic fit) during this time with the existing array and effective area 0.15 km^2 (after reconstruction cuts. see Section 4). We present preliminary results of comparison of experimental data and MC simulation, estimations of the energy threshold, angular resolution studies and analysis of reliability of the Crab events excess.

2. Status of the HiSCORE set-up in 2016-2017 season and event reconstruction method

TAIGA-HiSCORE array [2,8-10] consists of 28 stations distributed over area of 0.25 km^2. Each station contains 4 PMTs equipped with light-collecting Winston cones. The observation solid angle of the station is 0.6 sr and its sensitive light collection area 0.5 m^2. The station design, data acquisition system, electronics and other technical details are presented in [2,8-10]. To increase the observation time of Crab all stations are tilted towards South by 25 degrees (the experimental site is located at 51.81 latitude, 103.06 longitude). The optical stations record the traces of signal with step of 0.5 ns. Each station operates independently from the others. Condition for formation of the local trigger signal is an excess the sum of anode signals over a threshold level (approximately about 5 sigma above NSB level).

The method of registration was primarily developed, established and verified in the Tunka -133 experiment [11] for the energy range higher than 10 PeV. For the TAIGA-HiSCORE array the reconstruction method have been adopted [12,13] and verified at energies about hundred of TeV with the 9-stations of the HiSCORE array data in 2014-2015 [10, 14].

The main steps of events reconstruction are following:

1) Selection of events with a number of hit stations more than or equal 4. Selection of the time period with good weather condition, when event counting rate, R4, was larger than14 sec^{-1}.

2) Reconstruction of the EAS zenith and azimuth angle (θ, φ) by fitting of the station time delays with plane model of the shower front .

3) Reconstruction of the shower core position (X0,Y0) by fitting of the data with the amplitude distance function (ADF), developed for Tunka Experiment [11,12]. For events with small number (4-8) of hit stations X0,Y0 were reconstructed by the gravity center method.

4) Reconstruction of θ and φ with known core position X0, Y0 by fitting of the stations time delays with the curved model of shower front [11,12]. This step gives a significant improvement of angular resolution up to $d\theta$=0.1-0.4 degrees (the angle between real and measured direction for 67% of events, ψ67). Only events with core position in internal part of array were taken into account.

5) Fitting Cerenkov light flux Q_i (R_i) by LDF [11,12] and estimation of light flux at a distance 200 m from the shower core, Q_{200}. For events with small number of hit stations we estimate a different value Q_{mean}, averaged over light fluxes recorded at 4 stations closest to the EAS core. Energy estimators, E(Q), for primary gamma rays $E_{gam}(Q)$ and primary cosmic rays $E_{CR}(Q)$ are different, because for gamma induced showers Cherenkov light flux is larger by a factor ~1.7 in comparison with proton and helium induced showers of the same energy. $E_{gam}(Q)$, $E_{CR}(Q)$ were obtained from CORSIKA simulations.

6) Calculation of right ascension (Ra) and declination (Dec) of showers and analysis of the sample in the cone within 3 degrees and 0.4 degrees in Crab direction. Analysis of background and space maps of events. Search for statistical excess.

We have analyzed 38 nights when Crab was in the field of view of array. It was reconstructed near ~10^7 events with more than 4 hit stations. Nearly 6 10^6 events with core position in the internal part of array (distance from array boundary more than 50 m) were selected for future analysis. Eventually during the season 2016-2017 we collected and analyzed 36000 events in 3^o around the Crab direction, 3800 events in 1^o and 625 in 0.4^o .

3. Experimental data in comparison with MC simulations

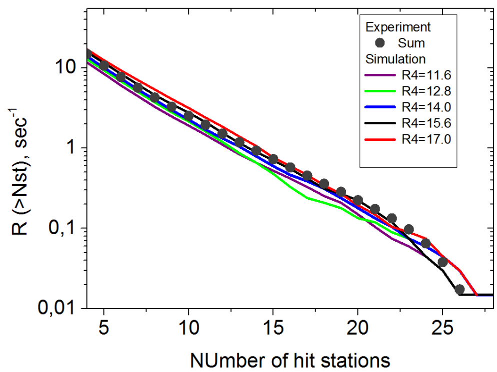
To study an accuracy of shower parameters reconstruction we used CORSIKA-simulated showers from primary gamma rays, protons, helium, oxygen and iron nuclei, distributed by power low energy spectrum with slope -2.67 in the range 30-3000 TeV. Simulation was performed for the zenith angle range 0–50° for tilted optical stations. The experimental procedure of reconstruction (from Cherenkov pulse processing and up to energy and arrival direction reconstruction) was fully implemented in the simulation. The analysis starts from study of energy threshold. First of all it depends on the trigger threshold of every station, and on the primary particle spectrum and composition. We consider several approximations and chose the next ones: all particle primary spectrum is fitted by function

