The trigger system preparation of the NUCLEON space experiment.

V. Boreiko, N. Gorbunov, V. Grebenyuk, A. Kalinin, Z. Krumstein, D. Naumov, Nguen Man Sat, E. Plotnikova, D. Podorozhnyi, S. Porokhovoy, B. Sabirov, A. Sadovsky, V. Stolupin, A.Tkachenko, and L. Tkachev

The main aim of the NUCLEON experiment is a measurement of cosmic rays flux in the energy range 10^{11}-5.10^{14} eV and charge range up to Z≈30 in the near-Earth space. Such a measurement is motivated by the "knee" problem: change of the slope and composition in cosmic rays energy spectrum from $E^{-2.7}$ to $E^{-3.0}$ at energies about 10^{15} eV. The NUCLEON mission is planned for operation at the COSMOS type satellite to be launched in 2009-2010 for 5 years of data taking. The design and production of the technological NUCLEON trigger modules are performed including front-end and digital electronics of the data acquisition system. The modules were successfully tested in 2008 at the CERN SPS accelerator pion beam. The main aim of this year is production of the flight NUCLEON apparatus that is being in progress. The trigger system conception, the results of beam tests and the Monte-Carlo analysis is presented.

1. Introduction

One of the old and crucial astrophysical problem is the origin of the knee in Galactic cosmic ray energy spectrum (change of the slope from $E^{-2.7}$ to $E^{-3.0}$) at ~10^{15} eV which was discovered by G.B.Khristiansen in 1958 [1]. Below 10^{13} eV, the spectrum and composition are well known from direct observations with detectors flown on balloons and earth satellites. However, at higher energies, the CR flux is smaller and thus is more difficult for direct observations. A lot of results were obtained with the EAS investigations by the ground based detectors but they are not yet conclusive due to discrepancies between them. Thus the knee location in cosmic ray energy spectrum of the different nuclei components remains still unknown as CR composition mostly due to the absence of reliable data. To improve situation the data of the individual elemental energy spectra from protons to nickel before the knee at 10 TeV to 1 PeV must be substantially improved. Among the wide arsenal of modern experimental methods for energy measurement in energy region > 1 TeV only the ionization calorimeter (IC) method may be applied over a wide energy range for all CR nuclei simultaneously. Even a thin calorimeter have rather large weight ~ about 2-3 tons, and as a result, such investigations become very expensive.

The main idea of the NUCLEON project is to design and to create scientific device with large aperture and a relatively light weight being able to measure elemental spectra of cosmic rays in a wide energy range E ~ 10^{11}-10^{14} eV. The method is based on event by event measurement of spatial density of a flux of the charged and neutral secondary particles which were produced in the first inelastic nuclear interaction in the target of the detector and have passed through layers of thin converters to produce e^+e^- pairs of the secondary gammas. This technique is known as KLEM (Kinematic Lightweight Energy Meter) [2, 3].

The natural task of the NUCLEON trigger system is to suppress the huge flux of low-energy cosmic rays (less than 100 GeV) and those CR which are beyond the detector aperture. Therefore, the main goal of the trigger system is the selection and rejection of data flux to a limited volume that can be transferred to the Earth. To investigate and to solve these problems the design and production of the technological NUCLEON trigger modules were performed including front-end and digital electronics of the data acquisition system. Thus, useful events should be selected and written down in memory of on-board computer for the further analysis. In the next section the technical conception of trigger system will be presented in detail. In the third section the possibility of optimization of trigger system's functionality by means of Monte-Carlo analysis is discussed. The fourth section is devoted to the brief review of the results obtained at testing of installation on a beam in CERN. In the last section some conclusions and current status of the project will be presented.

V. Boreiko (e-mail: borvlad@nusun.jinr.ru), N. Gorbunov (e-mail: GORBUNOV@sunse.jinr.ru), V. Grebenyuk (e-mail: greben@nusun.jinr.ru), A. Kalinin (e-mail: kalinin@nusun.jinr.ru) , Z. Krumstein (e-mail: Zinovii.Kroumchtein@cern.ch), D. Naumov (e-mail: naumov@nusun.jinr.ru), Nguen Man Sat (e-mail: sat@nusun.jinr.ru), E. Plotnikova (e-mail: plotnike@nusun.jinr.ru), S. Porokhovoy (e-mail: porokh@nusun.jinr.ru), B. Sabirov (e-mail: sabirov@jinr.ru), A. Sadovsky (e-mail: Andrei.Sadovski@cern.ch), V. Stolupin (e-mail: stolupin@jinr.ru), A. Tkachenko (e-mail: avt@nusun.jinr.ru) and L. Tkachev (e-mail: tkatchev@nusun.jinr.ru) are with the Joint Institute for Nuclear Research, 141980 Dubna Moscow region Russia.

D. Podorozhniy is with Skobeltsyn Institute of Nuclear Physics, Moscow State University, 119992 Moscow Russia (e-mail: dmp@eas.sinp.jinr.ru).

2. DEVICE GEOMETRY AND THE TRIGGER SYSTEM TECHNICAL CONCEPTION.

The schematic view of the NUCLEON device is shown in Fig. 1. It includes: charge measuring system, energy measuring system, the trigger system, control electronics. All systems are mounted inside a pressurized container. The thickness of the container wall is equal to 2.5 mm of aluminum.

The charge measuring system consists of 4 silicon detectors layers in the volume of 53 cm × 53 cm × 2.5 cm. Every silicon detector layer contains 64 subdetectors 6.2 cm × 6.2 cm × 0.3 cm, every of which is divided by 16 pads with the size ~ 2.4 см^2 . These layers are used for precise charge measurements.

The energy measuring system consists of the following elements: 6 identical layers of micro-strip silicon detectors, the carbon block with the size 50 cm × 50 cm × 9 cm served as a target, 2 identical tungsten layers with the size 50 cm × 50 cm × 0.7 cm served as a gamma-converter. Every layer of silicon micro-strip detectors occupies a volume of 53 cm × 53 cm × 1 cm. Every silicon micro-strip layer contains 72 detectors with the size 62 mm × 62 mm × 0.3 mm, arranged in 9 ladders with 8 detectors linked in series. A micro-strip pitch optimization has been done, and pitch size was reduced to 0.46 mm to reduce a power consumption of the device.

The trigger system represents 6 planes consisting of 16 scintillation strips [4] to measure the charged particle multiplicity that crossed the planes and the hitted strip locations. The strip size is 5 mm × 31 mm × 500 mm. In each strip the 7 multi-cladding WLS KURARAY Y-11 fibers are glued and grouped into 3 groups. Two groups of 2 fibers are connected to the single-channel PMT and the group of 3 fibers are connected to 16 channel PMT HAMAMATSU H8711 for all 16 strips. Two single-channel PMTs HAMAMATSU H5773 were used for each plane. Thus light gathers for each of two single-channel PMTs from the whole plane. It allows to provide reservation of the equipment and to raise reliability of work of a trigger part of the detector. The single –channel PMTs are used to provide the trigger of the 1-st layer and multichannel PMTs are used to provide the trigger of the 2-nd layer.

From single-channel PMT the signal acts on inverting amplifiers with gain 5 collected on AD8055. Such decision allows to manage one supply +12V both for DC-DC the converter of high-voltage feed PMT and for amplifiers, and also to use only one supply on a board of development of the trigger. Inconsistent enough demands are made to a board of development of the trigger - high speed of elements for processing short signals with PMT, and with another on the one hand is required-power dissipation should not exceed 1W. It imposes severe constraints on a choice of element base.

On a board of the trigger two identical groups of schemes (it is carried out "hot reservation"), realizing logic of development of the trigger are placed. The group contains 6

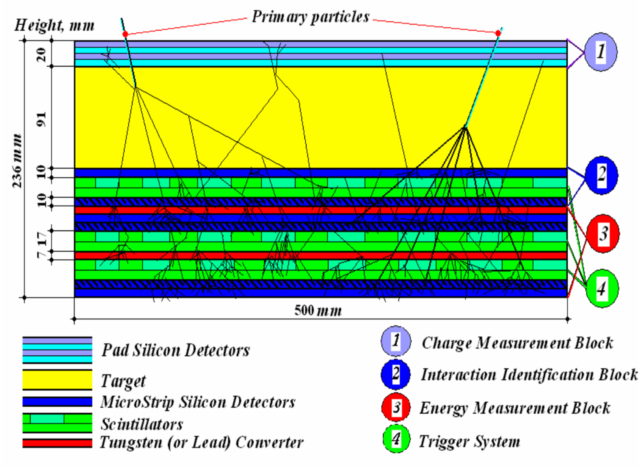

Fig. 1. Schematic view of the NUCLEON device.