$F_{all\_part}(E)=1.33\times10^4\times(E/10^5\ GeV)^{-2.66}m^{-2}sec^{-1}\ sr^{-1}\ GeV^{-1}$,

and light mass components (P and He) are fitted by

$F_{Pr\_He}(E)= 7.6\times10^3\times(E/10^5 GeV)^{-2.68}m^{-2}sec^{-1}\ sr^{-1}\ GeV^{-1}$.

These functions fit experimental data of the primary measurements (ATIC2, CREAM, Sokol, JACEE) and some ground-based experiments: ARGO YBJ, TUNKA25, HiSCORE (9 stations prototype data [14]) in the range 100-1000 TeV. These two fits are slightly higher (by factor 1.2) than fit [15].



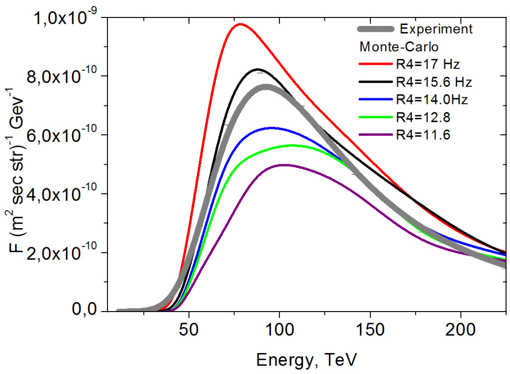


Figure 2 left:. Integral counting rate R(≥Nst) in dependence on number of hit stations. Corresponding values R4=R(≥4) are shown in the header. Lines - MC simulation with different threshold amplitude, black circles – experiment (statistical errors are within the circles).

Figure 2 right: Experimental cosmic ray spectra (thick gray line, statistical errors are less than a thickness of the line) in linear scale. Lines - MC simulations for different threshold amplitudes. In experiment R4 varies in the range 14-16 sec^{-1} from night to night, and corresponding peak energy varies from 85 TeV to 105 TeV.

In MC simulation we varied a threshold level for local trigger formation for each station, A_{thr} (in relative units from 55 to 75) , taken into account the number of working PMTs in each station. The change in threshold amplitude leads to a change in integral counting rate R(≥Nst), as well as to a change in a peak energy of cosmic ray (most probable energy) and, as a result, to a change in gamma rays peak energy. In Fig. 2 in the left panel we present the mean value of experimental counting rate R(≥N) (black circles with statistical errors being less than circles) in comparison with the set of simulation performed with different A_{thr}. Corresponding counting rate of showers with four and more hit stations, R4, are shown in the header. In the experiment R4 varies in the range 14-16 sec^{-1} from night to night for the main period of array operation. As seen from the right panel of Fig. 2 corresponding peak energy lays in the range from 85 TeV to 105 TeV. The expected spectra of gamma rays from Crab, calculated with different threshold amplitudes are presented in Fig.3 together with corresponding R4 values. For experimental range R4= 14 -16 sec^{-1} (corresponded to blue and red curves in Fig. 3) the expected peak energy of gamma rays should be around E_{peak}~50±5 TeV. The energy threshold is limited by the used station amplitude threshold. In the threshold region a detection efficiency can be described by the exponential function $1\text{-}\exp\{-(E/E_{peak})^5\}$.