channels of registration, each of which consists of the discriminator and DAC, the comparator setting a threshold (ADCMP601). Besides it the channel includes the monostable developing a signal by duration of 50 nanoseconds. All 6 signals act on the majority scheme of coincidences which the multiplicity of agreements can vary from 1 to 6 and, except for that each of channels can be switched off from coincidences. The majority scheme of coincidences is realized on PLM ALTERA EPM240. On an output of this scheme the signal of the trigger which acts on inputs of registers of micro-controllers of both groups and, through the shaper of LVDS-levels - in System Processing of the Scientific and Service Information (SPSSI) is developed. Management of change of parameters of the device is carried out by micro-controller ATMEGA165P. The block diagram is presented in Fig. 2.

Three variants of installation of selection modes are possible: thresholds and a configuration of coincidences are set on the Earth and loaded at inclusion of a feed; loading by a variant "AND" and change of thresholds and/or the multiplicity of agreements of coincidences; a choice of values of thresholds in an orbit, proceeding from speed of the account of each of channels (the multiplicity of agreements of coincidences gets out equal 1 and investigated channels join only). Modes of selection get out central processor SPSSI, and the algorithm of their work is realized by the micro-controller located on the trigger board.

Each micro-controller measures consumption of the current of that group to which it belongs, value of thresholds of channels of group and rate of registration of events in both groups. At a deviation of size of a voltage on 10%, power supplies 3.3V, develop a signal of a mistake which initializes the microprocessor and acts in SPSSI.

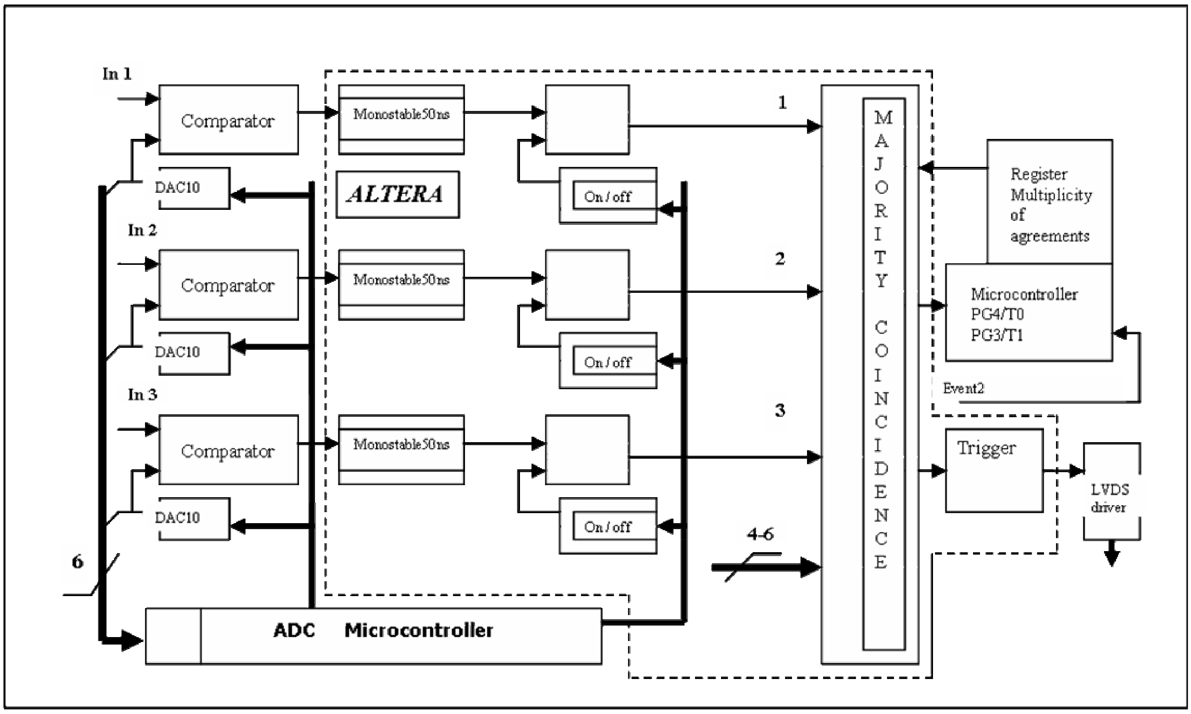

Fig. 2. Block diagram of one chipsets group.