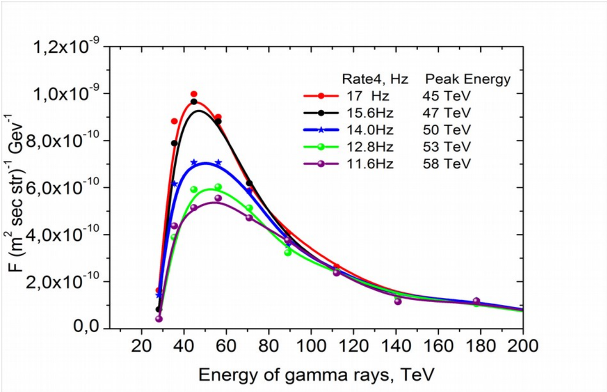


Figure 3: Expected gamma ray spectra, calculated with the same threshold amplitudes as in Figure. 2. Corresponding counting rate R4 and peak energy of gamma rays are shown in the header. For R4=14-16 sec^{-1}, the expected peak energy is about E_{peak}=50±5 TeV.

The accuracy of arrival direction reconstruction was checked on MC simulation with the samples of events with zenith angles 28-39 degrees (as the Crab is seen in Tunka valley) and energies more than 45 TeV. In simulation the reconstruction method reproduced all the steps of processing in experiment. In Fig. 4 we show the distribution of angles, ψ68, between real and measured directions for 68% of events, in dependence on a number of hit stations, $N_{st.}$. It strongly depends on N_{st}: ψ67=~0.4° at N_{st}=4 -5 triggered stations and ψ67 decreases to 0.12 at Nst >10. In the energy interval 40-100 TeV where the excess can be detected, the number of hit stations varies from 4 to 9. As a result we can consider the PSF function ~ as 0.2-0.3° in this energy interval(see also [8]).

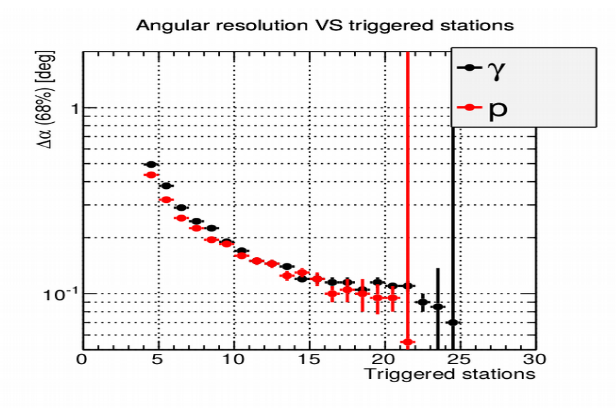


Figure 4: Arrival direction resolution. The distribution of angles, ψ68, between real and measured directions for 68% of events, in dependence on a number of hit stations. (See also [8])

The estimation of systematic pointing precision in HiSCORE was evaluated as 0.1 degree **i**n [17]. In [17] a unique method was developed to verify the absolute HiSCORE pointing. The method uses as artificial light source the 532nm laser of the CATS-LIDAR on the International Space Station (ISS), which was detected in the 2015/16 HiSCORE data set. Absolute pointing calibration is based on the simultaneous observation by the robotic optical telescope MASTER-Tunka [17].

4. Analysis of events in Crab direction

Search of gamma ray excess from Crab Nebular have been performed using the sample of 36000 events in the cone of 3° in Crab direction (Ra=83.63°, declination =22.01°) accumulated over 115 hours on the effective area 0.15 km^2 (excluding the boundary events). We divided the full coordinate space in Ra and Dec by cells with size 0.3°×0.3° and analysed the maps $N_i(Ra_i, Dec_i, E_{cut})$ introducing the set of upper energy cuts to decrease the cosmic ray background (energy was determined by gamma-ray energy estimator): E_{cut} = 40 TeV, 50 TeV, 63 TeV , 100 TeV. The background N_{bg} (E_{cut}) was calculated as a mean value over all cells inside distance 1.5° from expected Crab position excluding cells within 0.4°. The study of the background condition can be found in [8]. Significance maps, $S(Ra_i, Dec_i, E_{cut})$, were calculated by the formula (9) from [18] with alfa =0.04.

In Fig. 5 the example of map of events with energy E_{gam} < 63 TeV is demonstrated. The position of the excess occupies 3 cells around the expected position of the Crab with S=2.3, 1.96, 1.74 sigma significance, that corresponds to our PSF function.

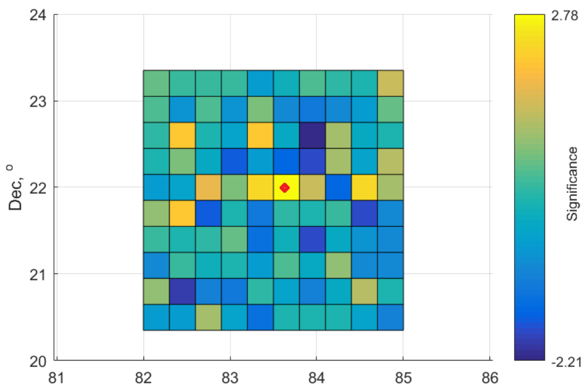


Figure 5. The significance map of events with energy 30- 63 TeV per 0.3°×0.3° cell. The red point denotes the expected position of the Crab. In this cell an excess is ~ 18, a significance ~ 2.7. In nearest two cells significance is 2.3 and 1.4 correspondingly.

The second approach for estimation of the excess was following. We calculated the flux of events within the cones with different angles Ψ relatively Crab direction: Ψ < 0.2°, <0.3°, <0.4°, Background was estimated as a mean density of events in the rings 0.4°-1.5° or in the ring 0.4°- 2.0° around Crab position and normalized to the circle of 0.4° (or 0.3° or 0.2°). Then we calculated the excess above background and significance without any additional gamma/hadron separation (Table 1). From the Table 1 one can see some systematic excess of events in all three bins at Ψ<0.4°, Ψ<0.3°,Ψ<0.4° and at all energies at low significance level. Around expected peak energy 50 TeV it reaches 2.25 sigma. In Fig.6 the dependence of the experimental excess on upper energy limit is presented and compared with the expectations calculated with different Crab spectra in accordance with fits, presented in Fig.1.

Table 1: The excess, background and significance of events in the cones with angle Ψ <0.4°, <0.3°, 0.2° at various upper limits in energy.

Upper $E_{gamma_}$cut, TeV		Ψ<0.4°	Ψ<0.3°	Ψ<0.2°	
<100 TeV	Excess	21	2.9	6.8	
	Background	332.6	187	83.2	
	Significance	1.12	0.20	0.73	
<63 TeV	Excess	25.1	16.7	7.5	
	Background	125.	75.3	33	
	Significance	2.20	1.87	1.28	
<40 TeV	Excess	9.9	3.6	3.7	
	Background	13.1	7.4	3.3	
	Significance	2.64	1.29	1.95	

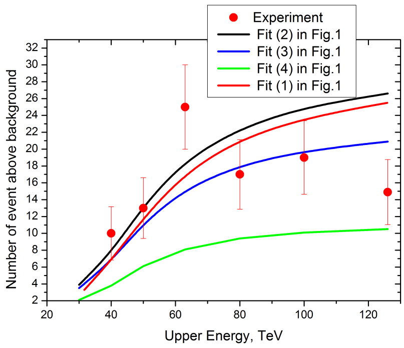


Figure 6: Experimental excess of events in dependence on upper energy limit E_{cut} (red circles with statistical errors). Lines - predicted excess for different fits of Crab spectra (see Fig. 1), calculated with experimental threshold function (peak energy 45-50 TeV). 'optimistic' fit (2) (black line), fit (3) (blue line) VERITAS, fit (4) (green line) MAGIC, fit (1) HEGRA - read line .

The analysis of Ra – Dec maps of events in Crab direction shows some excess above background with significance level ~ 2-2.5 sigma. The position of the excess is located in the expected position of the Crab Nebula and does not contradict to our optimistic expectation, based on the extrapolation of Crab spectrum to higher energies. A weak excess from Crab direction in the data from 2015/16 season also was reported earlier in a preliminary analysis [10]. The conditions of events detection were changed from 2016 to 2017 season due to upgrade of the array. A re-analysis of the joint sample of events detected over 2015-2017 years requires additional efforts and will be presented in nearest future.