Change of thresholds by a variant "b" is possible in two ways. The first - the task of value of a threshold directly from the Earth, the second - the task of rate of the account from the Earth and change of a threshold (thresholds) up to an establishment of the set rate of the account. The choice of values of thresholds by a variant "c" is carried out as follows - the multiplicity of agreements in both groups is set to equal unit. Serially, one of channels is connected to inputs of majority schemes of both groups. The threshold in these channels is established equal to 10 mV and then during 10s the quantity of operations is counted up. The result of calculation is kept in the RAM. In a following step the threshold is established equal 20 mV and procedure repeats 20 times. "Plateau" gets out of the received values of accounts and the value of a threshold corresponding the middle "plateau" gets out, accounts in both groups are simultaneously supervised and compared.

Then the following channel (each time in group is included only one channel) joins and for it the procedure repeats. Thus, 6 channels in both groups are adjusted all.

During a set of statistics it is necessary to supervise rate of its set. For this purpose each 30 minutes contents of registers PG3/T1 and PG4/T0 are written off in the RAM of the micro-controller and compared to the previous value. These values are transferred in SPSSI after request from the central processor. Besides in the central processor values of thresholds of all comparators, the multiplicity of agreements of coincidences, a joint account of events and values of consumption of currents in each group are transferred. The control of work of groups is carried out by comparison of quantity of the events registered in each groups. If groups were ideally identical accounts would be identical.

In real conditions of the account should not miss more than on (5-7) %. In case of a divergence of accounts values of thresholds are checked. If values of thresholds coincide, and accounts still differ, record of former values of thresholds in all channels is repeatedly carried out. If and after that accounts differ, audit of each channel begins. For this purpose accounts of the same channels of different groups are compared at the set size of a threshold. For comparison of accounts the multiplicity of agreements of coincidences majority scheme is established equal to 1 and by turns channels of registration will join. Thus the pair channels is established, accounts in which differ. Then accounts of this pair are compared to accounts of pairs inside of each of groups 1-2, 3-4, 5-6. As a result of these comparisons the channel with the changed parameters is established.

For restoration of accounts the threshold of the comparator of this channel changes. If the account are restored, new value of a threshold and a set of statistics is remembered proceeds. In case of impossibility of restoration of accounts, the group with the faulty channel is disconnected also the trigger developed only by the second group. In case of if rate of a set of statistics changes, begins process of check of channels. Accounts now can be compared only inside of pairs 1-2, 3-4, 5-6, and all over again in the RAM the account in the channel enters the name, for example, 1, and then-2, etc. there is a pair with various accounts. If rate of a set of statistics has increased, in the channel with the greater account the threshold increases until the account will not be restored, if rate has decreased, the threshold in the channel which account has decreased decreases.

In case of impossibility of comparison of accounts, the channel is switched off and, if necessary, the multiplicity of agreements of coincidences changes.

3. MONTE CARLO ANALYSIS

The Monte Carlo simulation of the trigger system properties was developed simultaneously with hardware activities according to main trigger ideas: 1. the total signals of scintillator planes of the single-channel PMTs that are proportional to the charged particle multiplicity are used to provide a first level trigger: 2. the trigger of the 2-nd level is based on the individual strip signals provided by multichannel PMTs. The trigger of the second level makes the further filtration of events in on-board computer. In this case, conditions can have more complicated form. Generally, the trigger conditions can be formulated in a way to select the useful events:

(a) the primary particle energy should be more than 100 GeV;

(b) the event axis crosses the top and bottom planes of the detector;

(c) the vertex of inelastic interaction should be in the carbon target.

All events which are not useful are considered as background events.

Therefore, the main goal of the MC-analysis for trigger consists in the evaluation of optimum threshold values for trigger modules situated in the different NUCLEON detector parts using the results of MC-simulation. The simulation is based on ROOT package and the VMC (Virtual Monte Carlo) that includes the following generators: GEANT4 (it used for protons events simulation), GEANT3 and FLUKA (for protons and nuclei events simulation).

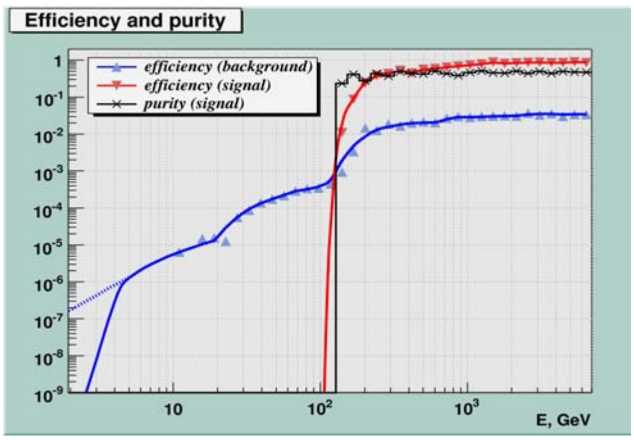

Fig.3. Efficiency, rejection efficiency for background events, expected purity as function of energy for a primary protons with energies 10 GeV – 5 TeV.

For the trigger condition estimation we are using concepts of efficiency and purity. Efficiency is defined as a part of the selected useful events from useful events (naturally, rejection efficiency for background is defined as a part of the selected background events from all background events). Purity is defined as a percentage of the selected useful events to the total selected events. Therefore, the requirement of the trigger condition optimality can be formulated as selection of useful events with maximal efficiency and purity.

For example, in Fig. 3 efficiency and purity as a function on energy of primary particle (proton) are presented. On this picture the result of both levels trigger is shown. The efficiency of protons selection with energy > 1 TeV is more than 90 % at corresponding purity of selection about 60 %.

4. BEAM TEST

Investigation of the NUCLEON scintillator and silicon detector prototypes, readout and data acquisition electronics has been carried out in the beam test experiment on SPS CERN with pions of 200 - 350 GeV. The structure of the NUCLEON setup is shown in Fig. 4. It consists of:

(a) 4 planes of silicon pads detectors;

(b) 6 micro-strip silicon planes;

(c) carbon target with the thickness of 68 mm;

(d) trigger system of two double layer 16-strip scintillator detectors.

(e) a few lead gamma-converter with the thickness of 3 mm.

The trigger layer consists of two planes of scintillator strips orthogonal to each other. Size of each plane ~ 160 mm × 160 mm and strip cross section 10 mm × 5 mm.

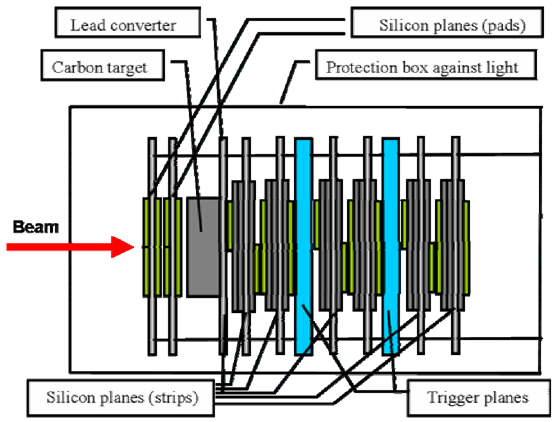

Fig. 4. NUCLEON installation on the beam in CERN.

The beam spot is ~ 1.5 cm × 1.5 cm and intensity 10^3-10^4 particles per second. The beam test of NUCLEON detector prototypes has been carried out mainly with pions of 200, 250, 300, 350 GeV/c and with muons (MIPs) also from the beam halo. The most part of the written data was received at normal setup orientation to the beam direction as it is shown in Fig. 4.

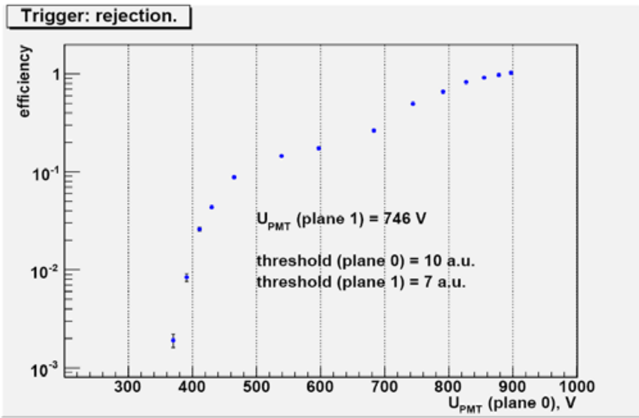

Fig. 5. Dependence of rejection efficiency on a PMT tension for up-stream plane.

Besides, small part of the data taking was done at 16 and 26 degrees between the beam and setup axis.