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Conclusions

We performed the search for HE gamma ray emission from Crab Nebula direction during 115 hours from October 2016 to February 2017 at the effective area 0.15 km^2. There have been selected 36000 showers from Crab direction within 3°, 3800 events within 1°, and 625 at < 0.4 degrees . The comparison of experimental data (counting rates, peak energies, multiplicity, core position distribution) with MC simulation shows a good agreement. We estimated a most probable (peak) energy of gamma rays to be detected from Crab direction as 45 - 55 TeV. The analysis of Ra – Dec maps of events in Crab direction shows a hint of a signal above background at the expected position of the Crab Nebula (25 events with energy around 50 TeV, about 2-2.5 sigma pre-trial). This is consistent with optimistic flux prediction in that energy interval. The data from 2015/16 season reported earlier [2,10] also showed some excess. A combined re-analysis of the 2015-2017 data with updated calibration is work in progress.

- We hope that in the next season of operation the joint work of HiSCORE and IACT, implemented in the array [8,9,16], will allow to suppress a background by ~10 times and

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check this year preliminary results at higher significance level. In nearest future (in 2019 year) the wide angle timing array HiSCORE will be extended up to 1 km^2 area and 2 additional IACTs will be included in the array. This hybrid array (1km^2, 3 IATs) is expected to have a sensitivity of 2.5 10^{13} TeV cm^{-2} s^{-1} at 100 TeV [8,9]. So expected statistics of events around 50 TeV can reach 100 events with the significance ~5 sigma.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (grant 16-29-13035) and the grant 15-12-20022 of the Russian Science Foundation (section).

References

[1] R. Mirzoyan, *TAIGA detector for cosmic and gamma rays for TeV - EeV energy range*, in 40th COSPAR Scientific Assembly (2014) Vol. 40 of COSPAR Meeting

[2] L. Kuzmichev et all,(TAIGA col.) *Tunka Advanced Instrument for cosmic rays and Gamma Astronomy (TAIGA): status, results and perspectives. EPJ Web of Conf.* 145 (2017) 01001.

[3] M. Tluczykont, D. Hampf, D. Horns, D. Spitschan, L. Kuzmichev, V. Prosin, C. Spiering,R. Wischnewski, *Astroparticle Physics* 56 (2014) 42

[4] Kevin Meagher_ for the VERITAS Collaboration. *Six years of VERITAS observations of the Crab* ***Nebula,*** in proceedings of ICRC_2015 PoS(ICCR2015)792.

[5] F. Aharonian et al, (HEGRA col.). *The Crab Nebula and Pulsar between 500 GeV and 80 TeV:Observations with the HEGRA stereoscopic air Cherenkov telescopes* (2004), arXiv:astro-ph/0407118

[6] J. Aleksi´ca , S. Ansoldib , L. A. Antonellic et al (MAGIC col.).*Measurement of the Crab Nebula spectrum over three decades in energy with the MAGIC telescopes. (2006)* arXiv:1406.6892

[7] *A.U. Abeysekara, A. Albert, R. Alfaro et al, (HAWC col.). Observation of the Crab Nebula with the HAWC gamma-ray observatory (2017).* arXiv:1701.01778

[8] M. Tluczykont et al (for the TAIGA col.) *Status of the HiSCORE detector component of the TAIGA experiment.*These proceedings

[9] N.M. Budnev, et al. (for the TAIGA collaboration), *TAIGA - a hybrid detector complex for high energy gamma-ray astro-physics and cosmic ray physics in the Tunka valley,* These proceedings

[10] M. Tluczykont, N. Budnev, I. Astapov, et al., *EPJ Web of Conf.* 136, (2017) 03008

[11] S. Berezhnev et al. (Tunka Collaboration), *NIM A* 692 (2012) 98

[12] V.V Prosin., et al. (Tunka Collaboration), *NIM A* 756 (2014) 94

[13] Hampf, M. Tluczykont, D. Horns *NIMA* 712 (2013) 137

[14] S.F. Berezhnev, N.M. Budnev et al. (Tunka Collaboration) *Results from the Operation of the Prototype Tunka_HiSCORE. Bul.of RAS. Phys.* 79 (2015) No. 3, 348

[15] J.Hoerandel, *Astropart. Phys.* 199 (2003) 193

[16] L.Sveshnikova (for TAIGA collaboration*) Commissioning the joint operation ...* These proceeding.

[17] A.Porelli, R.Wischnewski (for TAIGA col.). *TAIGA-HiSCORE observation of the CATS-LIDAR on the ISS as fast moving point source.* These proceeding.

[18] *Ti-Pei Li and Yu-qian Ma, Astrophysical J. 272 (1982) 317*