The trigger efficiency dependence was studied of the PMT HV and of the trigger electronic thresholds. Main results are presented in Fig. 5 - Fig. 7. Rejection efficiency is defined as a part of selected events by trigger respect to the total number the beam particles.

The rejection efficiency dependence of PMT HV - $U_{PMT}^{(0)}$ – for up-stream trigger module is presented in Fig. 5 with the threshold values - 10 and 7 a.u. for up- and down-stream plane electronics respectively (1 a.u. ≈ 2.5 mV). PMT HV on the down-stream plane is fixed $U_{PMT}^{(1)}$ = 746 V. At the initial HV value $U_{PMT}^{(0)}$ = 900 V, the number of selected events is equal to the beam particle number. At the final HV $U_{PMT}^{(0)}$ = 370 V, rejection efficiency becomes equal nearby 0.002.

At the next step the PMT HV values of up- and down-stream trigger modules were fixed $U_{PMT}^{(0)} = U_{PMT}^{(1)}$ = 413 V. The consecutive increasing of the threshold values on the up-stream module from 10 to 20 a.u. was carried out at the fixed value of a threshold on the down-steam plane (7 a.u). The rejection efficiency has changed from 0.041 to 0.014 and is shown in Fig. 6.

The same PMT HV values 413 V of up- and down-stream trigger modules were used in the final test. The threshold on the up-stream module has been fixed to 30 a.u., and the threshold on the down-stream module raised from 15 to 30 a.u. that leads to the rejection efficiency changing from 0.0027 to 0.00006 (Fig. 7).

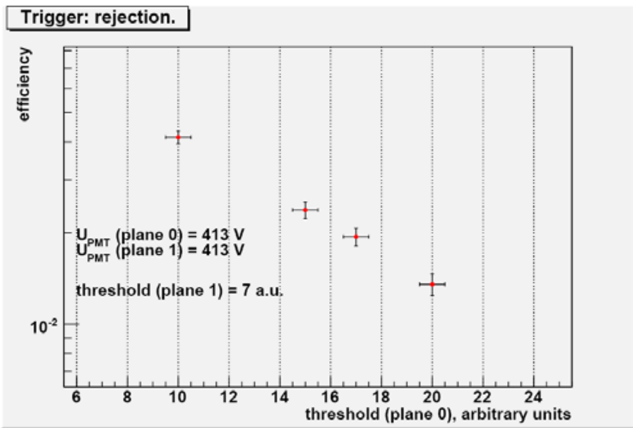

Fig. 6. Dependence of rejection efficiency on a threshold of up-stream plane.

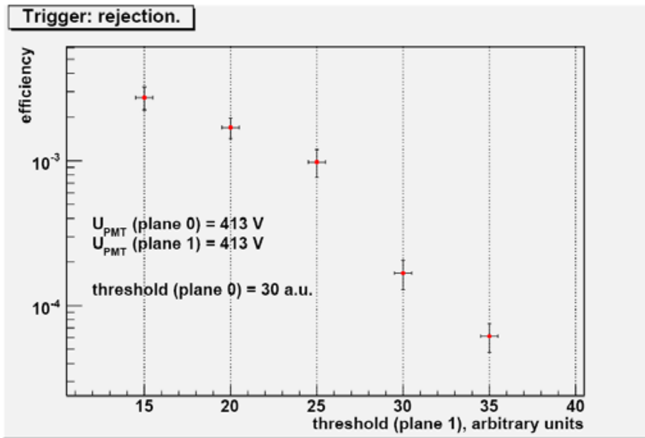

Fig. 7. Dependence of rejection efficiency on a threshold of down-stream plane.

5. Conclusion

MC simulation and the beam test of the NUCLEON trigger system were fulfilled. The rejection efficiency of the low energy 350 GeV pion events was obtained at the level up to 6×10^{-5} as is needed to study CR spectrum energy range E ~ 10^{11}-10^{14} eV that is the NUCLEON project aim.

References

1) G.V.Kulikov and G.B.Khristiansen. Soviet Physics JETR Vol.35(8), Number 3, March 1959, p.441.
2) G. Bashindzhagyan et al., 26th ICRC, Salt Lake City, 5, 132, (1999)
3) N. Korotkova et al., Physics of Atomic Nuclei 65, No. 5, 852 (2002)
4) V. Grebenyuk et al. Proceeding of NEC'2001p.97,Dubna,JINR (2002)